The future of Alpine Run-of-River hydropower production: climate change, environmental flow requirements, and technical production potential

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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

Abbreviations

CC	Climate change
CH2018	Swiss climate change scenarios
WFD	Water Framework Directive
FDC	Flow Duration Curve
HP	Hydropower
HRU	Hydrological Response Unit
Hydro-CH2018	Swiss streamflow scenarios
IPCC	Intergovernmental Panel on Climate Change
PREVAH	PREcipitation streamflow EVApotranspiration HRU related model
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RoR	Run-of-River (power plant)
SRES	Special Report on Emissions Scenarios
WASTA	Swiss statistics on hydropower plants

Notations

E	Actual electricity production [MWh]
E_{e}	Production loss due to environmental flow requirements
E_{opt}	Production increases by optimising the design discharge
F	Simplified overall efficiency [kg m^{-2} s^{-2}]
H	Hydraulic head [m]
P	Installed power [MW]
Q_{d}	Design discharge [m^{3} s^{-1}]
T	Time period

1 Introduction

Hydropower (HP) is a key renewable electricity source throughout the world (Gernaat et al. 2017; Schaefli et al. 2019; IHA 2020). This is especially the case in Alpine countries, where the topographic setting leads to high water input (Farinotti et al. 2012; Fatichi et al. 2015a) 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 (Köplin et al. 2010; Addor et al. 2014; Fatichi et al. 2015b; BAFU 2021; Muelchi et al. 2021), there has been a strong focus on high-head accumulation production (Ranzani et al. 2018; Bombelli et al. 2019; Farinotti et al. 2019; 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 and 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, 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 (Bernhard and Zappa 2009; Köplin et al. 2010; Addor et al. 2014; Brunner et al. 2019; Vázquez-Tarrío et al. 2019), with a corresponding decrease in summer production and an increase in winter production (Hänggi and Weingartner 2012; Savelsberg et al. 2018). The change will be more pronounced at higher elevations, especially in catchments dominated by snow and glaciers (Hänggi and Weingartner 2012;

François et al. 2018). 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 and Botter 2012; Bejarano et al. 2019; Kuriqi et al. 2019; Yildiz and 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; Kuriqi et al. 2019; Calapez et al. 2021; Carolli et al. 2022).

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 (BAFU 2021; Brunner et al. 2019). 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.

2 Material and methods

2.1 General change assessment framework

The analysis framework applied in our study (Figure 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).

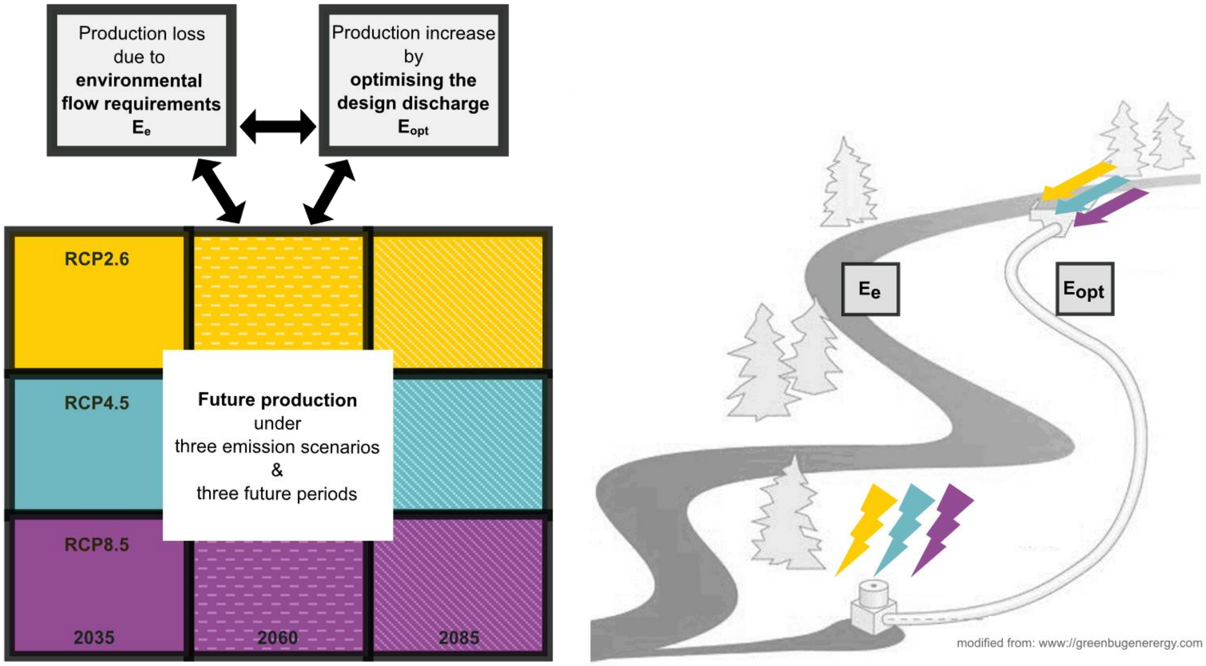

Figure 1. Summary of the analysis framework used in this study to simulate hydrological production potential scenarios.

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 3.3).

2.2 Data sets

We use three data sets: i) the streamflow scenarios Hydro-CH2018 (BAFU 2021); ii) the Swiss HP production statistics WASTA (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 2).

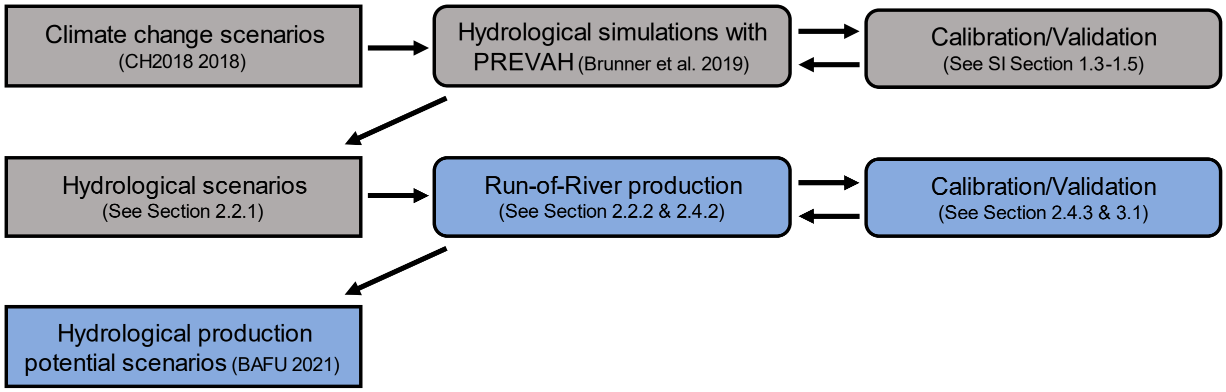

Figure 2: The flowchart used in this study to simulate hydrological production potential scenarios. The grey boxes represent simulated data and models obtained from external sources, while blue boxes represent the modelling carried out in this study.

