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The future of Swiss run-of-river hydropower production:

climate change, environmental flow requirements and technical production potential

Wechsler Tobias[1,2,4], Schaefli Bettina[2,4], Zappa Massimiliano[1,4], Jorde Klaus[3,4], Stähli Manfred[1,4]

[1]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, 8903 Birmensdorf, Switzerland

[2]Institute of Geography (GIUB) and Oeschger Centre for Climate Change Research (OCCR) University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

[3]KJ Consult, Ferdinand-Raunegger-Gasse 26, 9020 Klagenfurt, Austria

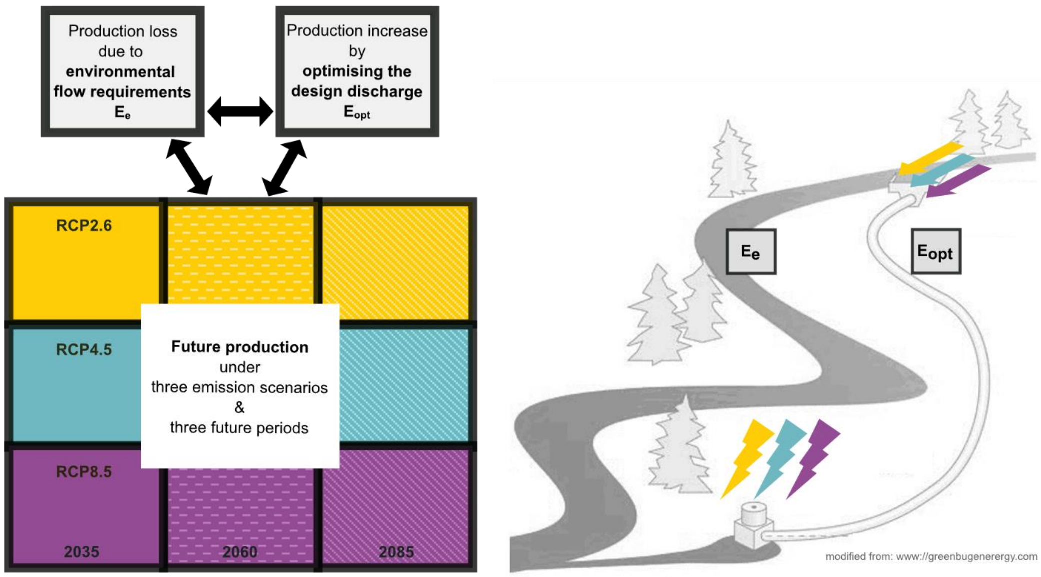
[4]Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE), Sonneggstrasse 5, 8092 Zurich, Switzerland

Abstract

Climate impact studies on Alpine hydropower production focused in the past on high-head accumulation power plants. We provide one of the first comprehensive, simulation-based studies on climate impacts on Alpine Run-of-River (RoR) production, including effects of environmental flow requirements and technical increase potential. We simulate future production for 21 Swiss RoR plants under three emission scenarios. The results show an increase in winter production and a decrease in summer production, which in conjunction leads to an annual decrease of about -2% to -7%. The key results are: i) there is no linear relationship between climate impacts on streamflow and on electricity 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 with the mean catchment elevation. The highest elevation plants even show an increase in annual production due to increased shares of precipitation falling as rain instead of snow. These general results are transferable to RoR production in similar settings at other Alpine locations and should be considered in future assessments. Future work could in particular focus on further technical optimisation potential, considering detailed operational data.

Keywords: Hydropower, Run-of-River power plants, Climate change, environmental flow, design discharge, Alps

Current RoR Production compared to:



Highlights

- Climate change will lead to more winter RoR production and less summer production
- Most of the analysed RoR power plants show a decrease in future annual production
- The changes depend strongly on the elevation and plant-specific characteristics
- Future RoR production does not depend linearly on projected changes in streamflow
- Changes in production do not necessarily mean a linear change in financial revenue

1 Introduction

Hydropower is a key renewable electricity source around the world [1–3], in particular also in Alpine countries, where the topographic setting leads to high water input [4,5] but also to locally high hydraulic heads. In the context of climate change (CC) impact assessment on hydropower production in Alpine countries, where CC is particularly strong [6–10], there was in the past a strong focus on high-head accumulation production [2,11–13], because of significant changes of snow- and glacier-melt feeding these plants.

