Climate Change Impact Framework For Assessing Swiss Alpine Water Resources Using Transient Streamflow Scenarios

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
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vorgelegt von

Tobias WECHSLER

Leiter:in / Leiter:innen der Arbeit:

Prof. Dr. Bettina SCHAEFLI
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Dr. Massimiliano ZAPPA
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Bern, November 21, 2023

Der Dekan/Die Dekanin
Prof. Dr. Marco Herwegh

“Too often, the perspective of hydrologists is confined to the visible river network; to achieve a moister and more balanced water system, hydrology requires considering water across the entire landscape.”

Klaus Lanz, International Water Affairs, 2021, personal communication

Abstract

In the Alpine region, global warming has led to a 2 °C increase in surface temperature compared to pre-industrial levels, which is approximately twice the global average. This warming impacts hydroclimatic variables and has further consequences for various sectors of water resources management (WRM). This thesis presents a climate change (CC) impact assessment framework applied to WRM sectors. It uses transient daily streamflow scenarios based on the EURO-CORDEX dataset and assesses changes over 30-year periods by comparing a reference period to future periods. The change framework comprehensively considers the CC impact on technical, legal, and ecological aspects and is applied to three critical Alpine WRM sectors: (i) Run-of-River (RoR) electricity production, (ii) environmental flow requirements, and (iii) lake level variability. RoR electricity production and the large prealpine lakes play a stabilising role due to their high turbine capacity and low volatility, while the lakes dampen inflows and can mitigate water level extremes. These two sectors are critical for alpine WRM and integral to national CC mitigation and adaptation strategies. However, However, the two sectors have received limited attention in past CC impact assessments.

RoR electricity production contributes to around half of Switzerland's hydropower production. The CC impact is assessed by using a Flow Duration Curve analysis and considering plant-specific characteristics. This enables CC impacts on RoR electricity production to be compared with loss due to environmental flow requirements and potential production increases through design discharge adjustments. The findings indicate a slight decrease in mean annual RoR electricity production (2 % to 7 %) by the end of the century, varying with catchment elevation. Seasonal projections suggest increased winter production (+4 % to 9 %) when electricity demand is highest. However, the technical potential for production increase in winter (2.5 %) is seven times smaller than in summer, and production loss due to environmental flow requirements is greater in winter (4.5 %).

Environmental flow requirements, mandated for water-diverting power plants, are essential for ecosystem function. The change framework assesses how CC impacts the determination of the 347-day-streamflow value (Q_{347}, 95th percentile), i.e. the threshold used to derive environmental flows according to the Swiss Water Protection Act. CC-induced increases in Q_{347} lead to a higher environmental flow, particularly for high-elevation catchments ($>$ 2000 m a.s.l.). However, an increase in Q_{347} results in a comparatively less pronounced increase in environmental flow. Taking this a step further, estimations of Alpine RoR electricity production alterations cannot be derived solely from changes in Q_{347}, as it necessitates considering the entire streamflow volume usable for HP production. The energy potential allocated to environmental flow requirements is estimated to be relatively small (1 % to 7 %) and plays a minor role compared to the overall energy potential. The dominant factors influencing changes in RoR electricity production are the CC-induced alterations in streamflow and the power plant's size of the design discharge.

Large perialpine lakes, vital for ecological, hydrologic, and socio-economic functions, are evaluated for the CC impact by combining hydrologic and hydrodynamic models. Annual mean lake levels indicate minor changes, but pronounced seasonal shifts. The extent of lake level management influences the magnitude of these changes: particularly summer lake levels are projected to decline by 0.04 m for the regulated lake and by 0.39 m for the unregulated lake (median, high-emission scenario). Such a shift could lead to more frequent and severe droughts in late summer, impacting the WRM of lakes.

The model-based change framework projects the CC impact on the three applied sectors of WRM. The CC impact assessments project changes already in the near future, with more pronounced effects expected over time and particularly in the absence of CC mitigation measures. Using 39 model chains over 30-year periods provides a robust foundation for assessing CC-induced mean changes, considering model uncertainty. The projected changes indicate shifts towards increased winter RoR electricity production and a higher prevalence of droughts in late summer. The energy potential share of environmental flow requirements in the overall energy potential remains relatively minor, but gains importance for aquatic life. Future research could explore interannual variability and the evolution of extremes, and consider more dynamic operational data, including water demand, to enhance the comprehensiveness of spatial coherence in WRM. Future climate services should support comprehensive decision-making processes related to CC mitigation and adaptation strategies, going beyond the sectoral perspective.

Keywords: climate change impact assessment, hydrology, hydropower, environmental flow, lake level variability, Switzerland

Declaration of generative AI and AI-assisted technologies in the writing process:
During the preparation of this work the author used DeepL, Grammarly, and ChatGPT to improve language and readability. After using these tools, the author reviewed and edited the content as needed and take full responsibility for the content of the publication.

Acknowledgements

Doing a PhD - that was not my original plan. Before starting this journey, I feared spending long hours alone in a silent room, plagued by back pain. The past four years (2019–2023) have not gone as expected either, with global crises such as the pandemic, the beginning of the war in Ukraine, and the ongoing climate and biodiversity crisis. Also, Swiss hydrology was marked by extremes, with drought years in 2020 and 2022 interrupted by floods in 2021, and now alternating droughts and floods in 2023.

Looking back on my four years of PhD research, my initial fears stand corrected: there was no such thing as the silent room, and I remained largely free of back pain. Instead, writing a dissertation on future water resources proved to be an immensely meaningful challenge to me. Throughout my PhD, I was fortunate to be surrounded by an extraordinarily supportive environment reinforcing the idea that science is a collective endeavour.

My greatest thanks go to both of my supervisors, Prof. Dr. Bettina Schaefli and Dr. Massimiliano Zappa, who contributed greatly to this environment. I am grateful for the valuable lessons I learned from them, both scientifically and personally. Their mix of humour, trust, eagerness to discuss, and unwavering work ethic created an environment where I could develop a passion for scientific work and, ultimately, rivers. Thank you very much!

I would also like to thank the two super cool research units I was privileged to work with: the Mountain Hydrology and Mass Movement Research Unit at WSL and the Hydrology Group at the University of Bern. The wonderful people not only improved the taste of the morning coffee break but were also an essential part of my fundamental motivation to get up in the morning.

I thank all the co-authors and project partners with whom I could exchange scientific ideas. Special thanks go to Manfred Stähli, who gave me the opportunity to work at WSL and accompanied my work with insightful discussions. My thanks also go to, Andreas Inderwildi, who introduced me to the comprehensive world of Swiss lakes; to Klaus Lanz, a sparring partner for generating new ideas and for repeatedly demonstrating to me the relevance of scientific work to its research object, the aquatic environment; and to Florian Lustenberger for his tremendous support and engaging exchange! I have met many more inspiring people over the past four years - including during the Swiss Climate Summer School 2021 on Monte Verita, a highlight of my PhD

In the last weeks of my PhD - a crazy time - I received invaluable support from Sarah Räz, Simon Schick, Sebastian Arnold, and Melissa Dawes to finalise this thesis - I would like to thank them and the people in my entire social network for their encouragement!

Contents

List of Abbreviations and Notations

Abbreviation	Description
CC	Climate change
CH2018	Swiss climate change scenarios
Hydro-CH2018	Swiss hydrological scenarios
IPCC	Intergovernmental Panel on Climate Change
GFCS	Global Framework for Climate Services
NCCS	National Centres for Climate Services
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SRES	Special Report on Emissions Scenarios
HP	hydropower
RoR	Run-of-River (power plant)
WRM	Water Resources Management
WASTA	Swiss statistics on hydropower plants
PREVAH	PREcipitation streamflow EVApotranspiration HRU related model
HRU	Hydrological Response Unit
WPA	Water Protection Act
WFD	Water Framework Directive
FDC	Flow Duration Curve
SI	Supplementary Information

Notation	Description	Unit
E	actual electricity production	GWh
E_e	E loss due to environmental flow requirements	GWh
E_{opt}	E increases by optimising the design discharge	GWh
Q_d	design discharge of a HP plant	m^3 s^{-1} or mm d^{-1}
ØQ	mean annual streamflow	m^3 s^{-1} or mm d^{-1}
$e\text{-}flow$	environmental flow	m^3 s^{-1}
Q_{347}	streamflow value exceeded on 347 days per year	m^3 s^{-1}
P	installed power	MW; 10^6 kg m^2 s^{-3}
H	hydraulic head	m
F	simplified overall efficiency	kg m^{-2} s^{-2}
ϕ	density of water	kg m^{-3}
η	specific efficiency of the machinery	-
g	gravitational acceleration	m s^{-2}
V_{exp}	integral of expected streamflow usable for E	m^3
$V_{I,min}$	integral of imposed minimum environmental flow	m^3
L	drought limit: minimum outflow of a lake	mm d^{-1}
F	flood limit: critical water level of a lake	m a.s.l.
T	time period	30 years

1 Introduction

1.1 Rationale for this work

This work was funded by ongoing research projects of the research unit for Mountain Hydrology and Mass Movements at the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), together with Swiss cantonal and federal environmental agencies. The specific contribution of this thesis to the larger projects is the development of climate change (CC) impact assessments on water resources management (WRM) systems in Switzerland. Part of the funding was provided by the Swiss Innovation Agency, Innosuisse, through the Swiss Competence Centre for Energy Research – Supply of Electricity (SCCER-SoE; Burgherr et al., 2021). The centre was dedicated to pioneering sustainable research in geo-energy and hydropower (HP) Additional funding was available from the Swiss Federal Office for the Environment (FOEN) as part of the action plan for adapting to CC in Switzerland (Measure W5). This plan, outlined in a recent report (FOEN, 2018), serves as the foundation for analysing the CC impact on lake level variability. The overarching goals of the action plan encompass minimising flood risks, mitigating ecological repercussions, and enhancing WRM strategies in the context of CC. The Hydrology Group at the University of Bern also contributed internal funds to complement the research endeavours.

1.2 Background

An increase in anthropogenic greenhouse gas emissions has led to global warming of approximately +0.9 °C compared to pre-industrial levels (Gillett et al., 2021). Global warming affects temperature and other hydro-climatic variables (Huss et al., 2017). These changes vary in magnitude depending on geographical location and seasonality. Alpine regions are particularly sensitive to global warming, with strong alterations in high-elevation areas primarily driven by the albedo effect (Winter et al., 2017). In Switzerland, where the Alps span the entire country from east to west, surface air temperature has increased by about 2.0 °C since the beginning of instrumental records in 1864, which is twice as high as the average global warming (Ceppi et al., 2012; NCCS, 2018a). The latest Swiss CC scenario report CH12018 (NCCS, 2018a) states that nine of the ten warmest years in Switzerland occurred in the 21st century and that the zero-degree line in winter has shifted upward by 300 to 400 metres since the 1960s. Over the past four decades, Swiss glaciers lost more than 40 % of their volume (Fischer et al., 2015; Huss et al., 2023), and actual evaporation has particularly increased in spring and autumn (Kummer, 2017; SCCER-SoE, 2019). While there are no robust signals for long-term trends in annual precipitation, winter precipitation has increased by about 20 % to 30 % since 1864 (NCCS, 2018a; SCCER-SoE, 2019). There is also robust evidence that heavy precipitation at the daily time scale has become 30 % more frequent and 12 % more intense than in the early 20th century (Scherrer et al., 2016).

For most catchments in Switzerland, the mean annual streamflow has not changed noticeably over the past decades, as long-term annual precipitation hardly changed (rain and snow contribute to approximately 98 % of the total streamflow of the Rhine river at Basel; FOEN, 2021b). However, heavily glaciated catchments exhibit increased streamflow as a result of intensified glacier melt (Muelchi et al., 2021). Over the last century, this is also reflected in large rivers, such as the Rhine river, which have been experiencing an increase in winter streamflow (25 %) and a decrease in summer streamflow (15 %) (NCCS, 2021b). Winter low-flow levels have increased by up to 50 % since 1960 in snow-dominated catchments (Weingartner & Schwanbeck, 2020). The increase in low-flow levels during winter is attributed to more liquid precipitation and earlier snowmelt, caused by higher surface temperatures. In contrast, decreased snowfall and earlier snowmelt lead to less water carry-over from winter to summer (via snow storage), potentially less groundwater recharge (Arnoux et al., 2021) and more evaporation in spring (SCCER-SoE, 2019), reducing jointly low-flows during summer (Muelchi et al., 2021). After the drought year of 1947 and a longer pause until the next drought year of 1976, there was another longer pause before Switzerland began experiencing an increasing trend of meteorological, hydrologic, and agricultural droughts (Blauhut et al., 2022; FOEN, 2023c). The drought year 2003 was the beginning of an accumulation of further drought years in 2011, 2015, 2018, 2020, 2022, and probably also in the current year 2023. In terms of floods, the temporal evolution in Switzerland, as derived from damage records (WSL, n.d.), has been characterised by a relatively regular succession of events in 1977, 1978, 1987, 1993, 1999, 2000, 2005, and 2007, followed by a longer gab until the next event in 2021 (FOEN, 2023c; Hilker et al., 2009). While warmer air can hold more moisture (Boroneant et al., 2006; Molnar et al., 2015b), and convective rain cells can intensify at higher temperatures (Peleg et al., 2018), the exact implications for flood events remain unclear (Brunner et al., 2021), and it has not yet been possible to identify a consistent CC-induced large-scale signal in flood magnitudes (Blöschl et al., 2017). The work of Mangini et al. (2018) suggests a future increase in the frequency and intensity of floods in alpine regions, while Stahl et al. (2022) project a decline for large Alpine catchments due to a reduced cryosphere contribution. In addition to causing changes in streamflow, global warming affects water temperatures. Since 1980, Swiss rivers have warmed on average by 1.3 °C (0.33 °C per decade), with accelerating warming over time (Michel et al., 2021). Summer water temperatures have increased nearly twice as much, increasing stress on aquatic life (FOEN, 2021b; Huss et al., 2017).

CC impact assessments on Alpine hydrology were first targeted by the Swiss National Research Program 31 (NRP 31; NFP31, 1998) on CC and natural disasters (1993–1997) and later the NRP 61 (NFP61, 2015) on sustainable water management (2010–2015). Meanwhile, advancements in global circulation models, regional climate models, regional glacier models, and catchment streamflow models have improved the understanding of relevant geophysical processes (FOEN, 2021b; Jacob et al., 2014). The research programmes CCHydro (Bernhard & Zappa, 2012), coordinated by the Swiss Federal Office for the Environment (FOEN), and later the Hydro-CH2018 programme (FOEN, 2021b) have assessed the CC impact on Switzerland's water balance throughout the 21st century. A key finding regarding streamflow projections is a slight CC-induced decrease in mean annual streamflow by the end of the century but a pronounced change in seasonal streamflow distribution.

While CC-induced changes in streamflow (FOEN, 2021b; Muelchi et al., 2021), lake mixing regimes (Råman Vinnå et al., 2021), and water temperatures (Michel et al., 2021) have been studied extensively, crucial knowledge gaps persist, especially concerning WRM (Lanz, 2021), which has received limited attention in past CC impact assessments. Recent CC impact studies on HP have often focused on high-head accumulation HP plants (Bombelli et al., 2019; Farinotti et al., 2019; Ranzani et al., 2018; Schaefli et al., 2019), while only a few looked at Run-of-River (RoR) electricity production (Hänggi & Weingartner, 2012; Savelsberg et al., 2018). RoR electricity production constitutes about half of Swiss HP production and is more directly affected by streamflow alterations, due to limited or nonexistent storage capacity. RoR electricity production is modulated by streamflow, the plant-specific design discharge, and environmental flow requirements (Hänggi & Weingartner, 2012). The interplay among these variables, particularly the mechanisms underlying environmental flow requirements under changing conditions, poses a fundamental knowledge gap, particularly when considering aspects of low-carbon electricity generation and resilient rivers (Kuriqi et al., 2019). The question of how environmental requirements influence HP production and vice versa is increasingly debated. Further, large perialpine lakes, most of which are regulated, play a crucial role as water reservoirs and are particularly sensitive to CC, as they are largely fed by snow and glacier melt (Muelchi et al., 2021). Previous studies on water resources primarily emphasised the influence of the cryosphere on streamflow changes (François et al., 2018; Hanus et al., 2021; Horton et al., 2022), while often overlooking changes in perialpine lake levels. Assessing CC impacts on RoR power plants, environmental flow requirements, and lake level variability underscores the challenges in understanding the complex interactions between CC, CC-induced streamflow alterations, and WRM. The knowledge gaps emphasise the relevance of this thesis in providing new insights into the CC impact on critical sectors of WRM in a selected Alpine region, Switzerland.

1.3 Research objective

The overarching goal of this thesis is to develop a CC impact framework to assess Alpine water resources and WRM, using transient daily streamflow scenarios. The change framework is applied to critical WRM sectors that have received limited attention in the past, namely: (i) RoR electricity production, (ii) legal environmental flow requirements, and (iii) lake level variability in perialpine lakes. In addition to providing new insights into CC impacts on these sectors, the objective is to provide future scenarios, e.g. for limnological, ecohydrological, or WRM follow-up studies, and information for model-based decision-making processes. To accomplish this, the following objectives are defined:

- Develop a model framework to assess the CC impact on future RoR electricity production by considering plant-specific effects of environmental flow requirements and technical increase potential.
- Investigate spatial and technical key variables to characterise the variability in RoR electricity production changes and to enhance the transferability of findings to HP production in other Alpine locations.
- Analyse the CC impact on legally required environmental minimum flows and impact on future RoR electricity production.
- Assess the CC impact on shares of energy potential originating from environmental flows, actual RoR power production, and spilled streamflow.
- Develop a model framework to incorporate lake level variability and management into hydrologic simulations and to disentangle climatic and regulatory impacts.

1.4 Thesis structure

The core of this thesis comprises three research papers, which are organised as individual chapters (Chapters 4, 5, and 6). The research topics are substantiated and anchored by Chapters 2 and 3. Chapter 2 provides a comprehensive literature review on CC impact assessments and the scientific foundation of Alpine WRM, and Chapter 3 provides a description of the case study area. All three research papers are based on transient streamflow scenarios to assess the CC impact on WRM sectors that have received limited attention.

The first paper (Chapter 4), accepted by Elsevier's "Science of the Total Environment" journal and scheduled for publication in September 2023, focuses on the CC impact on Alpine RoR electricity production. The assessment of the CC impact on RoR electricity production is compared with the production loss attributed to environmental flow requirements and the potential production increase through technical optimisations. The comprehensive change assessment framework of this study serves as the foundation for RoR electricity projections presented in several synthesis reports (FOEN, 2021b; Lanz, 2021; NCCS, 2021b; SCCER-SoE, 2019).

The second paper (Chapter 5), published in the application-oriented Swiss journal "Wasser Energie Luft", extends the work of the first paper. For inclusion in this thesis, the original paper was translated into English. Employing a methodologically simplified approach, the paper aims to explicitly quantify the CC impact on legally mandated environmental flow requirements and future HP production, as these are frequently heavily debated in the context of electricity shortages. The study represents a pioneering effort in quantifying energy potential shares, contributing to the scientific endeavour to provide data in support of more sustainable HP practices, as suggested in the white paper on "more data for sustainable hydropower" (Schaefli et al., 2022).

The third paper, Chapter 6, examines the CC impact on large perialpine lakes. Very few CC impact assessments consider lake level variability in Alpine regions, despite its critical role for water resources and WRM. We combine a hydrologic and a hydrodynamic model to simulate the evolving dynamics of four perialpine lakes and to disentangle climatic and regulatory impacts.

Chapter 7 presents the synthesis of this thesis, followed by the conclusion and outlook in Chapter 8. Finally, Chapter 9 compiles supplementary materials, and the Curriculum Vitae contains a list of the outcomes of this thesis.

2 Literature review

2.1 Climate change impact assessment: overview

Global CC impact assessment studies began in the early 1990s with the first Intergovernmental Panel on Climate Change (IPCC) report (IPCC, 1992; Schaefli, 2015). The aim of CC impact assessments was, and still is today, to develop sector-specific climate services to support decision-making for CC mitigation and CC adaptation (Muelchi et al., 2021). Initial studies focused on quantifying the CC impact on air temperature and precipitation on the water balance and hydrologic regime of individual catchments (Schaefli, 2015). Apart from streamflow changes, further aspects are evaluated, such as the evolution of extremes (Meresa et al., 2021; Romanowicz et al., 2016), HP potential (Horton et al., 2006), economic benefits (Vinke et al., 2022), environmental risk (Hirschberg et al., 2021), and ecosystem services (Zarrineh et al., 2020).

Schaefli (2015) summarises that early CC impact assessment studies employed climate sensitivity analyses (Nash & Gleick, 1991). More recently, most studies use climate model outputs as inputs for water resource systems (Brunner et al., 2019; Felder et al., 2018; Flaminio & Reynard, 2023). The core of CC impact assessments is the comparison of simulated data for the reference period (baseline) with data for future periods (Schaefli, 2015), commonly referred to as the delta change factor methodology (Anandhi et al., 2011). The different approaches are characterised by varying degrees of model complexity and spatio-temporal resolution (Anandhi et al., 2011; Tegegne & Melesse, 2020). CC impact assessments on water resources typically rely on streamflow time series and focus on distinct aspects of WRM, such as HP production or extreme indicators (Romanowicz et al., 2016; Wagner et al., 2017). Future time series are most often simulated using an impact modelling chain, employing global circulation models (GCMs) and regional climate models (RCMs) across various greenhouse gas emission scenarios (Jacob et al., 2014). These simulated CC scenarios for meteorological variables can be processed through either stochastic or deterministic downscaling methodologies and can serve as input data for water resource modelling (Felder et al., 2018; Maraun et al., 2010; Muelchi et al., 2021; Stein et al., 2020). The modelling chain can be extended by further ecological or socio-economic modelling (Figure 2.1; Bejarano et al., 2019; Savelsberg et al., 2018; Zarrineh et al., 2020).

2.1.1 Climate change impact assessment for climate services

In Alpine regions, the CC impacts already manifest themselves today (Michel et al., 2020; Vittoz et al., 2013) and are projected to intensify in the absence of CC mitigation measures (Hanus et al., 2021; Zekollari et al., 2019). The Global Framework for Climate Services (GFCS; GFCS, 2023) aims to provide climate services to support policy, economics, and society in confronting climate risks

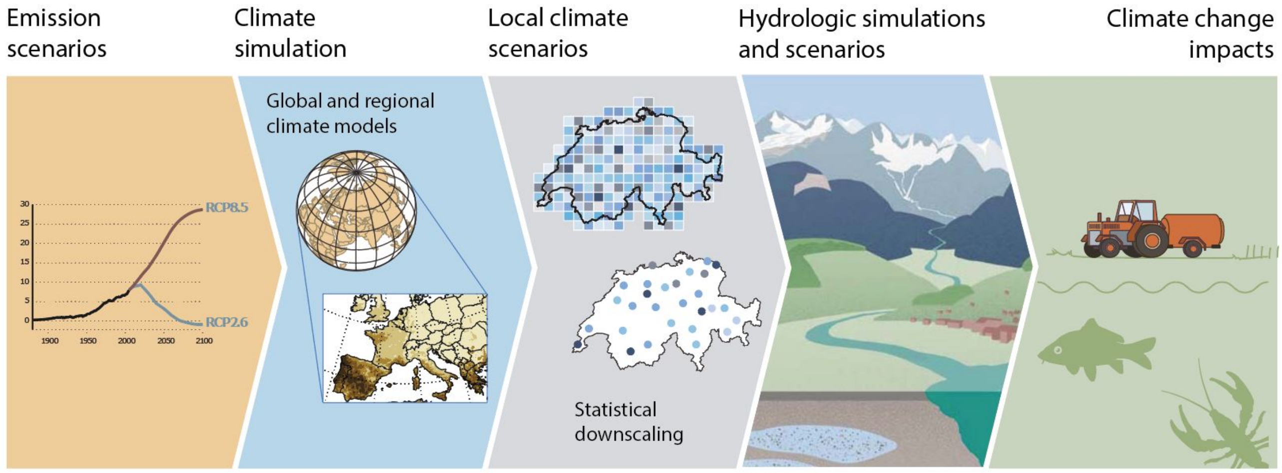

FIGURE 2.1: Basic description of the model chain framework of the Hydro-CH2018 CC impact assessments. The figure is slightly modified from the report by the FOEN (2021b).

and managing adaptation. The GFCS was established during the third World Meteorological Organization (WMO) World Climate Conference in Geneva in 2009 and aims to facilitate the generation, accessibility, and application of science-based climate services, with an emphasis on building capacities in regions with limited access to CC-relevant information.

The GFCS's recommendations prompted several countries, including Switzerland, France, Italy, Austria, and Germany – all situated within the Alpine region – to establish National Centres for Climate Services (NCCS). These centres predominantly make use of network structures involving federal government offices and research institutions. Their key functions encompass providing CC-related information, supporting interpretation, and fostering cross-sectoral exchange (GFCS, 2023). Within the realm of climate service provision, these countries have generated national and regional climate scenarios, the basis for hydrologic projections and subsequent impact assessments.

For instance, Switzerland founded its NCCS in 2015, which supports the development of CC scenarios (CH2018 NCCS, 2018a) and hydrologic scenarios (Hydro-CH2018 FOEN, 2021b). In France, the National Centre for Meteorological Research (CNRM), established in 2013, promotes the development of comprehensive CC scenarios (DRIAS, 2023). Furthermore, extended hydrologic scenarios reaching until 2070 have been developed (EXPLORE 2070; Chauveau et al., 2013), encompassing socio-economic impact on WRM (Carroget et al., 2017). Italy's National Climate Services Network (NCSNI) provides nationwide CC scenarios and regional hydrologic assessments of flood risk and WRM (Gualdi, 2023). The Austrian Panel on CC (APCC), founded in 2011, provides a consolidated perspective on climate services, including the CC impacts on hydrology and WRM (APCC, 2014). The German Climate Service Center (GERICS), established in 2009, provides climate services, including those related to future water resources (Bender et al., 2017). These nationwide CC scenarios are all based on the EURO-CORDEX dataset (Jacob et al., 2014), an initiative of the World Climate Research Programme (WCRP).

The ensemble of transient scenarios is based on varying greenhouse gas emission scenarios, global circulation models, regional climate models, and spatial resolutions (Table 9.3).

The EURO-CORDEX dataset is a high-resolution dataset generated from a multi-model, multi-scenario ensemble of regional climate simulations for CC impact research (Jacob et al., 2014). The EURO-CORDEX dataset encompasses a range of emission scenarios, denoted as Representative Concentration Pathways (RCPs), that extend from concerted CC mitigation efforts (RCP2.6) to scenarios without mitigation measures (RCP8.5). Projected changes result from the comparison between a reference period and future periods, each covering a period of 30 years. For the Alpine region, simulations based on the EURO-CORDEX dataset project the following changes by the end of the 21st century (median changes for the emission scenarios RCP2.6 and RCP8.5; Fischer et al., 2022; Jacob et al., 2014; NCCS, 2018a):

- an increase in annual average surface temperatures by 1.5 °C to 5 °C,
- a growing number of hot days, by between 2 % and 22 %,
- a seasonal shift in precipitation, with an increase in winter (8 % to 18 %) and a decrease in summer (2 % to 20 %), and
- a 5 % to 10 % increase in heavy precipitation intensity.

Rising temperatures, especially in winter, result in fewer days with snowfall and a shift in precipitation from snow to rain (NCCS, 2018a), reducing the snowmelt contribution to streamflow by up to 20 % (Stahl et al., 2022). Hydrologic simulations based on the EURO-CORDEX dataset project a 30 % increase in winter streamflow and a decrease in summer streamflow by as much as 40 % (Hanus et al., 2021; Muelchi et al., 2021). Alpine glaciers are projected to lose between 76 % and 98 % of their volume by the end of the century (Zekollari et al., 2019) and will contribute, depending on the location, up to 20 % less to summer streamflow (Stahl et al., 2022). Reduced summer streamflow, coupled with declining cold-water contributions from the cryosphere, leads to higher water temperatures (Michel et al., 2021) and can induce stress for aquatic life (de Vries et al., 2008; FOEN, 2021b). Both climatic and hydrologic changes are projected to intensify with time, especially in the absence of CC mitigation efforts (Fischer et al., 2022; Jacob et al., 2014; Muelchi et al., 2021).

Collectively, the various NCCSs continuously update their climate services. Current endeavours for enhancement encompass: (i) improved incorporation of physical processes and extreme events, (ii) a more precise alignment of observations and model simulations to apply information about global warming rates (and thus political objectives) directly into present conditions, and (iii) the provision of user-specific information (APCC, 2023; Jacob et al., 2014; MeteoSwiss, 2023a; Strohmenger et al., 2023; ZAMG, 2023). In addition to the above-mentioned NCCSs, other initiatives also offer regional climate services (e.g. EAURMC, 2023; KLIWA, 2023; Stahl et al., 2022).

2.2 Alpine water resources management under climate change

Alpine water resources are characterised by a typical seasonal pattern, with large meltwater inputs from the cryosphere from spring to summer and low streamflow rates in autumn and winter. In the past, snow and glacier melt, especially during dry and hot periods such as the heatwave of 2003, contributed up to 90 % of the streamflow (At Zweilütschine, Weisse Lütschine river), while in Basel it accounted for approximately 40 % (Stahl et al., 2016; Zappa & Kan, 2007). Due to CC, these melt contributions are expected to decrease throughout the 21st century (Figure 2.2), with reductions in Basel by as much as 20 % (Stahl et al., 2022). Further reductions are projected, due to increasing evapotranspiration (up to 20 % reduction, Figure 6.13; Kummer, 2017; SCCER-SoE, 2019).

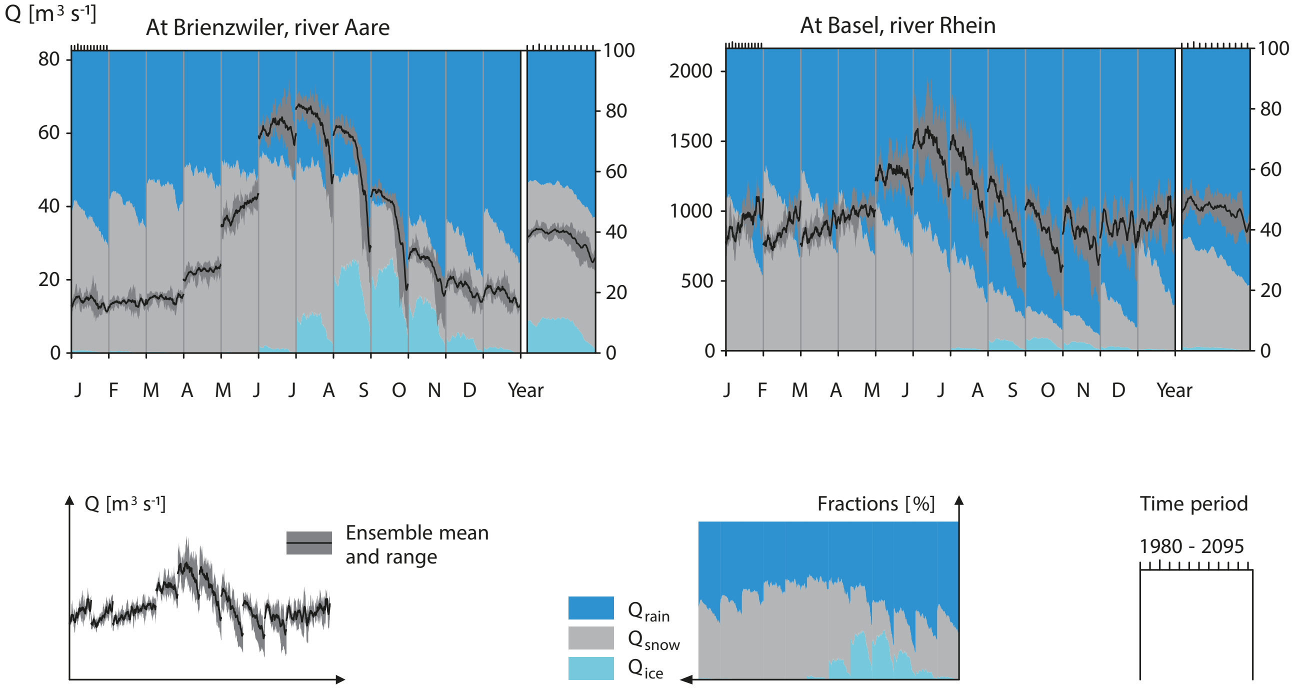

FIGURE 2.2: Projected monthly and annual streamflow contributions (ensemble means) from rain (Q_{rain}), snow (Q_{snow}), and ice (Q_{ice}) for the period 1980–2095 (represented as 11-year moving averages). The highly glaciated catchment at Brienzwiler (Aare river) and the largest Swiss catchment at Basel (Rhine river) are shown. The figure is modified from the report by Stahl et al. (2022).

CC is not only impacting Alpine water resources but also affecting WRM in the Alps considerably. WRM encompasses a wide range of sectors (Figure 2.3) with varying water objectives and can alter the natural hydrologic cycle, which complicates estimations of the CC impact on water resources.

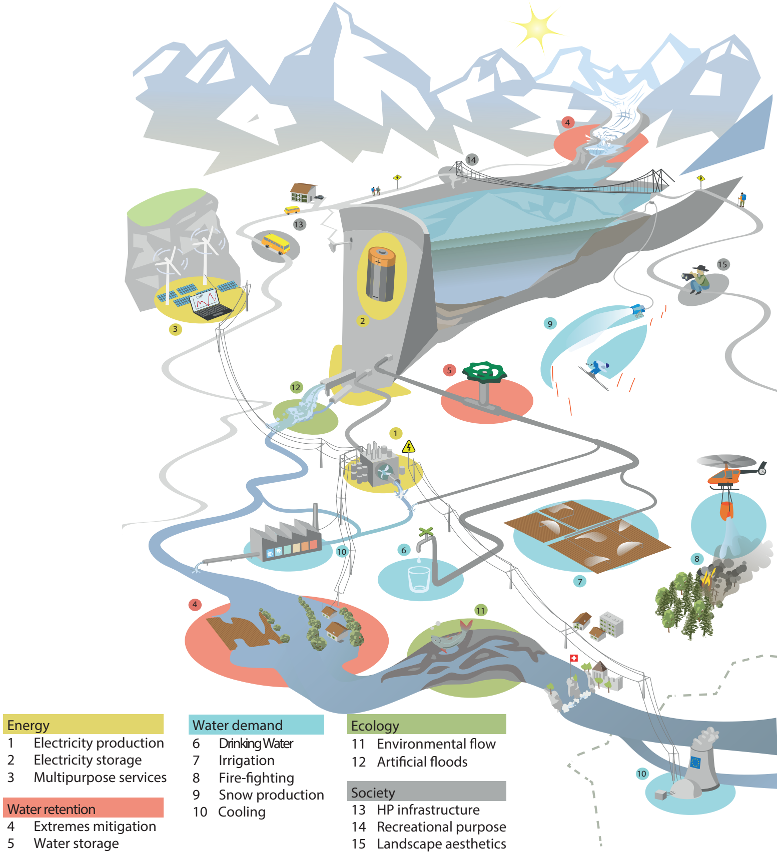

FIGURE 2.3: Illustration of a highly connected water resources management system, with a focus on multipurpose reservoirs, illustrated by Valentin Rüegg in collaboration with Astrid Björnsen Gurung (Jossen & Björnsen Gurung, 2018).

The UN report by Feenstra (1998) categorises water-related objectives into non-market and market ones. According to this report and further sources (Brunner et al., 2019; Lanz, 2021; NFP61, 2015; Rivers, 2022), market water objectives can be categorised into sectors, including:

- industry (industrial processes, mining, shipping, tourism, and fisheries),
- energy (hydropower generation, thermoelectric cooling/heating),
- agriculture (irrigation, livestock, and drainage),
- municipal (drinking water, water treatment, urban drainage, and river restoration),
- reservoir management (outlet control, storage, and mitigation of extremes).

Non-market water objectives include:

- maintenance of aquatic ecosystem integrity,
- recreational purposes,
- water quality preservation, and
- consideration of landscape aesthetics.

With surface water and groundwater, WRM comprises two physically connected water bodies, whose use is managed by separate infrastructures (Feenstra, 1998). WRM systems are regulated by different levels of government, spanning several policy sectors and institutional territories (Varone et al., 2013). The study conducted by Brunner et al. (2019) simulates water supply and demand across Switzerland, identifying spatio-temporal diverging water objectives, particularly during extreme events.

In recent years, growing water demands, particularly in summer for irrigation and cooling purposes (Brunner et al., 2019; Lanz, 2021), have become increasingly challenging for Alpine WRM (Kellner & Brunner, 2021). Shipping has temporarily suffered from reduced transport capacities due to low lake and river levels (Lanz, 2021; Stahl et al., 2022). Agriculture is demanding more water for irrigation and has been facing supply limitations (Lanz, 2021; Montanari et al., 2023). Nuclear power plants have had to reduce production to prevent overheating of rivers with cooling water (Heise, 2023; Reuters, 2023). Fisheries have experienced more frequent high temperatures and dried-up streams, leading to high fish mortality rates (SFV, 2019). The non-market water objectives are directly affected by the CC impact or indirectly influenced by WRM, including water abstractions, heat inputs, and higher nutrient and pollutant concentrations during low-flow situations (Akhtar et al., 2021). Alpine countries have initiated efforts to develop climate adaptation strategies (BMNT, 2023; BMUV, 2023; Castellari et al., 2014; FOEN, 2018; MTE, 2023).

The aim of CC impact assessment research is to determine CC-induced effects on socio-economic and biophysical factors (Feenstra, 1998). In the past, CC impact assessments on WRM have primarily focused on how hydrologic changes affect individual sectors (Hingray et al., 2007; Horton et al., 2006). Strong emphasis was placed on understanding the CC impact on high-head accumulation power plants (Bombelli et al., 2019; Farinotti et al., 2019; Ranzani et al., 2018; Schaefli et al., 2019). On the other hand, studies on RoR electricity production have been scarce (Hänggi & Weingartner, 2012; Savelsberg et al., 2018; Wagner et al., 2017). RoR power plants, with limited or no storage capacity, contribute about 50 % of Switzerland's HP production (SFOE, 2020). From a WRM perspective, RoR power plants are crucial because their production is more directly affected by streamflow changes and reservoir management strategies. Due to the desired decarbonisation and the stepwise phase-out of nuclear electricity production in Switzerland (Pattupara & Kannan, 2016), there is a higher demand for renewable electricity, especially during winter (SCCER-SoE, 2019). However, RoR power plants have negative impacts, e.g. aquatic connectivity (Grill et al., 2020). They often divert water from the main river, and depending on legal regulations, they may be required to maintain a minimum flow to preserve aquatic ecosystems (Carolli et al., 2022; Kuriqi et al., 2021). To evaluate both the HP and the biodiversity potential, methodological frameworks and improved data accessibility are needed (Bejarano et al., 2019; Hemund & Weingartner, 2012). Quantifying these potentials is a climate service, crucial for re-thinking water resource infrastructure and enabling data-based decision-making processes under CC (Feenstra, 1998; Lanz, 2021; Schaefli et al., 2022).

Other studies have been conducted to explore whether HP reservoirs might provide multiple services (Kellner & Weingartner, 2018; Schleiss, 2016; Viviroli et al., 2011), raising governance questions related to water usage rights (Kellner & Brunner, 2021) and CC (Flaminio & Reynard, 2023). Multipurpose reservoirs are considered potential mitigation and adaptation strategies to climate and socio-economic changes, providing services beyond electricity production, such as irrigation, drinking water supply, flood mitigation, tourism, shipping, and fishing (Flaminio & Reynard, 2023). Despite the importance of natural perialpine lakes for the hydrologic system, studies explicitly addressing the CC impact on water levels are rare. Large perialpine lakes are critical water reservoirs with numerous ecological, hydrologic, and socio-economic functions. They are vulnerable to CC due to alterations in water input, evaporation rates, and changing chemical and physical conditions (Muelchi et al., 2021; Salmaso et al., 2018). Previous studies on perialpine lakes focused on non-market water objectives like temperature, nutrient cycling, and mixing regimes (Moss, 2012; O'Reilly et al., 2015; Råman Vinnå et al., 2021). One of the few studies on lake level variability, conducted by Hingray et al. (2007) on the three lakes in the Jura region, projected a decrease of both annual water level fluctuations and maximum water level fluctuations under future scenarios. Lake level management involves numerous market and non-market water objectives, adding complexity to the CC impact assessments. Therefore, there is a need to understand how the CC impacts lake level variability and how practices to manage lake levels are affected (FOEN, 2018). So far, many hydrologic models fail to incorporate lake level variability and management, which limits the assessment of the CC impact on perialpine lake systems.