2.2.1 Hydrological scenarios Hydro-CH2018

The streamflow scenarios Hydro-CH2018 (BAFU 2021) are based on the most recent transient Swiss climate change scenarios CH2018 (CH2018 2018), 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 (CH2018 2018). 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 (SI) Table SI1). 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 are available from Brunner et al. (2019) (for details, see SI, Section SI1.4). The simulations used here are based on the hydrological model PREVAH (PREcipitation streamflow EVApotranspiration

HRU related model; Viviroli et al. 2009), which have been used for CC impact studies in Switzerland (BAFU 2021) and have been calibrated for diverse water resource applications in Switzerland (Bernhard and Zappa 2009; Köplin et al. 2014; Speich et al. 2015) (SI, Figure SI1 & Table SI2).

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).

2.2.2 Hydropower production characteristics

Two data sets are available to characterise the Swiss HP infrastructure: i) the HP plant database WASTA (WASTA 2019), which contains data on 697 powerhouses (>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 (Federal Act on the Protection of Water; 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.

2.3 Selected case studies

In Switzerland, 576 RoR plants (>300 kW) produce about 21.3 TWh a^{-1}, i.e. 31.5% of the total electricity production (BFE 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 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.

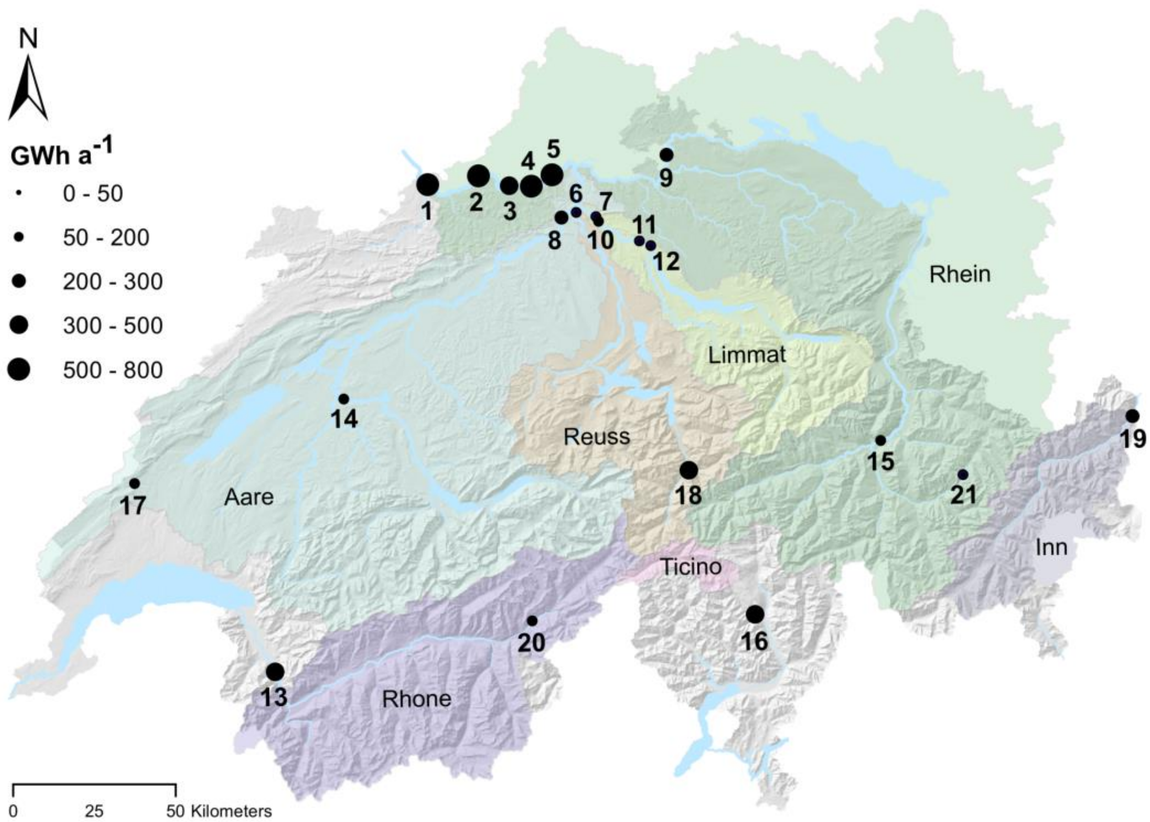

Figure 3. Location of the selected 21 RoR power plants in Switzerland. The size of the power plants corresponds to the annual production in GWh a^{-1}. The numbering (see Table 1) is arranged in ascending order according to the elevation [m a.s.l.] of the power plant's water intake. The coloured areas 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 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).