CC impact studies on Run-of-River (RoR) power plants are comparably rare (e.g. [14–16]). This is critical because these plants have typically a very different turbine operation pattern compared to storage power plants. The International Energy Agency (IEA) [17] estimates based on data from selected European countries (FR, DE, PRT, ESP, CH, AUT) that RoR operation is at full turbine capacity around 40% of the time, which is significantly higher than that of storage power plants (~15% of the time) and pumped storage power plants (~10% of the time).

Existing studies on Alpine RoR power production do not give insights into how to transfer the obtained results to other locations. This seriously limits larger-scale projections on how CC will impact RoR power production, and this despite of the now well-known general tendencies on Alpine streamflow evolution. These streamflow tendencies are a slight decrease in mean annual streamflow and a pronounced seasonal shift with less streamflow in summer and more streamflow in winter [6,8,18–20]. There is, however, no reason to assume a linear relationship between climate-induced changes in streamflow and corresponding changes in RoR power production [16]. Electricity production impacts, in fact, crucially depend on the range of streamflow that is used for production, which in turn depends on the Flow Duration Curve (cumulated probability distribution of streamflow) design discharge and on any water-use restrictions imposed by ecosystem protection [21–24].

Detailed CC impact studies on Alpine RoR power production based on catchment-scale streamflow projections generally conclude that future production will closely follow streamflow changes, with a corresponding decrease in summer production and an increase in winter production [15,25]. The change will be more pronounced in higher and especially snow and glacier dominated catchments [15,26]. François et al. [26] show for northern Italy that RoR power production in snow dominated catchments can increase even though streamflow is expected to decrease.

In addition to such catchment scale studies, there are a few regional CC impact assessments that rely on a coarse representation of hydrology and simplified treatment of RoR production. One such example is the work of Savelsberg et al. [25] who set-up a national-scale electricity market model for Switzerland including 400 hydropower plants (of which around 300 are RoR power plants); they find a relatively high change in winter production compared to the change in streamflow and explain this by excess turbine capacities in winter and early spring that can be used for production under future streamflow regime. The study compares future scenarios with individual years in the past that were either dry, wet or average. Compared to the average year 2008, Savelsberg et al. [25] simulate a future increase in annual production of 4%. Given the coarse resolution of their results, no detailed insights into the change of production along spatial gradients can, however, be obtained.

Similarly, Totschnig et al. [27] use a dynamical simulation model of the Austrian and German electricity, heating and cooling sectors in combination with climate change scenarios; their model includes around 400 RoR plants and simulates a reduction of 5.5% in the mean annual RoR power production for Austria and Germany by mid-century under the so-called SRES emission pathway A1B, without giving further insights into variables that might drive this change.

To our knowledge, there is a single study proposing an extrapolation of CC impacts on the entire Alpine region: Wagner et al. [16] find an annual decrease of RoR production of 8%, with a wide-spread increase in winter and decrease in summer. They used a simplified hydrological model on 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 are based on scenarios that preceded the ones currently in use (SRES emission pathway A1B).

These regional studies give clear indications on the general trend of RoR production in the Alpine region, they can however not explain how the simulated changes might be modulated by local hydro-climatic and technical and operational specificities and in particular water use restrictions. Such restrictions exist for all types of RoR, e.g. in the form of reserved flow for fish passability in the case of RoR plants built across a stream. 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, fish passage or sediment transport and is defined as environmental flow [23,24,28].

In addition to questions related to water use restrictions, we propose here to study how CC impacts relate to plant-scale production optimization potential. In fact, e.g. in Switzerland, most of the 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 with 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 recordings. Accordingly, some RoR plants might today show a considerable optimisation potential of the design discharge in relation to the actual streamflow regime [22].

In this context, we want to show, based on hydrological simulations, i) how RoR production could change under CC and ii) to assess how these impacts compare to impacts related to environmental flow requirements and iii) to production increases resulting from technical optimisation. We assess in detail the impacts on an annual and seasonal scale and analyse explanatory variables and their influence on RoR power production.