2.3 Model-based climate change impact assessments on Alpine water resources

There are various ways to assess model-based the CC impact on future water resources and their WRM. They vary in the use of data, models, and spatio-temporal resolutions. Common to these assessments is the comparison between a reference period and a future period under altered conditions. The focus can vary from examining changes over an entire climatic period (typically 30 years) to investigating individual events. The complexity of the modelling framework depends on the objectives and available resources.

CC impact assessments typically rely on model chain scenarios, such as the high-resolution dataset EURO-CORDEX from the European climate downscaling initiative (Jacob et al., 2014). These model chains consist of configurations comprising an emissions scenario (RCP = Representative Concentration Pathway), a Global Circulation Model (GCM), a Regional Climate Model (RCM), and different resolutions (see Table 9.3). Based on the RCPs, GCMs simulate climatic changes at a coarse resolution, which are then refined for regional and local-scale conditions (Jacob et al., 2014). The obtained climatic scenarios can then serve as input for water resources and their WRM simulations (see Figure 2.1). However, uncertainties exist throughout the entire CC impact assessment model chain, ranging from the choice of the RCP, climate simulation models (GCMs and RCMs), and downscaling methods to the simulations of water resources and WRM systems (Addor et al., 2014; Clark et al., 2016; Fischer et al., 2022). The methodological development and assumptions of RCPs have evolved since 1990, due to scientific improvements and political considerations (Pedersen et al., 2022). Observations of global CO_2 emissions indicate phases of slow and rapid increases, with regional variations (Pedersen et al., 2020). Pedersen et al. (2020) note that the long-term development of CO_2 emissions over the last three decades has fallen in the middle of the projected RCPs, making a high-emission scenario less likely; however, the unsteady trend in global CO_2 emissions challenges the projection. Based on GCM output, stochastic downscaling techniques refine coarse-resolution information for regional and local-scale conditions, using empirically derived transfer functions (Kotlarski et al., 2014). In contrast, physical downscaling techniques employ high-resolution RCMs (Grose et al., 2019).

In hydrologic simulations, Addor et al. (2014) identified uncertainties primarily arising from the climate models and natural climate variability, defined as the 10 % to 90 % percentile range. From mid-century onwards, uncertainty mainly stems from the choice of the RCP. For local-level climatic variables, Fatichi et al. (2016) projected significant changes in mean air temperature but simulate robust changes in mean and extreme precipitation. This is explained by the uncertainty in precipitation, which mainly arises from internal climate variability. To investigate CC-induced extreme events, Thompson et al. (2017) referred to what is known as unseen scenarios, potential scenarios that are beyond the scope of historical events. In the work of Molnar et al. (2015a), existing temperature time series were increased by 2 °C to study the effect on intense rainstorm properties. Ensemble boosting is another way to create potential extreme scenarios. This machine learning approach aims to enhance model performance by iteratively training sequences that were inaccurately predicted, such as extreme heavy precipitation events (Gessner, 2022) or heatwaves (Fischer et al., 2023).

High-resolution national CC scenarios in a transient resolution allow us to approach real-time WRM. However, this model-based impact assessment contains uncertainties that must be estimated by comparing multiple model chains (Bosshard et al., 2014; Muelchi et al., 2022). These model chains are crucial to assess highly complex sectors such as RoR power plants and lake level variability and to enable the consideration of technical, ecological, and socio-economic aspects.

3 Case study area

The scope of this thesis is confined to Switzerland, which displays a substantial hydro-climatic diversity across a relatively modest area (41285 km^2), featuring elevations from 193 to 4636 m a.s.l. Situated centrally within the Alps, Switzerland receives an annual average precipitation of 1397 mm (1981–2010; Bühlmann & Schwanbeck, 2023), rendering it one of Europe's most precipitation-rich regions (TE, 2023). Moisture converges from various directions, and local precipitation is subject to pronounced orographic effects (Napoli et al., 2019), resulting in considerable spatial variations, with values ranging from below 500 mm to over 3000 mm per year (Bühlmann & Schwanbeck, 2023). Notably, the Swiss Alps are the source of four major European rivers: Rhine river, Rhone river, Ticino river (Po), and Inn river (Danube). Despite experiencing substantial reductions, the current estimate for the glacial volume stands at approximately 49.2 km^3 (Huss et al., 2023). Typical for Alpine regions, accumulated snow is an important water reservoir and contributes critically to streamflow, exemplified by an annual share of 39 % at the Rhine river in Basel (Stahl et al., 2016).

3.1 Swiss water resources and their management

Switzerland features approximately 1500 lakes, 15 of which have a surface area exceeding 10 km^2. Their combined volume adds up to 232.5 km^3 (FSO, 2004). The spatial diversity of both water supply and water demand in Switzerland is pronounced and can be attributed to disparities across regions characterised by differing levels of urbanisation, land uses, industrial density, and other factors (Brunner et al., 2019; Lanz, 2021). Water dependencies are evident within Switzerland, but also with regard to neighbouring countries downstream. Through its surface and subsurface water reservoirs, Switzerland accounts for 6 % of Europe's drinking water reserves (Swisstopo, 2023). A substantial 40% of the drinking water in the Netherlands is sourced from the Rhine river (RIWA-Rijn, 2021), with 50% of the streamflow (at Lobith, Rhine river) originating from Switzerland (Stahl et al., 2016). The pronounced international inter-dependency in the WRM is reflected in the numerous water agreements with neighbouring countries (Figure 3.1), illustrating potential challenges regarding assessments of the CC impact on WRM.

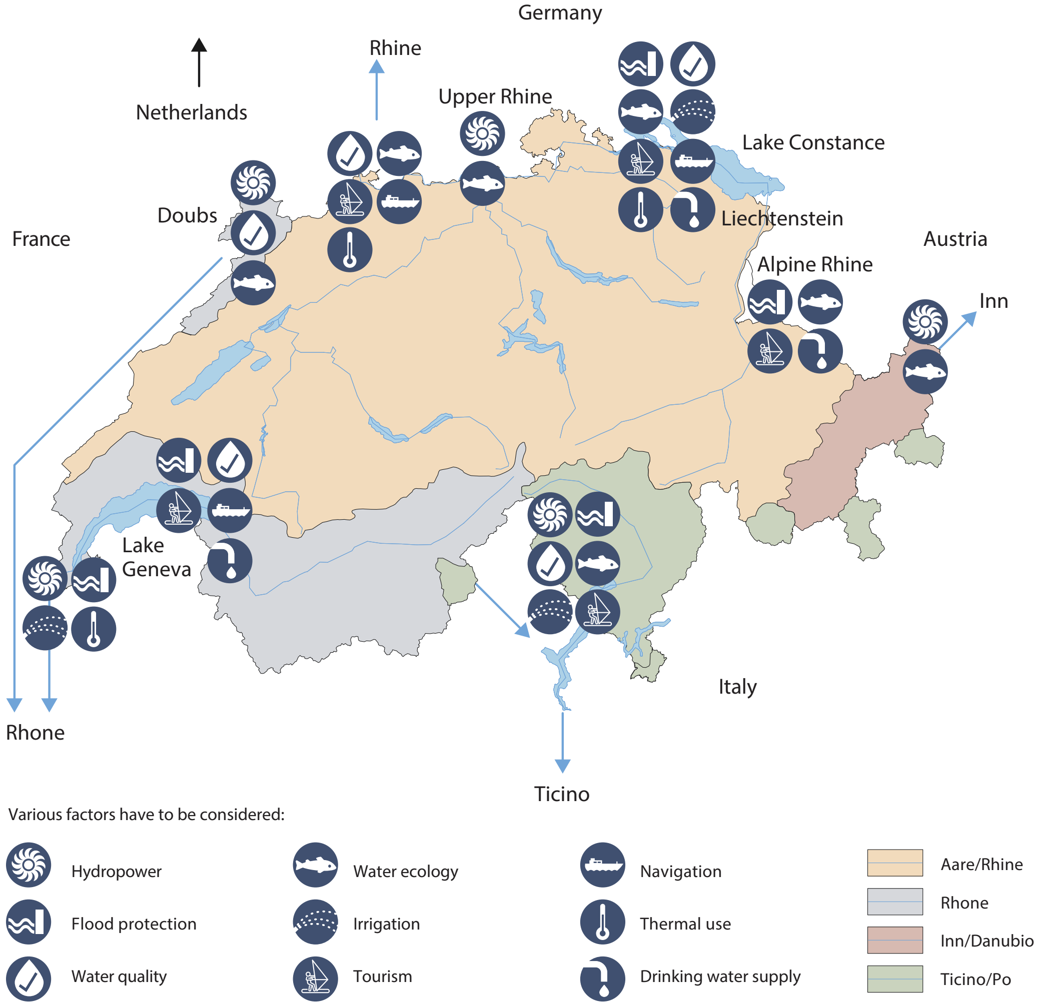

FIGURE 3.1: Illustration of Swiss international water resources management of cross-border water bodies and relevant international commissions and working groups. The figure is slightly modified from a report from the FOEN (2021b) and originates from the work of Lanz (2021).

3.2 State of the Swiss water bodies

Most Swiss lakes and rivers have undergone substantial correction works over the past centuries, altering their hydraulic dynamics (Vischer, 2003). Rivers have been diverted and channelled into straight courses to meet specific human objectives, such as flood mitigation and land reclamation. Wetlands have been reduced to just 10 % of their 1850 extent (Stuber & Bürgi, 2018). Most Swiss lakes have regulated water levels, which has reduced interannual fluctuations (Figure 6.7), posing a challenge regarding conflicting socio-economic and ecological needs (Hinegk et al., 2022; Veijalainen et al., 2010). Moreover, most Swiss lakes suffer from high nutrient inputs, with five of them requiring artificial oxygenation to maintain their vitality (Baldeggersee, Hallwilersee, Greifensee, Sempachersee, and Zugersee). Swiss water protection policies have undergone three distinct phases (Janz et al., 2023): (i) Up until 1991, the focus was primarily on water quality protection. A comprehensive network of wastewater treatment plants (Swisstopo, 2022) was established, which is currently being upgraded by further purification steps to address micro-pollutants (Wunderlin, 2017). (ii) The enactment of the Water Protection Act in 1991 marked a shift towards comprehensive water protection, addressing quantitative aspects such as environmental flow, competing water uses, and ecomorphology. Around 1700 HP installations (Lanz, 2021) and approximately 100000 additional artificial river falls exceeding 50 cm (Heiko et al., 2009) obstruct free flow and challenge the migration of aquatic organisms. (iii) The 2011 revision of the Water Protection Act introduced further aspects, mandating HP to reduce flow fluctuations (surge–sunk), normalise sediment transport, and enable fish passage. Cantons (with whom water sovereignty lies in Switzerland) are tasked with revitalising river and providing more space and a more natural environment. According to Heiko et al. (2009), 42 % of Swiss rivers lack sufficient space. And about 20 % of Swiss rivers (approximately 16,000 km) are classified as strongly impaired, 25 % (4000 km) of which need to be revitalised by 2090 (FOEN, 2022). River restoration also serves as an adaptation measure in light of increasing water temperatures: elevated water temperatures can induce stress or high mortality for various organisms (de Vries et al., 2008). The unsatisfactory state of Swiss rivers and streams is reflected by the fact that over 65 % of Swiss fish species are currently listed on the endangered red list (FOEN, 2022). In general, aquatic organisms are over-represented on that red list. Additionally, invasive species, such as the quagga mussel (*Dreissena rostriformis*), are spreading in Swiss lakes, strongly impacting aquatic ecosystems and management infrastructures (Haltiner et al., 2022).

3.3 Data

3.3.1 Hydro-meteorological data

A 160-year history of systematic hydrometric measurements (CHy, 2023) and meteorological observations (Brönnimann et al., 2018) establishes Switzerland's measurement network. Currently, around 250 national hydrometric stations (FOEN, 2023b) and around 150 meteorological stations (MeteoSwiss, 2023b) operate as part of a high-resolution measurement network (excluding cantonal and private measurement stations). Additionally, glacier and snow measurements have been conducted for over 100 years (Stöcklin, 2014; Wüthrich et al., 2010). Hydrologic catchment definitions are available for Switzerland at varying resolutions and can be downloaded for individual use (Bühlmann & Schwanbeck, 2023; Swisstopo, 2022). The Hydrological Atlas of Switzerland (HADES) compiles a multitude of hydro-meteorological variables and provides spatio-temporally aggregated data (Bühlmann & Schwanbeck, 2023).

3.3.2 Climate change streamflow scenarios

The Swiss National CC Services (NCCS) provides downscaled meteorological CC scenarios for Switzerland (CH2018; NCCS, 2018a), based on the EURO-CORDEX dataset (Jacob et al., 2014). The CH2018 scenarios are available and illustrated on the CH2018 web-atlas (NCCS, 2018b). From the CH2018 scenarios, the hydrologic streamflow scenarios Hydro-CH2018 were derived (FOEN, 2021b). The streamflow scenarios consist of 39 model chains (Table 9.3) computed by three research teams. One team focused on 30 large catchments (700–35900 km^2), another on 93 mesoscale catchments (10–1700 km^2), and a third on 190 glacier-influenced headwater catchments, with an emphasis on snow and glacier modelling. The Hydro-CH2018 streamflow scenarios are presented on the Hydro-CH2018 web-atlas (NCCS, 2021a) and the HADES platform (HADES, 2021).

3.3.3 Water resources management data

Maps of Switzerland (Swisstopo, 2022) compiles an extensive range of geospatial data, encompassing various dimensions of WRM, and offers accompanying metadata. In the context of water conservation and aquatic ecology, the available datasets contain a variety of water quality parameters, population data on fish and macrozoobenthos, and eco-morphological mapping. Concerning HP plants (exceeding 300 kW power capacity), data are available regarding water intake locations (excluding withdrawal quantities), HP schemes, and water releases. Further details are available in the WASTA dataset (WASTA, 2019), provided by the Swiss Federal Office of Energy (SFOE). Additionally, Maps of Switzerland illustrates groundwater depths, flood hazard maps, potential heat use of water bodies, and locations of water treatment plants. Figure 6.3 demonstrates the extent of lake level management applied to lakes in Switzerland. The website drought.ch (WSL, 2023) collects and provides current and up to 30-day forecasting information for early drought detection, encompassing the consideration of the weekly filling levels of HP reservoirs provided by the SFOE (2023).

Surprisingly, the spatio-temporal quantification of water usage in Switzerland is largely unknown, and in many cases no data has been collected. The pioneering study conducted by Brunner et al. (2019), simulated quantities of a comprehensive range of water uses, encompassing ecological needs, HP, technical snow production, agricultural irrigation, livestock, drinking water, and industrial uses. The lack of data or data accessibility is in contrast to the extensive network of water-related data in Switzerland, and hence was highlighted as a critical research gap by Lanz (2021) in the context of WRM under CC. Similarly, the white paper for sustainable WRM by Schaefli et al. (2022) underscores the relevance of comprehensive data on water usage for decision-making processes.

Collectively, the extensive and high-resolution measurement networks in Switzerland, in combination with data on a comprehensive range of hydro-climatic conditions and the availability of nationwide streamflow scenarios, provides a study area with intriguing data prerequisites. The solid data foundation, the severe impact of CC on Alpine regions, and the cross-border water interests (Figure 3.1) and increasing pressure on competing water uses all highlight the far-reaching relevance of CC impact assessments on Alpine WRM.

4 Climate change impact on Swiss hydropower production

Full title:

The future of Alpine Run-of-River hydropower production:

climate change, environmental flow requirements, and technical production potential

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This publication constitutes a climate change impact assessment on 21 Run-of-River (RoR) hydropower plants throughout Switzerland, spanning diverse hydro-climatological regimes, catchment elevations, and infrastructure characteristics. The simulation-based assessment also incorporates considerations of environmental flow requirements and the potential for technical optimisation, which modulate RoR production. The general change assessment framework presented in this study laid the basis for RoR electricity projections in the synthesis reports by SCCER-SoE (2019), Lanz (2021), FOEN (2021b) and NCCS (2021b).

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Abstract

Past studies on the impacts of climate change (CC) on Alpine hydropower production have focused on high-head accumulation power plants. We provide one of the first comprehensive, simulation-based studies on CC impacts on Alpine Run-of-River (RoR) production, also considering effects of environmental flow requirements and technical increase potential. We simulate future electricity production under three emissions scenarios for 21 Swiss RoR plants with a total production of 5.9 TWh a^{-1}. The simulations show an increase in winter production (4 % to 9 %) and a decrease in summer production (2 % to 22 %), which together lead to an annual decrease of about 2 % to 7 % by the end of the century. The production loss due to environmental flow requirements is estimated at 3.5 % of the annual production; the largest low-elevation RoR power plants show little loss, while small and medium-sized power plants are most affected. The potential for increasing production by optimising the design discharge amounts to 8 % of the annual production. The largest increase potential is related to small and medium-sized power plants at high elevations. The key results are: (i) there is no linear relationship between CC impacts on streamflow and on RoR production; the impacts depend on the usable streamflow volume, which is influenced by the Flow Duration Curve, environmental flow requirements, and design discharge; (ii), the simulated production impacts show a strong correlation (≥ 0.68) with the mean catchment elevation. The plants at the highest elevations even show an increase in annual production of 3 % to 23 %, due to larger shares of precipitation falling as rain instead of snow. These general results are transferable to RoR production in similar settings in other Alpine locations and should be considered in future assessments. Future work could focus on further technical optimisation potential, considering detailed operational data.

keywords: Hydropower, Run-of-River power plants, climate change, environmental flow, design discharge, Alps

4.1 Introduction

Hydropower (HP) is a key renewable electricity source throughout the world (Gernaat et al., 2017; IHA, 2020; Schaefli et al., 2019). This is especially the case in Alpine countries, where the topographic setting leads to high water input (Farinotti et al., 2012; Fatichi et al., 2015) but also to locally high hydraulic heads. In the context of climate change (CC) impact assessment on HP production in Alpine countries, where CC is particularly strong (Addor et al., 2014; Fatichi et al., 2015; FOEN, 2021b; Köplin et al., 2010; Muelchi et al., 2021), there has been a strong focus on high-head accumulation production (Bombelli et al., 2019; Farinotti et al., 2019; Ranzani et al., 2018; Schaefli et al., 2019), because of significant changes of the snow- and glacier-melt feeding these plants.

CC impact studies on Run-of-River (RoR) power plants are comparably rare (Hänggi & Weingartner, 2012; Mohor et al., 2015; Wagner et al., 2017). This is critical because these plants typically have a very different turbine operation pattern compared to storage power plants. The International Energy Agency (IEA, 2021) estimates, based on data from selected European countries (France, Germany, Portugal, Spain, Switzerland and Austria), that RoR operation is at full turbine capacity around 40 %

of the time, which is significantly greater than that of storage power plants (15 % of the time) and pumped storage power plants (10 % of the time).

Detailed CC impact studies on Alpine RoR electricity production based on catchment-scale streamflow projections generally conclude that future production will closely follow streamflow changes: a slight decrease in mean annual streamflow and a pronounced seasonal shift, with less streamflow in summer and more streamflow in winter (Addor et al., 2014; Bernhard & Zappa, 2009; Brunner et al., 2019; Köplin et al., 2010; Vázquez-Tarrio et al., 2019), with a corresponding decrease in summer production and an increase in winter production (Hänggi & Weingartner, 2012; Savelsberg et al., 2018). The change will be more pronounced at higher elevations, especially in catchments dominated by snow and glaciers (François et al., 2018; Hänggi & Weingartner, 2012). There is, however, no reason to assume a linear relationship between CC-induced changes in streamflow and corresponding changes in RoR electricity production (Wagner et al., 2017). François et al. (2018) showed, for northern Italy, that RoR electricity production in snow-dominated catchments can increase even though streamflow is expected to decrease. Indeed, impacts on electricity production crucially depend on the range of streamflow that is used for production, which in turn depends on the Flow Duration Curve (FDC; cumulative probability distribution of streamflow), the design discharge, and any water-use restrictions imposed for ecosystem protection (Basso & Botter, 2012; Bejarano et al., 2019; Kuriqi et al., 2019; Yildiz & Vrugt, 2019).

In addition, there are a few regional CC impact assessments that rely on a coarse representation of hydrology and simplified treatment of RoR production. For example, Savelsberg et al. (2018) set up a national-scale electricity market model for Switzerland including 400 HP plants (around 300 of which are RoR power plants); they found a relatively large change in winter production compared with the change in streamflow and explained this by excess turbine capacities in winter and early spring that could be used for production under the future streamflow regime. The authors compared future scenarios with individual years in the past that were either dry, wet or average. Compared with the average year 2008, they simulated a future increase in annual production of 4 %. Given the coarse resolution of the results, no detailed insights into the change in production along spatial gradients could be provided. Similarly, Totschnig et al. (2017) use a dynamic simulation model of the Austrian and German electricity, heating and cooling sectors in combination with CC scenarios; their model included around 400 RoR plants and simulated a reduction of 5.5 % in the mean annual RoR production for Austria and Germany by mid-century under emission pathway A1B of the IPCC's Special Report on Emissions Scenarios (SRES), but without giving further insights into variables that might drive this change.

Existing studies on Alpine RoR electricity production give hardly an insight into how to transfer the obtained results to other locations. This seriously limits larger-scale projections of how CC will impact RoR production, despite the now well-known general tendencies in Alpine streamflow evolution. To our knowledge, there is a single study proposing an extrapolation of CC impacts on the entire Alpine region: Wagner et al. (2017) found an annual decrease of RoR production of 8 %, with a widespread increase in winter and decrease in summer. They used a simplified hydrological model with a monthly time step and a mixed approach to convert streamflow changes to electricity production, using a detailed model based on technical parameters for Austria and a simple linear model elsewhere. The underlying CC scenarios were based on scenarios that preceded the ones currently in use (SRES emission pathway A1B). These regional studies give clear indications of the general trend in RoR production in the Alpine region, but they cannot explain how the simulated changes might be modulated by local hydroclimatic, technical and operational specificities, and water use restrictions. Such restrictions exist for all types of RoR power plants, e.g. reserved flow for fish passability in the case of RoR plants built across streams. The water use restrictions can be even more important in case of so-called diversion power plants, where water is locally diverted to increase the hydraulic head. In this case, a certain amount of streamflow has to be maintained in the main river to satisfy further water use interests, such as irrigation, water supply, groundwater recharge, ecosystem demand, habitat connectivity, fish passage or sediment transport, and is defined as environmental flow (Anderson et al., 2015; Bejarano et al., 2019; Calapez et al., 2021; Carolli et al., 2022; Kuriqi et al., 2019).

Therefore, the aim of our study is to understand, based on hydrological simulations, how RoR electricity production could change under CC. We assess in detail the impacts on an annual and seasonal scale and analyse explanatory variables and their influence on RoR production. We simulate for the first time the transient RoR electricity production throughout the century using daily streamflow scenarios (Brunner et al., 2019; FOEN, 2021b). The main innovation lies in the inclusion of both the environmental flow requirements and the technical optimisation potential, which modulate the RoR production. We use a comprehensive set of 21 RoR plants in Switzerland, representing different catchment sizes, streamflow regimes and infrastructure characteristics. The choice of Switzerland is relevant because of its general high share of HP and its pronounced variation in hydro-climatological regimes and in HP infrastructures within a small Alpine area. Accordingly, the results for the diverse RoR power plants presented here will be at least partly transferable to other Alpine regions.

4.2 Material and methods

4.2.1 General change assessment framework

The analysis framework applied in our study (Figure 4.1) is based on the comparison of current RoR production (reference period T_{ref}: 1981–2010) (i) future production under climate change (CC); (ii) production loss due to environmental flow requirements (E_e); and (iii) production increase potential resulting from an optimisation of the design discharge of the installed turbines (E_{opt}). For the CC impact assessment, we use three future periods (T_1/2035: 2020–2049, T_2/2060: 2045–2074, T_3/2085: 2070–2099) and three emissions scenarios (RCP2.6: concerted CC mitigation efforts; RCP4.5: limited CC mitigation measures; and RCP8.5 no CC mitigation measures).

Given that we do not have exact observations of actual RoR production at these sites, the entire analysis is based on the hydrological production potential, i.e. the production that could theoretically be possible given the available streamflow and the power plant characteristics and environmental flow requirements (but not accounting for real-time turbine operations or shut-downs).

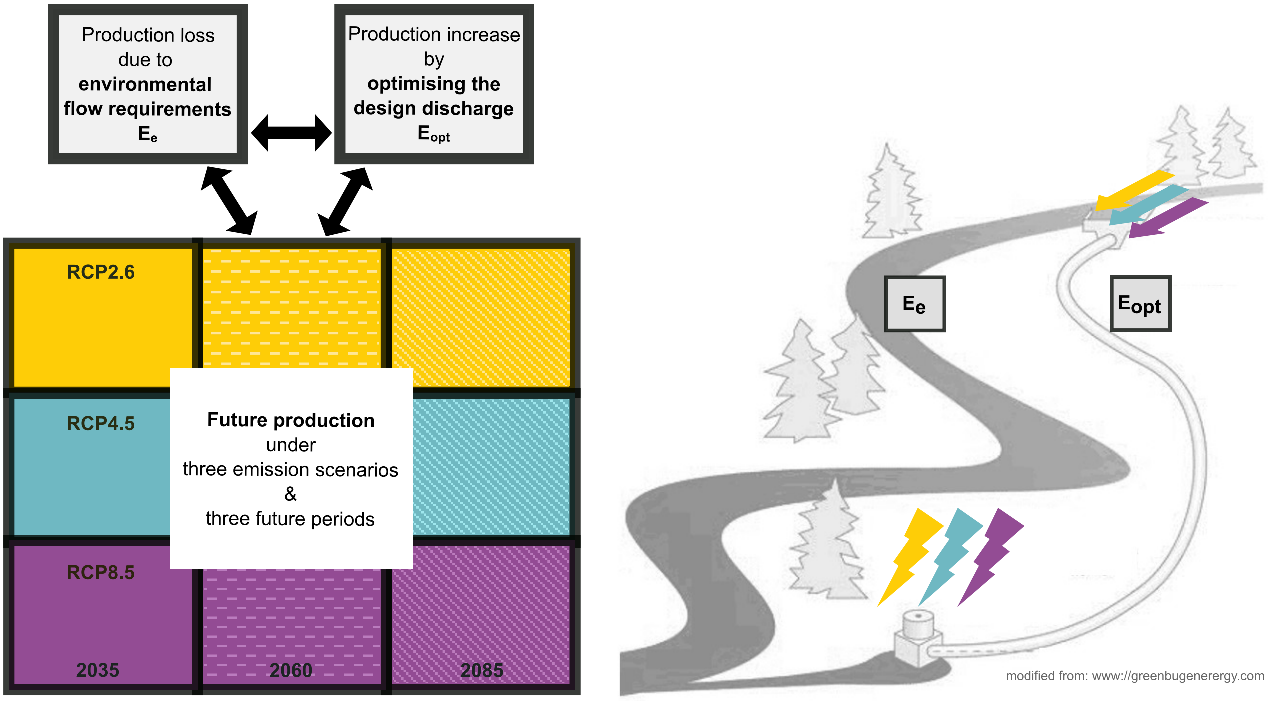


FIGURE 4.1: Summary of the analysis framework used in this study to simulate hydrological production potential scenarios

CC-induced RoR electricity production changes are assessed by comparing the production potential simulated for the reference period T_{ref} with that for the future periods T_1, T_2 and T_3 (for all available climate model ensembles), assuming unchanged installed machinery and environmental flow requirements. Changes induced by environmental flow or by design discharge modifications are assessed by comparing the production potential for the reference period to the simulated production potential with changed environmental requirements or modified design discharge, but keeping the climate equal to that in the reference period. The analysis is complemented by an analysis of correlation between simulated changes and potential explanatory variables (Section 4.3.3).

4.2.2 Data sets

We use three data sets: (i) the streamflow scenarios Hydro-CH2018 (FOEN, 2021b); (ii) the Swiss HP production statistics WASTA (2019); and (iii) a georeferenced database about Swiss HP infrastructure, called HydroGIS, created by Balmer (2012). With these data sets we simulate so-called hydrological production potential scenarios (Figure 4.2).

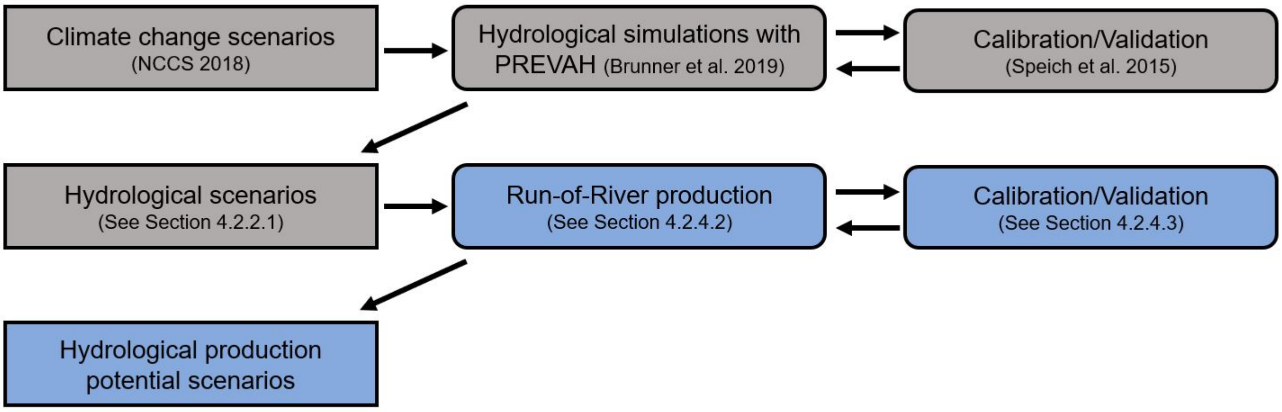


FIGURE 4.2: The flowchart used in this study to simulate hydrological production potential scenarios. The grey boxes represent simulated data and models obtained from external sources, while blue boxes represent the modelling carried out in this study.

4.2.2.1 Hydrological scenarios Hydro-CH2018

The streamflow scenarios Hydro-CH2018 (FOEN, 2021b) are based on the most recent transient Swiss climate change scenarios CH2018 (NCCS, 2018a), which are based on the EURO-CORDEX data set (Jacob et al., 2014). The CH2018 scenarios result from climate model simulations and subsequent statistical downscaling with the quantile mapping approach (NCCS, 2018a). The streamflow scenarios are based on a total of 39 CC scenarios, covering three Representative Concentration Pathways (RCPs): RCP2.6 (concerted CC mitigation efforts), RCP4.5 (limited CC mitigation measures), and RCP8.5 (no CC mitigation measures). For each RCP, a varying number of climate model ensembles is available, between 1981 and 2099, which are based on different combinations of Regional Climate Models (RCMs) and General Circulation Models (GCMs) and thus have different spatial resolutions (Supplementary Information Table SI 9.3). The reference period is 1981–2010 and the future, transient climate simulations are divided into three periods of 30 years (T_1: 2020–2049, T_2: 2045–2074, T_3: 2070–2099).

For the present work, daily streamflow scenarios corresponding to the 39 CC scenarios (Table 9.3) are available from Brunner et al. (2019). The simulations used here are based on the hydrological model PREVAH (PREcipitation streamflow EVApotranspiration HRU related model; Viviroli, Zappa, Gurtz, & Weingartner, 2009), which have been used for CC impact studies in Switzerland (FOEN, 2021b) and have been calibrated for diverse water resource applications in Switzerland (Figure SI 9.1, Table SI 9.1; Bernhard & Zappa, 2009; Köplin et al., 2014; Speich et al., 2015).

PREVAH is a reservoir-based hydrological model that transforms spatially distributed precipitation into streamflow at selected catchment outlets, accounting explicitly for snow accumulation and snow and glacier melt. Key hydrological processes, such as evapotranspiration, infiltration into the soil, and subsequent water release via surface and subsurface runoff, are represented. Besides key spatial data derived from a digital elevation model, input consists of air temperature, precipitation, and potential evapotranspiration (computed with the Penman–Monteith equation considering wind, relative humidity, air temperature and global radiation). Compared to early applications, the model version underlying the present scenarios is improved regarding the representation of snow accumulation at high elevations (Freudiger et al., 2017) and the representation of glaciers and their length evolution (Brunner et al., 2019).

4.2.2.2 Hydropower production characteristics

Two data sets are available to characterise the Swiss HP infrastructure: (i) the HP plant database WASTA (2019), which contains data on 697 powerhouses ($\geq$ 300 kW), including HP production type, design discharge [m^3 s^{-1}], installed power [MW], mean annual production [GWh a^{-1}], winter production (October to March), and summer production (April to September); (ii) the HydroGIS database (Balmer, 2012), which contains georeferenced information on 401 powerhouses and related infrastructure, including the hydrological catchment corresponding to each HP production scheme (which can be composed of several powerhouses). The data on powerhouses is directly related to WASTA (via a unique identifier). The key information extracted from HydroGIS for our work is the hydraulic head of each RoR power plant and the height difference between the water intake and the turbine axis. More details on these two data sources are available in the work of Schaefli et al. (2019). It is noteworthy that the methods used to estimate the expected production that is reported in WASTA are unclear but rely on estimation models applied by the HP producers, including expected average turbine operation hours.

There is no database for the specific environmental flow requirements of individual Swiss RoR plants. The general rules are fixed in Swiss law (Water Protection Act WPA; GSchG, 2011) but are adapted for each production location in the water use contracts, i.e. the so-called concessions. These requirements were obtained directly from the HP producers for the purpose of this study.

4.2.3 Selected case studies

In Switzerland, 576 RoR plants ($\geq$ 300 kW) produce about 21.3 TWh a^{-1}, i.e. 31.5 % of the total electricity production (SFOE, 2020). The largest RoR plants are located along the major streams in the so-called Plateau region of Switzerland (the low-elevation region). Similar to in other Alpine regions, there are also numerous small and medium-sized RoR plants (in terms of installed power) at higher elevations in the mountains. In this study we consider 21 RoR power plants (Figure 4.3). They span a wide variety of hydro-climatological regimes, but some of these RoR power plants are located along the same river to show differences between sequential plants.

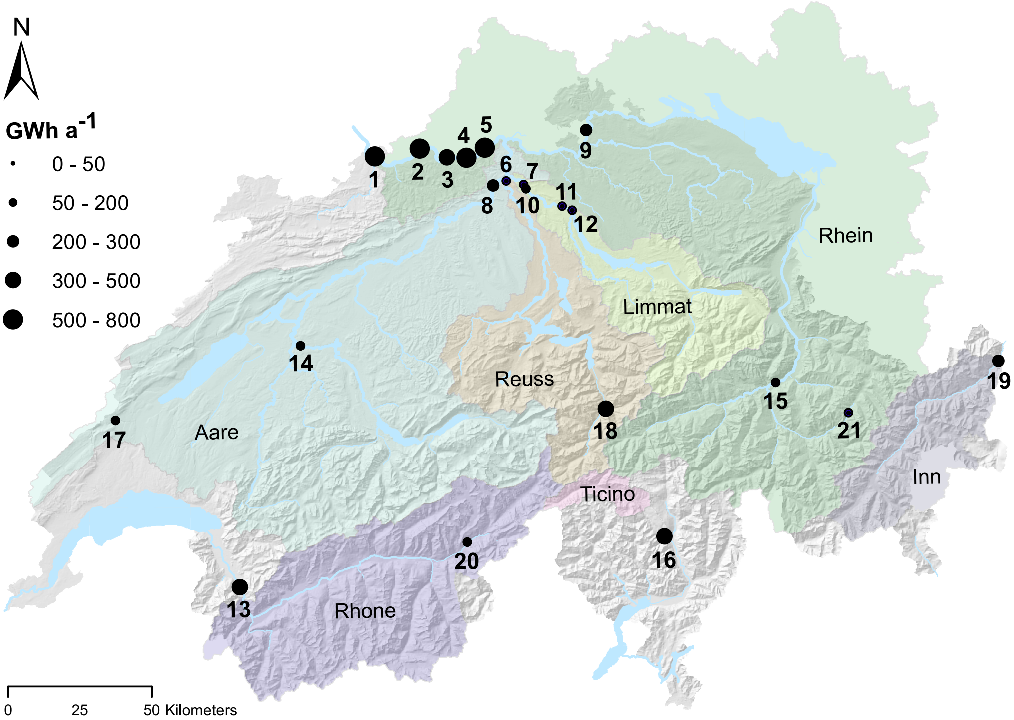


FIGURE 4.3: Location of the selected 21 RoR power plants in Switzerland. The size of the power plants corresponds to the annual production. The numbering (see Table 4.1) is arranged in ascending order according to the elevation of the power plant's water intake. The coloured areas represent the main hydrological catchment areas in Switzerland.

The 21 RoR power plants represent different infrastructure characteristics (in terms of installed turbine types and power), different catchment elevations, and streamflow regimes (Table 4.1). Some RoR power plants are located directly on the considered river, others divert the water, and some additionally have a limited storage reservoir. Details of all power plants are given in the provided data set (Wechsler, 2021).

The 21 selected RoR power plants produce a total of 5.9 TWh a^{-1}, corresponding to 36 % of the mean annual RoR production of Switzerland (2010–2019). Winter production amounts to 2.5 TWh w^{-1} (43 % of mean winter RoR production) and summer production to 3.4 TWh s^{-1} (31 % of mean summer RoR production). The ensemble of 21 plants includes 5 plants with a small annual production ($\leq$ 50 GWh a^{-1}), 12 plants with an annual production between 50 and 500 GWh a^{-1}, and 4 large plants with an annual production $\geq$ 500 GWh a^{-1}.