Table 1. The selected 21 RoR power plants of this study are ordered (Nr.) according to the elevation [m a.s.l.] of the power plant's water intake. This table gives an overview of each power plant's name, the river on which it is located, the area and mean elevation of the catchment contributing to the streamflow, the presence of a water diversion, 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	34’981	1064	N	97.5	557.7	1500	6
2	Ryburg-S.	Rhein	34’470	1072	N	120	698.2	1460	6
3	Saeckingen	Rhein	34’277	1074	N	72	479.4	1450	2
4	Laufenburg	Rhein	34’055	1078	N	106	630.7	1370	10
5	Albbruck-D.	Rhein	33’710	1081	Y	83.8	581.4	1100	2
6	Windisch	Reuss	3’421	1249	Y	2.01	12.3	55	10
7	Aue	Limmat	2’394	1131	Y	5	26	117	14
8	Wildegg-B.	Aare	11’640	1004	Y	49.7	289.3	400	20
9	Rheinau	Rhein	11’952	1241	Y	36	246.1	400	5
10	Wettingen	Limmat	2’394	1131	Y	24	134.7	133	1.9
11	Höngg	Limmat	2’186	1190	Y	1.3	10	50	5
12	Letten	Limmat	1’828	1222	Y	4.2	20.8	100	5
13	Lavey	Rhone	4’741	2192	Y	70	412.1	220	10
14	Mühleberg	Aare	3’168	1522	N	40	156.4	301	0
15	Reichenau	Rhein	3’210	2015	Y	18	111.8	120	4.3
16	Biaschina	Ticino	313	1913	Y	135	360.6	54	1
17	Les Clées	Orbe	299	1196	Y	30	103.3	21	0.7
18	Amsteg	Reuss	595	2167	Y	120	461.1	50	4
19	Kh. Prutz/Ried	Inn	1’941	2342	Y	86.9	411	75	7
20	Aletsch	Massa	196	2929	Y	35.3	184.8	7	0
21	Glaris	Landwasser	196	2209	Y	0.96	7.5	2.1	0.373

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 (< 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 > 500 GWh a^{-1}.

2.4 Methods

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 and Fennessey 1995) and is classically used for RoR design (Westerberg et al. 2011; Hänggi and Weingartner 2012; Wagner et al. 2017; Kuriqi et al. 2019). 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 $V_{\mathrm{l,min}}$, 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, V_{exp} is estimated as the integral of all streamflow values $Q(T)$ that are smaller than the design discharge Q_{d} (exceeding streamflow cannot be turbined) minus the volume lost to minimum flow $V_{\mathrm{l,min}}$ and minus additional production loss $V_{\mathrm{l,max}}$. $V_{\mathrm{l,max}}$ 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, V_{exp} can thus be calculated as follows (Hänggi and Weingartner 2012):

$$V_{\mathrm{exp}} = V_1 + V_2 = Q_d\,(\tau(Q_x) - \tau(Q_{\mathrm{max}})) + \sum\nolimits_{\tau(Q_x)}^{\tau(Q_{\mathrm{min}})} (Q_d + Q_{\mathrm{min}}), \qquad (1)$$

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

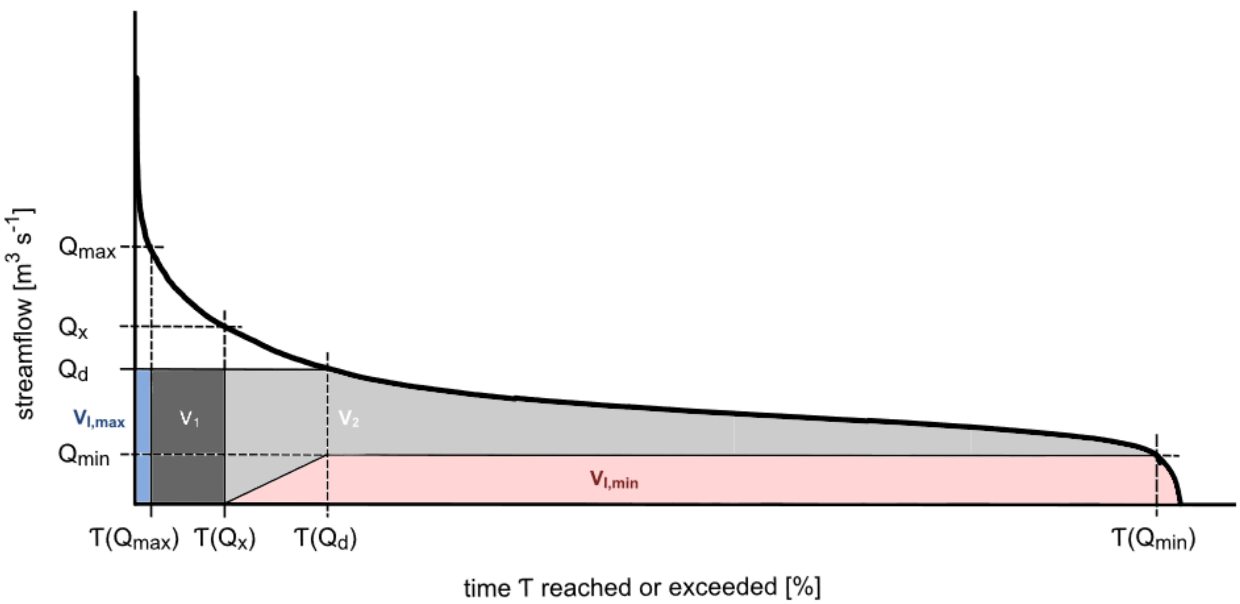

Figure 4. Illustration of the estimation of the hydrological production potential based on the Flow Duration Curve (FDC), characterised by the parameters Q_{max} [m^3 s^{-1}], Q_d [m^3 s^{-1}] and Q_{min} [m^3 s^{-1}]. $\tau(Q_x)$ [%] designates the duration during which the streamflow reaches Q_d+Q_{min}, adapted from the work of Hänggi and Weingartner (2012). $V_{l,max}$ and $V_{l,min}$ 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 $T(Q_{max})$ = 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 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.

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:

$$P = Q_d \, H \, \varphi \eta g, \tag{2}$$

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:

$$F = \varphi \eta g\,. \tag{3}$$

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 and Botter 2012; Yildiz and 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 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):

$$F = \frac{P}{Q_d \; H}\,. \tag{4}$$

The corresponding specific efficiency η is thus:

$$\eta = \frac{P}{Q_d \; H \; \varphi \; g}\,, \tag{5}$$

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 2 and by multiplying by the turbine operation time T_{Turb} (=1 day):

$$E'(t) = Q(t) H F \tau_{Turb}(t) = V(t) H F \,. \tag{6}$$

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 1:

$$E = V_{exp} H F \,. \tag{7}$$

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) is calculated as:

$$E_e = V_{l,min} H F \,. \tag{8}$$

We also quantify an optimised annual production, Q_{opt} [m^3 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 and 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 1.

$$E_{opt} = V_{exp,opt} H F \cdot \tag{9}$$

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 2.2.2), the hydraulic head H [m] is from the HydroGIS data set (Section 2.2.2), Q_{min} (underlying V_{exp}) is from detailed personal enquiry, and streamflow (underlying V_{exp}) is from hydrological simulations (Section 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).