We use the example of 21 representative RoR plants in Switzerland, whose streamflow was simulated with a hydrological model in the context of pre-existing research [10,20]. The choice of Switzerland is relevant because of its general high share of hydropower and of its pronounced variety of hydro-climatological regimes and hydropower infrastructures within a small Alpine area. Accordingly, the results presented here will be at least partly transferable to other Alpine regions. The simulation-based results of our study allow a quantification of future annual and seasonal RoR power production; whereby the change in winter production is currently of particular importance for the Alpine region.

2 Material and methods

We hereafter first present the analysis framework, followed by the used data sets, the selected case studies and the used methods.

2.1 General change assessment framework

The analysis framework of our study (Figure 1) is based on the comparison of current Run-of-River *(*RoR*)* production (reference period T_{ref}: 1981-2010) to i) future production under climate change (CC) ii) to production loss due to environmental flow requirements (E_e) and iii) to production increase potential resulting from an optimisation of the design discharge of the installed turbines *(*E_{opt}*)*. For 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 emission scenarios, RCP2.6 (concerted mitigation efforts), RCP4.5 (limited climate mitigation) and RCP8.5 (no climate mitigation measures).

Given that we do not have exact observations of actual RoR production at these sites, the entire analysis is based on what we call "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).

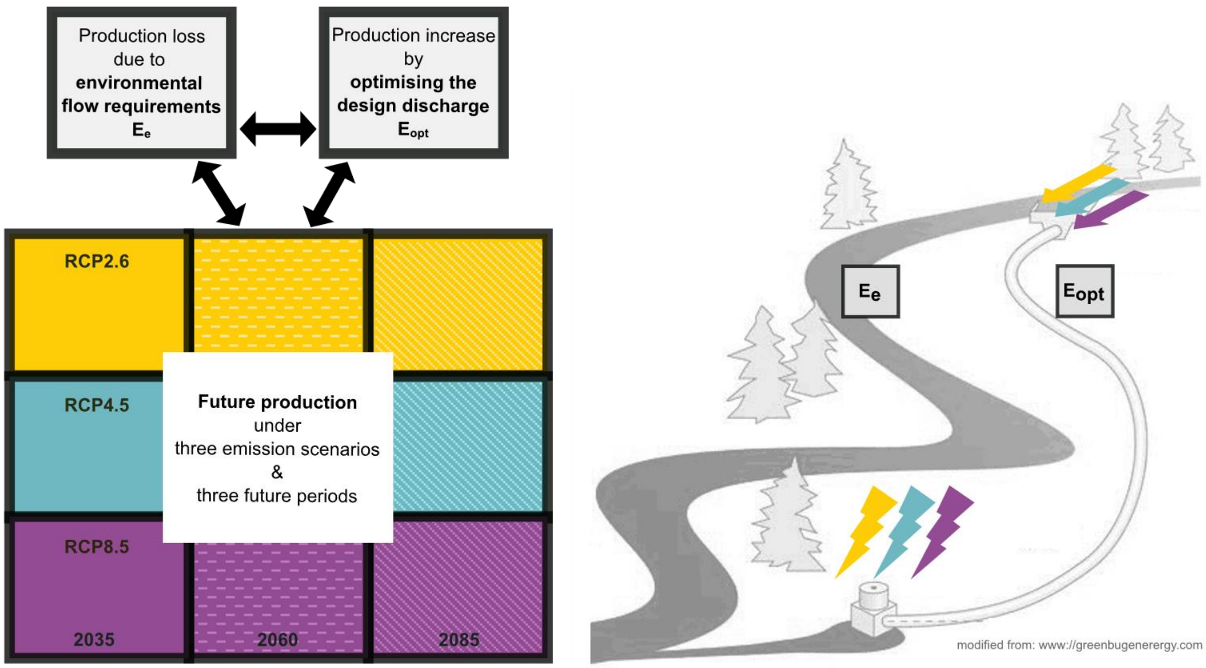


Figure 1. Summary of the analysis framework of this study to simulate hydrological production potential scenarios.

CC induced RoR power production changes are assessed by comparing the production potential simulated for the reference period T_{ref} and for all available climate model ensembles for the future periods T_1, T_2, T_3, 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 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 [10] resulting from the CH2018 climate change scenarios [29], ii) the Swiss hydropower production statistics WASTA [30] and iii) a georeferenced database about Swiss HP infrastructure, called HydroGIS, produced by Balmer [31]. With these data sets we were able to simulate so-called hydrological production potential scenarios (Figure 2).