4.2.4 Methods

4.2.4.1 Quantification of usable streamflow volume for electricity production

The first step in the estimation of RoR production potential is the estimation of the expected available streamflow volume, which is based on the Flow Duration Curve (FDC); this is an inverse representation of the cumulative probability distribution of streamflow (Vogel & Fennessey, 1995) and is classically used for RoR design (Hänggi & Weingartner, 2012; Kuriqi et al., 2019; Wagner et al., 2017;

Table 4.1: The selected 21 RoR power plants of this study are ordered according to the elevation of the power plant's water intake. This table gives an overview of each power plant's catchment area, mean catchment elevation contributing to the streamflow, the presence of a water diversion for HP production, the installed power (P), the simulated electricity production for the reference period (E_{ref}), the power plants' design discharge (Q_d), and the minimum flow that has to be provided for environmental flow requirements or fish passability (Q_e). More details on the specific technical characteristics of each power plant are available in the provided data set (Wechsler, 2021).

nr.	power plant	river	area [km^2]	Øelevation [m a.s.l.]	diversion [yes:no]	P [MW]	E_{ref} [GWh a^{-1}]	Q_d [m^3 s^{-1}]	Q_e [m^3 s^{-1}]
1	Birsfelden	Rhein	34981	1064	no	97.5	557.7	1500	6
2	Ryburg-S.	Rhein	34470	1072	no	120	698.2	1460	6
3	Saeckingen	Rhein	34277	1074	no	72	479.4	1450	2
4	Laufenburg	Rhein	34055	1078	no	106	630.7	1370	10
5	Albbruck-D.	Rhein	33710	1081	yes	83.8	581.4	1100	2
6	Windisch	Reuss	3421	1249	yes	2.01	12.3	55	10
7	Aue	Limmat	2394	1131	yes	5	26	117	14
8	Wildegg-B.	Aare	11640	1004	yes	49.7	289.3	400	20
9	Rheinau	Rhein	11952	1241	yes	36	246.1	400	5
10	Wettingen	Limmat	2394	1131	yes	24	134.7	133	1.9
11	Höngg	Limmat	2186	1190	yes	1.3	10	50	5
12	Letten	Limmat	1828	1222	yes	4.2	20.8	100	5
13	Lavey	Rhone	4741	2192	yes	70	412.1	220	10
14	Mühleberg	Aare	3168	1522	no	40	156.4	301	0
15	Reichenau	Rhein	3210	2015	yes	18	111.8	120	4.3
16	Biaschina	Ticino	313	1913	yes	135	360.6	54	1
17	Les Clées	Orbe	299	1196	yes	30	103.3	21	0.7
18	Amsteg	Reuss	595	2167	yes	120	461.1	50	4
19	Prutz/Ried	Inn	1941	2342	yes	86.9	411	75	7
20	Aletsch	Massa	196	2929	yes	35.3	184.8	7	0
21	Glaris	Landwasser	196	2209	yes	0.96	7.5	2.1	0.37

Westerberg et al., 2011). It allows the quantification of the expected available streamflow volume for production V_{exp}, accounting for the full distribution of streamflow, for the design discharge Q_d, and for the non-usable streamflow volume $V_{I,max}$, e.g. because of known water abstractions for irrigation or because of environmental flow requirements, i.e. water flows reserved for ecological purposes. As illustrated in Figure 4.4, V_{exp} is estimated as the integral of all streamflow values $Q(\tau)$ that are smaller than the design discharge Q_d (exceeding streamflow cannot be turbined) minus the volume lost to minimum flow $V_{I,max}$ and minus additional production loss $V_{I,max}$. $V_{I,max}$ results from the maximum streamflow Q_{max} during which the system still can be safely operated. Beyond Q_{max}, the production system is shut down to prevent damage, to the water intake, e.g. by driftwood. As can be seen in Figure 4.4, V_{exp} can thus be calculated as follows (Hänggi & Weingartner, 2012):

$$V_{\mathrm{exp}} = V_1 + V_2 = Q_d \left(\tau(Q_x) - \tau(Q_{\mathrm{max}})\right) + \sum_{\tau(Q_x)}^{\tau(Q_{\mathrm{min}})} \left(Q_d + Q_{\mathrm{min}}\right), \tag{4.1}$$

where τ is the duration during which a streamflow is reached or exceeded.

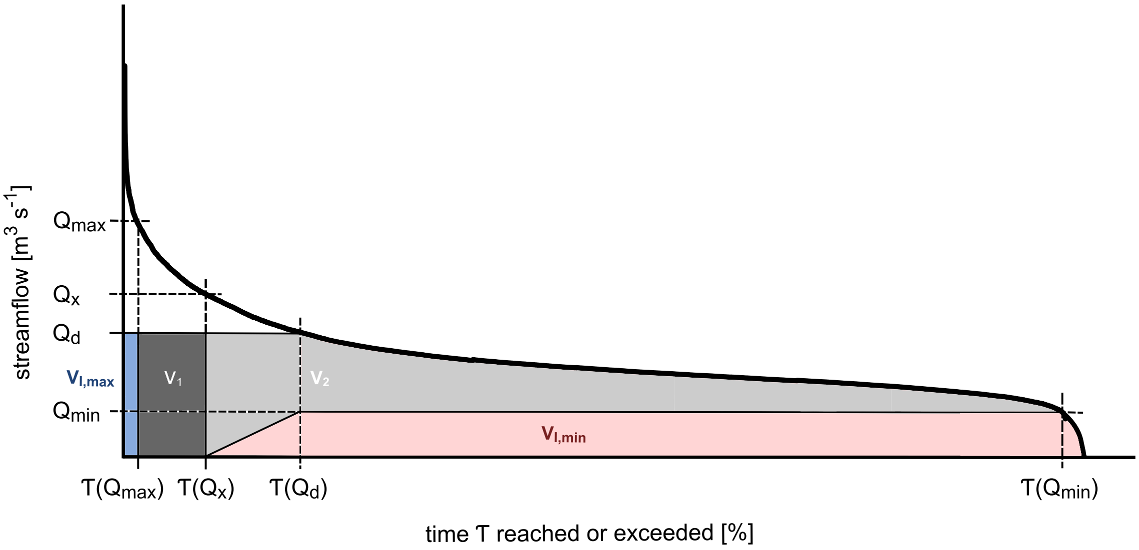


FIGURE 4.4: Illustration of the estimation of the hydrological production potential based on the Flow Duration Curve (FDC), characterised by the parameters Q_{max}, Q_d and Q_{min}. $\tau(Q_x)$ designates the duration during which the streamflow reaches Q_d + Q_{min}, adapted from the work of Hänggi and Weingartner (2012). $V_{I,max}$ and $V_{I,max}$ indicate the loss due to Q_{max} or Q_{min}.

Q_d values are specific to the installed turbines and are available via the WASTA database. Q_{min} values must be collected from HP concessions, i.e. the plant-specific water use contracts. Q_{max} values are difficult to determine in practice because these values are not formally fixed; we ignore them in this study, resulting in $\tau(Q_{max})$ = 1 day. The resulting error can be assumed to be small. In this study, the production estimation is based on daily streamflow values, which increases the uncertainty, especially for RoR plants in small catchments, as they are exposed to stronger sub-daily streamflow fluctuations than plants operating with streamflow from larger catchments. RoR plants downstream of lakes are less affected. FDCs (i.e. streamflow distributions) are obtained here by ranking the entire streamflow time series, available from daily simulations (Section 4.2.2.1). FDCs for winter are based on the daily streamflow values for October to March, and those for summer are based on values for April to September.

4.2.4.2 Calculation of RoR electricity production

The installed power P [MW; 10^6 kg m^2 s^{-3}] of a RoR power plant is computed as:

$$P = Q_d \, H \, \phi \, \eta \, g, \tag{4.2}$$

where H [m] is the hydraulic head (the difference in height between the water intake and the turbine axis), ϕ [kg m^{-3}] is the density of water, η [-] is the specific efficiency of the machinery, g [m s^{-2}] is the gravitation, and Q_d [m^3 s^{-1}] is the design discharge of the installed turbines.

The three parameters ϕ, η and g can be combined into a single factor F [kg m^{-2} s^{-2}], a simplified overall efficiency:

$$F = \phi\, \eta\, g, \tag{4.3}$$

The specific efficiency η of a HP plant depends on several factors, including the runner, turbine type, generator capacity, or friction loss in the penstock (Basso & Botter, 2012; Yildiz & Vrugt, 2019). We consider η to be constant here, but it is in principle time-variant, depending in particular on the actual discharge through each turbine (if there are several). We make the assumption that the machinery of all RoR plants allows HP production at a relatively constant efficiency.

The actual value of F is unknown; it can be estimated from Equation 4.4 if the installed power is known and if we make the assumption that the hydraulic head H is constant (a simplification necessary here since we do not have data on actual hydraulic heads):

$$F = \frac{P}{Q_d\, H}. \tag{4.4}$$

The corresponding specific efficiency η is thus:

$$\eta = \frac{P}{Q_d\, H\, \phi\, g}, \tag{4.5}$$

which theoretically is between 0.7 and 0.9 (Laufer et al., 2004). η [-] is usually somewhat higher for RoR power plants than for storage power plants, because the penstocks are mostly shorter and thus the loss due to friction is smaller.

The actual RoR electricity production $E'(t)$ [MWh] at a given time step t is obtained by replacing the design discharge Q_d by actual discharge $Q(t)$ in Equation 4.2 and by multiplying by the turbine operation time τ_{Turb} (=1 day):

$$E'(t) = Q(t)\, H\, F\, \tau_{\text{Turb}}(t) = V(t)\, H\, F. \tag{4.6}$$

The ′ in $E'(t)$ highlights here the instantaneous production and differentiates it from the expected production E. This expected production E is obtained by replacing $V(t)$ in the above equation by V_{exp} from Equation 4.1:

$$E = V_{\text{exp}}\, H\, F. \tag{4.7}$$

In this formulation, we assume that the turbines are fully operational whenever there is water to produce.

The production loss E_e arising from an imposed minimum environmental flow (Figure 4.4) is calculated as:

$$E_e = V_{\text{I,min}}\, H\, F. \tag{4.8}$$

We also quantify an optimised annual production, Q_{opt} [$\text{m}^3\ \text{s}^{-1}$], that could be obtained by increasing the design discharge (which is theoretical because it would require replacing the turbines). In fact, most of the Swiss RoR power plants were built in the period 1920–1970 with the technology and requirements of the time. The design of the earliest RoR power plants was based on little streamflow data and sometimes based on local electricity need considerations (e.g. of a nearby factory) rather than from an optimal streamflow use perspective. In the meantime, production technology has become more efficient, and actual streamflow variability can be assessed based on streamflow or electricity production records. Accordingly, some RoR plants might today show a considerable optimisation potential of the design discharge in relation to the actual streamflow regime (Yildiz & Vrugt, 2019). The theoretical optimised design discharge considered here corresponds to streamflow that is exceeded 20 % of the time, as a rough benchmark for new power plants. We thus obtain a new $V_{exp,opt}$ by replacing Q_d by Q_{opt} = Q_{20} in Equation 4.1.

$$E_{\text{opt}} = V_{\text{exp,opt}}\, H\, F. \tag{4.9}$$

The data required to estimate E, E_e and E_{opt} are obtained as follows: installed power P and design discharge Q_d are from WASTA (Section 4.2.2.2), the hydraulic head H [m] is from the HydroGIS data set (Section 4.2.2.2), Q_{min} (underlying V_{exp}) is from detailed personal enquiry, and streamflow (underlying V_{exp}) is from hydrological simulations (Section 4.2.2.1). WASTA also provides estimates of expected annual production. This data is used to optimise η and thus F in cases where there are any major discrepancies (see full data set in the Supplementary Data; Wechsler, 2021).

4.2.4.3 Uncertainty quantification

Uncertainties inherent in the hydroclimatic scenarios are handled in this study via the use of streamflow ensemble simulations resulting from the simulation framework (see Section 4.2.2.1). To gain further insights into uncertainties related to simulated production, we compare the collected production data (Section 4.2.2.2) to the simulated RoR production based on the climate model ensembles (Section 4.3.1). The uncertainties in this simulated production result from our simplified assumptions of constant hydraulic head H [m] and of constant overall efficiency F [kg m^{-2} s^{-2}], which both depend on actual streamflow conditions. To more accurately account for the impacts of varying hydraulic head H [m] and of varying streamflow on overall efficiency F [kg m^{-2} s^{-2}], operational RoR power plant data would be needed.

4.3 Results

4.3.1 Validation of the current RoR electricity production

In a first step, the reference period simulations are compared to the expected production listed in the HP infrastructure database WASTA (Section 4.2.2.2), on the annual and seasonal level. The estimated production considers environmental flow requirements and infrastructure characteristics for the 21 RoR power plants in this study. The estimated total mean annual production of all 21 RoR power plants during the reference period (5895.2 GWh a^{-1}) agrees well with WASTA data (5782.5 GWh a^{-1}); winter production (October to March) tends to be slightly overestimated ($\Delta\ +192.7$ GWh w^{-1}) and summer production (April to September) tends to be slightly underestimated ($\Delta\ -43.3$ GWh s^{-1};

Figure 4.5). Given these good validation results, we do not further analyse production uncertainties arising from the simplified production model. Details on streamflow validation are available in the Supplementary Information (Table SI 9.1, Figure SI 9.2).

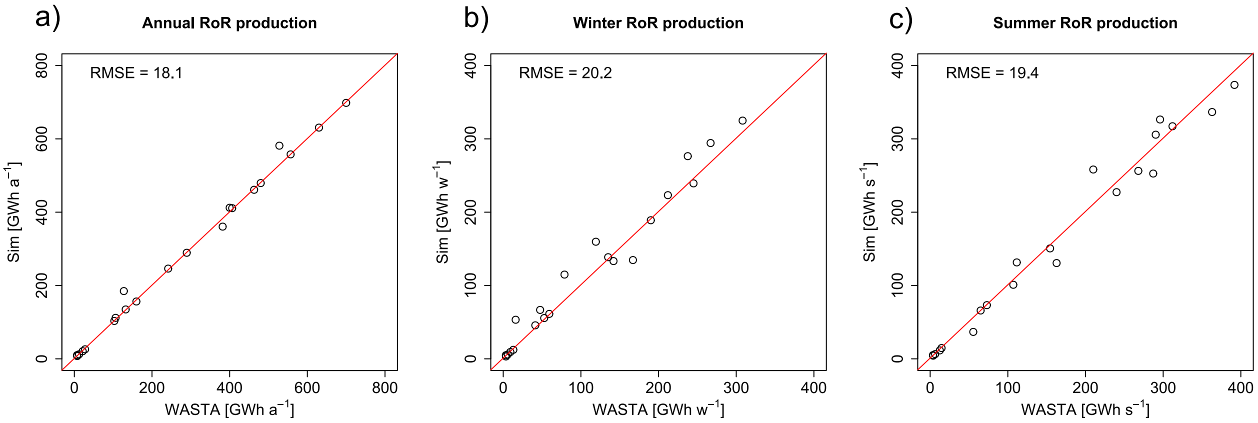


FIGURE 4.5: Comparison of the mean simulated production with production reported in the WASTA database for the 21 RoR plants: annual production, winter production (October to March), and summer production (April to September).

4.3.2 Change in RoR electricity production

4.3.2.1 Case study of two RoR power plants

The impacts of CC, environmental flow requirements, and optimised design discharge on RoR electricity production are calculated with the FDC for each of the 21 RoR power plants. We illustrate here the detailed results for two representative plants, the Wildegg-Brugg power plant and the Glaris, Davos power plant. Full results are available in the Supplementary Data (Wechsler, 2021). The Wildegg-Brugg power plant shows both a decrease in annual streamflow and a reduction in annual production by the end of the century (Figure 4.6a); the Glaris, Davos power plant shows only minor changes in streamflow, but an increase in annual production (Figure 4.6b).

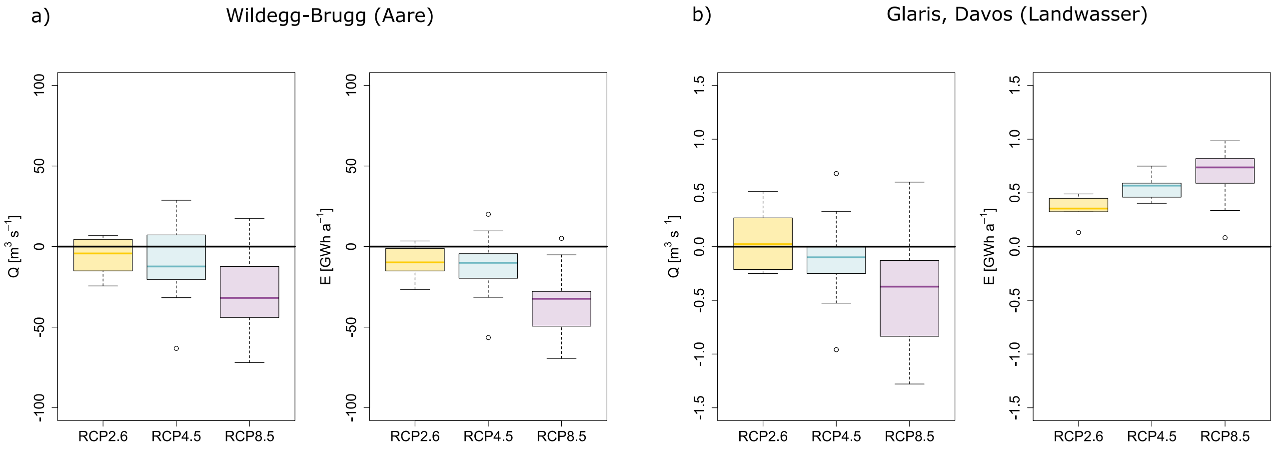


FIGURE 4.6: Simulated changes in the mean annual streamflow (Q) and mean electricity production (E) by the end of the century (2070–2099) at the Wildegg-Brugg power plant and the Glaris, Davos power plant. The black line indicates the median value of the reference period (1981–2010). The boxplots represent the range of the different model ensembles based on the three emissions scenarios RCP2.6, RCP4.5 and RCP8.5.

This difference is caused by differences in the infrastructure characteristics of the power plants. If the changes in streamflow are in the range that can be used for RoR electricity production, this has an immediate influence. At the Glaris, Davos power plant, the streamflow increases in the low water range, which has a positive impact on production (Figure 4.7).

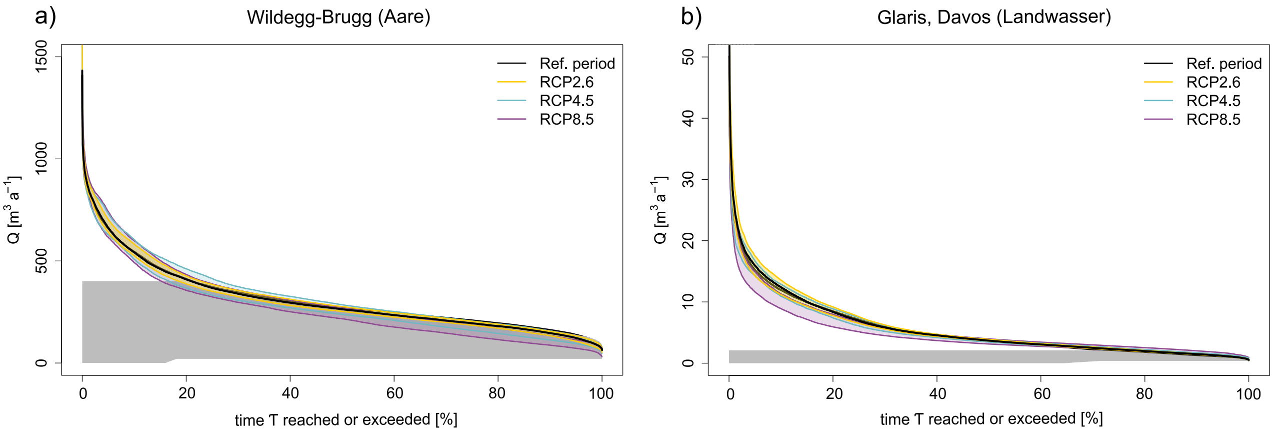


FIGURE 4.7: Flow Duration Curves (FDCs) for the power plants Wildegg-Brugg and Glaris, Davos. The black line represents the reference period (1981–2010), the grey shaded area represents the expected available streamflow (V_{exp}), and the coloured areas bounded by curves represent the range of FDCs for the projected model ensembles based on the three emissions scenarios (RCP2.6, RCP4.5 and RCP8.5) by the end of the century.

The production loss due to environmental flow requirements (E_e) is estimated at 17.5 GWh a^{-1}, i.e. -6 % of the annual production, at the Wildegg-Brugg RoR power plant and 0.5 GWh a^{-1}, i.e. -6 %, at the Glaris, Davos plant. The potential for increasing production by optimising the design discharge (E_{opt}), so that it corresponds to streamflow that is exceeded 20 % of the time, amounts to 2.5 GWh

a^{-1}, i.e. 1 % of the annual production, at the Wildegg-Brugg plant and 9.8 GWh a^{-1}, i.e. 128 % at the Glaris, Davos plant (see Supplementary Data; Wechsler, 2021).

4.3.2.2 Spatial analysis of 21 RoR power plants

Considering all 21 RoR power plants, the future mean annual production is predicted to decrease slightly over the century under the given CC projections (Table 4.2). Exceptions are the high-elevation power plants, which are strongly influenced by snow- and ice-melt processes (Figure 4.8). The total production loss due to environmental flow requirements (E_e) for the 21 RoR power plants is estimated at 207 GWh a^{-1}, i.e. 3.5 % of the annual production (see Supplementary Data; Wechsler, 2021). The largest RoR power plants along the Rhine show little loss, while small and medium-sized power plants with diversions are most affected. The potential for increasing production by optimising the design discharge (E_{opt}) amounts to 467 GWh a^{-1}, i.e. 8 % of the annual production. The largest increase potential is related to small and medium-sized power plants in the Alpine region (Figure 4.8).

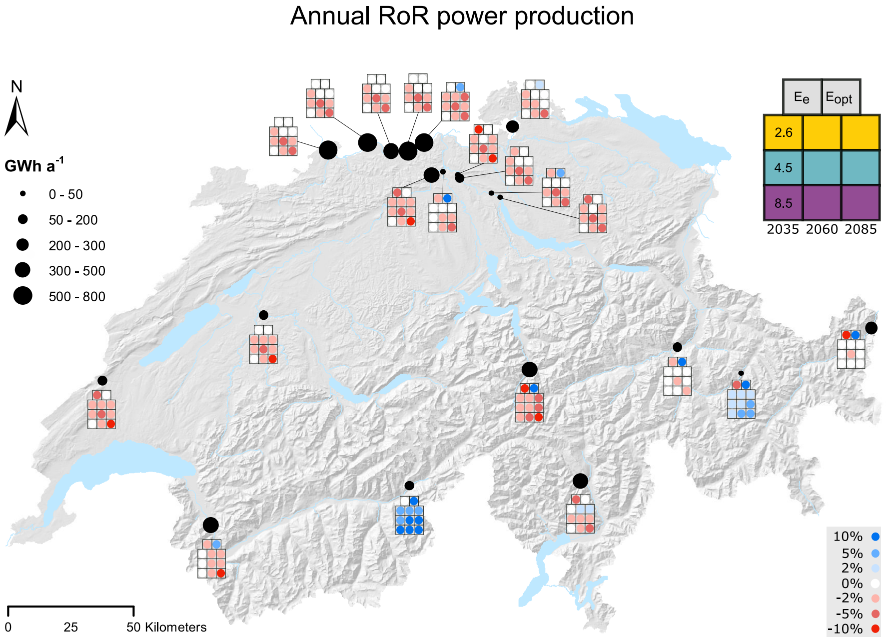


FIGURE 4.8: Simulated changes in production at the 21 RoR power plants; the size of the dots (power plants) represents the annual production. The coloured dots in the grids represent the loss due to environmental flow requirements (E_e), the increase potential resulting from optimisation of the design discharge (E_{opt}), and the climate change impact for the time periods 2035, 2060, 2085 and the three emissions scenarios RCP2.6, RCP4.5 and RCP8.5.

The annual changes in production due to CC range from +0 % to -7 % (Table 4.2). An annual loss of 7 % corresponds to the electricity consumption of around 82500 households in Switzerland (±5000 kWh a^{-1} per household). The projected decrease is more pronounced for later time periods and in the absence of CC mitigation measures. The CC-induced decrease in production is of a similar magnitude as the production loss due to environmental flow requirements (E_e -3.5 %) and as the increase potential resulting from optimisation of the design discharge (E_{opt} +8 %).

TABLE 4.2: Simulated change in annual RoR electricity production for the periods T_1 (2020–2049), T_2 (2045–2074), and T_3 (2070–2099) under the emissions scenarios RCP2.6, RCP4.5 and RCP8.5.

annual E	T_1	T_2	T_3
RCP2.6	-2 %	-1 %	-2 %
RCP4.5	-1 %	-5 %	-2 %
RCP8.5	+0 %	-3 %	-7 %

4.3.2.3 Overall change in seasonal RoR electricity production

Future winter (October to March) mean RoR electricity production is predicted to increase over the century (Figure 4.9). The increases are most pronounced at high elevations, where the shift from solid to more liquid precipitation increases the streamflow during winter because less water is stored in the snowpack. On the other hand, at -4.5 % (E_e 115 GWh w^{-1}), the production loss due to environmental flow requirements in the winter half-year are slightly greater than the annual average. The optimisation of the design discharge can cause an increase in production by 2.5 % (E_{opt} 60 GWh w^{-1}) in the winter half-year because streamflow in winter is usually below the design discharge and thus full capacity is not reached. The winter changes in RoR production due to CC range from +2 % to +9 % (Table 4.3a). The projected increase becomes more pronounced over time and without CC mitigation measures (RCP8.5). The CC-induced increase is of a similar magnitude as the production loss due to environmental flow requirements (E_e 4.5 %) and the increase potential due to the optimisation of design discharge (E_{opt} 2.5 %). However, the projected increase in winter production does not outweigh the negative change in annual production, as winter production only accounts for 43 % of the total annual production.

In summer (April to September), RoR production declines under CC (Figure 4.9b). The absence of CC mitigation measures and the time period make a large difference. The loss due to environmental flow requirements is 2.5 % (E_e 91 GWh s^{-1}) and therefore less during the summer. Optimising the design discharge results in a production increase by 12 % (E_{opt} 404 GWh s^{-1}). The increase potential tends to lie more at high elevations. The changes in summer RoR production due to CC range from -2 % to -21 % (Table 4.3b). The projected decrease is more pronounced in later time periods and when CC mitigation measures are absent. The CC-induced decrease in production during summer is therefore larger than the production loss due to environmental flow requirements and the increase potential due to optimisation of the design discharge.

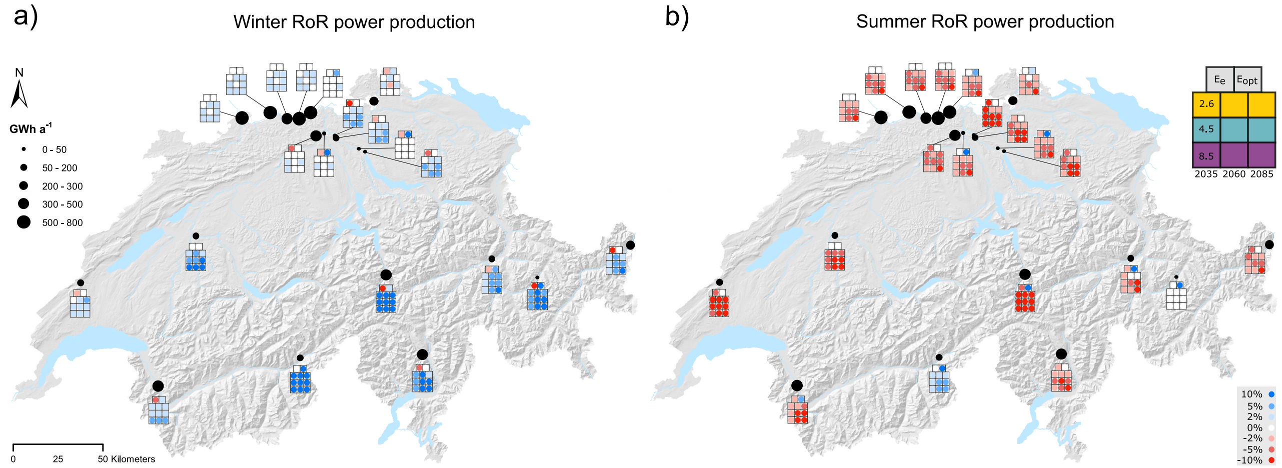


FIGURE 4.9: Same as Figure 4.8 but for winter (October to March) and summer (April to September).

TABLE 4.3: Same as Table 4.2 but for change in winter (October to March) and summer (April to September) RoR electricity production.

(a) winter	T_1	T_2	T_3	(b) summer	T_1	T_2	T_3
RCP2.6	+2%	+5%	+4%	RCP2.6	-5%	-4%	-2%
RCP4.5	+5%	+4%	+7%	RCP4.5	-6%	-11%	-9%
RCP8.5	+5%	+7%	+9%	RCP8.5	-5%	-10%	-22%

4.3.2.4 Synthesis of the simulated electricity production projections

The simulated CC impacts are, from mid-century onwards, similar to the estimated annual production loss due to environmental flow requirements, which equals, on average, 3.5 % of the simulated production during the reference period (1981–2010). For 11 of the 21 plants, design discharge optimisation would lead to a production increase of between 1 % and 149 % (average increase of 45 % for these 11 plants; total increase corresponds to 8 % of the current production). For six of these 11 plants, this could compensate the loss due to environmental flow requirements. For five of them, design discharge optimisation would compensate expected CC-induced loss under the most extreme scenario (RCP8.5) by the end of the century.

4.3.3 Key variables explaining the change in RoR electricity production

To gain further insight into what might explain the observed changes in RoR production, we analyse the correlations (linear and rank correlations) between the simulated production changes and (i) underlying streamflow changes due to CC and (ii) technical plant characteristics. The impacts on production that are related to the different scenarios and time periods are strongly correlated to each other (lowest linear correlation of 0.78); accordingly, we only present the results for RCP8.5 below. The data for RCP2.6 and RCP4.5 are available in the Supplementary Data (Wechsler, 2021).

A correlation analysis with selected power plant characteristics (Figure 4.10) reveals that mean catchment elevation [m a.s.l.] is an important variable influencing future changes in RoR electricity production. There is a distinct positive correlation (> 0.68) between the mean catchment elevation (Øelevation) and the CC-induced production changes (at T_2 and T_3 for the emissions scenario RCP8.5). The plants at the highest elevations show a production increase under all emissions scenarios and for all time periods. With one exception (see full results table in Supplementary Data; Wechsler, 2021), such positive production changes are only simulated for power plants with a mean elevation higher than 1900 m a.s.l. This elevation dependence needs to be considered in relation to the actual production, which is the highest for the large low-elevation HP plants that turbine large streamflow volumes and for which the mean annual production will systematically decrease. Furthermore, a seasonal analysis (Figure 4.10) shows that the mean catchment elevation correlates more strongly with the changes in winter production (> 0.79) than with the changes in summer production (> 0.35).

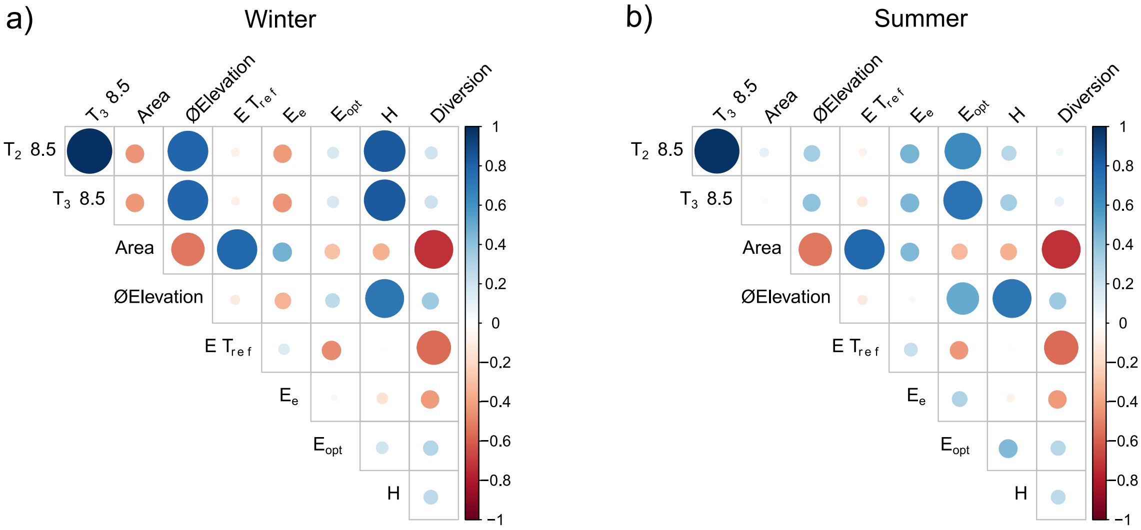


FIGURE 4.10: Correlation matrix for winter (October to March) and summer (April to September) RoR electricity production: the simulated production changes under the emissions scenario RCP8.5 for: the two future periods T_2 (2060) and T_3 (2085), the catchment area, the mean elevation of the catchment, the mean annual production during the reference period ($E\ T_{ref}$), the loss due to environmental flow requirements (E_e), the increase potential resulting from optimisation of the design discharge (E_{opt}), the hydraulic head (H), and presence of streamflow diversion. Blue dots indicate a positive correlation and red dots indicate a negative correlation, with larger dots indicating stronger correlations.

This relationship between mean catchment elevation and CC-induced changes in production potentially results from several factors related to: (i) infrastructure characteristics: higher-elevation plants have higher hydraulic heads and smaller catchments, i.e. less average streamflow and smaller design discharge; and (ii) hydrological regime: higher-elevation plants have a regime with marked differences between summer and winter streamflow.

There is additionally a marked negative rank correlation (-0.6) between annual production changes and the range of usable streamflow volume, i.e. the difference between normalised (by the mean streamflow) design discharge and normalised environmental flow; the plants for which this range is very large are most likely to see a production decrease (Figure 4.11a). This is explained by the fact that if this usable streamflow volume range is large, the projected streamflow decreases will more directly translate to production decreases.

We do not detect any further relationships in terms of linear correlations or Spearman rank correlations between production changes and other infrastructure characteristics, in particular the ratio between Q_{20} and the design discharge, a proxy for how much of the streamflow is currently used for production.

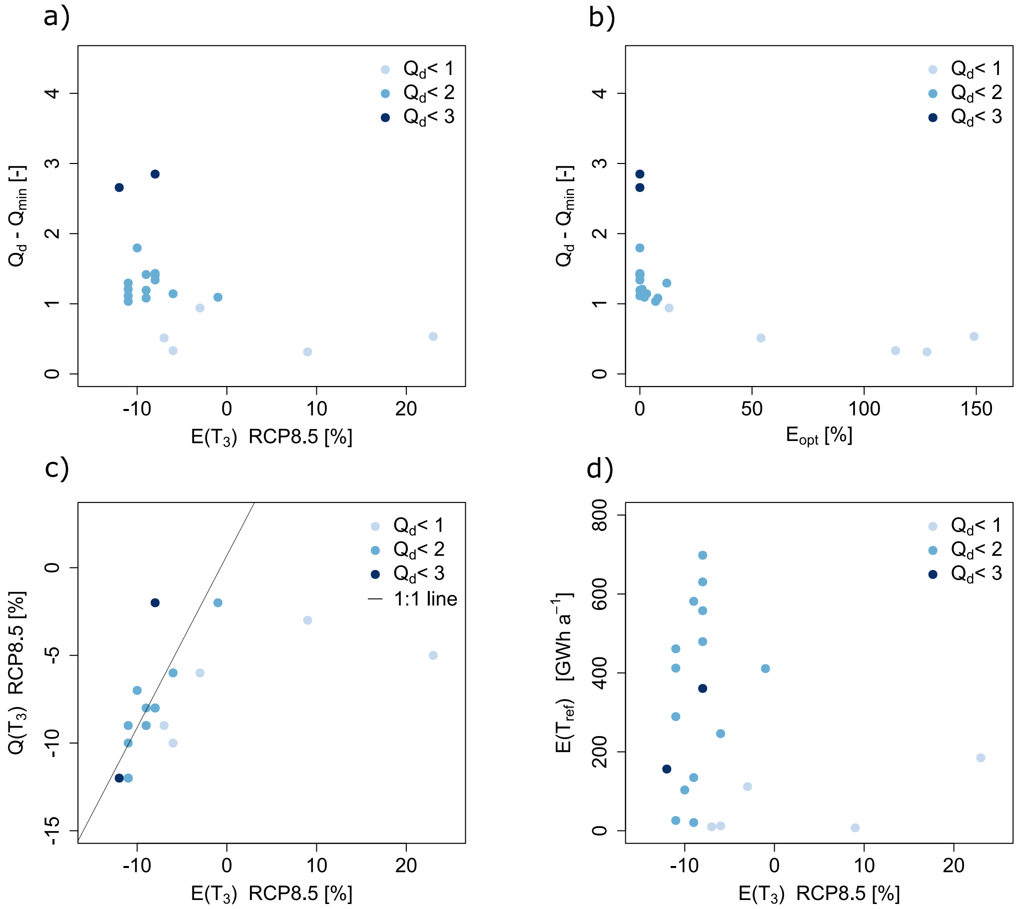


FIGURE 4.11: Negative Spearman correlations (a) between future annual electricity production (E) changes by time period T_3 (2070–2099) under emissions scenario RCP8.5 and the range of usable streamflow volume (the difference between normalised design discharge (Q_d) and normalised environmental flow (Q_{min}) and (b) between the production increase potential (E_{opt}) and the range of usable streamflow volume. Comparisons of (c) streamflow changes (Q) and E changes by T_3, indicating also the linear 1:1 line, and of (d) E during T_{ref} and projected E changes by T_3. The colours of the dots represent the normalised Q_d (by the mean streamflow) of the 21 RoR power plants, with darker shades indicating higher Q_d values.

There is no significant linear or rank correlation between the annual production loss due to environmental flow requirements (E_e) and the CC-induced production changes or between production increase potential (E_{opt}) and CC impacts. However, the plants that have the greatest optimisation potential are those that currently have a small usable streamflow range (small difference between normalised Q_d and normalised environmental flow Q_{min}; Figure 4.11b).

Changes in streamflow do not show a linear relationship with CC-induced changes in production (Figure 4.11c). Production changes are instead modulated by the currently used range of streamflow (which is influenced by environmental flow requirements and design discharge) and by how this range is affected by CC.

The RoR power plants with small design discharge ($Q_d \leq 1$) show a non-linear relationship between streamflow changes and production changes, with two of them showing an increase in production despite decreasing streamflow (Figure 4.11c). The power plants with a small Q_d are predominantly small or medium-sized (Figure 4.11d).

At the seasonal scale, we see some additional patterns: In winter, loss due to environmental flow requirements are more likely to occur for higher-elevation plants with streamflow diversion, where a stronger increase in winter production is predicted (Figure 4.9 and results in Supplementary Data; Wechsler, 2021). The summer half-year is less affected by production reductions resulting from environmental flow requirements, whereas optimising the design discharge (E_{opt}) is more important in summer and mainly affects the power plants at higher elevations.

4.4 Discussion

In this study, we estimate the extent to which RoR electricity production will be affected by climate change (CC). Due to its steep gradients, the Alps are particularly affected by CC, which particularly affects RoR power plants because they have no or limited storage. Because the study area is limited to Switzerland, the institutional framework conditions are comparable across all the studied power plants, which is especially important for the analysis of environmental flow requirements. The optimisation of the design discharge is included here to shed additional light on the implications of anticipated CC impacts. Optimisation of the design discharge can only be achieved in combination with replacement of the turbine or the runner.

The present study confirms the CC trends observed in previous streamflow studies in the Alps (François et al., 2018; Hänggi & Weingartner, 2012; Savelsberg et al., 2018; Schaefli et al., 2019; Totschnig et al., 2017; Wagner et al., 2017), i.e. slightly decreased annual production but increased production in winter, the most critical period for electricity demand matching. The transient projections presented here include mean annual and seasonal production over 30 years, but they do not address interannual changes. In contrast to the study by Savelsberg et al. (2018), who compared individual years with future periods, we compare the future periods with the entire reference period (T_{ref}: 1981–2010); as a result, we show here a decrease in RoR annual production by up to 7 %, which is in contradiction to the predicted increase of 4 % in the Swiss mean annual RoR production by

Savelsberg et al. (2018).

The novelty of our study, compared to previous simplified models (Wagner et al., 2017), is the consideration of both the legal framework and the infrastructure characteristics of the power plants. Even if the CC-induced decreases in annual production are similar to those reported in studies with simpler RoR models (Totschnig et al., 2017; Wagner et al., 2017), our joint analysis of the three variables CC, environmental flow requirements, and optimisation of the design discharge allows – for the first time – a comparison of the orders of magnitude of these changes that will inevitably arise in the coming decades. The analysis of the interplay of environmental flow requirements and design discharge also shows that a change in streamflow does not mean a linear change in production (François et al., 2014; Mohor et al., 2015) and, taken a step further, that a change in production does not mean a linear change in financial revenue (Cassagnole et al., 2020; Ranzani et al., 2018; Savelsberg et al., 2018).