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 2.2.1). To gain further insights into uncertainties related to simulated production, we compare the collected production data (WASTA, Section 2.2.2) to the simulated RoR production based on the climate model ensembles (Section 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.

3 Results

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 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 (Δ +192.7 GWh w^{-1}) and summer production (April to September) tends to be slightly underestimated (Δ -43.3 GWh s^{-1}; Figure 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 SI2, Figure SI2).

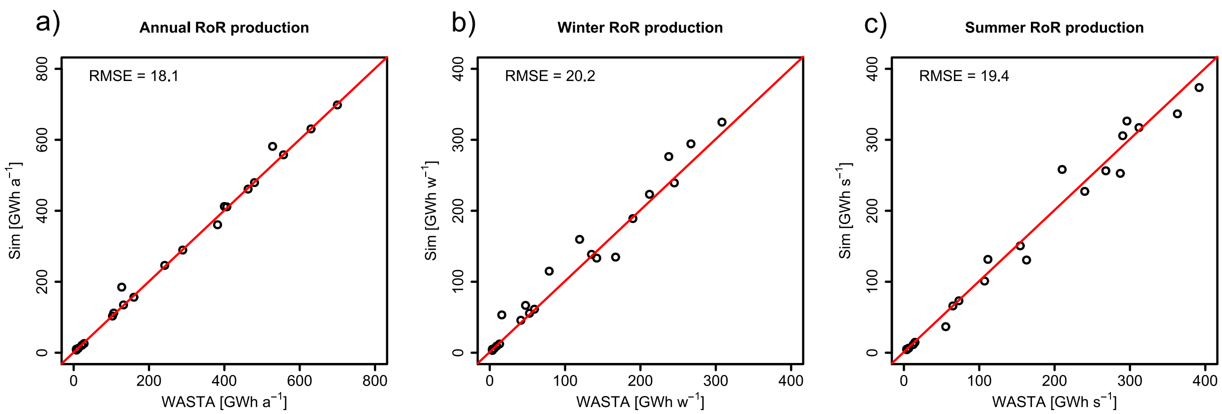

Figure 5. Comparison of the mean simulated production with production reported in the WASTA database for the 21 RoR plants: a) annual production, b) winter production (October to March), and c) summer production (April to September).

3.2 Change in RoR electricity production

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 6a); the Glaris, Davos power plant shows only minor changes in streamflow, but an increase in annual production (Figure 6b).

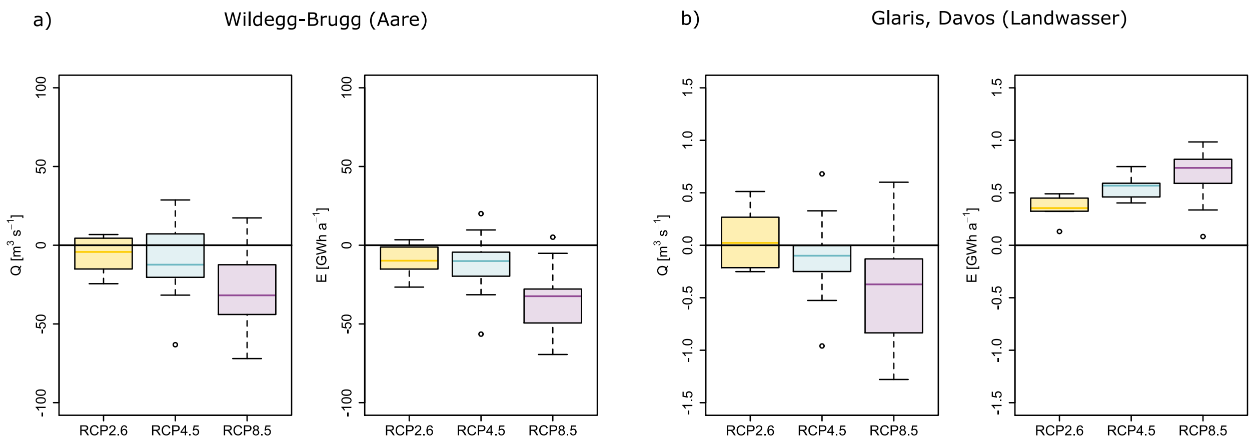

Figure 6. Simulated changes in the mean annual streamflow (Q) and mean electricity production (E) by the end of the century (2070–2099) at a) the Wildegg-Brugg power plant and b) the Glaris, Davos power plant. The black line indicates the median value of the reference period (1981–2010). The yellow (RCP2.6),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

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 7).

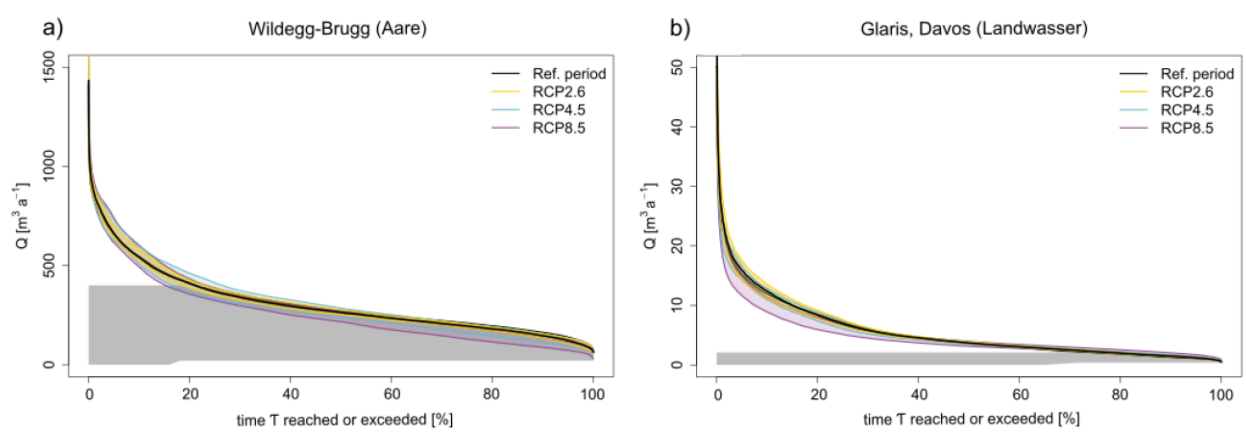

Figure 7. Flow Duration Curves (FDCs) for the power plants a) Wildegg-Brugg and b) Glaris, Davos. The black line represents the reference period (1981–2010), the grey shaded area represents the expected available streamflow (V_{exp}), and the areas bounded by yellow (RCP2.6), blue (RCP4.5) and purple (RCP8.5) curves represent the range of FDCs for the projected model ensembles based on the three emissions scenarios for 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).

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 2). Exceptions are the high-elevation power plants, which are strongly influenced by snow- and ice-melt processes (Figure 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 8).

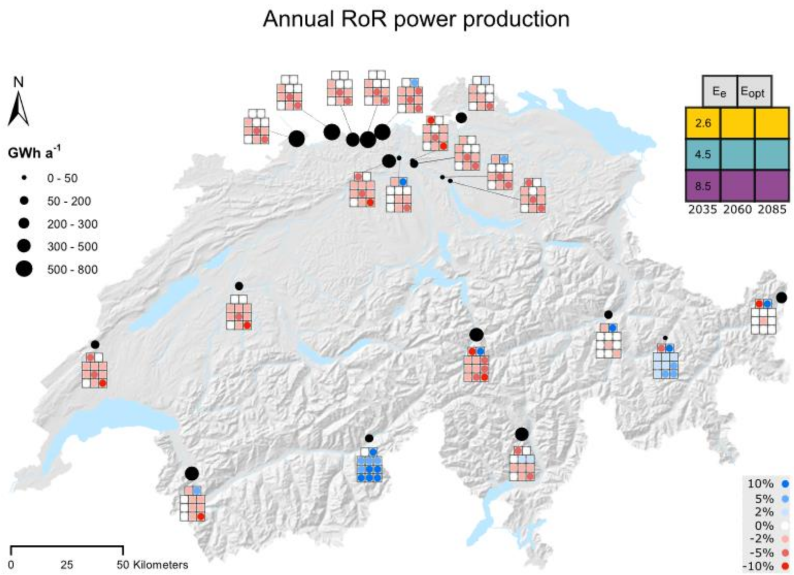

Figure 8. Simulated changes in production at the 21 RoR power plants; the size of the dots (power plants) represents the annual production in GWh a^{-1}. The coloured dots in the grids represent the loss due to environmental flow requirements (E_e), the increase potential resulting from optimisation of the design discharge (E_{opt}), and the climate change impact for the periods 2035 (near future, 2020–2049), 2060 (mid-century, 2045–2074) and 2085 (end of century, 2070–2099) under the three emissions scenarios RCP2.6 (yellow), RCP4.5 (blue), and RCP8.5 (purple).

The annual changes in production due to CC range from 0% to -7% (Table 2). An annual loss of 7% corresponds to the electricity consumption of around 82,500 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 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	T_1	T_2	T_3
RCP2.6	-2%	-1%	-2%
RCP4.5	-1%	-5%	-2%
RCP8.5	0%	-3%	-7%

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 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 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 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 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.

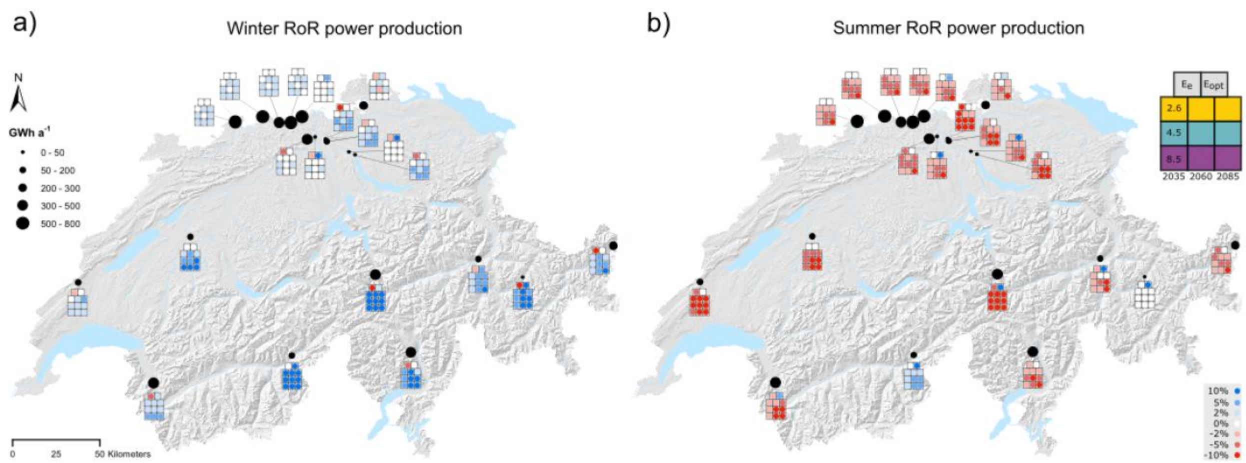

Figure 9. Same as Figure 8 but for a) winter (October to March) and b) summer (April to September).

Table 3. Simulated change in a) winter (October to March) and b) summer (April to September) 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.

a) Winter	T_1	T_2	T_3
RCP2.6	+2%	+5%	+4%
RCP4.5	+5%	+4%	+7%
RCP8.5	+5%	+7%	+9%

b) Summer	T_1	T_2	T_3
RCP2.6	-5%	-4%	-2%
RCP4.5	-6%	-11%	-9%
RCP8.5	-5%	-10%	-22%

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.

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 corresponding data for RCP2.6 and RCP4.5 are available in the Supplementary Data (Wechsler 2021).

A correlation analysis with selected power plant characteristics (Figure 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 9) 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).