The available national-scale data sets (Balmer, 2012; WASTA, 2019) provide a solid basis to estimate the impacts based on the specific infrastructure characteristics of RoR power plants. Although influencing variables, such as hydraulic head (H) and factor of efficiency (F), are simplified, the consideration of plant-specific parameters nevertheless identifies key variables that are relevant for production impacts. The real efficiency of a power plant varies in time with streamflow, which influences the hydraulic head; both head and streamflow influence the operating point of the turbines and the water-to-electricity conversion efficiency. Due to the lack of operational RoR power plant data, we could not consider further the varying efficiency as done in technical HP studies (Quaranta et al., 2022; Skjelbred & Kong, 2019). The added value of considering the specific infrastructure characteristics, compared to previous studies, is that the loss due to the environmental flow requirements and the technical increase potential resulting from an adjusted design discharge can be analysed.

Production reductions due to environmental flow requirements are greater in the winter half-year and tend to affect small and medium-sized power plants at higher elevations and with diversions. The loss due to environmental flow requirements (E_e) do not show a correlation with CC production loss, despite the fact that E_e influences the usable streamflow volume; this is because environmental flow affects all plants similarly, whereas design discharge is plant specific. RoR power plants with a relatively small design discharge (Q_d) are less affected by CC.

The production increase potential related to a systematic application of a more optimal design discharge shows a large spread between the studied HP plants. This stems from the considerable differences in the design and construction standards underlying the different plants. The selected optimised design discharge, corresponding to streamflow that is exceeded 20 % of the time, does not represent an agreed-upon reference design value, but rather shows the potentially important HP production gain that is related to technical choices. It is noteworthy that the optimisation of the design discharge corresponds only to a single factor in terms of technical efficiency increase and ultimately in terms of production increase. Future CC impact studies on RoR electricity production should focus on further technical optimisation potential, considering operational RoR power plant data.

Finally, we acknowledge that we include only a single environmental aspect of HP production, which is the minimum flow. With regard to the future of RoR electricity production, many other environmental aspects are relevant, including sediment or fish connectivity and the problem of streamflow variability for ecosystem function (Carolli et al., 2022; Gabbud & Lane, 2016; Gorla & Perona, 2013; Kuriqi et al., 2019, 2021). Future work could potentially address such aspects, which are already part of the Swiss Water Protection Act (GSchG, 2009) and the European Water Framework Directive (WFD) (Kaika, 2003), to integrate the water-energy-ecosystem nexus into regional development processes (Temel et al., 2023). This could ultimately contribute to the balancing of socio-economic and environmental interests in RoR development. Switzerland has a legal framework regarding environmental flow that differs from Europe. Europe's WFD defines more the principles for determining the environmental flow requirements, which should be considered in the respective national frameworks. The WFD not only foresees a minimum flow, but also states that the flow regime should allow a good ecological river status (EU, 2016). In the Swiss legal framework, the streamflow value Q_{347} (95 % percentile) serves as a reference for the determination of the minimum flow (GSchG, 2011). These differences in the legal frameworks need to be considered before transferring results to other settings.

4.5 Conclusions

Our study of 21 hydropower plants represents one of the first comprehensive analyses of climate change (CC) impacts on Run-of-River (RoR) electricity production in an Alpine context. The simulated CC impacts result in a minor change of about -2 % to -7 % in mean annual production by the end of the century. The simulated production changes show a clear positive correlation with elevation; some RoR power plants with high-elevation catchments (i.e. fed by snow and glacier melt) show an increase in annual production, while plants with a mean catchment elevation below 1900 m a.s.l. show a decrease in production. The RoR production changes for three future time periods under three emissions scenarios indicate an intensifying loss over time and without CC mitigation measures.

The seasonal analysis shows that the overall decrease in annual production results from a general increase of winter production (4 % to 9 %) and a decrease of summer production (2 % to 22 %). The simulated annual CC impacts on production are, from mid-century onwards, similar to the estimated annual production loss due to environmental flow requirements, which equals, on average 3.5 % of the simulated production during the reference period (1981 - 2010). Design discharge optimisation would lead to a production increase for 11 of the 21 plants and thereby compensate production loss from CC impacts for about half of those plants under all scenarios; the optimisation can, however, compensate the loss due to environmental flow for 6 plants only.

The key results from this study can be summarised as follows:

- Winter RoR production, which is the most critical period for electricity demand matching, will increase under the future climate; the production increase potential by optimising the design discharge is limited during winter and is about seven times smaller than in summer.
- CC-induced future RoR production is not linearly related to the projected CC-induced changes in streamflow; production changes rather depend on the currently used range of streamflow (modulated by environmental streamflow requirements and design discharge) and by how this range is affected by CC. If the usable streamflow volume range is large, the changes in streamflow will more directly translate to production changes.
- CC impacts, as well as production potentials, should be interpreted in light of environmental flow impacts, which in turn depend on local needs and infrastructure characteristics, in particular the presence of diversions.

These results might be of key importance for decision making in the field of renewable electricity production. Further work could focus on ecological impacts of changing environmental flow requirements and technical optimisation potentials. Future studies could additionally address how to deal with the two contrasting goals of energy transition, which are aiming for more renewable electricity production while reducing negative impacts on freshwater ecosystems.

Acknowledgements

The authors gratefully acknowledge funding from the Swiss Innovation Agency Innosuisse through the Swiss Competence Centre for Energy Research – Supply of Electricity (SCCER-SoE). The HydroGIS database was provided by M. Balmer, and WASTA is updated annually by the Swiss Federal Office of Energy and made publicly available. The latest climate change scenarios were produced and made available by MeteoSwiss, and transposed into hydrological future scenarios in the framework of the Federal Office of the Environment (FOEN) programme Hydro-CH2018.

5 Climate change impact on Swiss environmental flow requirements

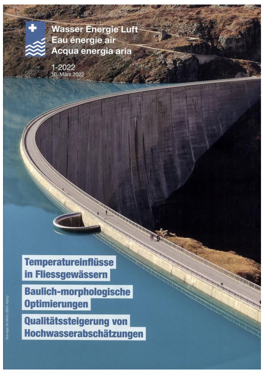
Full title:

Does a higher Q_{347} value reduce hydropower production?

The Swiss environmental flow requirements based on four Run-of-River power plants.

Tobias Wechsler*[1,2], Florian Lustenberger[2], Regula Muelchi[2], Bettina Schaefli[2], Massimiliano Zappa[1]

Wasser Energie Luft



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This manuscript extends the work presented in the previous paper, which assessed the impacts of climate change on Run-of-River (RoR) power plants. In this study, our focus shifts towards examining climate change impacts on environmental flow requirements — an uncertainty that has been frequently debated. This study marks a pioneering endeavor in quantifying the shares of energy potential, thereby addressing the scientific demand to provide data to enhance more sustainable hydropower, as proposed by Schaefli et al. (2022). The following manuscript is translated from German to English (using ChatGPT) and was originally published in the journal Wasser Energie Luft.

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Abstract

Climate change modifies the annual streamflow and its seasonal distribution in Switzerland. Changes in the low-flow range have implications for the low-flow indicator Q_{347}, the corresponding streamflow value reached or exceeded on 347 days per year (95 % of the time). In Switzerland, Q_{347} serves as a reference value to derive the environmental flow according to the Swiss Water Protection Act (WPA). Based on four exemplary Run-of-River (RoR) power plants, we demonstrate with numeric simulations how an altered Q_{347} value affects the determination of environmental flow and the hydropower production in case of a (re-)concession process. Our results show a change in Q_{347}, according to the Water Protection Act, implies a change in the environmental flow. However, there is no 1:1 relationship: an increase in Q_{347} results in a comparatively less pronounced increase in environmental flow. By the end of the century, due to climate change, an increase of up to 63 % in Q_{347} is projected for high-elevation catchments ($>$ 2000 m a.s.l.), leading to a potential rise of up to of 43 % in environmental flow in the case of a (re-)concession process. For low-elevation catchments ($<$ 1500 m a.s.l.), Q_{347} decreases up to 35 %, and therefore, the environmental flow decreases as well up to 28 %. However, an assessment of future hydropower production changes cannot be solely derived from the change in the reference value Q_{347}; it requires considering the entire streamflow volume usable for hydropower production. In the power plant with the highest increase in environmental flow (43 %), the simulations indicate an increase of electricity production by 7 %. For future production changes, the environmental flow requirements play a minor role; dominant are the climate-induced changes in streamflow and the design discharge of a power plant.

keywords: climate change impact assessment, environmental flow requirements, Q_{347}, Run-of-River power plants, Switzerland

5.1 Introduction

Diversion hydropower plants locally abstract water to augment the hydraulic potential (Anderson et al., 2015; Wechsler et al., 2023c). In the presence of existing legal requirements, a minimum flow rate (environmental flow) must be maintained in the main river to fulfill interests of river ecology, water resources management, and landscape aesthetics (Bejarano et al., 2019; Calapez et al., 2021; Kuriqi et al., 2019; Uhlmann & Wehrli, 2006). In Switzerland, the Q_{347} value serves as a crucial low-flow indicator and, according to the Water Protection Act (WPA), is defined as a reference value to determine environmental flow. Q_{347} corresponds to the amount of streamflow reached or exceeded on 347 days per year (95 % of the time). The amount of environmental flow can be increased or decreased according to additional requirements (Article 31(2), Article 32, and Article 33 WPA). In principle, the environmental flow requirements defined in the WPA apply to hydropower (HP) plants that were either built, modified, or (re-)concessioned after 1992 (FOEN, 2023e).

Due to climate change (CC), the mean annual streamflow and its seasonal distribution are changing, which also leads to a change in Q_{347} (Muelchi et al., 2021; Weingartner & Schwanbeck, 2020). All available CC impact studies project an increase in Q_{347} for high-elevation catchments ($>$ 2000 m a.s.l.). According to the WPA, this means an increase in the environmental flow in case of a (re-)concession process, which in turn may suggest a reduction in HP production. However, no study exists for determining the relationship between a CC-induced change in Q_{347} values and the Swiss HP production. Based on four exemplary Run-of-River (RoR) power plants (Figure 5.2 and Table 5.1), we analyse the impact of a CC-induced change in Q_{347} values on the determination of environmental flow according to Article 31(1) of the WPA and its impact on future HP production.

TABLE 5.1: Catchment characteristics of the four Run-of-River power plants, with their mean catchment elevation (Øelevation), simulated mean annual streamflow ($\O Q$), simulated annual electricity production ($\O E$) and design discharge (Q_d)

power plant	river	Øelevation [m a.s.l.]	$\O Q$ [m^3 s^{-1}]	$\O E$ [GWh a^{-1}]	Q_d [m^3 s^{-1}]
Davos	Landwasser	2209	6	7.5	2.1
Domat Ems	Rhein	2015	123	111.8	120
Windisch	Reuss	1249	136	12.3	55
Wettingen	Limmat	1131	93	134.7	133

5.2 Estimation of current and future Q_{347}

To determine the environmental flow, the Q_{347} value is calculated as the average over ten years according to the definition in the WPA (Article 4, para. *h* WPA). For the construction, modification or (re-)concession process of an HP plant, the Q_{347} value is determined based on streamflow observations or on simulations of the past (Article 59 WPA). For over 35 years, it has been known that a seasonally differentiated determination of environmental flow would be essential for landscape aesthetics and river ecology (Bundeskanzlei, 1987; Estoppey et al., 2000). However, this aspect is rarely considered in HP design (Uhlmann & Wehrli, 2007). Therefore, we solely rely on Q_{347} and do not consider the seasonal distribution of streamflow. This study uses streamflow scenarios to determine the change of Q_{347} between the present to the future. The scenarios were developed within the framework of Hydro-CH2018 (FOEN, 2021b) and are based on the Swiss climate scenarios CH2018 from the National Centre for Climate Services (NCCS, 2018a). We use the streamflow scenarios from the works of Muelchi et al. (2022) and Brunner et al. (2019). Both datasets are based on the conceptual, process-based model PREVAH (Viviroli, Zappa, Gurtz, & Weingartner, 2009; Zappa et al., 2017). Daily data are available for three emission scenarios and 39 climate model chains. A comparison between the reference period (1981–2010) and the end of the century (2070–2099, also referred to as "2085") is performed using the RCP8.5 emission scenario. RCP8.5 represents a high-emission scenario, where no CC mitigation measures are taken, and greenhouse gas emissions continue to increase (NCCS, 2018a).

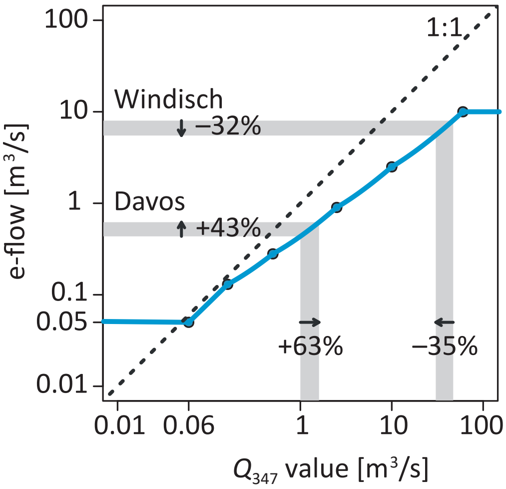


FIGURE 5.1: Determination of the environmental flow (*e-flow*) based on the Q_{347} value according to Article 31(1) of the WPA. The dots represent the defined reference values, and the line depicts the actual relationship between Q_{347} and the environmental flow, which does not follow a 1:1 relationship. Two power plant examples illustrate the simulated changes by the end of the century. The figure was inspired by the documentation by the Bundeskanzlei (1987).

5.3 Case studies

We selected (Figure 5.2 and Table 5.1) two power plants with a mean catchment elevation above 2000 m a.s.l. (Davos and Domat Ems) and two with a mean catchment elevation below 1500 m a.s.l. (Windisch and Wettingen). One power plant per elevation range has a relatively high design discharge (Domat Ems and Wettingen), while the other two have a low one (Davos and Windisch). The design discharge is the maximum streamflow that can be used for HP production, determined by the size of the water intakes and of the turbines. To compare the four RoR power plants, we show the median and standard deviation of the 18 CC model chains of the high-emission emission scenario (RCP8.5). For the power plant Davos, an increase of 63 % (±18 %) in the Q_{347} value is simulated by the end of the century. For the second high-elevation power plant, Domat Ems, an increase of 9 % (±12 %) is projected. For the two low-elevation power plants, Windisch and Wettingen, a decrease of 35 % (±16 %) and 32 % (±12 %) are projected (Table 5.2). These changes are consistent with the previously described developments of future Q_{347} changes (FOEN, 2021b; Muelchi et al., 2021). There are uncertainties of a similar magnitude in the further simulations, although they are not listed here.

TABLE 5.2: Simulated changes of Q_{347} (Δ Q_{347}) and environmental flow (Δ*e-flow*) by the end of the century (2085, RCP8.5) at all four RoR power plant locations.

power plant	Δ Q_{347} [%]	Δ*e-flow* [%]
Davos	+63	+43
Domat Ems	+9	+8
Windisch	-35	-32
Wettingen	-32	-28

5.4 Environmental flow

We determine the environmental flow required in the case of water extractions for the four RoR power plants according to Article 31(1) of the WPA. This article defines that rivers with a constant streamflow ($Q_{347} > 0$; Article 4, para. i WPA) are subject to the requirements of environmental flow. This applies to all four RoR power plants. In this study, we do not consider the additional requirements of Article 31(2), Article 32, and Article 33, that allow for increasing or decreasing the environmental flow. Table 5.3 provides the legal requirements: if Q_{347} is less than or equal to 0.06 m^3 s^{-1}, a minimum of 0.05 m^3 s^{-1} must be provided as environmental flow. Above 0.06 m^3 s^{-1} five additional Q_{347} reference values and their corresponding environmental flows are defined. However, Article 31(1) of the WPA does not follow a 1:1 relationship: for high Q_{347} values, the corresponding environmental flow is relatively low (Figure 5.1), whereas for low Q_{347} the corresponding environmental flow is relatively higher.

TABLE 5.3: Determination of the environmental flow ($e\text{-}flow$) based on Q_{347} according to Article 31(1) of the WPA.

Q_{347} $[m^3\ s^{-1}]$	$e\text{-}flow$ $[m^3\ s^{-1}]$
$\leq$ 0.06	0.05
then, each 0.01	+0.008 more
0.16	0.13
then, each 0.01	+0.0044 more
0.5	0.28
then, each 0.1	+0.031 more
2.5	0.9
then, each 0.1	+0.0213 more
10	2.5
then, each 1	+0.15 more
$\geq$60	10

Environmental flow is determined based on simulated streamflows in this study. This means that the simulations for the reference period do not precisely match the observed streamflow of the reference period. The resulting environmental flows are determined according to a strict application of Article 31(1) of the WPA. They are higher than the values noted in the concessions of the four RoR power plants. The exact reasons cannot be known since we do not have access to the data basis used for the historic estimates. The simulation-based values for future environmental flow indicate a similar but attenuated development as the Q_{347} values: an increase by the end of the century for the power plants Davos (43 %) and Domat Ems (8 %), and a decrease for Windisch (32 %) and Wettingen (28 %) (Table 5.2).

5.5 Change in environmental flow volume

This high-emission scenario leads to a decrease in Q_{347} by the end of the century at elevations below 1500 m a.s.l. At elevations between 1500 and 2000 m a.s.l., simulated streamflow changes are small and can be positive or negative. At elevations above 2000 m a.s.l., Q_{347} increases (Figure 5.2). CC alters the type of precipitation: higher temperatures lead to a shift from snowfall to rainfall, even at high elevations. This means that in the future less precipitation will be stored temporarily as snow in winter, increasing streamflow and snowmelt peak streamflow. Additionally, spring snowmelt will start earlier. At high elevations, the low-flow period continues to occur in winter. However, due to increased winter streamflow, Q_{347} also increases. The additional water in winter (during the cold and dark season when electricity demand is high) is considered an advantage for HP production. At low elevations, low-flow periods mostly occur in summer. With CC, these low-flow periods will extend into late summer and autumn (FOEN, 2021b; Muelchi et al., 2021; Weingartner & Schwanbeck, 2020). The production changes are estimated based on Equation 5.1 in Section 5.6.

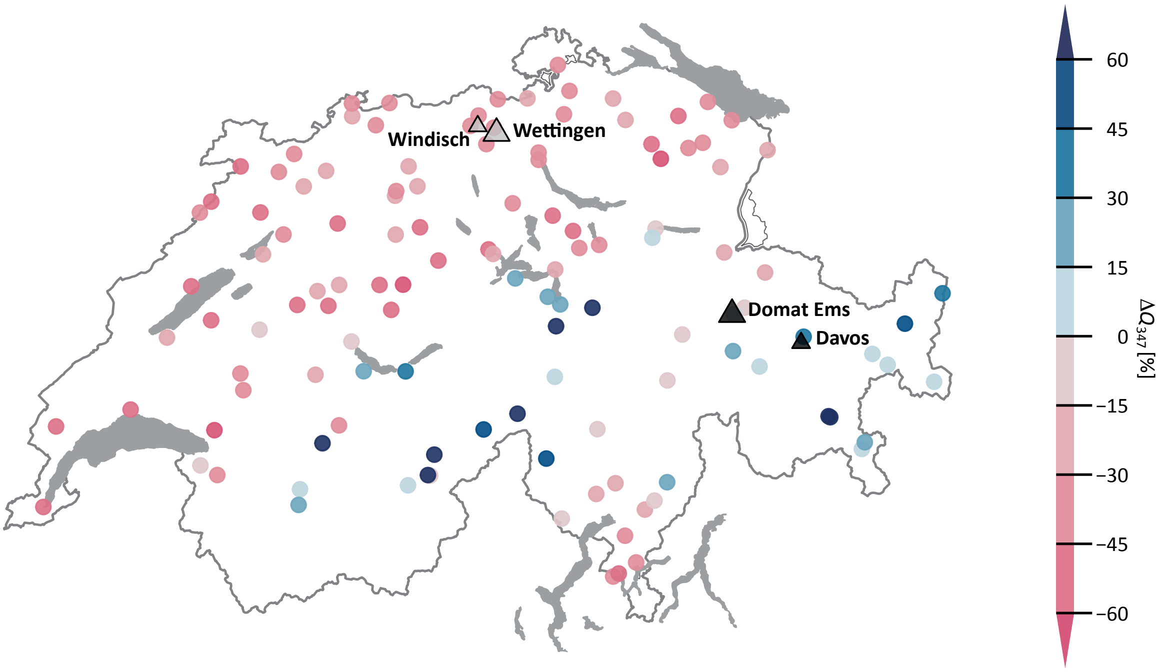


FIGURE 5.2: Locations of the four RoR plants in Switzerland analyzed in this study. The two black triangles represent the high-elevation power plants (Davos and Domat Ems), while the two gray triangles represent the two low-elevation ones (Windisch and Wettingen). The large triangles represent power plants with a high design discharge, whereas the small triangles represent those with a small one. In the background, the percentage change of Q_{347} (without CC mitigation measures, RCP8.5) between the reference period and the end of the century is shown. The figure was adapted from the publication by Muelchi et al. (2021).

A reference value consideration (environmental flow derived from Q_{347}) does not provide any temporal information and does not allow estimating the effects on the usable streamflow volume for HP production (V_{exp}). An estimation of V_{exp} requires the consideration of environmental flow over a specific period, yielding the environmental flow volume ($V_{I,min}$). The effects of a change of V_{exp} by the end of the century are analysed based on Flow Duration Curves for the four RoR power plants. A Flow Duration Curve shows the probability of occurrence of daily streamflow (Figure 5.3). Here, we estimate the FDCs based on 30 years of streamflow, as suggested by Wechsler et al. (2023c). V_{exp} is limited by the design discharge (Q_d) and the environmental flow volume ($V_{I,min}$). If the streamflow at a certain time exceeds Q_d of a power plant, the excess cannot be used for electricity production and flows over (spilling). In this study we do not consider days when production is not possible (e.g. due to flood events or maintenance work). To estimate the change in V_{exp} between the reference period and the future period (2085), we consider the changes in streamflow volume and the changes in $V_{I,min}$. The design discharge (Q_d) is assumed to be unchanged.

The two high-elevation RoR power plants (Davos and Domat Ems) show a CC-induced increase in Q_{347} and in the low-flow range by the end of the century (Figure 5.4). This increase in Q_{347} implies that V_{exp} will increase in the low-water range and thus have an impact on HP production. For the two low-elevation power plants (Windisch and Wettingen, Figure 5.4), the low-flow range decreases by the end of the century.

RoR power plants with a high Q_d use a large portion of the streamflow volume for electricity production. Hence, there is a stronger correlation between V_{exp} and changes in the mean streamflow for two power plants (Table 5.4). This applies to the high-elevation power plant Domat Ems (-3 % V_{exp}) and the low-elevation power plant Wettingen (-7 % V_{exp}).

The CC-induced change in $V_{I,min}$ shows a stronger correlation with the relative design discharge than with the mean catchment elevation: the two power plants with a high design discharge are affected by more significant changes (Domat Ems: +23 %, Wettingen: -27 %) in $V_{I,min}$ by the end of the century (Table 5.4) than the two power plants with low Q_d (Davos: +0 %, Windisch: +3 %).

TABLE 5.4: Simulated changes in mean annual streamflow (Δ ØQ), usable streamflow volume for HP production (ΔQ_{use}), environmental flow volume (ΔQ_e), mean annual electricity production (ΔE), and mean annual loss due to environmental flow requirements (ΔE_e) between the reference period and the future period (2085, RCP8.5) of the four RoR power plants.

power plant	Δ ØQ [%]	ΔV_{exp} [%]	$\Delta V_{I,min}$ [%]	ΔE [%]	ΔE_e [%]
Davos	-7	+7	+0	+7	+3
Domat Ems	-9	-3	+23	-3	+23
Windisch	-10	-4	+3	-4	+4
Wettingen	-8	-7	-27	-7	-27

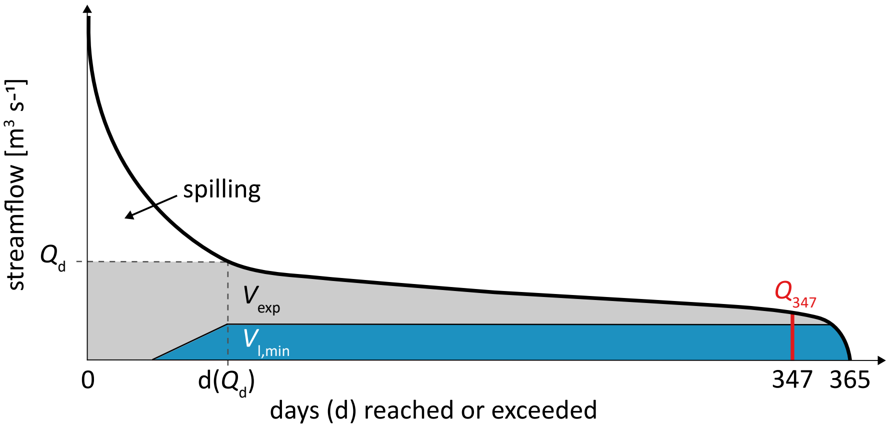


FIGURE 5.3: Illustration of a Flow Duration Curve (FDC) to analyse the environmental flow volume ($V_{I,min}$), the usable streamflow volume for HP production (V_{exp}), and the spilled steamflow volume due to the limitation imposed by the design discharge (Q_d). Q_{347} indicates the streamflow value reached or exceeded on 347 days per year. The figure was inspired by the work of Hänggi and Weingartner (2012).

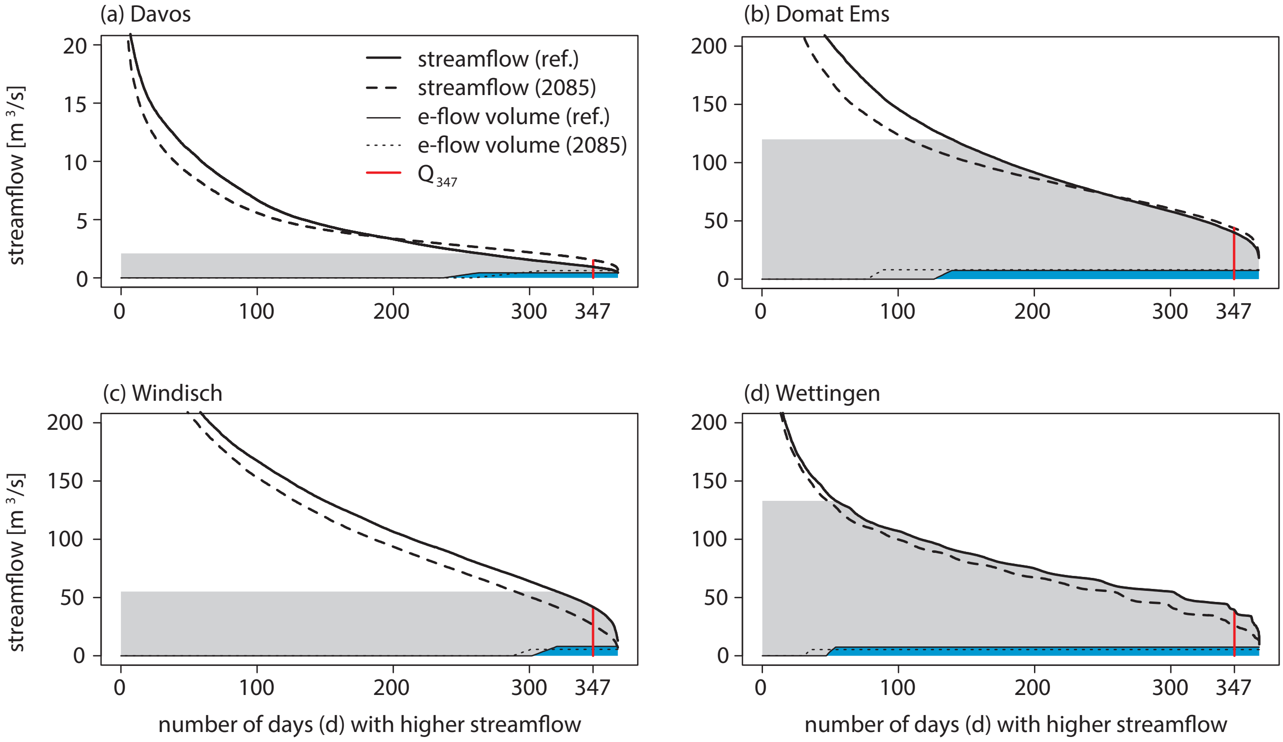


FIGURE 5.4: Flow Duration Curves of the for RoR power plants Davos, Domat Ems, Windisch, and Wettingen. Each plot illustrates the Flow Duration Curves and the environmental flow volume ($V_{I,min}$) for the reference period and the future period 2085, the usable streamflow volume for HP production (V_{exp}) and Q_{347}.

5.5.1 Environmental flow and relative shares of streamflow

Concerning Article 31(1) of the WPA, it is often stated that "power plants are allowed to use 88 % to 94 % of the streamflow for HP production, providing only 6 % to 12 % for nature" (Bittner & Bischof, 2022; FOEN, 2023f). Considering the entire streamflow (including spilling), we estimate the following shares for the four RoR power plants (Figure 5.5): 1 % to 7 % for the environmental flow volume ($V_{I,min}$) and 32 % to 85 % for the usable streamflow volume for HP production (V_{exp}); 9 % to 66 % of the streamflow are spilled, due to the limitation imposed by the design discharge (Q_d). The ratio between changes in $V_{I,min}$ and changes in streamflow only changes slightly by the end of the century, at around 1 % for all four power plants. This is also evident for changes in electricity production (Section 5.6 and Figure 5.5).

Based on the four RoR power plants, the numbers suggest the above mentioned quantified environmental flow volume ($V_{I,min}$) from 6 % to 12 % is too high, as it only accounts for the ratio between the usable streamflow volume for HP production (V_{exp}) and the environmental flow volume ($V_{I,min}$), rather than the entire streamflow.

5.6 Change in RoR electricity production

Various studies have shown that there is not a linear relationship between changes in streamflow and changes in HP production (e.g. François et al., 2018; Savelsberg et al., 2018; Wechsler et al., 2023c). Crucial are the changes in the usable streamflow volume for HP production (V_{exp}). The production changes of the four RoR power plants are estimated using the methodology described in the works by Hänggi and Weingartner (2012) and Wechsler et al. (2023c). We consider the CC-induced changes in streamflow, the specific design discharge of each power plant, and the environmental flow requirements according to Article 31(1) of the WPA.

The HP production (E) [GWh] is estimated as follows:

$$E = V_{exp}\ H\ F, \tag{5.1}$$

where V_{exp} [m^3] corresponds to the usable streamflow volume over a specific period (30 years), H [m] is the hydraulic head (vertical difference between the water intake and the turbine axis), and F [kg m^{-2} s^{-2}] is the factor determining the gross efficiency of a specific power plant. In this study, we assume H and F to be constant, independent of the actual streamflow. Further details on the power plants can be found in the dataset RoRCC (Wechsler, 2021), and detailed descriptions of the estimation are provided in the works by SCCER-SoE (2019) and Wechsler et al. (2023c).

Despite the decrease in mean annual streamflow for all four power plants by the end of the century, the simulations indicate different changes in electricity production (Table 5.4, estimated based on Equation 5.1). The RoR power plants with a high design discharge (Domat Ems and Wettingen) show stronger correlate between changes in production (-3 %, -7 %) and changes in mean annual

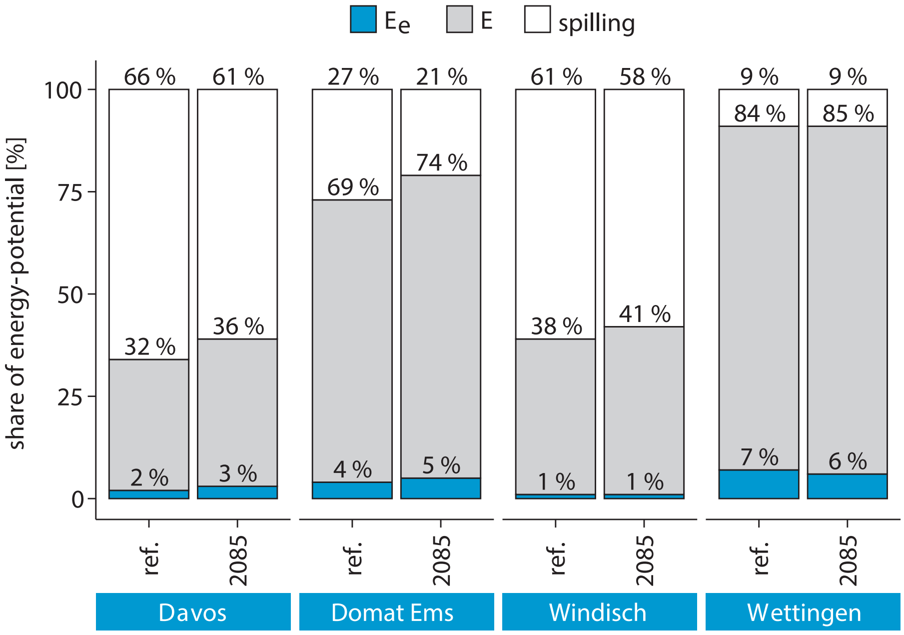


FIGURE 5.5: Relative shares of the four RoR power plants' energy potential for the two periods (reference period and 2085). The shares differentiate between the electricity production loss due to environmental flow requirements (E_e), RoR power production (E), and the spilled streamflow due to the limitation imposed by the design discharge.

streamflow (-9 %, -8 %). The low-elevation power plants (Windisch and Wettingen) both show a decrease in production (4 %, 7 %). The electricity production for the RoR power plant Davos is projected to increase by 7 %.

The so-called production loss due to environmental flow requirements (E_e), which are mandated by law to protect ecosystems and, thus, should not primarily be perceived as a loss, are estimated analogously to Equation 5.1. Instead of V_{exp}, Equation 5.2 uses the environmental flow volume ($V_{I,min}$):

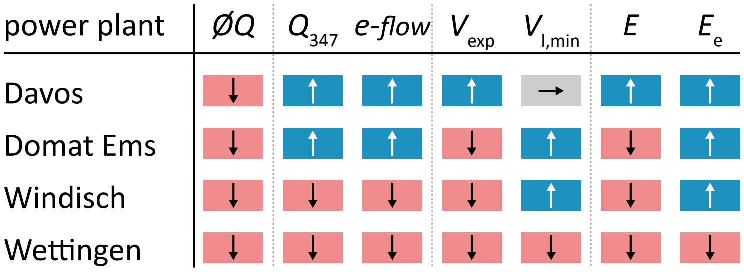
$$E_e = V_{I,min}\ H\ F. \tag{5.2}$$

The production loss due to environmental flow requirements, mainly changes for power plants with a high design discharge (Table 5.4). For the high-elevation power plant Domat Ems, the simulations project an increase in E_e of +23 % by the end of the century, while the low-elevation power plant Wettingen shows a decrease of -27 %. For power plants with a low design discharge, minor changes in E_e are projected (Davos: +3 %, Windisch: +4 %).

The environmental flow requirements result in a production loss betwen 1 % and 7 % (Figure 5.5). Compared to the RoR power production (between 32 % and 85 %) and the spilled streamflow due to the limited design discharge (between 9 % and 66 %), the production loss due to environmental flow requirements (E_e) represents the smallest share during the reference period and in the future. Even if the share of RoR power production (E) increases relative to the total energy potential for all four RoR power plants by the end of the century (Figure 5.5), a reduction in mean annual production is projected, except for the RoR power plant Davos (Table 5.4).

5.7 Conclusion

In this study and based on four RoR power plants in Switzerland, we demonstrate how a CC-induced change in Q_{347} affects the environmental flow requirements and what consequences this may have for future HP production. These four case studies exemplify many other power plants in Switzerland and illustrate how CC-induced changes affect the legal requirements for environmental flow. A higher Q_{347}, according to Article 31(1) of the WPA, also means a higher environmental flow. For the two high-elevation power plants (Davos and Domat Ems), a higher Q_{347} and higher environmental flow are projected. In comparison, for the two low-elevation power plants (Windisch and Wettingen), a lower Q_{347} and lower environmental flow are projected. However, there is no direct link between this development and future HP production. For the power plant with the highest increase in environmental flow (Davos), electricity production increases due to the rise in the low-flow range. Conversely, for the second power plant with an increase in environmental flow (Domat Ems) and for the two power plants with a reduced environmental flow (Windisch and Wettingen), the simulations indicate a decrease in electricity production. The changes in production primarily depend on CC-induced changes in streamflow and on the design discharge of a power plant. Power plants with a high design discharge use a large share of the streamflow, resulting in a stronger correlation between streamflow changes and electricity production changes. Accordingly, the production loss due to environmental flow requirements is relatively small and plays a minor role compared to the overall energy potential. The foremost important conclusion of this work is that, for typical Alpine RoR power plants, estimating changes in future HP production cannot be based on the change of Q_{347}. Such estimations require a consideration of the entire usable streamflow volume for HP production. Future studies apply this analysis to the entire Switzerland to estimate the spatial and temporal shares of energy potentials.



power plant	$ØQ$	Q_{347}	*e-flow*	V_{exp}	$V_{I,min}$	E	E_e
Davos	↓	↑	↑	↑	→	↑	↑
Domat Ems	↓	↑	↑	↓	↑	↓	↑
Windisch	↓	↓	↓	↓	↑	↓	↑
Wettingen	↓	↓	↓	↓	↓	↓	↓

FIGURE 5.6: Summary of changes in mean annual streamflow ($ØQ$), Q_{347}, environmental flow ($e\text{-}flow$), usable streamflow volume for HP production (V_{exp}), environmental flow volume ($V_{I,min}$), mean annual hydropower production (E), and mean annual production loss due to environmental flow requirements (E_e). Arrows pointing upwards represent an increase, arrows pointing downwards represent a decrease, while a horizontal arrow indicates no significant change.

Competing interests

The authors declare no conflict of interest.

Data statement

The data, which were also used for Paper 1, are publicly available in the provided dataset RoRCC by Wechsler (2021).

6 Climate change impact on Swiss lake level variability

Full title:

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

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The first version of the paper was rejected by the journal Science of the Total Environment because of its narrow regional focus and other criticisms. A carefully revised resubmission of the paper to another journal is currently in preparation.

Preprint:
https://eartharxiv.org/repository/view/5710/
DOI: 10.31223/X59D4V

This manuscript builds upon the same dataset as the previous papers: the transient streamflow scenarios from the Hydro-CH2018 project (FOEN, 2021b). The CC impact assessment framework is applied to the management of lake levels in large perialpine lakes. Despite their crucial role in the hydrologic cycle, studies involving hydrologic modeling of perialpine lakes have been sparse, with the vast majority omitting the explicit consideration of effects stemming from lake level management. We combine a hydrologic and a hydrodynamic model to incorporate lake level management into our projections and to disentangle climatic and regulatory impacts.

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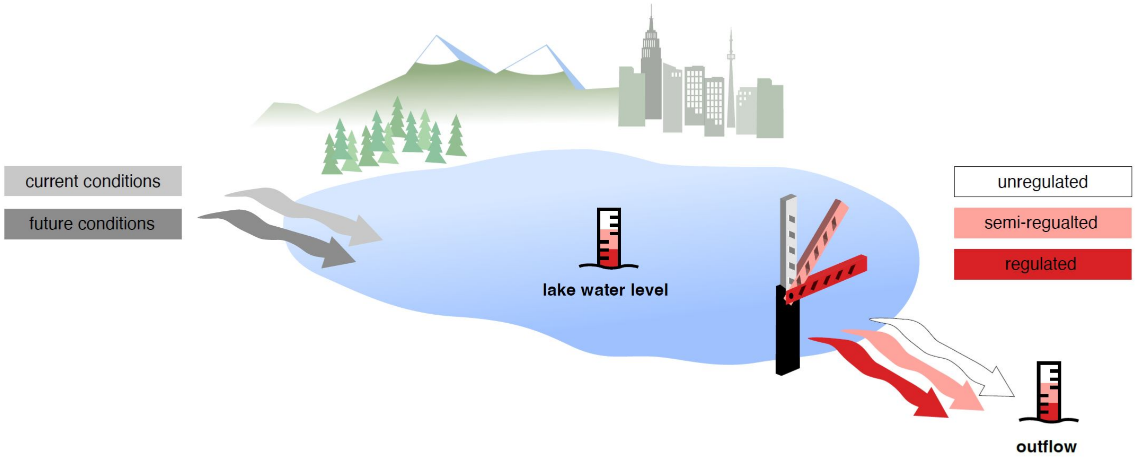


FIGURE 6.1: Graphical Abstract for the paper: lower summer lake levels in regulated perialpine lakes, caused by climate change.