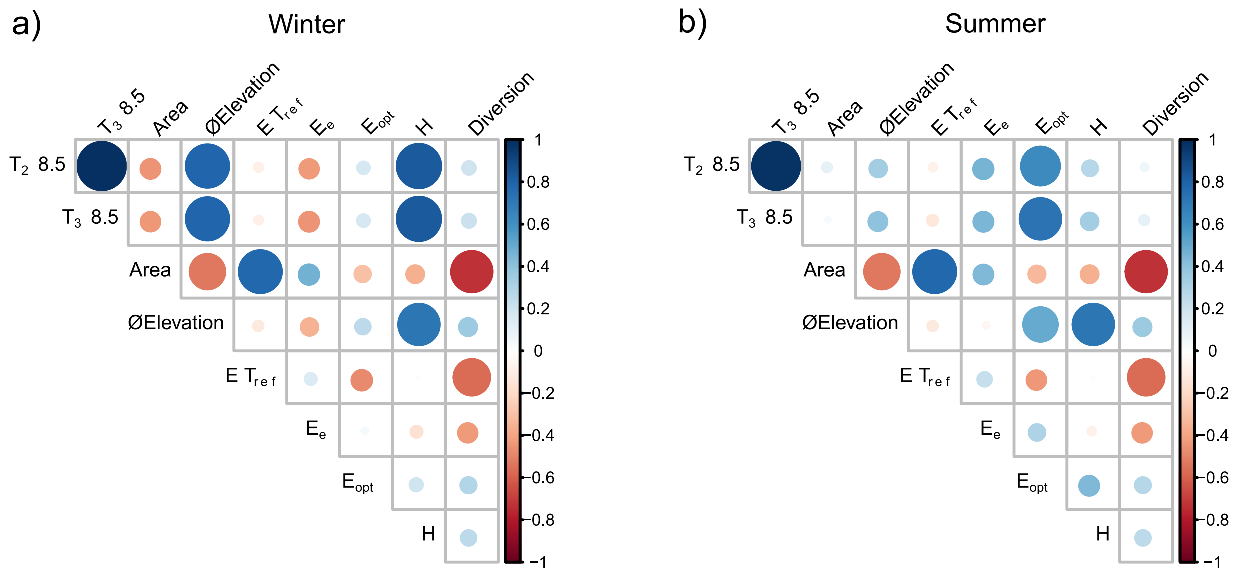

Figure 10. Correlation matrix for a) winter (October to March) and b) summer (April to September) RoR electricity production: the simulated production changes under the emissions scenario RCP8.5 for: the two future periods T_2 (2060) [%] and T_3 (2085) [%], the catchment area [km^2], the mean elevation of the catchment [m a.s.l.], the mean annual production during the reference period (E T_{ref} [GWh a^{-1}]), 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 [m], and streamflow diversion (Diversion [Yes/No]). 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 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.

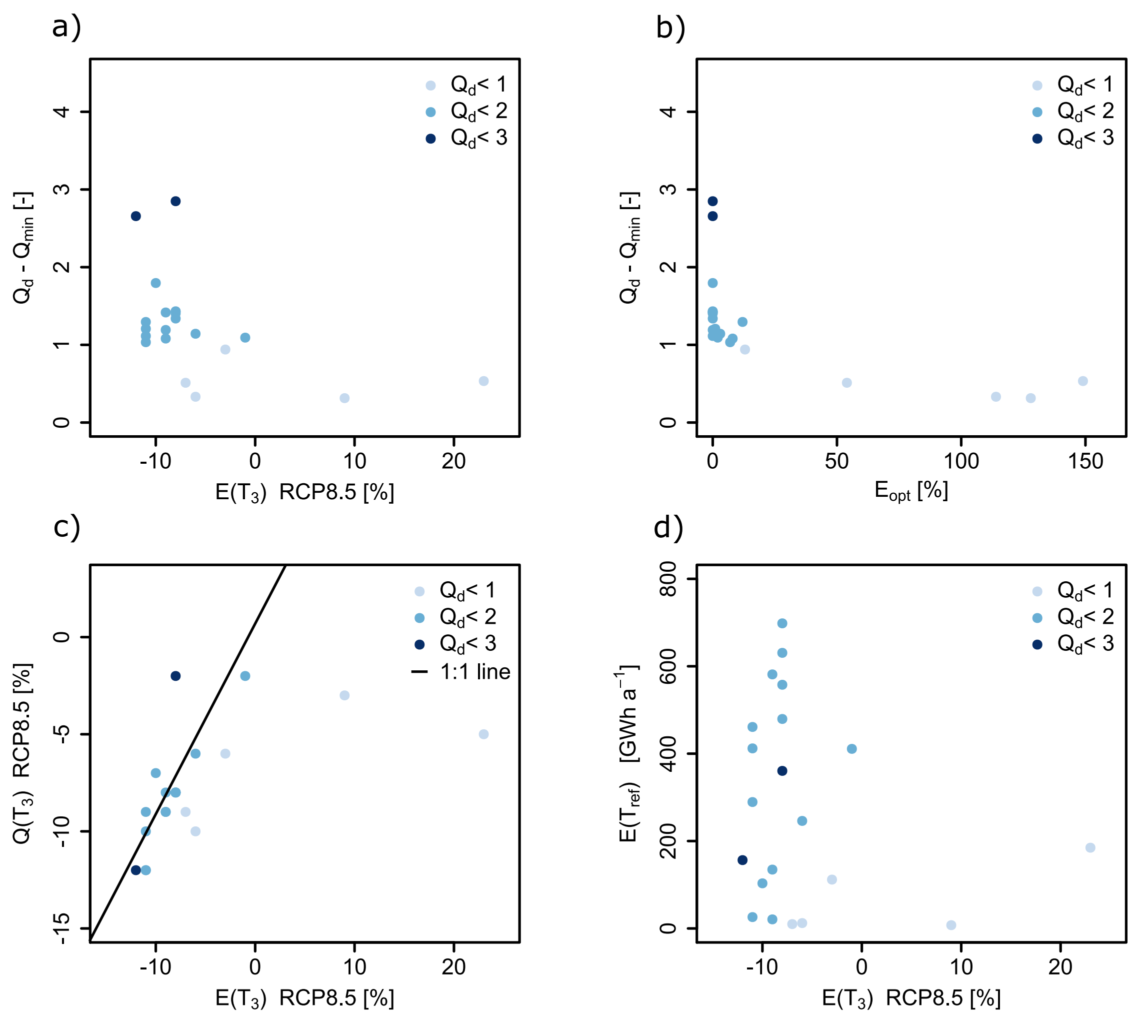

Figure 11. Negative Spearman correlations a) between future annual electricity production (E) changes by time period T_3 (2070–2099) under emissions scenario RCP8.5 and the range of usable streamflow volume (the difference between normalised design discharge Q_d and normalised environmental flow Q_{min}) and b) between the production increase potential (E_{opt}) and the range of usable streamflow volume. Comparisons of c) streamflow changes (Q) and production changes (E) by T_3 under RCP8.5, indicating also a linear 1:1 line, and d) annual production during the reference period (E T_{ref}) and projected production (E) changes by T_3 under RCP8.5. The colours of the dots represent the normalised (by the mean streamflow) design discharge (Q_d) of the 21 run-of-river 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 11b).

Changes in streamflow do not show a linear relationship with CC-induced changes in production (Figure 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<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 11c). The power plants with a small Q_d are predominantly small or medium-sized (Figure 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 9 and results table 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 (Figure 9 and results table in Supplementary Data; Wechsler 2021).

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 (Hänggi and Weingartner 2012; Wagner et al. 2017; Totschnig et al. 2017; Savelsberg et al. 2018; François et al. 2018; Schaefli et al. 2019), 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 (Wagner et al. 2017; Totschnig 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 (Ranzani et al. 2018; Savelsberg et al. 2018; Cassagnole et al. 2020).

The available national-scale data sets (WASTA 2019; Balmer 2012) 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 (Skjelbred and Kong 2019; Quaranta et al. 2022). 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 (Gorla and Perona 2013; Gabbud and Lane 2016; Kuriqi et al. 2019; 2021; Carolli et al. 2022). Future work could potentially address such aspects, which are already part of the Swiss (GSchG 2009) and European legislation (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 Water Framework Directive (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 2015). 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.

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.

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1 Supplementary Information

1.1 Climate change scenarios CH2018

Table SI1. The 39 climate model ensembles used in this study are based on the CH2018 climate scenarios (CH2018 2018)*. The combination of TEAM (responsible institute), RCM (Regional Climate Model), GCM (General Circulation Models), RES (spatial resolution), and RCP (Representative Concentration Pathway = emissions scenario) is shown for each ensemble. The colours correspond to the three RCPs (RCP2.6, RCP4.5, RCP8.5).*

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

1.2 Model calibration

Table SI2. Results of the calibration and verification by Bernhard and Zappa (2012) *and Speich et al.* (2015) *of the hydrological modelled discharge at selected stations (Figure SI1) for the calibration period (1984–1996) and verification periods (1980–1983 & 1997–2009). Nr. corresponds to the number in Figure SI1; Name indicates the name of the discharge measurement station; Cal/Val indicate calibration and validation; NS is the Nash criterion [no unit]; NSL is the logarithmic Nash criterion [no unit]; DV is the volume error [%]. The link is to the web atlas* (HADES 2021) *where the streamflow regimes and hydrological future projections are visualised.*

Nr.	Name	Cal/Val	NS	NSL	DV	Link
1	Rhine, Basel	Cal	0.953	0.95	0.3	https://hydromapscc.ch/#en/9/47.3379/7.8662/bl_hds--l02_standorte$CH-0146+0/NULL
		Val	0.927	0.931	-3.4	
2	Aare, Brugg	Cal	0.9	0.9	-0.9	https://hydromapscc.ch/#en/10/47.2657/8.2892/bl_hds--l01_standorte$CH-0200--l02_standorte$CH-0064+0/NULL
		Val	0.883	0.887	-2.7	
3	Reuss, Mellingen	Cal	0.932	0.918	-1.8	https://hydromapscc.ch/#en/11/47.2795/8.4512/bl_hds--l02_standorte$CH-0051+0/NULL
		Val	0.919	0.902	-2.2	
4	Limmatt, Unterhard	Cal	0.9	0.885	-0.3	https://hydromapscc.ch/#en/10/47.2191/8.5625/bl_hds--l02_standorte$CH-0075+0/NULL
		Val	0.883	0.874	-2.2	
5	Rhein, Neuhausen	Cal	0.954	0.935	2.6	https://hydromapscc.ch/#en/9/47.5367/8.8770/bl_hds--l02_standorte$CH-0145+0/NULL
		Val	0.903	0.898	-2.4	
6	Rhone, Porte	Cal	0.529	0.449	5.2	https://hydromapscc.ch/#en/9/46.5787/7.4899/bl_hds--l02_standorte$CH-0047+0/NULL
		Val	0.571	0.523	3.2	
7	Aare, Schoenau	Cal	0.897	0.895	-1.6	https://hydromapscc.ch/#en/9/46.5787/7.4927/bl_hds--l02_standorte$CH-0092+0/NULL
		Val	0.907	0.911	-3.3	
8	Rhein, Domat, Ems	Cal	0.752	0.635	5.7	https://hydromapscc.ch/#en/9/46.8949/9.0720/bl_hds--l02_standorte$CH-0235+0/NULL
		Val	0.782	0.682	0.7	
9	Ticino, Bellinzona	Cal	0.793	0.735	0.7	https://hydromapscc.ch/#en/10/46.2848/9.1544/bl_hds--l02_standorte$CH-0053+0/NULL
		Val	0.816	0.698	-2.5	
10	Reuss, Seedorf	Cal	0.857	0.778	-0.3	https://hydromapscc.ch/#en/10/46.7667/8.6215/bl_hds--l02_standorte$CH-0138--l01_standorte$CH-0061+0/NULL
		Val	0.821	0.779	-3.3	
11	Inn, Martina	Cal	0.727	0.645	-3.6	https://hydromapscc.ch/#en/8/46.840/10.563/bl_hds--l02_standorte$CH-0289+0/NULL
		Val	0.732	0.698	-8.0	
12	Landwasser, Davos	Cal	0.862	0.919	6.8	https://hydromapscc.ch/#en/10/46.7093/10.1376/bl_hds--l02_standorte$CH-0138--l01_standorte$CH-0169+0/NULL
		Val	0.851	0.884	2.9	