Abstract

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

keywords: lake level regulation, climate change, impact assessment, hydrologic & hydrodynamic modelling, perialpine lakes

6.1 Introduction

Natural and artificial lakes are essential elements of the water cycle, e.g. in terms of habitat, water retention and release, nutrient cycling or flood attenuation. Their hydrologic and limnologic regime is highly likely to be impacted by climate change (CC) in most world regions due to modifications in water input (streamflow) and output (evaporation; Fan et al., 2020; Zajac et al., 2017), but also due to alterations of chemical and physical conditions related to climate warming (Fink et al., 2016; Woolway et al., 2020) and CO_2 concentrations in the atmosphere (Perga et al., 2016). Most CC impact studies on lakes focus on limnologic aspects, i.e. how climate warming modifies temperature (O'Reilly et al., 2015), mixing regimes (Råman Vinnå et al., 2021) or nutrient cycles (Moss, 2012). Ecological studies also analyse how lake level regulation impacts littoral habitats (Aroviita & Hamalainen, 2008; Cifoni et al., 2022) and the work by Zohary and Ostrovsky (2011) discusses that the ecosystem functioning even of deep lakes "respond(s) adversely to excessive water level fluctuations". Despite growing pressure on the European large perialpine lakes (Salmaso et al., 2018) and the apparent importance of lake level variability for ecology and socio-economic activities, hydrologic analyses of lakes in terms of lake level variability are rare (e.g. Hinegk et al., 2022; Hingray et al., 2007; Veijalainen et al., 2010). This represents a critical knowledge gap given that the water level of many large perialpine lakes is heavily regulated to meet numerous natural resources and hazards management goals related to drinking and irrigation water supply, fishery, shipping, energy production, nature conservation, tourism and flood protection (Clites & Quinn, 2003; Hinegk et al., 2022; Hingray et al., 2007). These manifold objectives are generally implemented through lake level management rules that mitigate high and low extremes (AWA, 2014; Veijalainen et al., 2010).

For perialpine lake systems which are influenced by snow and glacier melt, the lake level management typically consists of raising the winter levels (when there is little inflow due to snow accumulation in the catchment) and of lowering the water levels before the melt period onset to avoid flooding (FOEN, 2023g; Gibson et al., 2006a; Hinegk et al., 2022). The question of how CC impacts the resulting lake level variability naturally arises: ongoing CC alters streamflow seasonality (Addor et al., 2014; Muelchi et al., 2021; Rössler et al., 2019) and thus the seasonal water input to lakes as well as evaporative losses (Gibson et al., 2006a).

In their study, Gibson et al. (2006a) investigate how climate and lake level management have influenced water level variability in the Great Slave Lake (Canada) from the mid-20th century. They employ a comparison of pre-regulated and naturalised simulations to disentangle the individual impacts of these factors. The results reveal that lake level regulation has decreased the magnitude of annual water level variations and an earlier occurrence of peak water levels. This shift in timing is attributed to both climatic and regulatory impacts and is consistent with the observed trend of earlier spring snow-cover disappearance since the 1950s.

Large perialpine lakes (Salmaso et al., 2018), the focus of this study, are particularly sensitive to CC due to the CC's pronounced effect on snow and glacier melt (Muelchi et al., 2021). Numerous water resources studies, therefore, focused on the cryosphere's role in modulating how CC impacts streamflow (François et al., 2018; Hanus et al., 2021; Horton et al., 2022). However, the large perialpine lakes were rarely the focus of hydrologic studies; they were often omitted or modelled in a simplified manner. In fact, besides the few modelling studies that specifically target the interplay of streamflow (lake input) and lake levels (Gibson et al., 2006b; Veijalainen et al., 2010; Yu et al., 2022), the vast majority of hydrological modelling studies do not explicitly address the effect of lake level variations or regulations on streamflow, even for catchments including large lake systems (e.g. in the works of Bosshard et al., 2014; Jasper & Ebel, 2016; Legrand et al., 2023; Zischg et al., 2018). According to Paiva et al. (2011), the relatively high computational costs associated with hydrodynamic models, as mentioned in several studies (Hoch et al., 2017; Papadimos et al., 2022), can probably explain the omission of lake level management. To overcome corresponding limitations, the lake system is often considered as the control point (outlet) of the hydrologic model (e.g. Dembélé et al., 2022; Hicks et al., 1995).

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

In this context of missing CC studies on natural perialpine lake water levels, we address the following research question: How does CC impact lake water level variability and how are these impacts modulated by varying levels of lake level management? We selected four Swiss lakes with different levels of lake level management. Compared to previous work (Hingray et al., 2007), the focus on regulated and unregulated lakes allows for disentangling the effect of lake level management and of CC impacts. Our analysis is based on a modelling framework that uses existing streamflow simulations from a catchment-scale precipitation-streamflow model (PREVAH; Speich et al., 2015; Viviroli, Zappa, Gurtz, & Weingartner, 2009) for 39 CC modelling chains as input to a hydrodynamic model (MIKE11; DHI, 2003), for which we developed a specific methodology to account for lake level management rules. The conceptual hydrologic model PREVAH has frequently been used for water resources applications and CC impact studies in Switzerland (FOEN, 2021b; Speich et al., 2015). MIKE11, a 1D hydrodynamic model, is widely used for modelling river systems (Doulgeris et al., 2012), sediment transport (Haghiabi, Zaredehdasht, et al., 2012), water quality (Cox, 2003) and lake systems (Papadimos et al., 2022).

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

6.2 Material and methods

6.2.1 General change assessment framework

In this study, we focus on large natural lakes and do not consider artificial reservoirs. In Switzerland, all large lakes (surface area > 10 km^2), except for two, are managed (Table 6.1 and Figure 6.3). Lake level management affects both the lake water levels and outflows. Accordingly, lake level management is crucial for downstream streamflow dynamics, as all major rivers in Switzerland flow through at least one lake before leaving the country. In today's Swiss context, stakeholder interests both linked to upstream lake water levels and downstream river flow act upon lake level management, regarding ecosystem protection, water supply, further water-dependant economic interests and extreme event prevention (AWA, 2014; FOEN, 2023g).

TABLE 6.1: Characteristics of Swiss lakes with a surface area greater than 10 km^2 (FSO, 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

The analysis framework of our study is based on comparing the current conditions of daily lake water levels and outflows and future conditions under CC. As current conditions, we define the reference period, T_{ref}: 1981–2010, and as future conditions, the three future periods: 2035: 2020–2049, 2060: 2045–2074, 2085: 2070–2099. These periods are typically used in studies with CH2018 data (NCCS, 2018a). The change analysis compares the simulations resulting from each available climate model ensemble member for the reference period and future periods. Thereby, we assume unchanged regulatory practices. The simulations are all based on climate model outputs (also for the reference period). Accordingly, the projected conditions are compared with the simulated current conditions but cannot be directly compared to lake level or outflow observations of the reference period. To disentangle climatic and regulatory impacts on lake levels and outflow, we combine a hydrologic model and a hydrodynamic model (Section 6.2.6) applied to the two catchments I and II (Figure 6.3). For the change assessment, we consider mean annual and mean monthly CC impacts over 30 years. Changes in extremes are assessed based on the 10 % and 90 % percentiles and based on indicators such as the frequency of reaching the drought and flood limits.

6.2.2 Lake level management

In Switzerland, lake levels are regulated by floodgates according to specific regulation diagrams. These are so-called line diagrams (Spreafico, 1980) that define a target lake outflow as a function of the calendar day and of the current lake water level (Figure 6.2). 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, 2023g). The line diagrams result from compromises between level management targets formulated by different stakeholder groups for different periods of the year. Some of them were elaborated based on modelling (Spreafico, 1980). Lake water level targets include, e.g. maintaining sufficiently high levels during winter to guarantee access to harbours or sufficiently high levels during fish spawning periods to ensure habitat availability for selected species (Neumann, 1983). Downstream river flow targets consist of maintaining river flow below flood limits at selected river cross sections (e.g. FOEN, 2020d). A line diagram can be completed by a set of exceptions, e.g. a preventive water level lowering to avoid flood events, a temporary minimum lake water level to ensure navigability or a certain minimum water level fluctuation to satisfy ecological needs (Kaderli, 2021; Spreafico, 1977).

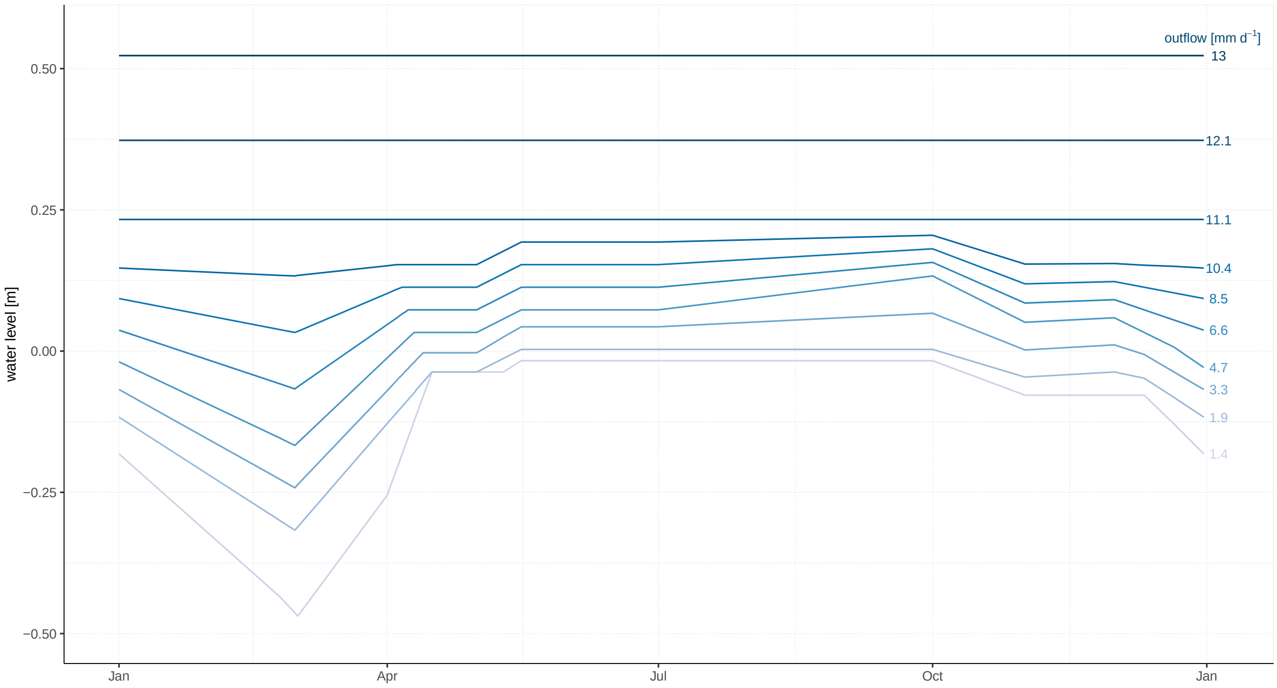


FIGURE 6.2: Example of a line diagram that defines a target outflow (blue lines) for each calendar day (x-axis) and for given lake water levels (y-axis).

6.2.3 Selected case studies

We retained a set of four Swiss lakes (Figure 6.3) 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 interconnected lakes Walen (unregulated) and Zurich (regulated). Catchment II contains the two interconnected lakes Brienz (semi-regulated) and Thun (regulated). The lakes cover between 2 % and 5 % of their hydrological catchment area (Table 6.2). The corresponding catchments show glacier covers between 1 % and 16 %. Catchment I with 1 % has a lower glacier cover than catchment II with 9 % (Table 6.2). Both lake systems have experienced flooding in the recent past (e.g. in the years 1999, 2005 or 2021; FOEN, 2023c; Hilker et al., 2009). The unregulated Lake Walen had very low levels during the recent 2018 drought year (Blauhut et al., 2022; FOEN, 2023c) when the level dropped down to the 97.5 % exceedance percentile. The lowest observed August and September water levels of Lake Walen occurred in the drought year 2003. All lakes show consistently lower lake water levels in winter than in summer (Figure 6.4). For all four lakes, the monthly lowest observed levels date back to the late 1940s, early 1950s (FOEN, 2023b), i.e., before the onset of modern lake level management (Table 6.2).

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

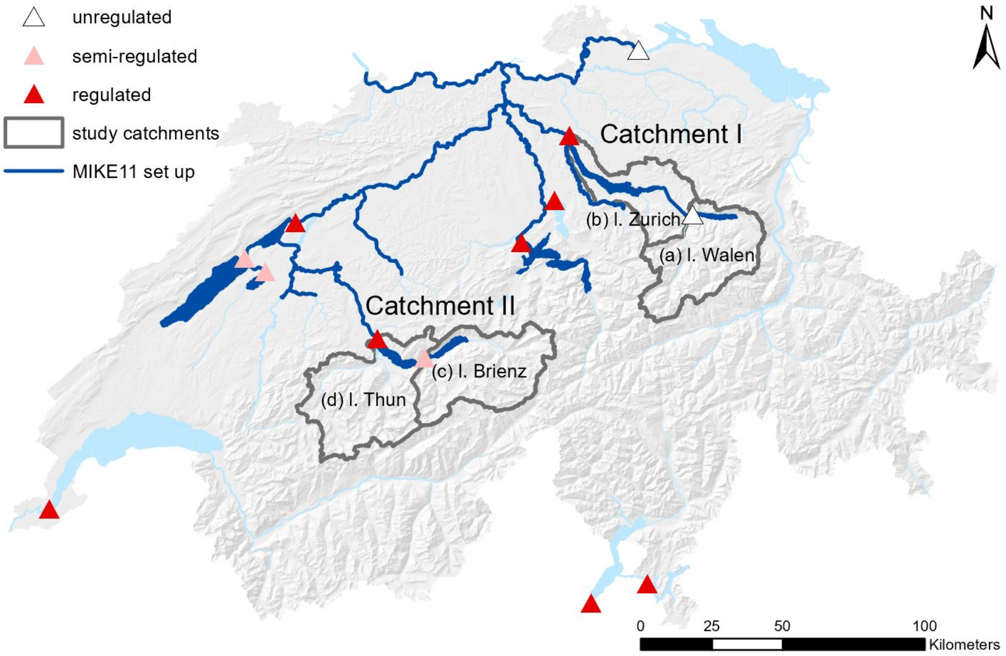


FIGURE 6.3: Location of the four case study lakes, located in pairwise nested catchments I and II. Rivers and lakes in dark blue represent the model set-up of the hydrodynamic model MIKE11. The coloured triangles indicate the level of lake level management of all large lakes (surface area > 10 km^2) in Switzerland.

catchment area. Further downstream, the floodplain was corrected to gain cultural land. As a result of the correction, the mean lake water level of Lake Walen dropped by more than five meters. The outlet floodplain at the downstream of Lake Zurich was also exposed to flood risk (FOEN, 2020c). Around 1900, the mills at the lake outlet were removed and the riverbed deepened. In the 1950s, the 'needle dam' was replaced by a regulating weir, which significantly reduced the annual water level fluctuations, from two meters down to 50 cm (see Figure 6.7 in the Results Section). The lake water level of Lake Brienz has been regulated by a sill since medieval times (FOEN, 2020a). It was removed in 1850 for fishing, shipping and land reclamation, which lowered the lake level by two meters. The lowering left a relatively large fluctuation range without immediate flood risk, which only required a weak regulation, carried out by two floodgates and two small hydropower plants. Similarly to Lake Walen, the main tributary of Lake Thun was diverted directly into the lake, but already 300 years ago. This significantly increased the catchment area (FOEN, 2020b). In addition, mills were removed at the lake outlet to enhance the outflow capacity. The floodgates were built in the late 18th century. However, the outflow capacity remained too low during flood events and even today, there is only a margin of 50 cm between the average summer water level and the flood limit. Consequently, a spillway has been operational since 2009 to increase the lake's outflow capacity during flood events.

6.2.4 Water level regimes

Lake level management reduces the seasonal water level fluctuations as clearly visible by comparing the within-year water level fluctuations of the four studied other lakes (Figure 6.4, top row). The unregulated Lake Walen shows the most natural water level dynamic, which is, however, slightly

TABLE 6.2: Catchment characteristics of the four case study lakes (FSO, 2004; Schwanbeck & Bühlmann, 2023); 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

impacted by the seasonal redistribution of streamflow resulting from the hydropower production along the main tributary (SI Figures 9.3 and 9.4). The lake level of the regulated Lake Zurich is artificially lowered in late winter to provide retention capacity for the melt period in spring and is kept artificially high in summer for touristic purposes and fishery. The lake water level dynamics of Lake Brienz and Lake Thun are less impacted by water correction works than those of Lake Zurich and Lake Walen. The current management rules lead to annual lake water level fluctuations that are more narrow for Lake Thun than for Lake Brienz.

All lakes analysed here are large enough to strongly dampen daily inflow variability, but small enough to not (naturally) dampen the seasonal inflow variability. Accordingly, the annual streamflow cycle, with high flows in summer and low flows in winter (resulting mainly from snow and glacier melt), is clearly visible in all outflow regimes (Figure 6.4, bottom row). Lake level management imprints, however, a modification on the outflow regimes in spring: the melt-related increase in outflow is less steep for the downstream regulated lakes than for the upstream semi- or unregulated lakes. This results from the artificial water level lowering in winter to provide additional retention capacity for snowmelt in spring. The two lakes Brienz and Thun (catchment II) show a higher and longer-lasting summer outflow peak, due to the more snow and glacier melt influence inflow regime (see Table 6.2 and the work of Stahl et al., 2016). Finally, it is important to note that highly dampened lake water level dynamics do not necessarily translate into similarly dampened outflow dynamics (see Lake Zurich and Lake Thun in Figure 6.4). This depends on the stage–discharge relationship and on the line diagram.

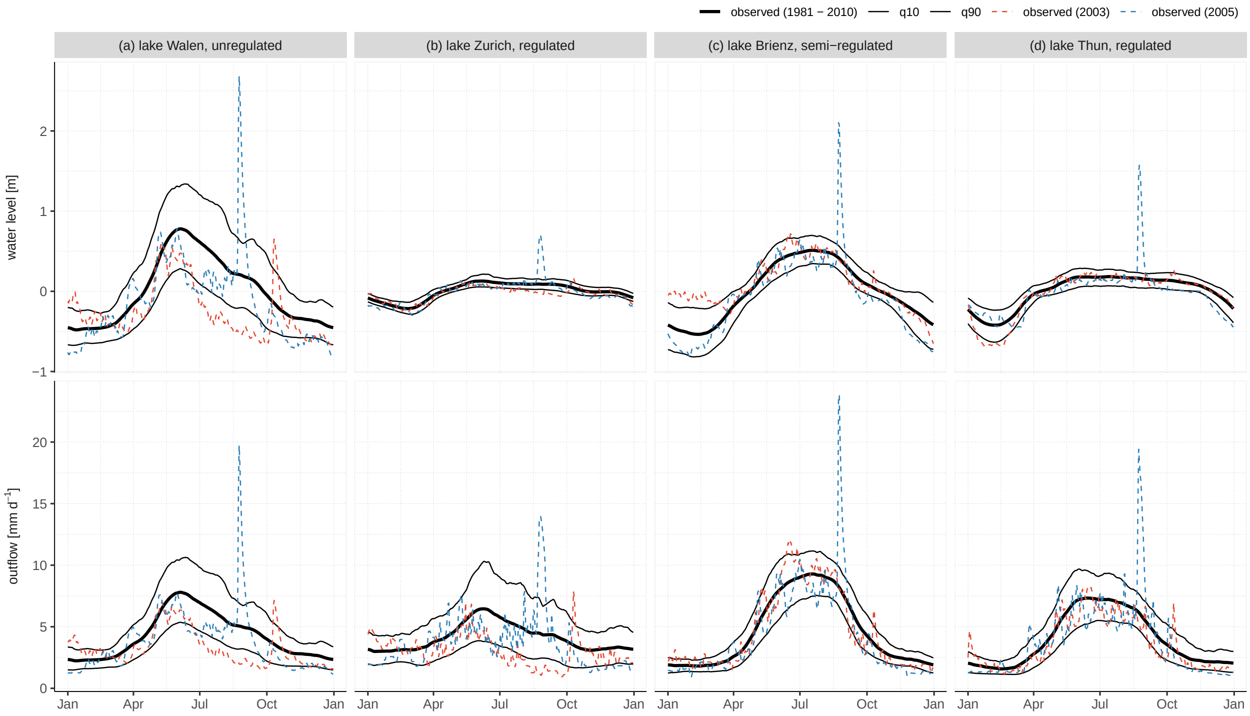


FIGURE 6.4: Observed mean 31-day (moving average ±15 days) lake water levels (top line) and outflows (bottom line) as well as the 10 % and 90 % percentile (confidence interval) for the reference period (1981 - 2010). Also shown is the extreme drought year of 2003 and the flood year of 2005.

6.2.5 Hydrologic climate change scenarios

The transient daily streamflow scenarios used in this study were derived from the latest downscaled and de-biased Swiss CC Scenarios CH2018 (NCCS, 2018a), which are based on the EURO-CORDEX dataset (Jacob et al., 2014). The climate model ensemble CH2018 contains a total of 39 model members for three Representative Concentration Pathways, RCP2.6 (concerted mitigation efforts), RCP4.5 (limited climate mitigation) and RCP8.5 (no climate mitigation measures). The CH2018 ensemble consists of different combinations of Regional Climate Models (RCMs) and General Circulation Models (GCMs) and the ensemble members are listed in Table SI 9.3. The model ensemble provides daily air temperature, precipitation, relative humidity, global radiation and near-surface wind speed (Brunner et al., 2019).

6.2.6 Hydrologic and hydrodynamic models

The CC scenarios were translated into streamflow scenarios (FOEN, 2021b) with the conceptual hydrologic model PREVAH (PREcipitation streamflow EVApotranspiration HRU related Model; Viviroli, Zappa, Gurtz, & Weingartner, 2009) in its spatially explicit version (Speich et al., 2015). PREVAH computes streamflow by solving the water balance equation and uses air temperature, precipitation, potential evapotranspiration, wind speed, global radiation, sunshine duration and relative humidity as input. The model was previously calibrated for diverse water resources applications in Switzerland (Bernhard & Zappa, 2009; Köplin et al., 2014; Speich et al., 2015). It accounts for snow accumulation, snow and glacier melt, evapotranspiration, soil infiltration, water release via surface and subsurface runoff and streamflow routing (Brunner et al., 2019). PREVAH considers the seasonal redistribution of water resulting from high-head accumulation hydropower plants in a simplified manner: it does not use exact water turbining schedules but it contains the main diversions and dams in the headwater of our study area (SI Figures 9.3 and 9.4). The model has recently been improved in terms of both snow accumulation simulation at high elevations (Freudiger et al., 2017) and glacier evolution simulation (Brunner et al., 2019). PREVAH includes a rough simulation of the lake dynamics, with a simple mass balance approach assuming the filling of a reservoir with a fixed area and a known stage–discharge function. This allows to simulate the water retention but not lake level management.

The hydrodynamic model MIKE11 is a 1D routing model developed by the Danish Hydraulic Institute (DHI, 2003; Papadimos et al., 2022) and allows for the modelling of river systems, including reservoirs and lakes, and their associated regulation structures. It was previously set up and calibrated by the FOEN for several large Swiss rivers and lakes (Figure 6.3) and is used for real-time simulation of lake levels during flood events (Inderwildi & 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 6.2.6.1). The model allows the specification of the cross-sections, such as river geometry, roughness, lake characteristics to capture the hydraulic behaviour (DHI, 2003). To simulate the fluid dynamics, MIKE11 employs the Saint-Venant equation, which accounts for flow velocity, water depth, and channel slope. Furthermore, lakes are modelled as a control volume at a cross-section at the lake outlet following the stage–discharge relation for natural lakes or the lake level management rules for regulated lakes, as defined in a look-up table. The time-dependent lake level management rules define a target lake outflow as a function of the calendar day and the current lake water level. The lake outflow changes when the lake water level exceeds a certain limit, defined in the lake level management rules. The combination of the hydrologic and hydrodynamic models is essential to assess the CC impacts on water-level-outflow dynamics, which is an expression of a complex balance of interests. MIKE11 is run at a one-minute time step (a numerical choice related to its use in real-time applications), which we aggregate to daily values. For model evaluation purposes, we assess the model performance (Section 6.3.1) by comparing daily observed lake water levels and outflows to simulated values (Table SI 9.2), where the simulations are obtained with observed meteorological data from the reference period (rather than with the climate model outputs). We assume that the model developed with observed input data remains valid with the downscaled climate model outputs as input, a standard assumption in comparable studies.

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

6.2.6.1 Lake and river characteristics

The lake and river characteristics described here are used for the hydrodynamic simulations with MIKE 11 (Section 6.2.6). 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. All data is available in the provided data set (Wechsler et al., 2023a). The stage-area relationships were determined for different elevations and areas by the Federal Office for the Environment (FOEN), which we then linearly interpolated. For the unregulated Lake Walen, the observed stage–discharge relation is parameterised by constructing a median observed lake level for observed discharges and then extrapolating the relation between discharge and stage with a polynomial function (degree 3). The cross-sections, used for the hydrodynamic simulations (Section 6.2.6) are surveyed by the FOEN every 10 years (FOEN, 2023d). This data is assumed to remain constant throughout the entire simulation period.

6.2.7 Climate change impact assessment

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

$$\Delta h_m = \frac{1}{n_{m,fut}} \sum_{\forall i \in m} h_{i,fut} - \frac{1}{n_{m,ref}} \sum_{\forall i \in m} h_{i,ref} = \overline{h_{m,fut}} - \overline{h_{m,ref}}, \tag{6.1}$$

where Δh_m [m] is the future monthly lake level change of month m, computed based on the daily simulations $h(t)$. n_m is the number of daily simulation steps within a month over the 30 years period. For February, the number of future time steps $n_{m,fut}$ can differ from the number of reference time steps $n_{m,ref}$. The average annual change (Δh_a) is computed analogously. The relative annual and monthly mean changes in lake outflow (ΔQ_m) are computed as:

$$\Delta Q_m = \frac{\frac{1}{n_{m,fut}} \sum_{\forall i \in m} Q_{i,fut} - \frac{1}{n_{m,ref}} \sum_{\forall i \in m} Q_{i,ref}}{\frac{1}{n_{m,ref}} \sum_{\forall i \in m} Q_{i,ref}} = \frac{\overline{Q_{m,fut}} - \overline{Q_{m,ref}}}{\overline{Q_{m,ref}}}. \tag{6.2}$$

The CH2018 projections are more reliable in capturing long-term changes in general trends than changes in extremes, due to the larger sample size of long-term means (NCCS, 2018a). However, short-duration extreme events (daily to hourly scale) have less significant impacts on large lake systems. Therefore, we analyse the changes in extreme lake water levels and outflows in two ways: (1) by using the 10 % and 90 % percentiles of a moving average over 31 days (± 15 days) and (2) by looking at changes in frequency indicators. The flood frequency indicator (I_F) describes the average number of days per month m (or per year a) for which the simulated daily lake water level $h(t)$ exceeds the flood limit (F), which is the critical water level that would lead to damage to infrastructure (defined for each lake, the so-called hazard level 4 (FOEN, 2023a)):

$$I_{F,m} = \frac{\sum_{\forall i \in p} (h_i > F)}{n_p}, \tag{6.3}$$

where n_p is the number of years in the simulation period p (n_p=30 for all periods). The critical (hazard) water levels are given in Table 6.2. There are no comparable critical low-water level limits but critical low-outflow levels, for which we define an additional indicator: The low-outflow frequency indicator (I_L) describes the average number of days per month, for which the simulated daily outflow $Q(t)$ undercuts the drought limit (L):

$$I_{L,m} = \frac{\sum_{\forall i \in p}(Q_i < L)}{n_p}, \tag{6.4}$$

where (L) is the minimum outflow, specified in the lake level management rules for regulated lakes. For semi-regulated and unregulated lakes, we choose a value corresponding to the 30-year return period (Table 6.2).

6.3 Results

6.3.1 Model validation

The model combination demonstrates a good agreement with the observed lake water levels (Figure 6.5) and with the observed outflows (Figure 6.6). The fit to water levels and outflows is significantly better than for the hydrologic model alone, not only for the regulated lakes but also for the unregulated Lake Walen. The simulated monthly lake water levels and outflows with the hydrologic-hydrodynamic framework and using the streamflow scenarios (Hydro-CH2018) show a certain deviation form the observed levels. This deviation is inherited from the hydrologic simulations that do not perfectly reproduce the observed mean monthly averages for the reference period (Brunner et al., 2019). On an annual basis, the simulations effectively capture the seasonal variations.

By combining the hydrologic and the hydrodynamic models, we enhance the model's ability to simulate daily lake water levels and outflows (Table 6.3). The computation time for the 39 model members over the entire period (1981–2099) on a personal computer with 64 gigabytes of RAM and 20 cores takes one day for the hydrologic model and one week for the hydrodynamic model.

TABLE 6.3: 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 & Lebel, 2009) and the percent volume error (DV).

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

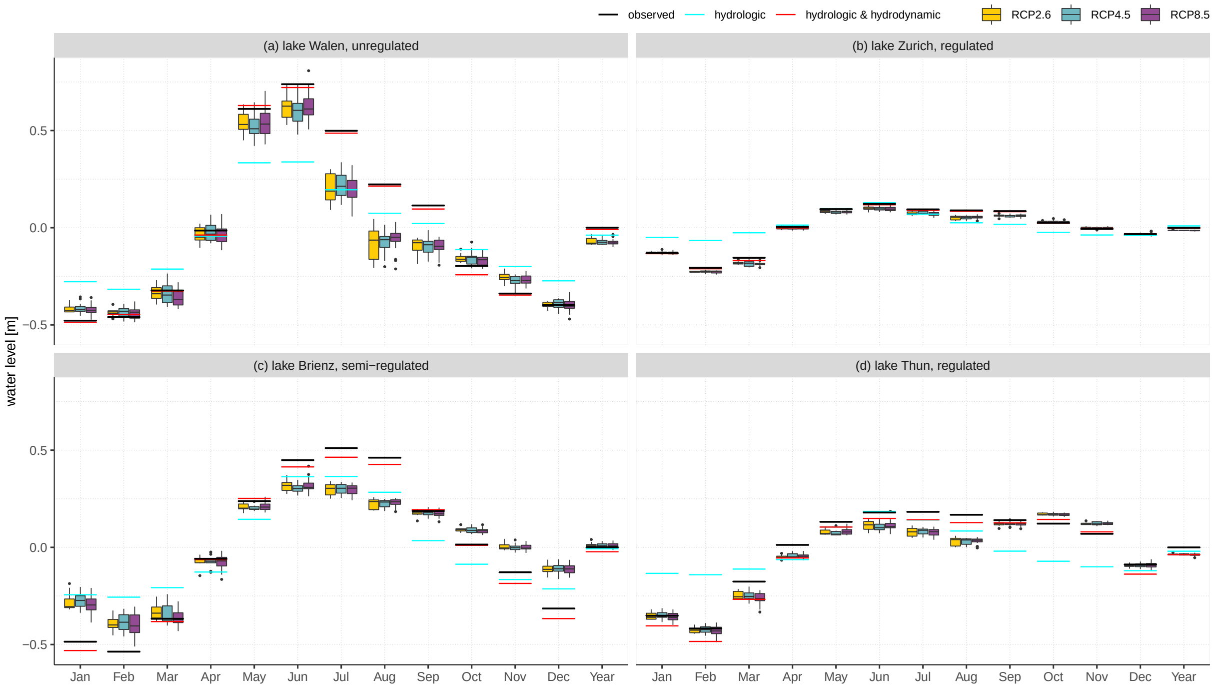


FIGURE 6.5: Normalised observed and simulated annual and monthly lake water levels for the four considered lakes during the reference period (1981–2010). The observations are compared to the hydrologic simulations with PREVAH and to the combination of the hydrologic and hydrodynamic models PREVAH and MIKE11. The coloured boxplots show the model variability of the 39 streamflow scenarios, divided into three emission scenarios (RCP2.6, RCP4.5 and RCP8.5).

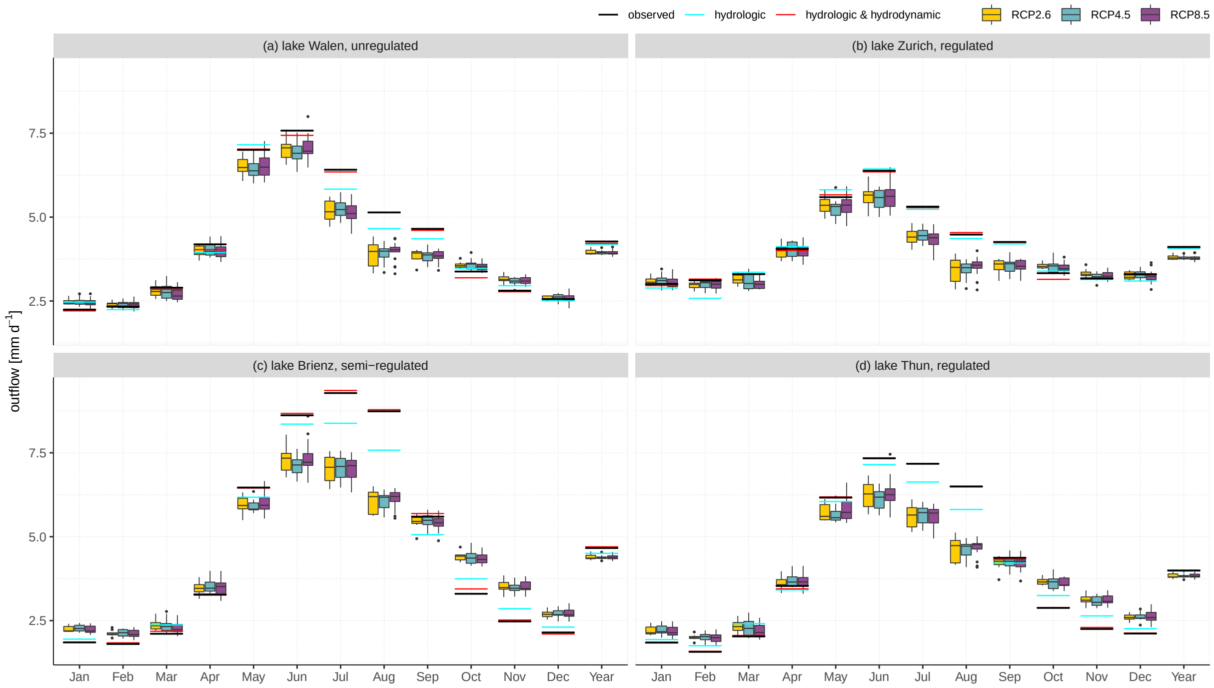


FIGURE 6.6: As Figure 6.5 but for the normalised observed and simulated annual and monthly lake outflows for the four considered lakes.

6.3.2 Climate change impact projections on lakes

6.3.2.1 Change in mean water levels and outflows

Figure 6.7 shows the observed and projected annual lake level variations for all four lakes, which underlines that historic lake level changes due to river diversion works (Lake Walen, Lake Brienz) and the introduction of lake level management (Lake Zurich, Brienz, Thun) had a far more substantial impact on annual lake levels than projected CC.

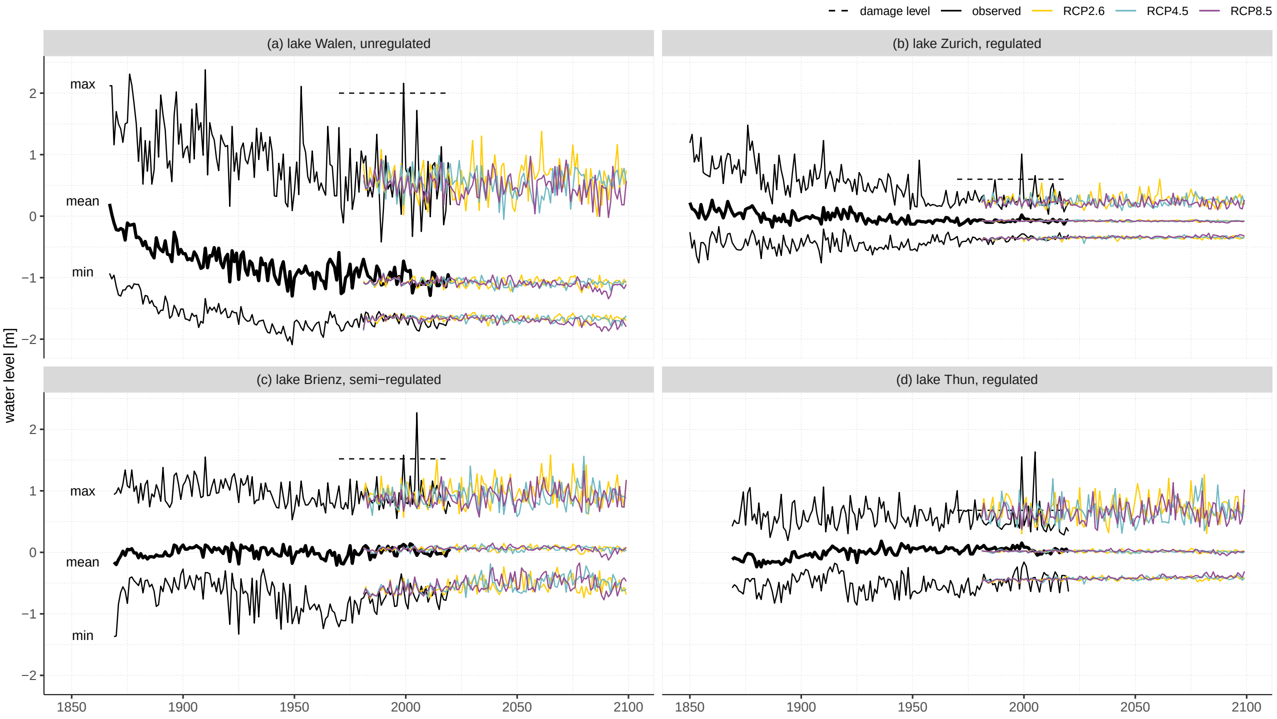


FIGURE 6.7: Normalised observed annual lake level variations: Shown are the observed annual mean, minimum and maximum water levels between 1850 and 2020 (black) and the future scenarios (Section 6.2.5) until the end of the century under CC (RCP2.6, RCP4.5, RCP8.5). The dashed line indicates the current flood limit for each lake.

The simulations indicate a slight annual decrease in lake water levels for all four lakes, but a significant redistribution from summer to winter (Figure 6.8). This redistribution intensifies with time (2085) and without climate mitigation measures (RCP8.5). The extent of lake level management of a lake has a direct impact on the simulated lake water level changes: for Lake Zurich, which is the most strongly regulated lake of the four (Figure 6.4), changes range from -0.05 m in summer to +0.04 m in winter. Lake Thun, also regulated, exhibits changes between -0.14 m and +0.08 m. The semi-regulated Lake Brienz shows changes ranging from -0.25 m to +0.19 m, while the unregulated Lake Walen shows the largest variations, with -0.40 m in summer to +0.30 m in winter. Monthly changes in lake water levels are shown in Figures SI 9.5, 9.9, 9.15 and 9.21.

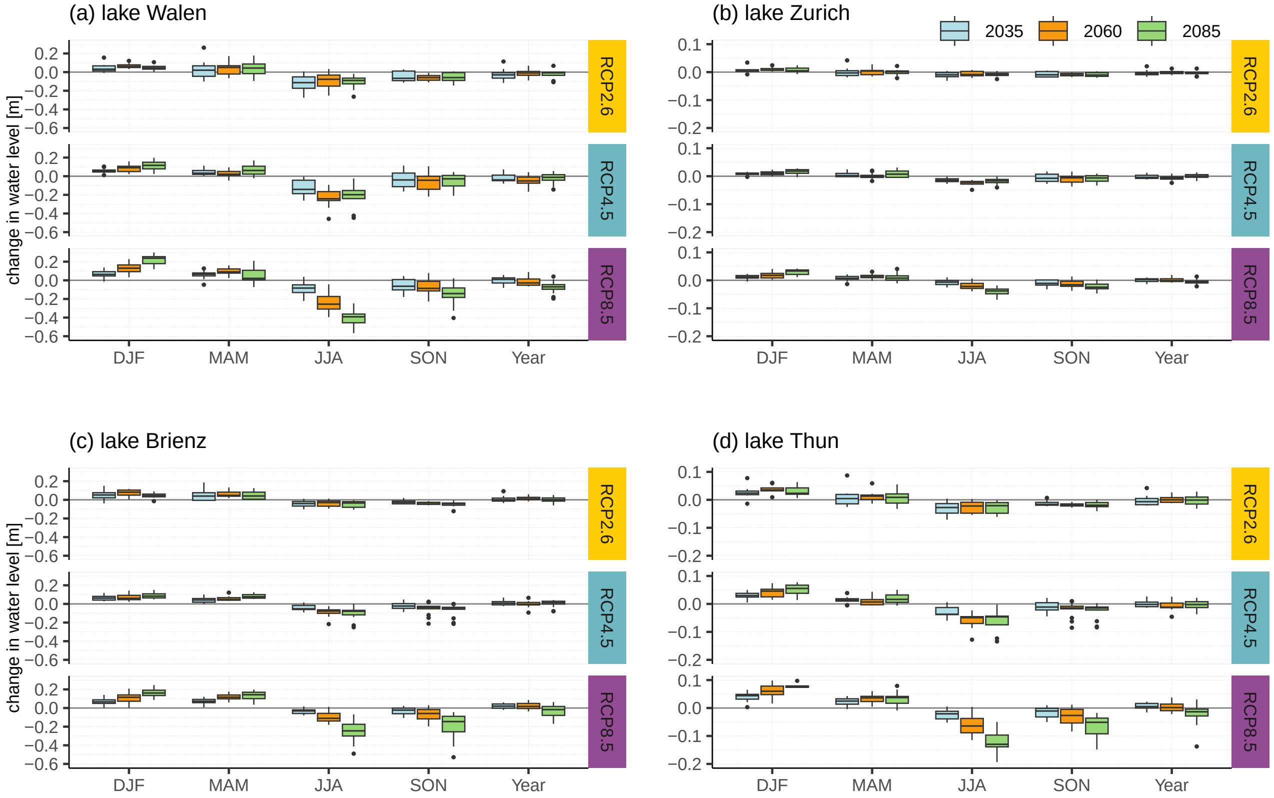


FIGURE 6.8: Simulated changes in seasonal mean lake water levels of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated), divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

Despite the simulated lower summer lake water levels, summer remains the season with the highest lake water levels. Towards the end of the century, the glacier- and snowmelt-influenced regime of lake water levels is still noticeable. However, the simulated mean melting peak ($q50$ = 50 % percentile in Figure 6.10) for the unregulated Lake Walen shifts from currently June to May and is expected to drop by 0.50 m due to less melt contribution. This temporal shift is not simulated for the two regulated and the semi-regulated lakes, which still follow the temporal level management rules (Figures SI 9.11, 9.17 and 9.23). However, a lower mean lake water level ($q50$) in late summer is visible for the regulated and semi-regulated lakes. For the lakes Brienz and Thun, the mean summer water levels decrease down to the current 10 % percentile. In conjunction with higher winter water levels, the simulation indicates a more balanced lake level regime for the end of the century, with less seasonal fluctuation on average.

The simulations for annual outflows also indicate relatively small changes, reaching up to -10 % without CC mitigation measures (RCP8.5) by the end of the century (Figure 6.9). As seen in observed data (Figure 6.4), the level of lake level management has a smaller impact on lake outflows than on the lake water levels. This is also true for the simulated outflow changes (median): for the unregulated Lake Walen, a change of -35 % in summer and +21 % in winter is simulated, while for the regulated Lake Thun, the changes range from -39 % in summer to +22 % in winter. The changes in summer outflow intensify with the mean catchment elevation and with the share of glacier cover: the glacier area for catchment II is 8 times higher than for catchment I and the mean catchment elevation is 521 m higher (Table 6.2). The simulations for the semi-regulated Lake Brienz and the regulated Lake Thun indicate a more significant change in summer outflow (median) with -39 %, compared to -35 % for Lake Walen and -31 % for Lake Zurich. The monthly changes in outflows are even more pronounced than the seasonal changes (see Supplementary Information, Figures SI 9.6, 9.10, 9.16 and 9.22).

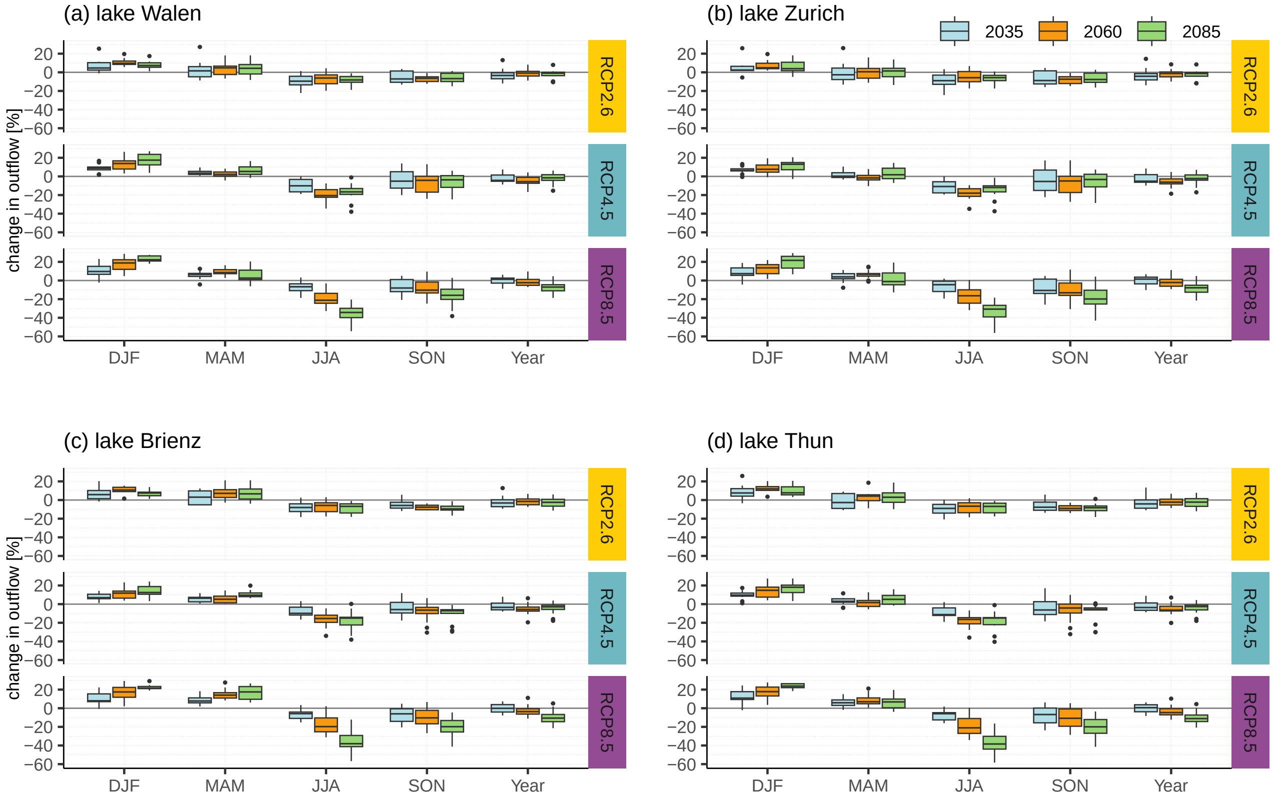


FIGURE 6.9: As Figure 6.8 but for the simulated changes in seasonal outflows.

The simulations indicate that mean peak outflows ($q50$ in Figure 6.11 and Figures SI 9.12, 9.18 and 9.24) continue to occur in June and little change is expected in terms of timing and magnitude, for all four perialpine lakes. Significant changes of lake outflows are simulated throughout the year: as a result of higher winter outflows and lower summer outflows, the simulated outflows show, already by mid-century, lower summer outflows than in winter (today, we see exactly the opposite). The simulated average summer outflows ($q50$ in Figure 6.11, Figures SI 9.12, 9.18 and 9.24) are roughly reduced to 50 % compared to the reference period and towards the end of the century.

6.3.2.2 Change in extremes

The simulations indicate an increase of high-water levels ($q90$) in winter but remain lower than in summer (Figure 6.10 and Figures SI 9.11, 9.17 and 9.23). The simulated high-peak lake water levels ($q90$) occur in early summer, similar to the reference period, and decrease noticeably throughout the summer. For the low-water levels ($q10$), the simulations indicate an increase in winter and a significant decrease in summer and autumn. Due to lake level management, the lake water level of the regulated lakes Zurich and Thun are artificially lowered in late winter (Section 6.2.4). For the two regulated lakes Zurich and Thun, and similarly for the semi-regulated Lake Brienz, less pronounced changes in the 90 % and 10 % percentiles and smaller shifts of the seasonal pattern are simulated (Figures SI 9.11, 9.17 and 9.23). The lowest $q10$ for these lakes continue to occur during winter. For the unregulated Lake Walen, the simulations indicate a decreases in $q10$ during summer and autumn and fall below the winter low-water levels of the reference period (Figure 6.10). Consequently, the lowest $q10$ in Lake Walen could shift from winter to late summer in the future. Similarly to the mean lake water levels, the $q90$ and the $q10$ also indicate more pronounced changes with time and without CC mitigation measures (RCP8.5).

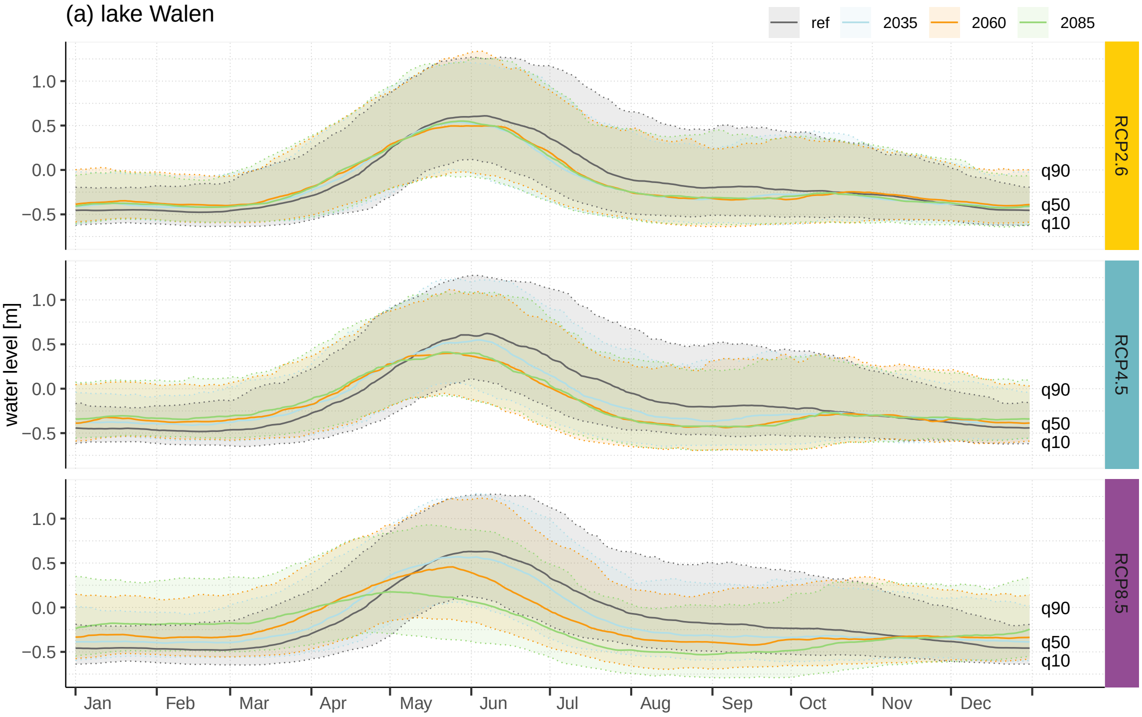


FIGURE 6.10: Simulated changes in the 10 % ($q10$) and 90 % ($q90$) percentiles of lake water levels (moving average ±15 days) of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

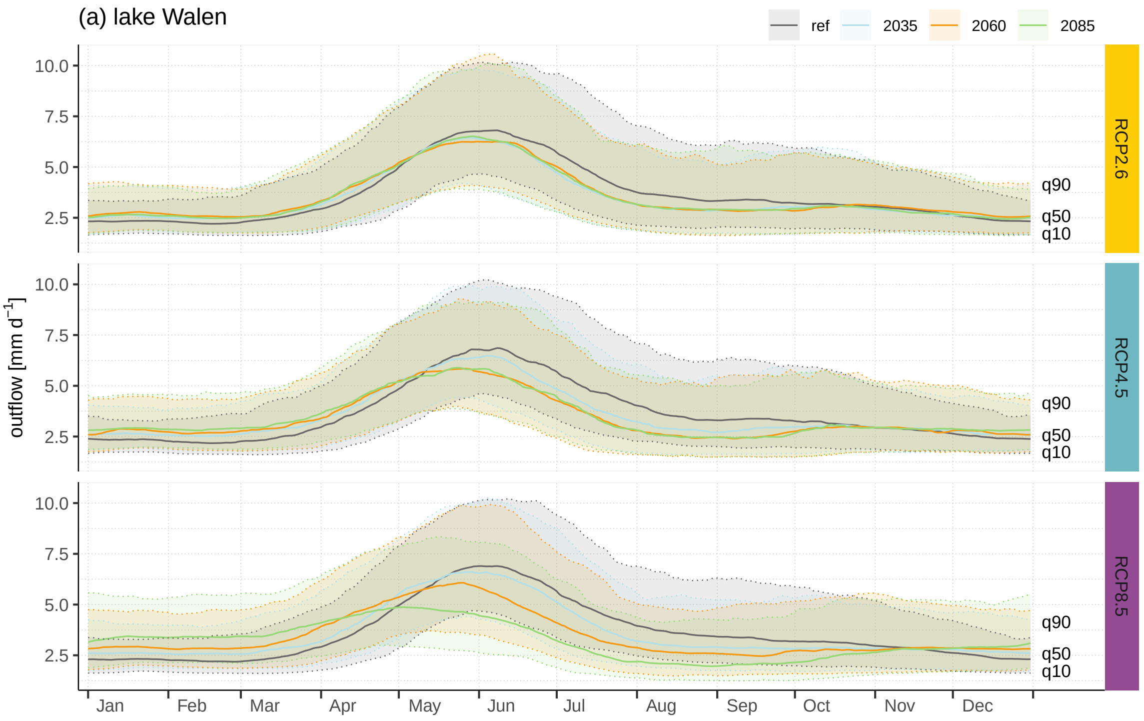


FIGURE 6.11: As Figure 6.10 but for the simulated changes in the 10 % (*q*10) and 90 % (*q*90) percentiles of outflows of Lake Walen.

For the simulated high (*q*90) and low (*q*10) outflows, the level of lake level management has a lower impact compared to lake water levels (Figure 6.11 and Figures SI 9.12, 9.18 and 9.24). Outflow changes in both the 90 % and 10 % percentiles are visible in the simulations, with increases in winter and decreases in late summer. The simulated peak outflows (*q*90) continue to occur in June and show little changes in terms of timing and magnitude. A significant decline of *q*90 is simulated in late summer high-outflows, approaching or even falling below the average outflows (*q*50) during the reference period. The simulated *q*10 in winter indicate a noticeable increase, approaching the *q*50 outflows of the reference period. By the end of the century and without CC mitigation measures (RCP8.5), the lowest outflows are simulated in late summer; for the two lakes of catchment I, for Lake Walen and Lake Zurich (Figure 6.11 and Figures SI 9.12), late summer *q*10 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 6.2), does not indicate clear changes. In the simulations, there are some occasional outlier years, but no significant trend is visible (Figures SI 9.7, 9.13, 9.19 and 9.25). For the reference period (and for observed data, not simulations), flood limit exceedences were only observed in May 1999 and August 2005. Only for Lake Thun, there were four additional occurrences where the flood limit was exceeded, all taking place between June and August. Our monthly projections do not indicate clear changes throughout the century under any of the emissions scenarios. The frequency indicator for droughts (*L*), which counts the average number of simulated days with the water level falling below a defined minimum outflow (Table 6.2), indicates an increasing trend in the CC simulations (Figure 6.12). Lakes with a higher level 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 it significantly increases by the end of the century and with missing CC mitigation meassures. On the other hand, the two lakes in the lower catchment I show an increasing trend throughout the entire century. For the regulated Lake Zurich, an increase of 400 % up to 60 days per year under the emission scenario RCP8.5 is simulated for the end of the century. This corresponds to an increase of 45 days compared to the reference period, with a strong increase in summer and autumn. The unregulated Lake Walen also shows strong increases of 400 % but, with up to 8 days per year, on a much lower level (monthly variations are depicted in Figures SI 9.8, 9.14, 9.20 and 9.26).

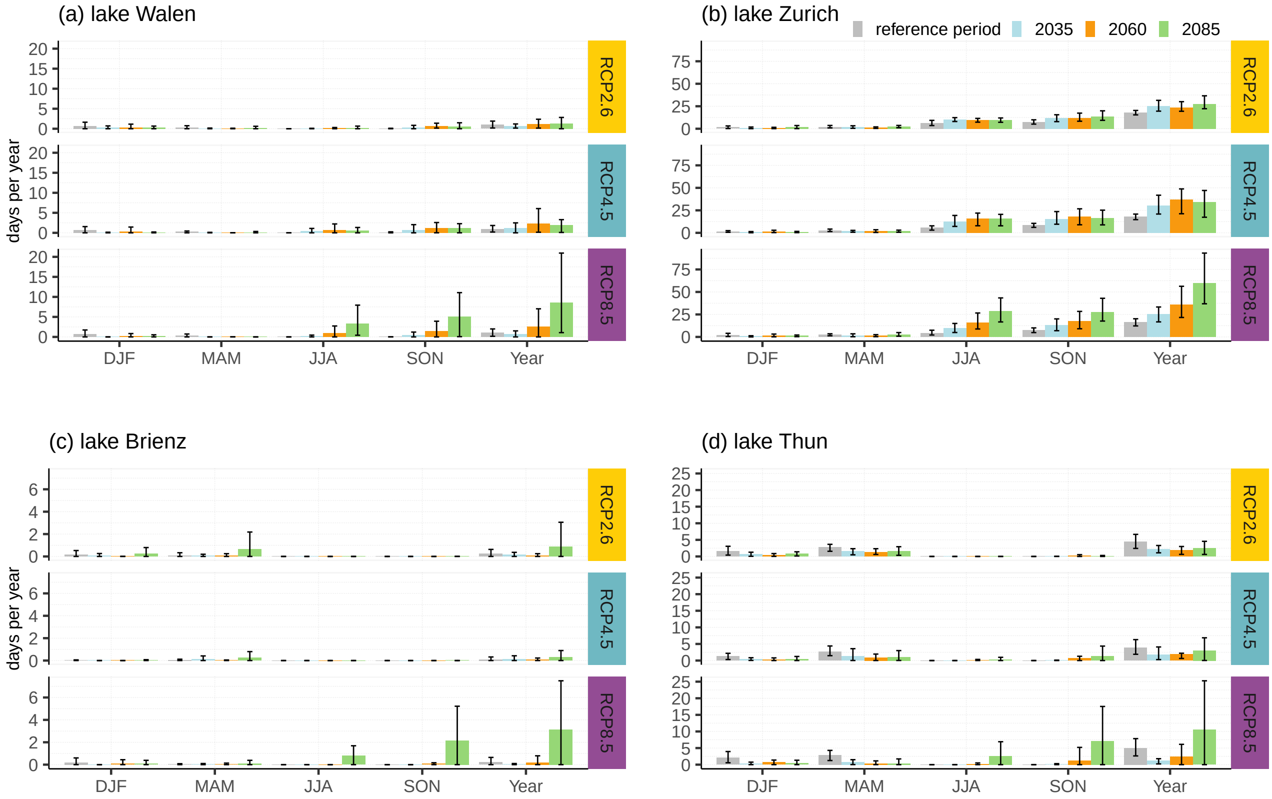


FIGURE 6.12: Simulated changes in days per month and per year the outflow undercuts the drought limit (L) of Lake Walen (unregulated), Lake Zurich (regulated), Lake Brienz (semi-regulated) and Lake Thun (regulated). Error bars refer to the 10 % and 90 % percentile range.

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

The simulations of lake water levels and outflows for the studied lakes show a slight decrease of annual lake water levels across all four lakes and a significant redistribution from summer to winter. The simulated changes intensify with time and particularly in the absence of CC mitigation measures. The level of lake level management has a direct impact on the simulated changes: regulated lakes exhibit smaller variations of a few centimeters compared to the unregulated Lake Walen, which shows variations of up to 0.39 m. Summer remains the season with the highest lake water levels, despite the drastic decrease in summer. For the unregulated Lake Walen, the simulations show a temporal shift in the melt-influenced peak from June to May by the end of the century; for the regulated lakes, no similar shift is simulated. Additionally, the simulations indicate a more balanced seasonal lake level regime, with less seasonal fluctuations due to higher winter lake levels. For annual outflows, the projected reductions of up to 10 % are smaller than the projected seasonal redistribution, which ranges from -39 % in summer to +21 % in winter. The impact of lake level management on outflows is less significant than for lake water levels. Changes in summer outflows are more influenced by the mean catchment elevation than by the level of lake level management. The simulations also show changes in extremes, with decreases in high-water levels (90 % percentiles) in summer and autumn and also with decreases in low-water levels (10 % percentiles) in late summer already for the near future. For the unregulated Lake Walen, the lowest lake water levels may shift from winter to late summer by mid-century. Based on our simulations, the indicator for drought frequency is expected to increase, particularly in lakes with a higher level of lake level management and lower catchment elevation. Flood frequency does not exhibit clear changes between the reference period and the end of the century for none of the emissions scenarios.

6.4 Discussion

The presented data set as well as our simulations show the extremely strong influence of lake level management on the lake water levels of the analysed perialpine lakes (Figure 6.4). This emphasises the importance of incorporating lake level management in hydrologic simulations. Furthermore, our simulations show that combining a hydrologic and hydrodynamic model significantly improves the model performance for lake outflows, especially for lake water levels (Section 6.3.1). The enhanced model performance specifically for regulated lakes (Table 6.3) underlines again the importance of considering lake management in hydrologic simulations. Depending on the level of lake level management CC affects lake water levels and outflows differently in magnitude and timing. The study by Gibson et al. (2006a) attributes the observed shift in peak water levels to climatic and regulatory impacts. In contrast, our simulations of the unregulated perialpine lake indicate a seasonal shift in the peak-melt water level occurring one month earlier (Figure 6.10), which aligns with the findings of other studies (Muelchi et al., 2021; Stahl et al., 2022). However, we do not observe a seasonal shift for the regulated lakes (Figures SI 9.11 and 9.23), and only a minor shift is observed for the semi-regulated lakes (Figure SI 9.17). These findings are crucial regarding the transferability of our results, as it suggests that similar analyses should be completed for other perialpine lakes to confirm this result.

The presented solution of using a hydrodynamic model resulted in a sevenfold increase of the computational costs and an increase of input data (the cross sections), compared to only using the hydrologic model. This increase in overall modelling work is related to the choice of simulating the entire lake system and the connecting water ways with the hydrodynamic approach at a 1 minute resolution. This temporal resolution was selected because the model is also used for real-time purposes. Besides the computational and data costs, the modelling solution presented here has the significant limitation that the software is not open source or freely available. The question arises as to whether a more straightforward approach, such as using time-dependent (e.g. in 2-week intervals) stage–discharge relations, could be employed to incorporate lake level management in a simplified manner into the hydrologic model. This is left for future work.

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

The simulations of the future annual water balance in catchments I and II (Figure 6.3) show changes in precipitation, evapotranspiration and icemelt contribution (Figure 6.13). On the input side, the simulations indicate no clear trend in precipitation for both catchments; for catchment II, the icemelt contribution is simulated to increase slightly in the near future and will decrease from mid-century on. The glacierised area in catchment I is very small (Table 6.2) and its change under the CC scenarios is hardly noticeable in the lake input simulations used for the current study. On the output side, the simulations show an increasing water loss via evapotranspiration for both catchments, intensifying with time and missing CC mitigation measures. This increase of ET leads to an overall reduction of simulated streamflow throughout all simulated periods, with a more substantial decrease in the higher-elevation catchment II for all periods, despite the increased melt contribution in the near future (2035) compared to the reference period.

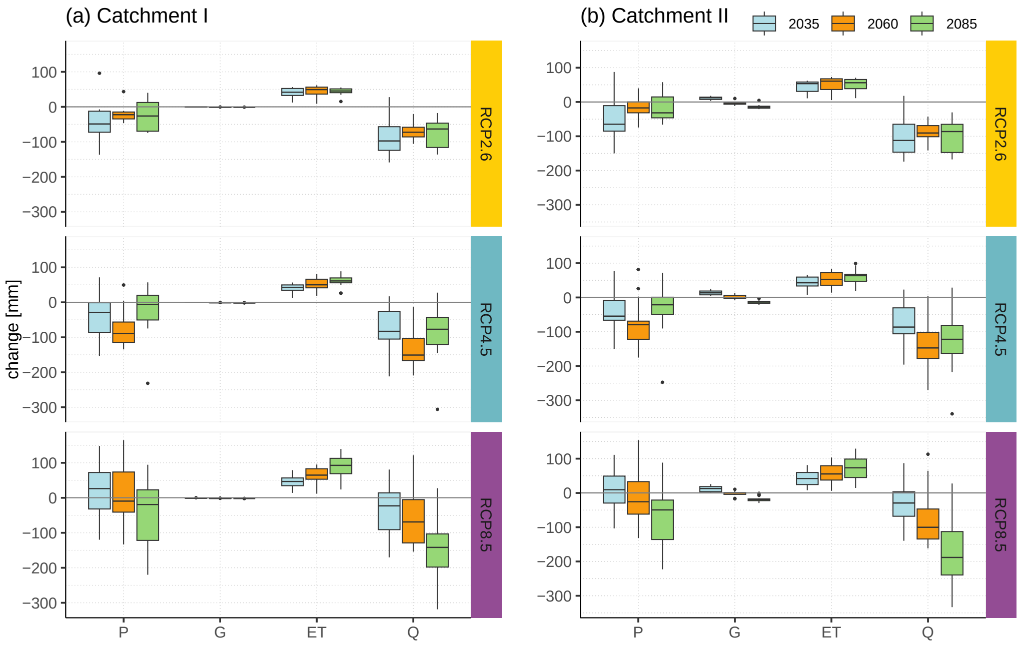


FIGURE 6.13: Simulated CC-induced changes in precipitation (P), glacier melt contribution (G), evapotranspiration for the entire catchment area (ET) and streamflow (Q) for catchment I (Lake Walen and Lake Zurich) and catchment II (Lake Brienz and Lake Thun).

Our CC simulations further show a strong seasonal redistribution pattern of mean monthly lake water levels and mean outflows, with a water level decrease in summer of up to 0.39 m for the unregulated lake and between 0.05 m and 0.22 m for the regulated and semi-regulated lakes (RCP8.5, 2085). This seasonal redistribution is in agreement with published streamflow regime changes (Muelchi et al., 2021; Rössler et al., 2019) and is, among other things, a consequence of higher temperatures and the associated higher snowfall line, leading to less snow-storage and more streamflow in winter and to less snowmelt in spring and summer (Muelchi et al., 2021; Stahl et al., 2016). This redistribution due to reduced snowfall and snowmelt is enhanced by increased losses by evapotranspiration (Figure 6.13) and a decrease in summer precipitation by up to 39 % by the end of the century (NCCS, 2018a). Additionally, a reduced snow-cover extent leads to longer periods when larger catchment areas are not snow-covered (Brunner et al., 2019; Woolway et al., 2020) and consequently to more losses through evapotranspiration. The glaciers in the simulated catchments are already to date too small to significantly compensate for this reduction of available water. The potential CC-induced changes to lake water levels and outflows can accentuate the pressure from competing water uses, especially in the case of water shortages (Brunner et al., 2019; Kellner, 2021). Our simulations suggest that especially Lake Zurich could face serious drought problems in the future, with more than 35 days per year where the drought limit is not met for the intermediate scenario RCP4.5 by 2060 already (Figure 6.12). 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, 2018a), our results show no clear changes (Figures SI 9.7, 9.13, 9.19 and 9.25). This can be explained by the reduced contribution from snowmelt, which despite of being more concentrated in time, leads to less critically high-water levels.

It is important to keep in mind that we assume current lake level management practices remain constant for future simulations, which permits disentangling climatic and regulatory impacts. A limit of our work is, however, the existing hydropower production in the headwater catchments of the analysed lakes (Figures SI 9.3 and 9.4), which results in transferring water from summer to winter, which complicates the ability to entirely disentangle the climatic and regulatory impacts. In this study, we do not consider potential adaptation measures for lake level management practices. Nevertheless, these projections can provide a foundation for considering potential adjustments in the early stages. Finally, we would like to underline that our results should not be used to judge as far as lake level management can be used as a CC adaptation measure. In fact, (1) lake level management controlled by floodgates may conflict with diverse interest groups such as the negative ecological impacts caused by smaller fluctuations in lake water levels (Wantzen et al., 2008), (2) it may affect the longitudinal disconnection of aquatic habitats (Erős & Campbell Grant, 2015; Stanford & Hauer, 1992) and (3) despite the controlled lake outflow, smaller lake water level changes do not necessarily lead to less water scarcity or enhanced resilience (Kellner, 2021).

Finally, the projected changes in our study are limited to water supply and do not consider changes in water demand. In particular, such changes could become evident on a large scale with more frequent and severe drought years (Spinoni et al., 2016; Vicente-Serrano et al., 2022). As Brunner et al. (2019) demonstrate, low-water levels can result in reduced outflows, imposing restrictions on competing water uses. However, it is important to note that low-water levels can also lead to elevated water temperatures (Michel et al., 2021), negatively impacting water quality (Hinegk et al., 2022) and exerting additional pressure on aquatic habitats (Salmaso et al., 2018; Woolway et al., 2020). 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, 2023c). Our results, 30-year annual and monthly mean values, describe long-term trends, but no interannual variability. Future work could investigate the interannual variability, aiming to enhance our comprehension of year-to-year variations and estimate the occurrences of extreme events, including the possibility of several extreme years in a row.

6.5 Conclusion

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

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

The main findings of our study are as follows:

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

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

Acknowledgement

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

Competing interests

The authors declare no conflict of interest.

Data statement

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

7 Synthesis

The three climate change (CC) impact assessments of this thesis apply a change framework based on transient streamflow projections. This change framework is employed to assess the CC impact on Run-of-River (RoR) electricity production, environmental flow requirements, and lake level variability. The novelty of this change framework lies in its use of transient streamflow projections and the consideration of the CC impact on technical, legal, and ecological aspects. RoR electricity production and large perialpine lakes are characterised by their stabilising effect: RoR electricity production boasts a high full turbine capacity and comparatively low volatility, while lakes dampen inflows and mitigate low and high water extremes. Both sectors are highly relevant for Alpine water resources management (WRM) and play pivotal roles in national climate mitigation and adaptation strategies, but surprisingly have received little attention in the past.

7.1 Climate change impact assessment framework

The change framework applied in this thesis to RoR electricity production and lake level variability is based on a 30-year comparison of current conditions (defined as reference period T_{ref}: 1981–2010) and future conditions (near future 2035: 2020–2049; mid-century 2060: 2045–2074; and end of the century 2085: 2070–2099). The change framework uses transient daily streamflow scenarios from 1981 to 2099 as model input. These scenarios are based on the EURO-CORDEX dataset (Jacob et al., 2014) and were downscaled by MeteoSwiss as part of the National Centre for Climate Services (NCCS) NCCS (2018a). The national CC scenarios result from climate model simulations and subsequent statistical downscaling using quantile mapping. They consist of 39 model chains (Table 9.3), covering the three Representative Concentration Pathways RCP2.6 (concerted CC mitigation efforts), RCP4.5 (limited CC mitigation measures), and RCP8.5 (no CC mitigation measures). For each RCP, various model chains are available based on combinations of General Circulation Models (GCMs), Regional Climate Models (RCMs), and different spatial resolutions.

The streamflow scenarios used in this change framework are based on the CC scenarios CH2018, which were generated as part of the Swiss project Hydro-CH2018 (FOEN, 2021a). The streamflow scenarios were generated with the conceptual, process-oriented model PREVAH (PREcipitation streamflow EVApotranspiration HRU related model; Viviroli, Zappa, Gurtz, & Weingartner, 2009), which had been used for earlier CC impact studies in Switzerland (Bernhard & Zappa, 2012; Speich et al., 2015). PREVAH runs at a spatial (grid) resolution of 200 m × 200 m (Speich et al., 2015) and comprises model components covering the hydrologic cycle (Viviroli, Zappa, Gurtz, & Weingartner, 2009), land uses (Brunner et al., 2019), snow accumulation (Freudiger et al., 2017), and glacier evolution (Brunner et al., 2019). The model parameters have been calibrated, validated, and regionalised (Bernhard & Zappa, 2012; Köplin et al., 2010; Speich et al., 2015). We expanded the change framework to focus on the CC impact on specific sectors in detail, using the streamflow scenarios (Hydro-CH2018; FOEN, 2021b) as input data.

7.2 Change assessment novelties

To assess the CC impact on RoR electricity plants and lake level variability, encompassing technical, ecological, and legal aspects, we incorporated additional models into the change framework. There are uncertainties throughout the entire model chain in the climate change impact assessment framework. However, a comparison of the three hydrological models that generated the Hydro-CH2018 scenarios (Section 3.3.2) revealed a strong agreement in the projections (FOEN, 2021b; Muelchi et al., 2022). Compared with prior CC impact assessments, daily input data from 1981 to 2099, consisting of 39 model chains, increased both the temporal resolution and the robustness of the projections, while considering model uncertainties. The change framework developed and elaborated in this thesis makes it possible to assess the CC impact on WRM sectors, which have received little attention in the past.

Previous RoR studies primarily involved comparing future scenarios with individual past years (dry, wet, or average; Savelsberg et al., 2018), while this change framework focuses on long-term trends by comparing 30-year periods across a diverse range of hydro-climatic regions in the Alpine region. Recent CC impact assessments of regional RoR electricity production have relied on a coarse representation of hydrology and simplified treatment of RoR electricity production, or even have converted changes in streamflow to electricity production (Totschnig et al., 2017; Wagner et al., 2017). In Paper 1 (Chapter 4), the change framework was enhanced by considering specific infrastructure characteristics, such as hydraulic head, design discharge, environmental flow requirements, and overall efficiency. By considering the non-linear relationship between the CC impact on streamflow and RoR production (François et al., 2018; Mohor et al., 2015), the model evaluates the CC impact on future RoR electricity production, which is influenced by the flow duration curve (Vogel & Fennessey, 1995), environmental flow requirements, and the design discharge of the power plant. The expanded change framework makes it possible to simulate production loss due to environmental flow requirements, as well as potential production increases through design discharge adjustments.

The environmental flow requirements, mandated by the Swiss Water Protection Act (WPA), are pivotal to protect aquatic ecosystems and thus should not be primarily perceived as a loss. According to the Swiss WPA, a minimum downstream flow rate (environmental flow) must be guaranteed if streamflow is diverted from a river. In Paper 2 (Chapter 5) we therefore slightly expanded the change framework to assess the CC impact on the legal determination of environmental flow requirements. To that avail, we reduced the 39 model chains to one median high-emission scenario. Reducing the number of model chains decreases the robustness of the CC projections. However, it better demonstrates the mechanism of environmental flow requirements under CC. The change framework makes it possible to assess the CC impact on the determination of environmental minimum flow rates and, consequently, on future RoR electricity production. Additionally, the model expansion enables the estimation of current and future shares of energy potentials, which depend on different ranges of streamflow: (i) the low-flow reserved for environmental minimum flow, (ii) the streamflow usable for electricity production, and (iii) the spilling of high-flows due to limitations imposed by the design discharge.

In Paper 3 (Chapter 6) we presented an in-depth CC impact assessments on lake level variability and management, combining the conceptual hydrologic model PREVAH with the 1D hydrodynamic model MIKE11. In previous CC impact assessments on water resources, lake level variability was omitted or modelled in a simplified manner (Bosshard et al., 2014; Rössler et al., 2019; Zischg et al., 2018). The combination of hydrologic and hydrodynamic models significantly enhances model performance, enabling a more accurate simulation of lake levels and outflows. Despite increasing pressures on large perialpine lakes (Salmaso et al., 2018), this change framework is one of the first to incorporate lake level variability (Hingray et al., 2007; Veijalainen et al., 2010). The change framework enables analysis of the interplay between lake levels and outflows to project changes in extremes. The evolution of extremes is assessed by examining percentile levels or extreme indicators, such as the frequency of exceeding flood limits or reaching drought limits.

The proposed change framework improves the understanding of the CC impact on WRM sectors and provides model-based projections for further research in fields such as limnology, ecohydrology, and WRM. The findings suggest that this change framework can be at least partially applied to other Alpine regions.

7.3 Transferability

The study's national focus is built upon a coherent set of streamflow scenarios and legal requirements. The case study area comprises various hydro-climatic regimes, a large share of RoR power plants, and large lakes with different extents of lake level management. Consequently, valuable insights can be gained regarding the CC impact assessment framework and are at least partially transferable to other Alpine regions.

The comprehensive CC impact assessment on RoR electricity production also includes plant-specific technical characteristics. This facilitates comparisons of projected RoR electricity production with production loss due to environmental flow requirements and potential production increases through design discharge adjustments. This comparison is relevant because of the non-linear relationship between changes in streamflow and RoR electricity production (François et al., 2014; Mohor et al., 2015). The projected changes in RoR electricity production strongly depend on catchment elevation and the size of the design discharge. The production loss due to environmental flow requirements is relatively small and plays a minor role compared to the overall energy potential. These general results are transferable to other Alpine areas with RoR electricity production and should be considered in future impact assessments.

To assess the CC impact on environmental flow requirements, we strictly adhered to the Swiss Water Protection Act, which derives the minimum flow rate from long-term streamflow conditions. The change framework can be applied to any other Swiss RoR power plant subject to environmental flow requirements. Transferring the change framework to other Alpine regions would require consideration of the respective legal requirements and available streamflow scenarios. In cases where technical plant-specific characteristics are unavailable, they could be derived from streamflow thresholds, as demonstrated by Hänggi and Weingartner (2012).

Regarding lake level variability, the methodological change framework, although not the specific numerical results, could be applied to other perialpine lakes. Lake level management considerably alters hydrologic patterns, and the CC impact on lake level variability is closely tied to the extent of lake level management. Seasonal shifts in regulated and semi-regulated lakes are vital considerations when assessing the applicability of these findings to other perialpine lakes. Combining a hydrologic and a hydrodynamic model significantly enhances the performance of simulations of lake levels and outflows, irrespective of the extent of lake level management. On the other hand, the combination of a hydrologic and hydrodynamic model results in a considerable increase in computational costs and input data requirements (e.g. cross sections) compared to using only the hydrologic model. This prompts the question of whether a simpler approach, such as using time-dependent (e.g. 2-week intervals) stage–discharge relationships, could enhance the transferability.