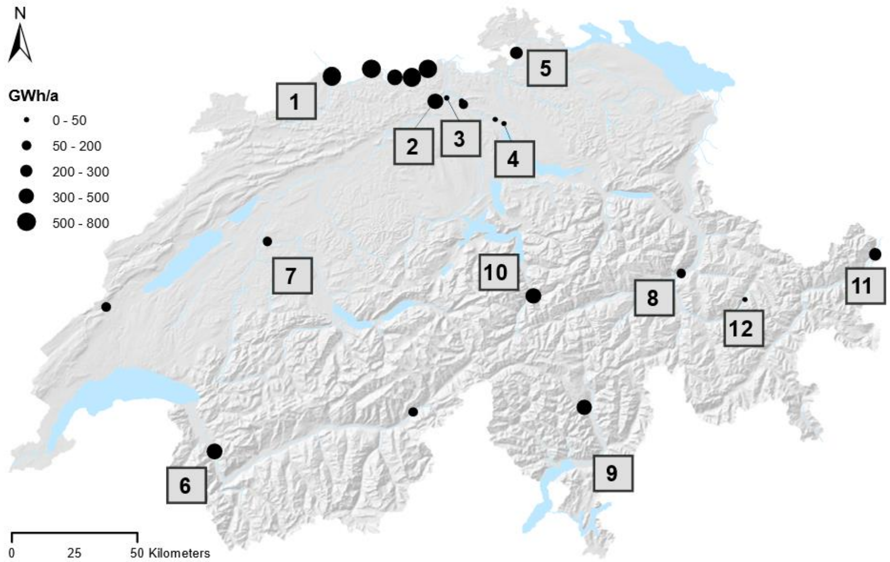

Figure SI1. The 21 Swiss run-of-river power plants considered in this study. The size of the dots represents the annual production in GWh a^{-1}. The numbers correspond to the discharge measuring stations in Table SI2 that were used for calibration and validation.

1.3 Hydrological regimes

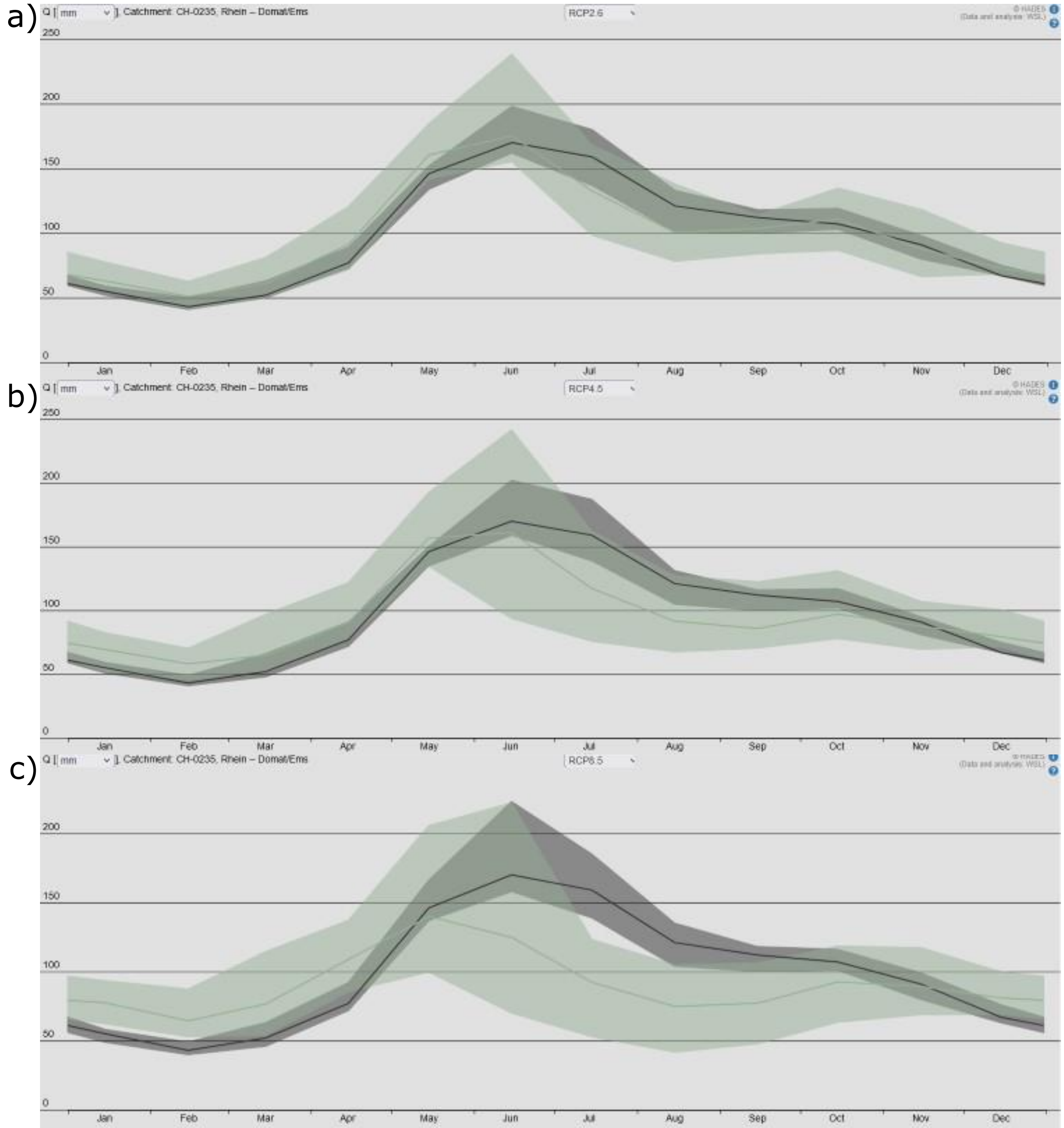

Figure SI2. Changes in mean monthly streamflow under the three emissions scenarios a) RCP2.6, b) RCP4.5, and c) RCP8.5 by the end of the century (2070–2099, green) in comparison to the reference period (1981–2010, black) at Domat Ems (Nr. 8 in Table SI2 and Figure SI1) shown at https://hydromapscc.ch.

1.4 Hydrological scenarios CH2018

PREVAH is a conceptual, process-oriented model (Viviroli et al. 2009), which has been continuously improved since its development (Gurtz et al. 1999). As part of the CCHydro study (Bernhard and Zappa 2012), a spatially explicit (grid) version was created for PREVAH, with a resolution of 200 m × 200 m (Schattan et al. 2013; Speich et al. 2015; Brunner et al. 2019). PREVAH consists of several model components covering the following hydrological processes (Viviroli et al. 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 (Viviroli et al. 2009; Viviroli et al. 2009; Köplin et al. 2010; Bernhard and Zappa 2012; Speich et al. 2015). 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; Viviroli et al. 2009; Bernhard and Zappa 2012). Snow accumulation and melting in PREVAH are determined by temperature and global radiation (Viviroli et al. 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. Excess snow is then relocated, based on the DEM, 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 and Hock 2015) and with the newer, extended version of GloGEM (GloGEMflow) 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 2004) has been created to take lake regulation into account (Wechsler et al. 2021).