7.4 Change assessment limitations

Despite the novelties and contributions to science of the change framework applied in this thesis, there are shortcomings related to the CC impact assessment of water resources and WRM. The change framework, using daily streamflow scenarios, relies on mean annual and seasonal production data over 30 years and does not address interannual variability. It thus fails to capture year-to-year variations, which can generally be important for WRM (Wechsler et al., 2023b). Likewise, the applied change framework approaches the evolution of extreme events solely by using percentile levels and extreme indicators, but does not include event-based methods such as unseen scenarios (Thompson et al., 2017).

An important shortcoming of the change framework is that it does not consider potential changes in the future water demand of specific WRM sectors, even though they may have relevant effects on water resources and WRM (Brunner et al., 2019; Vicente-Serrano et al., 2022). The change framework is based on static assumptions, such as unchanged legal requirements and technical constraints, regardless of projected changes in streamflow. Due to the lack of operational data in WRM sectors, the change framework does not account for time-dependent variables, such as the efficiency of power plants, which vary with the amount of streamflow or the hydraulic head (Quaranta et al., 2022; Skjelbred & Kong, 2019).

While the change framework provides model-based projections to analyse different energy potentials and the interdependencies between upstream and downstream lake dynamics, it falls short of assessing impacts on non-market water objectives. The consideration of environmental flow is an exception but is limited to the CC impact on the legal requirements of the minimum flow rate, omitting critical environmental aspects like sediment management, habitat connectivity, water quality, or hydro- and thermopeaking (Carolli et al., 2022; Gorla & Perona, 2013; Kuriqi et al., 2021). The change framework also lacks a comprehensive consideration of the CC impact on socio-economic aspects, such as market dynamics, financial revenues, or recreational uses (Brunner et al., 2019; Cassagnole et al., 2020; Savelsberg et al., 2018). Further, it does not address the societal acceptance of energy systems (Stadelmann-Steffen & Dermont, 2021) or reservoirs, topics that are currently under intense debate (Kellner, 2021). Specifically, the framework's scope of water reservoirs is limited to natural lakes and artificial reservoirs, and does not consider nature-based water reservoirs, such as soil water and groundwater (Somers & McKenzie, 2020), and their interaction with surface water.

Regarding lake level variability, the results of the change framework do not determine the suitability of lake level management as a CC adaptation measure. Lakes with smaller projected lake level changes, due to controlled lake outlet, do not necessarily lead to reduced water scarcity (Kellner, 2021). Lake level management controlled by floodgates may even have adverse ecological impacts due to reduced lake level fluctuations (Wantzen et al., 2008) and disrupted connectivity of aquatic habitats (Erős & Campbell Grant, 2015). In general, the change framework does not provide information on mitigation or adaptation potentials of lake level management (Flaminio & Reynard, 2023; Olmstead, 2014), but offers model-based projections for such decision-making processes (Dermont, 2019; Temel et al., 2023).

Finally, while a hydrodynamic model adds the great benefit of incorporating lake level variability and management, it generates high computational costs (Paiva et al., 2011; Papadimos et al., 2022). The change framework relies on non-open-source software, limiting its accessibility and flexibility. Addressing these limitations and incorporating more dynamic operational data would enhance the accuracy and applicability of the change framework for assessing the CC impact on WRM.

8 Conclusions

The climate change (CC) impact assessment framework developed in this thesis is based on transient daily streamflow scenarios. These streamflow scenarios for Switzerland rely on the EURO-CORDEX dataset. The change framework enables the assessment of critical sectors in Alpine WRM by the comparison of current conditions with future conditions under different emission scenarios. Using 30-year periods (near future, mid-century, and end of the century) and 39 model chains provides a robust foundation for projecting CC-induced mean changes, considering the model uncertainty. In this thesis, the change framework is applied to Run-of-River (RoR) electricity production, environmental flow requirements, and lake level variability. These three critical sectors are essential for Alpine water resources management (WRM) but surprisingly have received little attention in the past.

Anthropogenic greenhouse gas emissions have led to global warming of approximately +0.9 °C compared to pre-industrial levels, with a notable accentuation in Alpine regions, primarily due to the albedo effect. Global warming affects all hydro-climatic variables associated with the hydrologic cycle. In Alpine regions, observations in most catchments, except for heavily glaciated ones, have indicated little change in mean annual streamflow. However, a pronounced seasonal shift is occurring in streamflow patterns, with increased winter streamflow and reduced summer streamflow. CC projections suggest that these patterns will intensify over time, particularly in the absence of CC mitigation efforts. In Switzerland, there has been an increasing trend in meteorological, hydrologic, and agricultural droughts in recent years, which is in line with key findings from hydrologic CC projections. The complex interactions between CC and streamflow alterations impact both market and non-market objectives of WRM. However, there is no reason to assume a linear relationship between CC-induced changes in streamflow and corresponding changes in WRM.

RoR power plants contribute approximately half of Switzerland's hydropower (HP) electricity production. The CC impact assessment conducted on 21 Alpine RoR power plants predicts a minor decrease in mean annual electricity production, ranging from 2 % to 7 % by the end of the century. This reduction varies with elevation: low-elevation catchments ($<$ 1900 m a.s.l.) are projected to experience decreased production, while high-elevation catchments show a potential increase. The assessment considers plant-specific characteristics to be able to compare the impact of CC on RoR electricity production to production loss due to environmental flow requirements and potential production increases through adjustments in the design discharge. Environmental flow requirements and the design discharge are crucial in determining the infrastructure characteristics needed to meet local ecological needs. Future RoR electricity production is not linearly related to projected climate-induced changes in streamflow. Instead, it depends on the usable streamflow volume, which is modulated by environmental flow requirements and design discharge. The simulated annual CC impact on RoR electricity production, from mid-century onwards (-1 % to -5 %) closely align with the currently estimated current annual loss due to environmental flow requirements (-3.5 %). There is potential for a production increase by optimising the design discharge for half of the considered RoR power plants, amounting to +8 %. Seasonal projections indicate that future RoR electricity production will rise in winter (4 % to 9 %) and decline in summer (2 % to 22 %). However, it is important to note that in winter, when electricity demand is highest, the potential for production increase is limited and seven times smaller than in summer. Additionally, the production loss due to environmental flow requirements is most considerable in winter (-4.5 %), particularly for small and medium-sized power plants.

The environmental flow requirements, mandated by the Swiss Water Protection Act (WPA), for water-diverting power plants are pivotal to protect aquatic ecosystems and thus should not be primarily perceived as a loss. In this thesis, the impact of CC on environmental flow requirements is assessed through the examination of four representative Alpine RoR power plants, each representing different catchment elevations and design discharge sizes. This analysis reveals how climate-induced changes in the 347-day low-flow streamflow (Q_{347}, 95th percentile) affect legal environmental flow requirements and, subsequently, future RoR electricity production. The findings indicate that, in accordance with the WPA, an increase in Q_{347} leads to higher environmental flow requirements, particularly in the context of a (re-)concession process. This change predominantly impacts high-elevation power plants ($>$ 2000 m a.s.l.) by increasing low-flows and low-elevation ones ($<$ 1500 m a.s.l.) by decreasing low-flows. For instance, a CC-induced increase of up to 63 % in Q_{347} may result in a rise of up to 43 % in environmental flow. However, the relationship between changes in Q_{347} and future HP production is more complex. Estimating alterations in Alpine RoR electricity production cannot be derived solely from changes in Q_{347}, as it necessitates considering the entire usable streamflow volume for HP production. The energy potential allocated to environmental flow requirements is estimated to be relatively small (1 % to 7 %) and plays a minor role compared to the overall energy potential. The key factors influencing future production changes are the CC-induced alterations in streamflow and the size of the design discharge of a power plant.

Large perialpine lakes in Switzerland face the challenge of balancing a wide variety of water-related objectives, including those related to fisheries, shipping, energy production, nature conservation, and extreme event mitigation. This study represents one of the first CC impact assessments on lake level variability, combining a hydrologic and hydrodynamic model. This model combination significantly enhances performance but comes at the cost of a seven-fold increase in computational time. Annual mean projections, even under the high emission scenario RCP8.5, indicate minor changes in lake levels, with changes of just a few centimetres, and increases in outflows by up to 10 %. However, CC can lead to a pronounced shift in seasonal lake water levels, particularly with declining summer levels. The extent of lake level management plays a substantial role in these changes. Simulations for a regulated lake show median changes ranging from +0.04 m to -0.04 m under RCP8.5, while for an unregulated lake changes vary between +0.26 m and -0.39 m. In comparison, lake level management exerts a smaller influence on lake outflows than on lake water levels. Winter lake outflows are projected to increase by 15 % to 22 %, with a corresponding decrease in summer ranging from

30 % to 39 %. The reduction of summer outflow intensifies with increasing catchment elevation and cryosphere area. An extreme indicator for droughts, which counts days with outflows below the minimum threshold, projects an increased frequency of drought events during late summer. Such a shift could lead to more frequent and severe drought events, considerably impacting the WRM of lakes.

In this thesis, the change framework is applied to three sectors within WRM, encompassing a diverse range of hydro-climatic regions and site-specific characteristics. This approach facilitates the integration of technical, legal, and ecological considerations into the change framework and is at least partially transferable to other Alpine regions. The key findings of this thesis can be summarised as follows:

- All considered WRM sectors are affected by CC. The CC impact assessments project changes already in the near future, even with concerted CC mitigation efforts (RCP2.6). These changes will intensify over time, and more so in the absence of CC mitigation measures (RCP8.5).
- The 39 model chains covering 30-year periods provide a robust foundation for projecting CC-induced mean changes, with general increases in winter and decreases in summer. The assessment of the evolution of extremes, using percentile levels and extreme indicators, projects an increase in drought frequency in summer and autumn.
- The CC impact on WRM sectors differs, depending on technical, geographical, or legal aspects, and specifically relying on changes in different ranges of streamflow. For example, RoR power production depends on the usable streamflow, which is modulated by environmental flow requirements and the limitations imposed by the design discharge.

8.1 Outlook

The CC impact assessment framework developed and applied in this thesis represents a considerable advancement; however, it faces limitations that could be addressed in future research. First, the change framework focuses on sectoral mean annual and seasonal changes over 30-year periods but does not address interannual variations. Future work could involve investigating year-to-year variations and estimating the occurrences of extreme events, including the possibility of several consecutive extreme years. Second, the change framework assesses the evolution of extremes solely with percentile levels or extreme indicators. An expanded change framework could incorporate an event-based approach to consider extreme scenarios beyond the scope of historical reference events. Both the interannual variations and the evolution of extremes could focus on the regional interplay of comprehensive WRM systems and their spatial coherence, overcoming the sectoral perspective.

In terms of RoR electricity production, the change framework also considers production increase potentials and environmental flow requirements. In the context of energy transition, this provides a basis for balancing the goals of increasing renewable electricity production and minimising negative impacts on aquatic ecosystems. Future research could investigate ecological impacts of changing environmental flow requirements and could consider more dynamic operational data to explore technical optimisation potentials. In the context of an increase in the share of renewable energy, characterised by volatility, HP could provide flexible and stabilising services. Future work could examine the adaptation potential of existing high-head accumulation reservoirs or RoR power plants in gaining flexibility through added reservoirs and added pumps. To mitigate negative impacts of HP on rivers, a future assessment could explore the potential of power plants operating between existing Alpine lakes.

Regarding lake level variability, the simulations call for further research to address potential management adaptations under CC. Beyond our case studies, this might be applicable to similar large perialpine lakes with similar extents of lake level management or even to large-scale areas consisting of multiple lakes. Therefore, future work could focus on providing less computationally intense open-source software associated with the hydrodynamic model. Lake level management could be incorporated into a simpler approach, such as one using time-dependent (e.g. 2-week interval) stage–discharge relationships.

The change framework assumes time-dependent variables to be static, and primarily focuses on water supply without considering changes in future water demand. Considering more dynamic operational data, including market and non-market water objectives, would provide a more comprehensive basis for WRM. Water is experiencing increasing demand pressure driven by socio-economic activity, as a consequence of adapting to warmer and drier conditions (e.g. higher consumption and increased cooling). This impacts not only water in surface water bodies but also in soils, vegetation, and the overall landscape. Therefore, future work could expand the change framework to assess moister and more balanced water systems, investigating how the storage capacity of interconnected surface water and groundwater could help alleviate pressure on water bodies. Additionally, the establishment of more nature-based water bodies, achieved through providing sufficient space and adequate habitats, has the potential to limit increases in both local surface and water temperatures. Future research could expand upon the proposed change framework to holistically assess the effectiveness of various landscape evolution strategies and offer climate services for resilient water bodies.

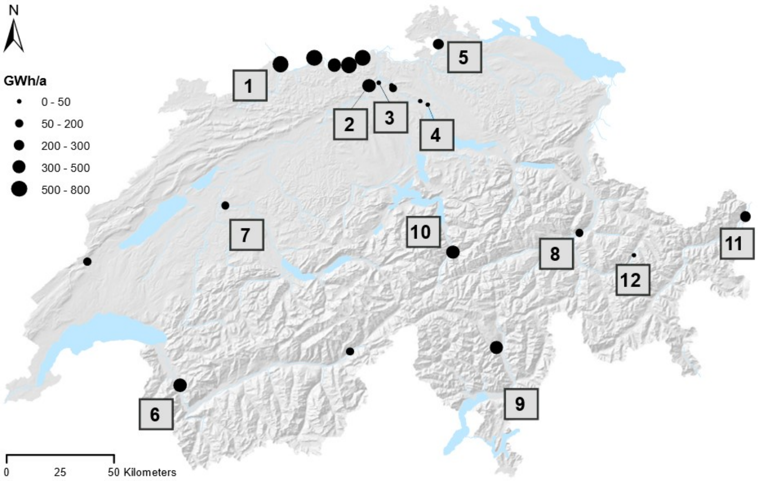
9 Supplementary Information

Paper 1

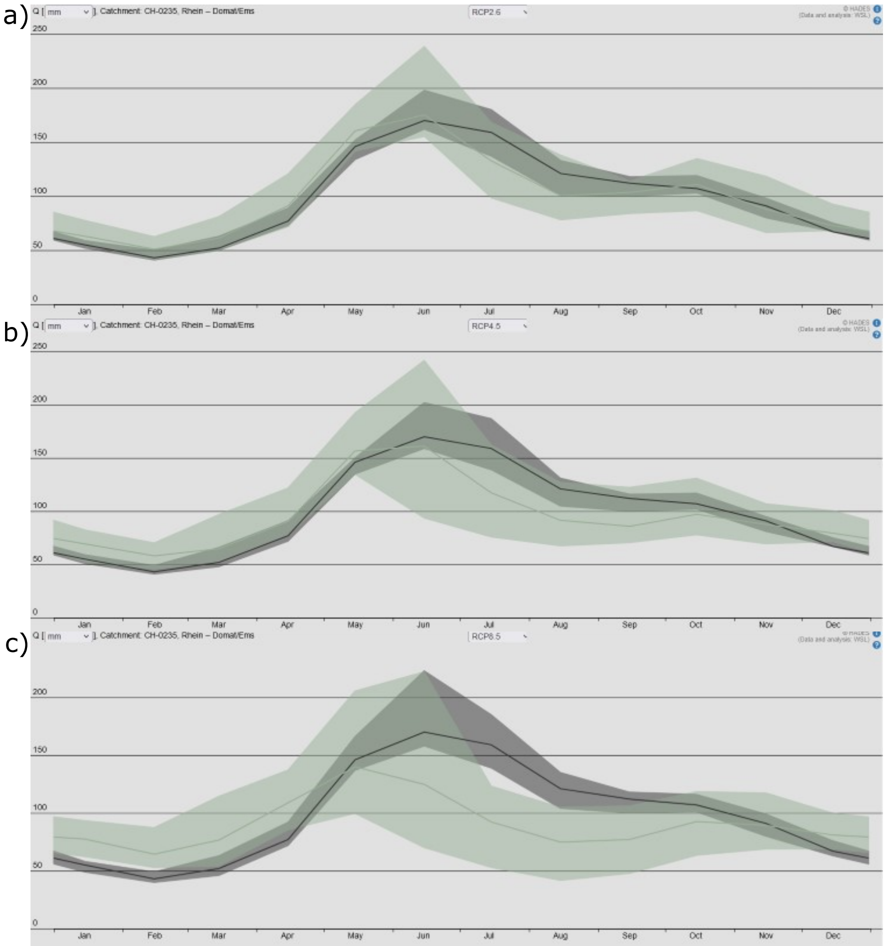
Supplementary Information submitted with the manuscript "The future of Alpine Run-of-River hydropower production: Climate change, environmental flow requirements, and technical production potential" by Wechsler et al. (2023c).

SI TABLE 9.1: Results of the calibration and verification by Bernhard and Zappa (2009) and Speich et al. (2015) of the hydrological modelled streamflow at selected stations (Figure SI 9.1) for the calibration period (1984–1996) and verification periods (1980–1983 & 1997–2009). The table contains the number that also corresponds to the number in Figure SI 9.1, the name of the streamflow measurement station, the calibration and validation (Cal/Val), the Nash criterion NS, the logarithmic Nash criterion NSL and the error in streamflow volume DV. The hydrologic future projections are visualised on the web atlas HADES (Schwanbeck & Bühlmann, 2023).

nr.	name	cal/val	NS [-]	NSL [-]	DV [%]
1	Rhine, Basel	Cal	0.953	0.95	0.3
		Val	0.927	0.931	-3.4
2	Aare, Brugg	Cal	0.9	0.9	-0.9
		Val	0.883	0.887	-2.7
3	Reuss, Mellingen	Cal	0.932	0.918	-1.8
		Val	0.919	0.902	-2.2
4	Limmatt, Unterhard	Cal	0.9	0.885	-0.3
		Val	0.883	0.874	-2.2
5	Rhein, Neuhausen	Cal	0.954	0.935	2.6
		Val	0.903	0.898	-2.4
6	Rhone, Porte	Cal	0.529	0.449	5.2
		Val	0.571	0.523	3.2
7	Aare, Schoenau	Cal	0.897	0.895	-1.6
		Val	0.907	0.911	-3.3
8	Rhein, Domat, Ems	Cal	0.752	0.635	5.7
		Val	0.782	0.682	0.7
9	Ticino, Bellinzona	Cal	0.793	0.735	0.7
		Val	0.816	0.698	-2.5
10	Reuss, Seedorf	Cal	0.857	0.778	-0.3
		Val	0.821	0.779	-3.3
11	Inn, Martina	Cal	0.727	0.645	-3.6
		Val	0.732	0.698	-8.0
12	Landwasser, Davos	Cal	0.862	0.919	6.8
		Val	0.851	0.884	2.9



SI FIGURE 9.1: The 21 Swiss RoR power plants considered in this study. The size of the dots represents the annual production. The numbers correspond to the discharge measuring stations in Table SI 9.1 that were used for calibration and validation.



SI FIGURE 9.2: Changes in mean monthly streamflow under the three emissions scenarios (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5 at Domat Ems by the end of the century (Nr. 8 in Table SI 9.1 and Figure SI 9.1) shown at the web atlas HADES (Schwanbeck & Bühlmann, 2023).

Hydrologic simulations using PREVAH

PREVAH is a conceptual, process-oriented model (Viviroli, Zappa, Gurtz, & Weingartner, 2009), which has been continuously improved since its development (Gurtz et al., 1999). As part of the CCHydro study (Bernhard & Zappa, 2012), a spatially explicit (grid) version was created for PREVAH, with a resolution of 200 m × 200 m (Brunner et al., 2019; Schattan et al., 2013; Speich et al., 2015). PREVAH consists of several model components covering the following hydrological processes (Viviroli, Zappa, Gurtz, & Weingartner, 2009): interception, evapotranspiration, snow accumulation and melt, glacier melt, soil water storage evolution, groundwater recharge and ensuing baseflow, surface and subsurface discharge formation, and discharge transfer. The model parameters have already been calibrated, validated and regionalised (Bernhard & Zappa, 2012; Köplin et al., 2010; Speich et al., 2015; Viviroli, Mittelbach, et al., 2009; Viviroli, Zappa, Schwanbeck, et al., 2009). The digital elevation model (DEM), land-use data, glacier inventory and meteorological data are then inserted as inputs into the calibrated model (Brunner et al., 2019). The meteorological data are spatially interpolated by inverse distance weighting (IDW) and a combination of IDW and elevation-dependent regression (EDR; Bernhard & Zappa, 2012; Viviroli, Zappa, Gurtz, & Weingartner, 2009). Snow accumulation and melting in PREVAH are determined by temperature and global radiation (Viviroli, Zappa, Gurtz, & Weingartner, 2009). Compared with early applications, the model version underlying the present scenarios has been improved with regard to the representation of snow accumulation at high elevations (Freudiger et al., 2017) and to the representation of glaciers and their length evolution (Brunner et al., 2019). Only a certain amount of snow can accumulate per grid cell, which depends on the slope of the terrain. Based on the DEM, excess snow is then relocated to lower elevations where snowmelt is more likely. The glaciers are divided into short (> 1 km) and long glaciers (< 1 km) (RGI Consortium, 2017). The future glacier extent is modelled with the Global Glacier Evolution Model (GloGEM) for short glaciers (Huss & Hock, 2015) and with the newer, extended version of GloGEM (GloGEM-flow) for long glaciers (Zekollari et al., 2019). The simulated glacier lengths are finally converted to the PREVAH model grid (Brunner et al., 2019; Zekollari et al., 2019). In addition to incorporating the mass balance due to freezing and thawing at the glacier surface, the model considers changes due to glacier flow. The resulting melt-water quantities are determined from the changes in the glacier surfaces over intervals of 5 years and fed into the precipitation-discharge model. For Lake Zurich, an interface with the hydrodynamic model Mike11 (DHI, 2003) has been created to take lake regulation into account (Wechsler et al., 2023b).

Paper 3

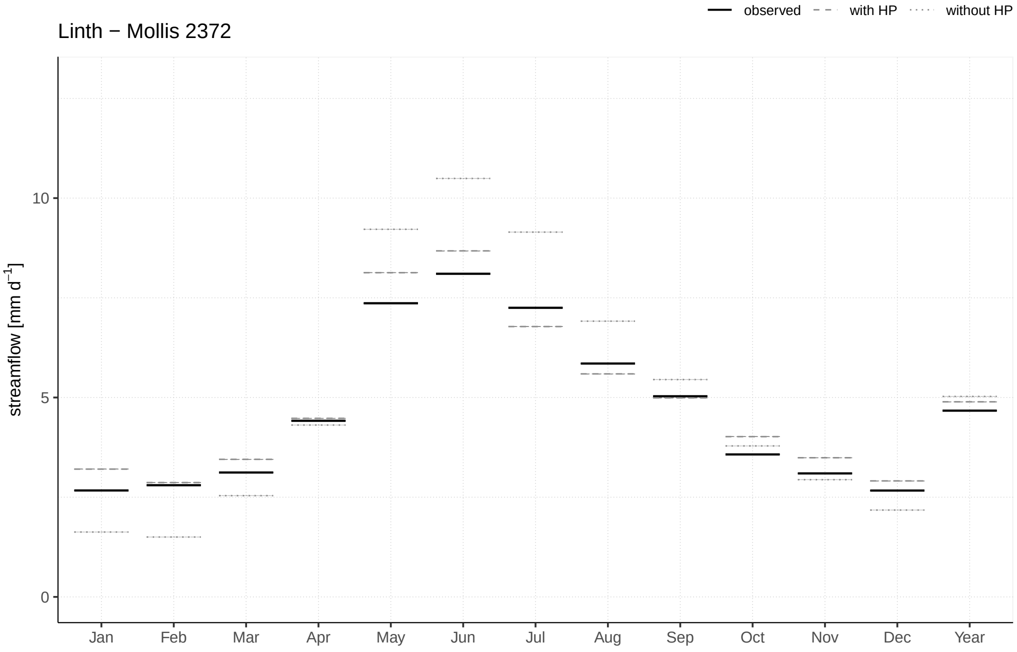
Tables and Figures submitted with the manuscript "Lower summer lake levels in regulated perialpine lakes, caused by climate change" by Wechsler et al. (2023b).

SI TABLE 9.2: Gauging stations from which observed lake water levels and outflows were used, provided by the Federal Office for the Environment (FOEN).

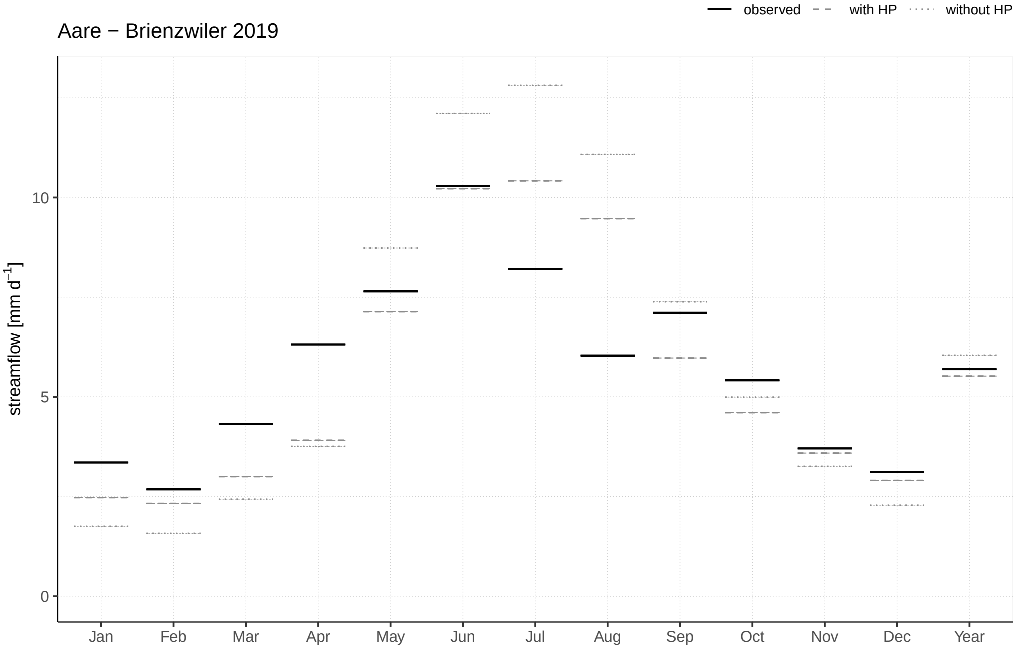
lake names	lake water levels [m]		outflows [mm d^{-1}]	
	ID	Station	ID	Station
Walen	2118	Murg	2104	Weesen
Zurich	2209	Zurich	2099 2176	Unterhard Sihlhölzli
Brienz	2023	Ringgenberg	2457	Goldswil
Thun	2093	Kraftwerk BKW	2030	Thun

SI TABLE 9.3: The 39 climate model ensembles derived from the climate scenarios NCCS (2018a). Each ensemble is a combination of TEAM (institute responsible), RCM (Regional Climate Model), GCM (General Circulation Models), RES (spatial resolution) and RCP (Representative Concentration Pathway, representing emissions scenarios).

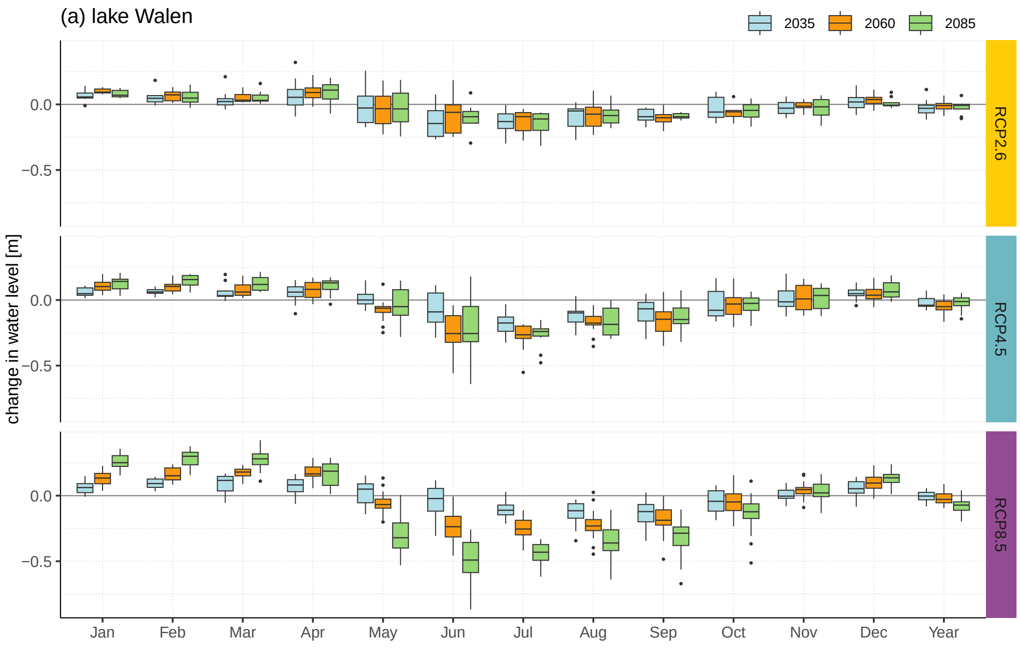
TEAM	RCM	GCM	RES	RCP	TEAM	RCM	GCM	RES	RCP
DMI	HIRHAM	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM4	HADGEM	EUR44	RCP8.5
KNMI	RACMO	HADGEM	EUR44	RCP2.6	CLMCOM	CCLM5	ECEARTH	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR11	RCP2.6	CLMCOM	CCLM5	HADGEM	EUR44	RCP8.5
SMHI	RCA	ECEARTH	EUR44	RCP2.6	CLMCOM	CCLM5	MIROC	EUR44	RCP8.5
SMHI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



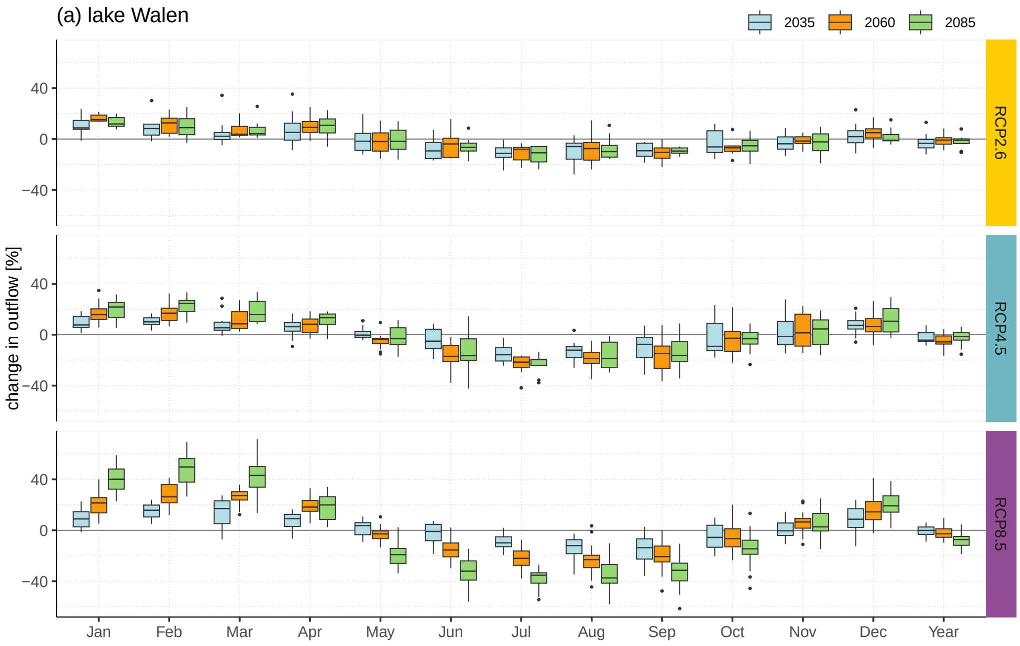
SI FIGURE 9.3: Hydropower impact in catchment I (Linth - Mollis 2372). The comparison of observed and simulated monthly mean streamflow. The black line represents the observed monthly mean streamflow, the dashed lines the simulated monthly means with and without consideration of hydropower, simulated with the hydrologic model PREVAH (section 6.2.5).



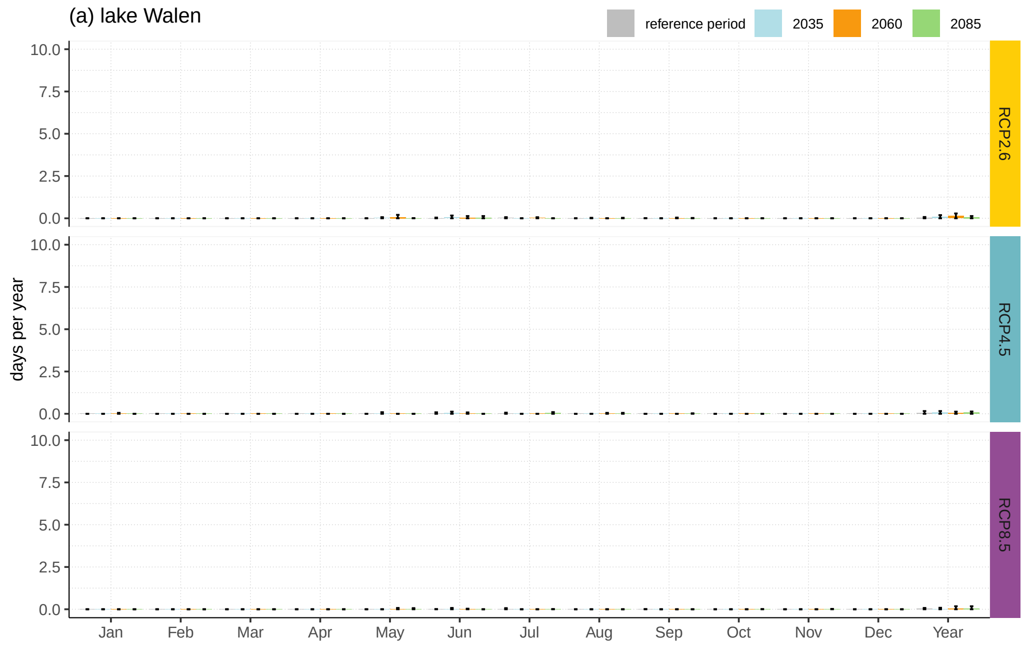
SI FIGURE 9.4: As Figure 9.3 but for hydropower impact in catchment II (Aare - Brienzwiler 2019).



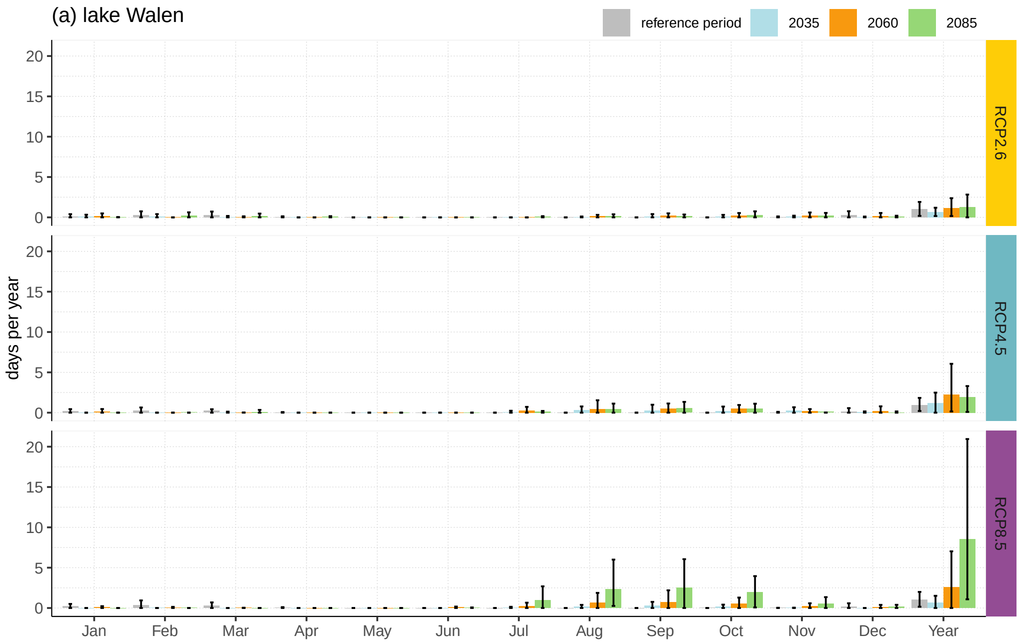
SI FIGURE 9.5: Simulated changes in annual and monthly mean lake water levels of Lake Walen, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



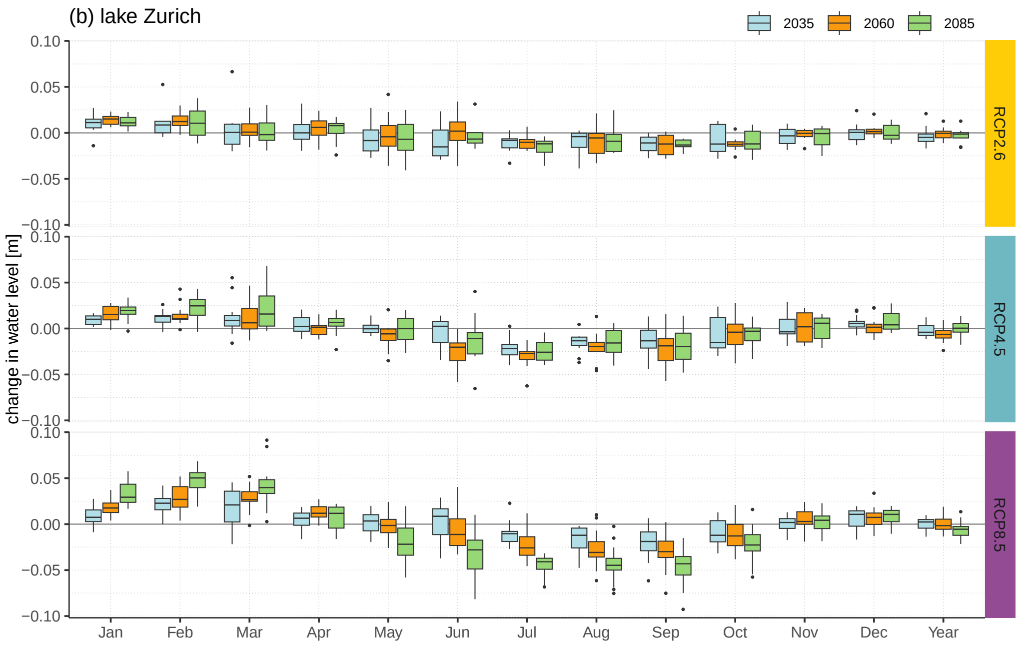
SI FIGURE 9.6: As Figure 9.5 but for the simulated changes in monthly and annual mean outflows of Lake Walen.



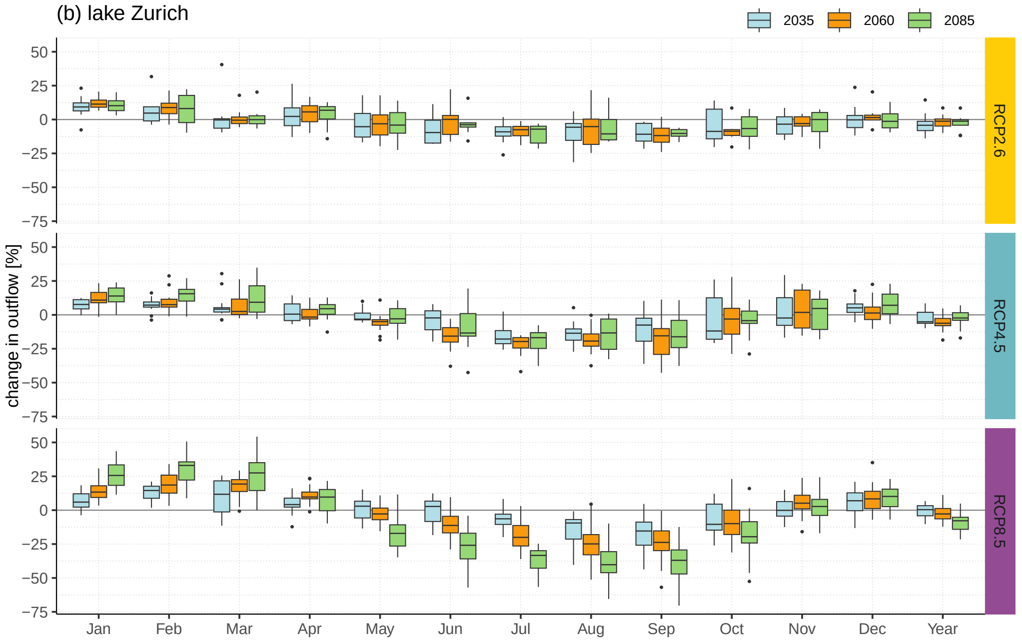
SI FIGURE 9.7: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Walen. Error bars refer to the 10 % and 90 % percentile range.



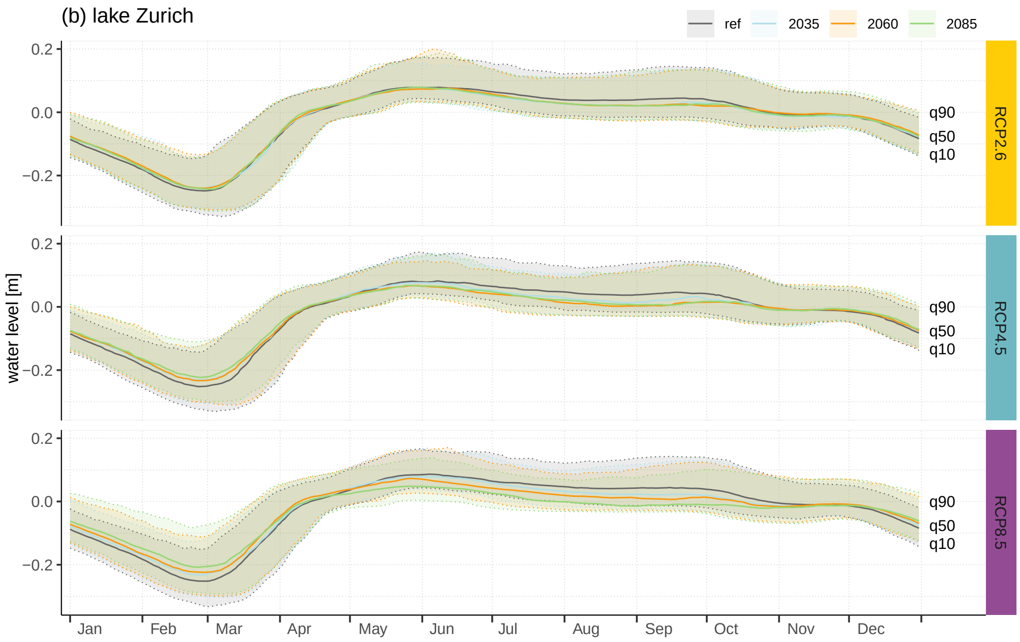
SI FIGURE 9.8: As Figure SI 9.7 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Walen.



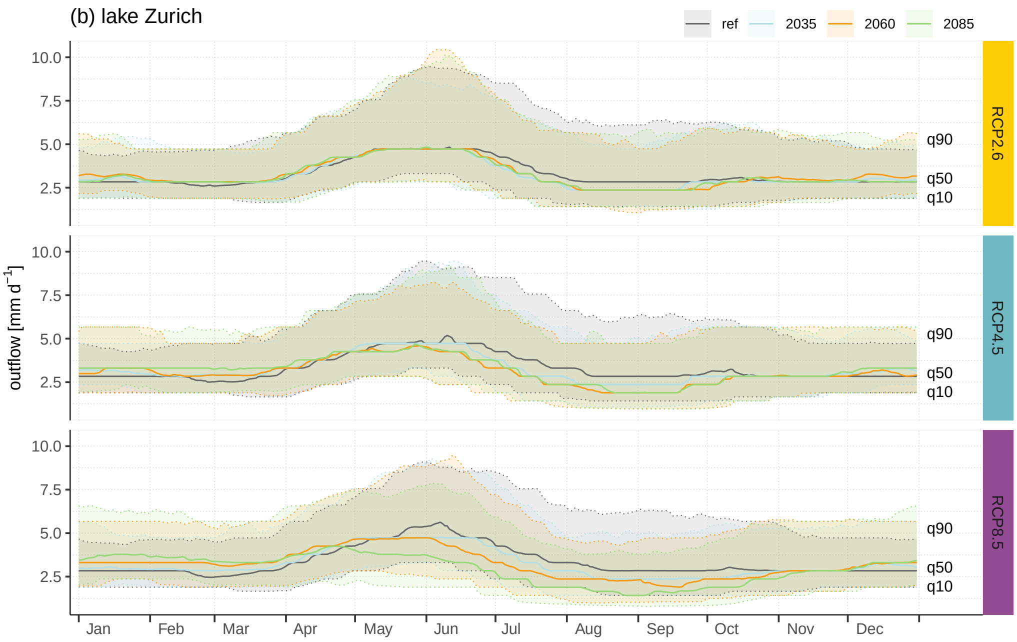
SI FIGURE 9.9: Simulated changes in monthly and annual mean lake water levels of lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



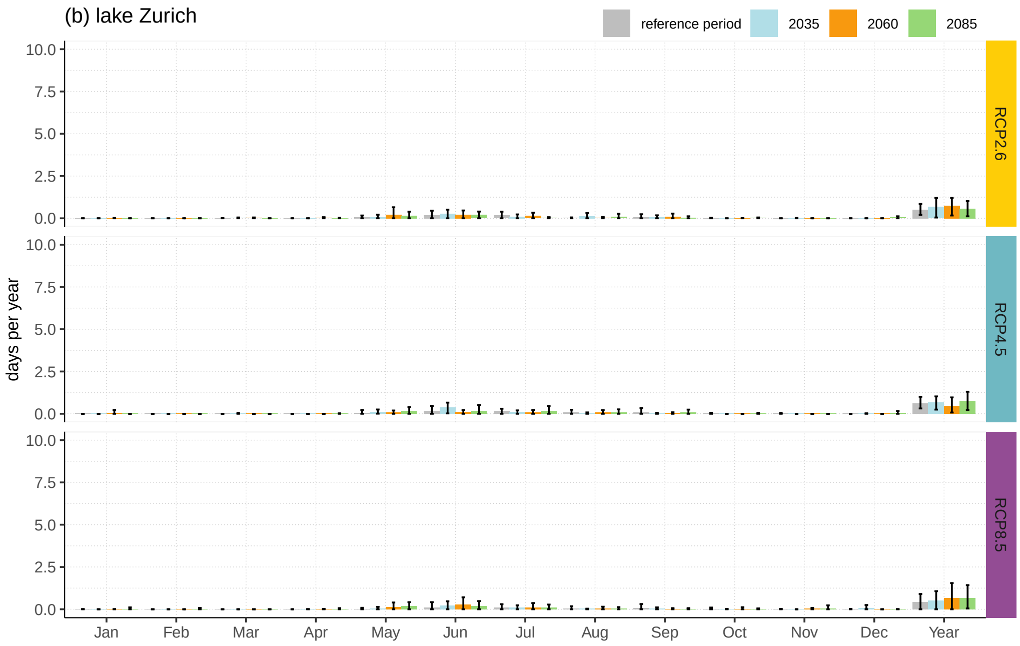
SI FIGURE 9.10: As Figure SI 9.9 but for the simulated changes in monthly and annual mean outflows of Lake Zurich.



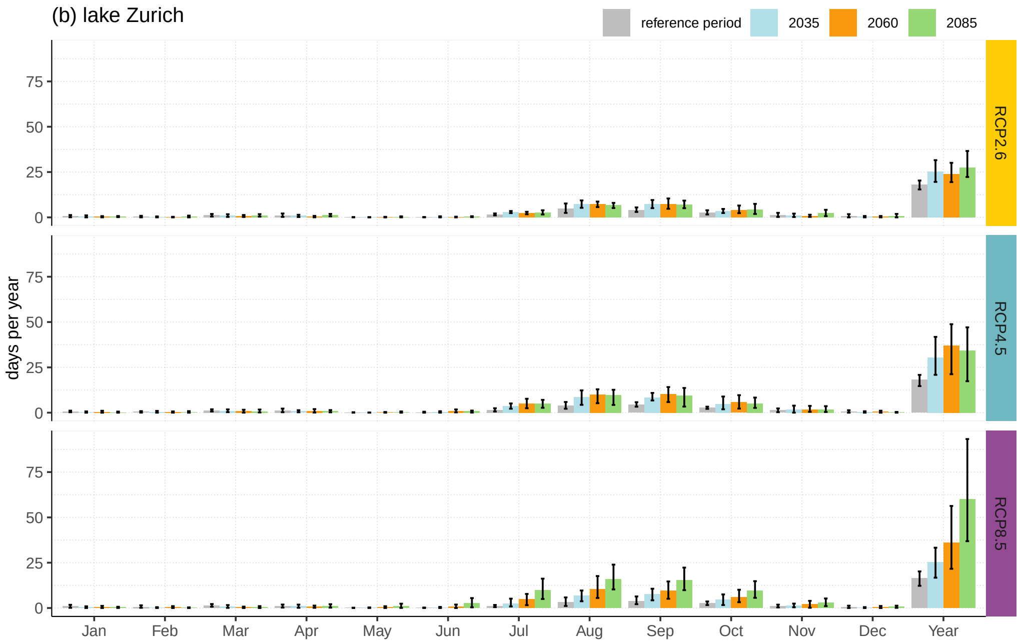
SI FIGURE 9.11: Simulated changes in the 10 % and 90 % percentiles of lake water levels (moving average ±15 days) of Lake Zurich, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



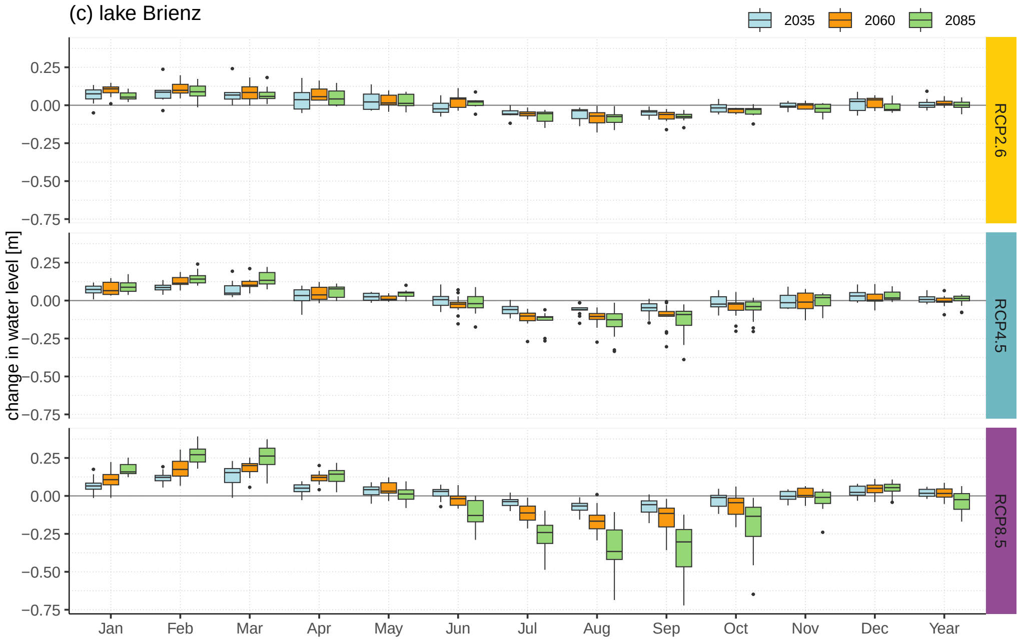
SI FIGURE 9.12: As Figure SI 9.11 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Zurich.



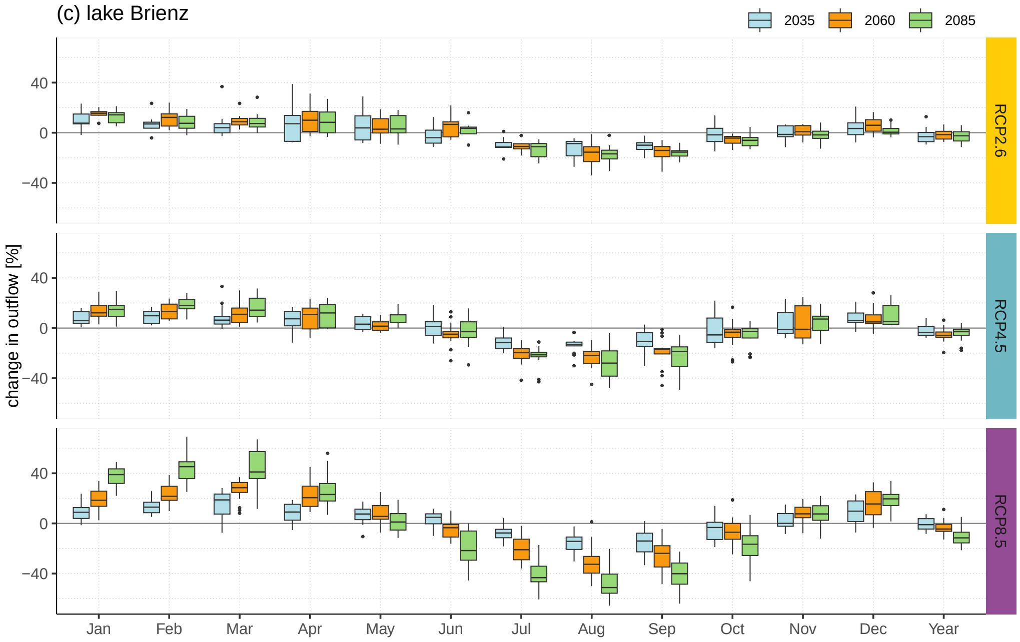
SI FIGURE 9.13: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Zurich. Error bars refer to the 10 % and 90 % percentile range.



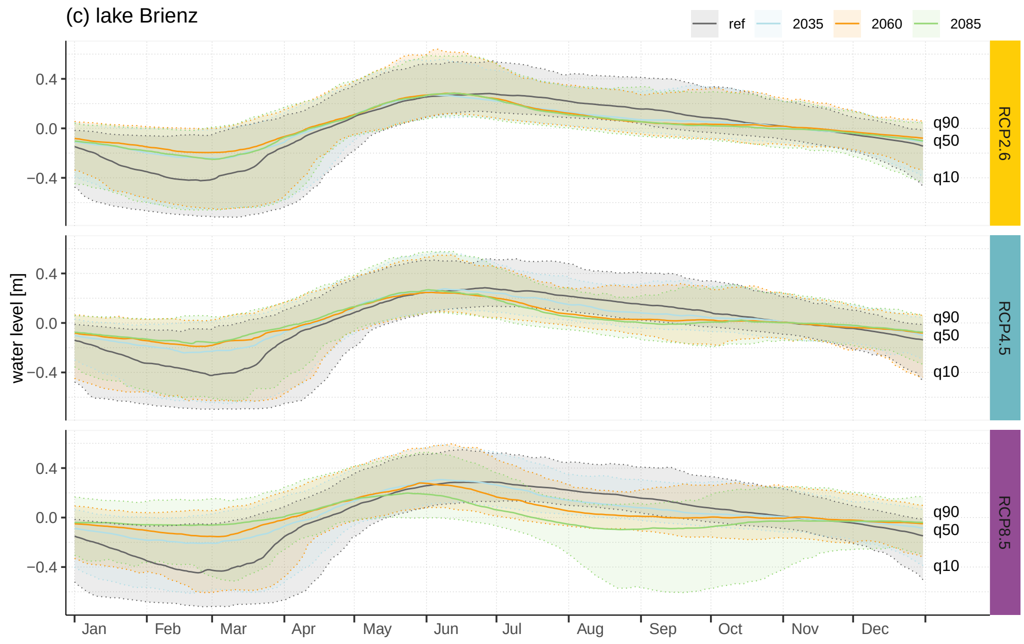
SI FIGURE 9.14: As Figure SI 9.13 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Zurich.



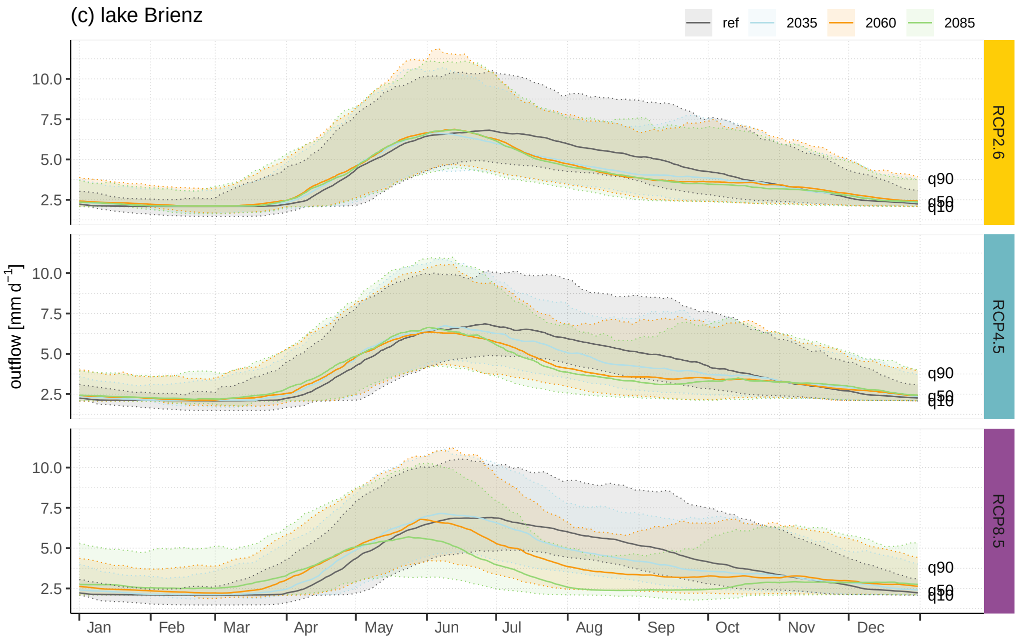
SI FIGURE 9.15: Simulated changes in monthly and annual mean lake water levels of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



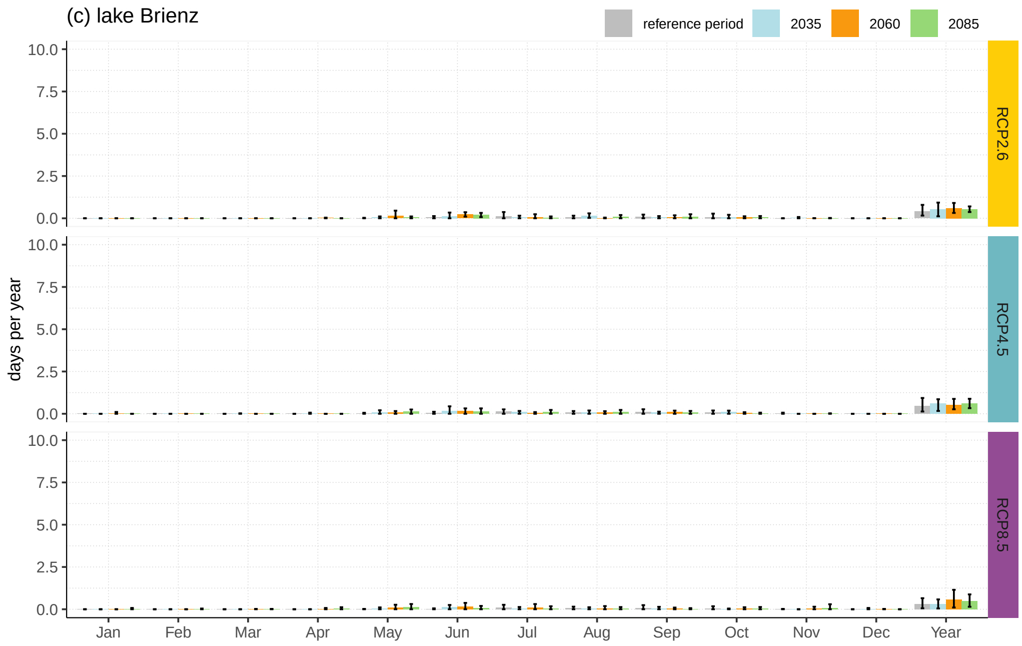
SI FIGURE 9.16: As Figure SI 9.15 but for the simulated changes in monthly and annual mean outflows of Lake Brienz.



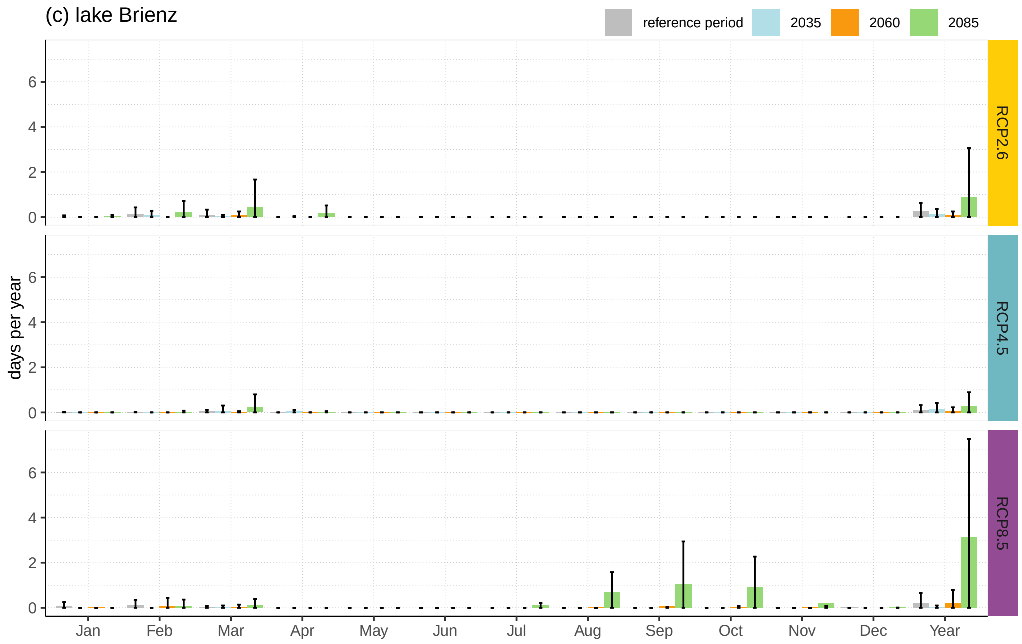
SI FIGURE 9.17: Simulated changes in the 10 % and 90 % percentiles of lake water levels (moving average ±15 days) of Lake Brienz, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



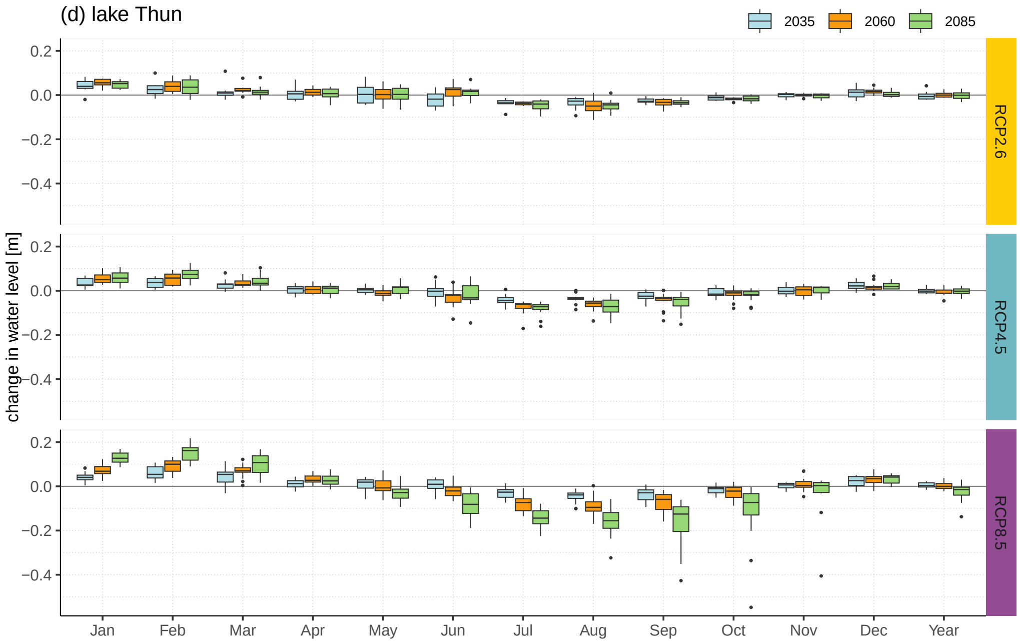
SI FIGURE 9.18: As Figure SI 9.17 but for the simulated changes in the 10 % and 90 % percentiles of outflows of Lake Brienz.



SI FIGURE 9.19: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (F) of Lake Brienz. Error bars refer to the 10 % and 90 % percentile range.

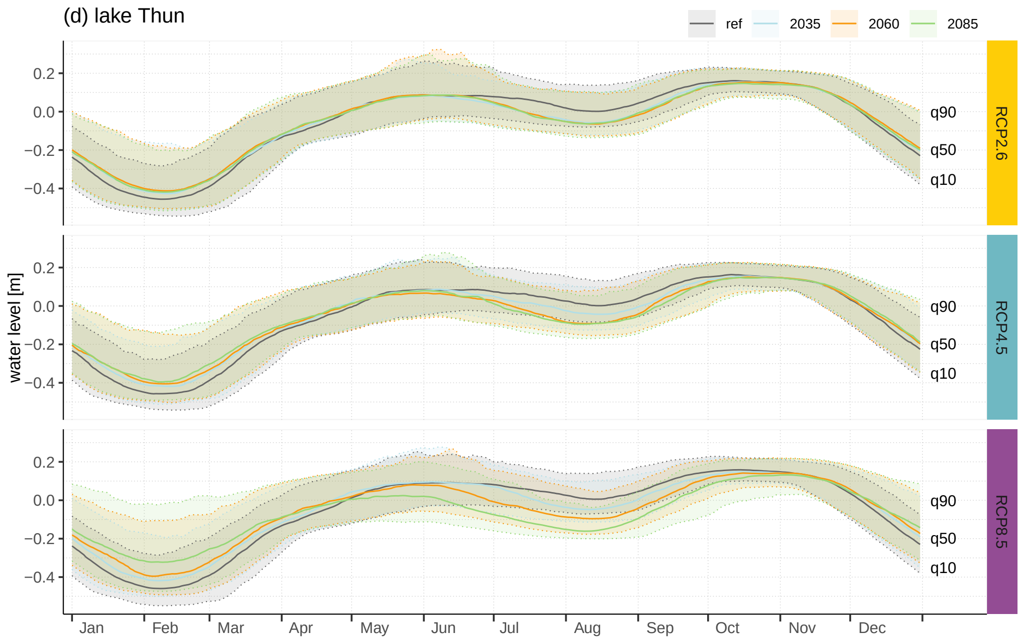


SI FIGURE 9.20: As Figure SI 9.19 but for the simulated changes the outflow undercuts the drought limit (L) of Lake Brienz.

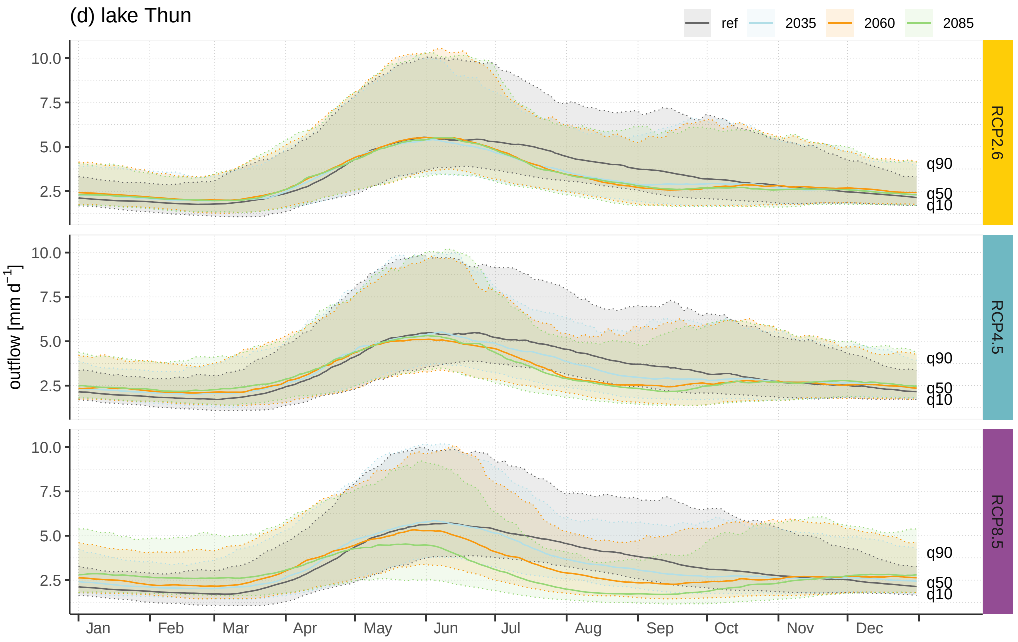


SI FIGURE 9.21: Simulated changes in monthly and annual mean lake water levels of lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).

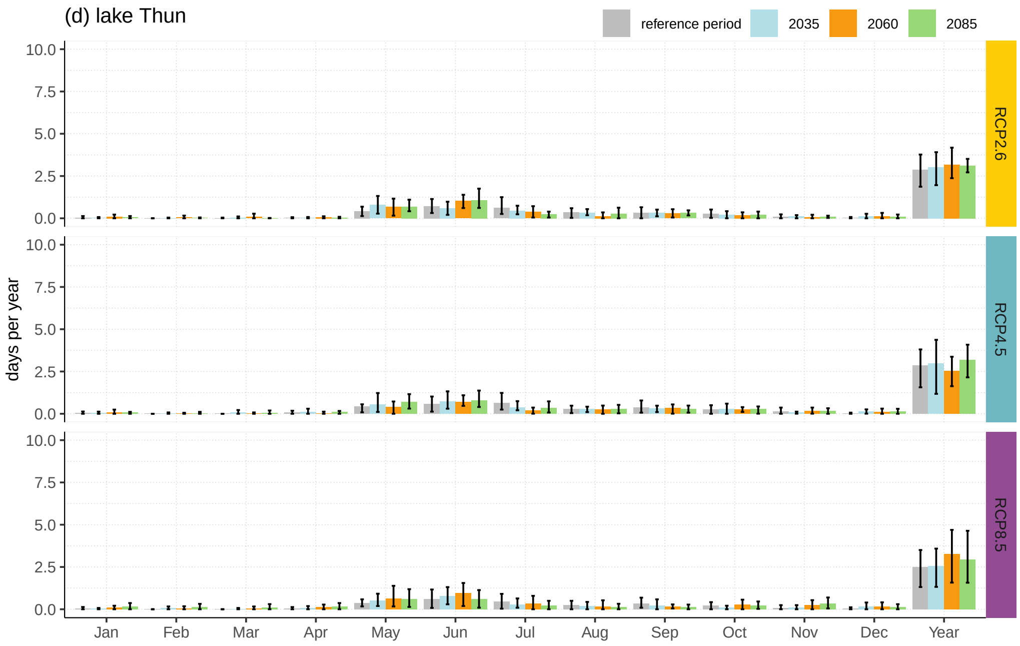
SI FIGURE 9.22: As Figure SI 9.21 but for the simulated changes in monthly and annual mean outflows of Lake Thun.



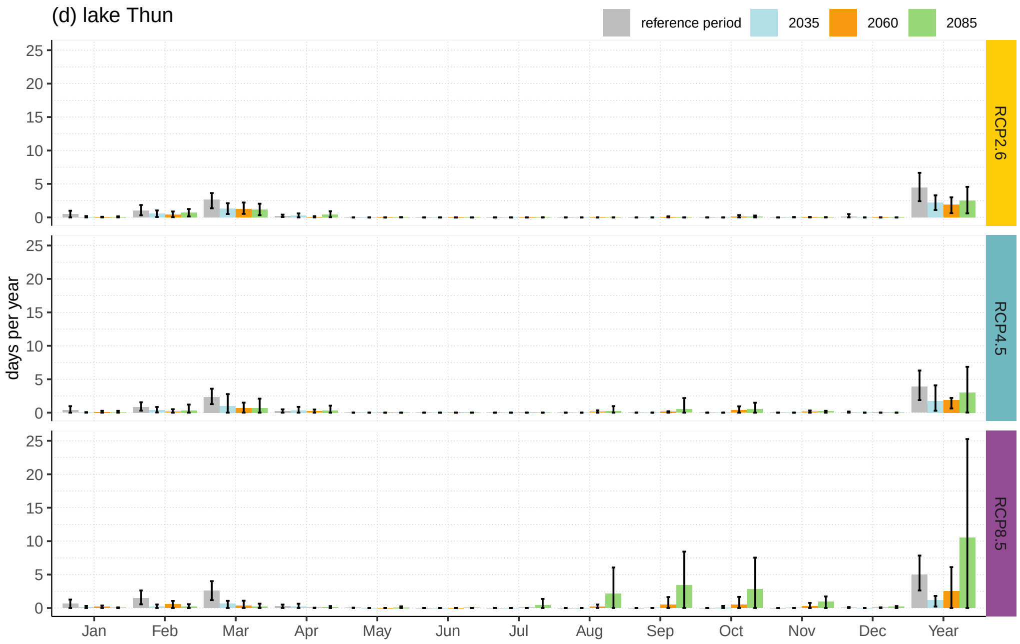
SI FIGURE 9.23: Simulated changes in the 10 % and 90 % percentiles of lake water levels (moving average ±15 days) of Lake Thun, divided into the three future scenarios (2035, 2060, 2085) and three emission scenarios (RCP2.6, RCP4.5, RCP8.5).



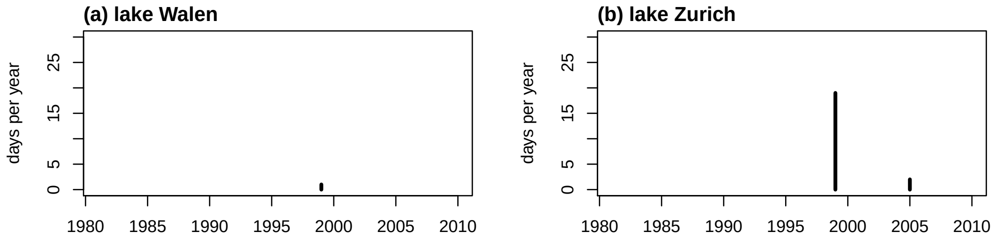
SI FIGURE 9.24: As Figure SI 9.23 but for the simulated changes in the 10 % and 90 % percentiles of outflows of lake Thun.

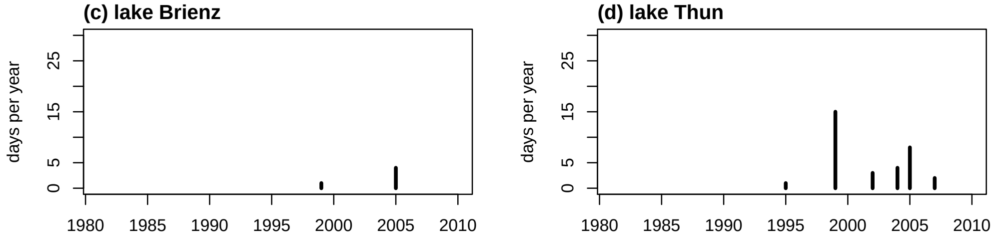


SI FIGURE 9.25: Simulated changes of the average number of days per year and month the lake water level exceeds the flood limit (*F*) of Lake Thun. Error bars refer to the 10 % and 90 % percentile range.

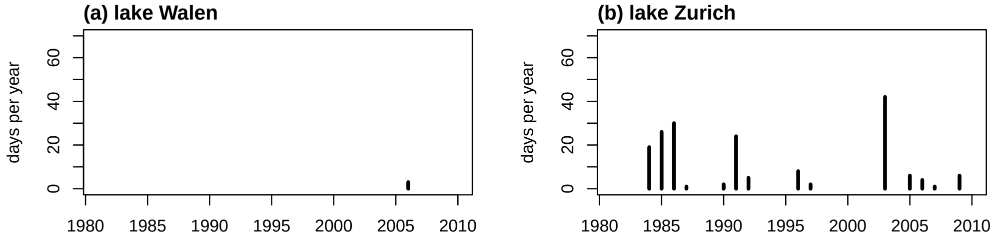


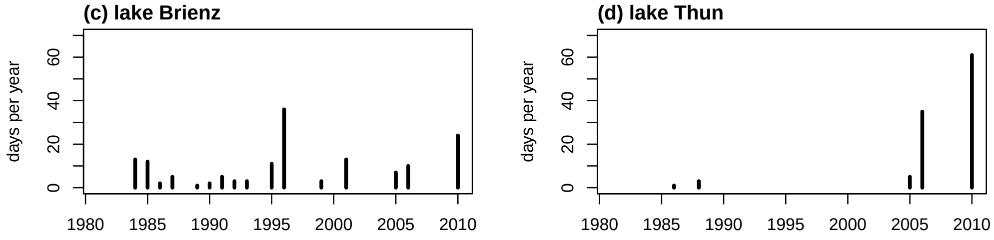
SI FIGURE 9.26: As Figure SI 9.25 but for the simulated changes the outflow undercuts the drought limit (*L*) of Lake Thun.





SI FIGURE 9.27: Observed days per year the lake water levels exceed the flood limit (*F*) for Lake Walen (unregulated), lake Zurich (regulated), lake Brienz (semi-regulated) and Lake Thun (regulated).





SI FIGURE 9.28: As Figure SI 9.27 but for the observed outflows undercutting the drought limit (*L*).

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Declaration of Authorship

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Titel der Arbeit:	Climate Change Impact Framework For Assessing Swiss Alpine Water Resources Using Transient Streamflow Scenarios
Leiter der Arbeit:	Prof. Dr. Bettina Schaefli, Dr. Massimiliano Zappa

"I declare herewith that this thesis is my own work and that I have not used any sources other than those stated. I have indicated the adoption of quotations as well as thoughts taken from other authors as such in the thesis. I am aware that the Senate pursuant to Article 36 paragraph 1 literature of the University Act of September 5th, 1996 and Article 69 of the University Statute of June 7th, 2011 is authorized to revoke the doctoral degree awarded on the basis of this thesis. For the purposes of evaluation and verification of compliance with the declaration of originality and the regulations governing plagiarism, I hereby grant the University of Bern the right to process my personal data and to perform the acts of use this requires, in particular, to reproduce the written thesis and to store it permanently in a database, and to use said database, or to make said database available, to enable comparison with theses submitted by others."

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Publications

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- Schenk, R. (2023): Complementing a hydropower plant with solar and wind power plants: a conceptual study in the canton of Valais. Master's thesis. Swiss Federal Research Institute (WSL) & department of Environmental Systems Science (D-USYS), ETH Zurich.
- Kaderli, R. (2021): Reglemente für die Zukunft Untersuchung der Seeregulierung des Brienzer- und Thunersees unter den Klimaszenarien CH2018 und Suche nach einem optimalen Reglement für den Thunersee. Masterarbeit. Eidgenössische Forschungsanstalt für Wald, Schnee und Landschaft (WSL) & Institut für Umweltingenieurwissenschaften (IfU), ETH Zurich.
- Schmid, B. (2020): Pegel-Flächen-Beziehung der Schweizer Seen mit SwissBathy3D- und SwissAlti3D-Daten. Bachelorarbeit. Geographisches Institut der Universität Bern.
- Grüter, M. (2020): Technisches Optimierungspotential bestehender Wasserkraftwerke in der Schweiz. Bachelorarbeite. Geographisches Institut der Universität Bern.
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Talks and Lectures

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