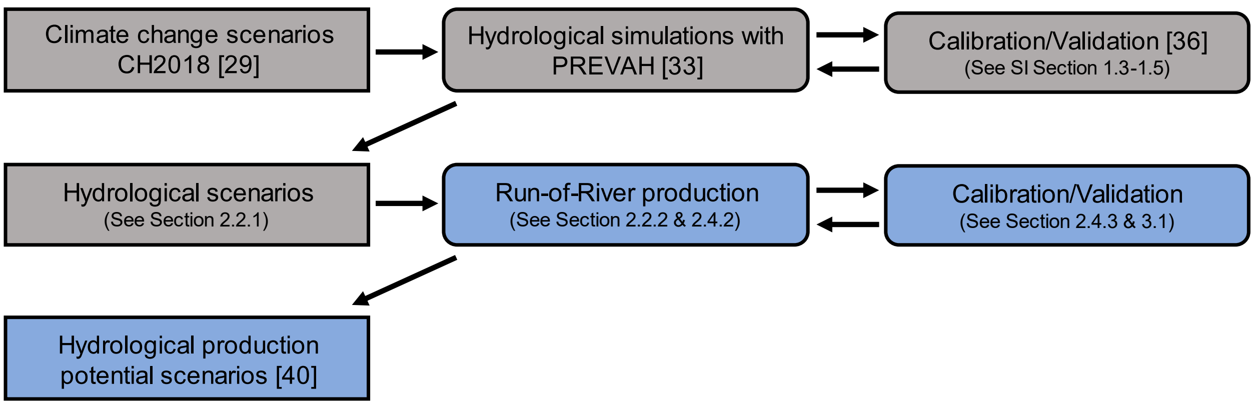


Figure 2: The flowchart of this study to simulate hydrological production potential scenarios. The grey boxes represent simulated data and models obtained from external sources, while blue boxes represent the modelling carried out in this study.

2.2.1 Hydrological scenarios Hydro-CH2018

The streamflow scenarios Hydro-CH2018 [10] are based on the most recent transient Swiss Climate Change Scenarios CH2018 [29], which are based on the EURO-CORDEX dataset [32]. The CH2018 climate scenarios result from climate model simulations and subsequent statistical downscaling with the quantile mapping approach [29]. The streamflow scenarios are based on a total of 39 CC scenarios, covering three Representative Concentration Pathways (RCP), RCP2.6 (concerted mitigation efforts), RCP4.5 (limited climate mitigation) and RCP8.5 (no climate mitigation measures). For each RCP, a varying number of climate model ensembles was 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 S1). 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 the work of Brunner et al. [33] (for details, see SI, Section SI1.4). The simulations used here are based on the hydrological model PREVAH (PREcipitation streamflow

EVApotranspiration HRU related Model [34]), which were used for CC impact studies in Switzerland [10] and were calibrated for diverse water resources applications in Switzerland [18,35,36] (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 some 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 improved with regards to the representation of snow accumulation at high elevations [37] and with regards to the representation of glaciers and their length evolution [20].

2.2.2 Hydropower production characteristics

Two data sets are available to characterize the Swiss hydropower infrastructure: i) the hydropower plants database WASTA [30], which contains data on 697 powerhouses (>300 kW), including hydropower production type, design discharge [m^3 s^{-1}], installed power [MW], mean annual production [GWh a^{-1}], winter production (Oct-Mar) and summer production (Apr-Sep); ii) the data base HydroGIS [31], which contains georeferenced information on 401 powerhouses and related infrastructure, including the hydrological catchment corresponding to each hydropower 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 for our work from HydroGIS is the hydraulic head of each RoR power plant, 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. [2]. It is noteworthy that the methods used to estimate the expected production that is reported in WASTA remain unclear but rely on estimation models applied by the hydropower producers, including expected average turbine operation hours.

There is no database for specific environmental flow requirements of individual Swiss RoR plants; the general rules are fixed in the Swiss law (Federal Act on the Protection of Water [38]) but are adapted for each production location in the water use contracts, the so-called concessions. These requirements were obtained directly from the hydropower 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}, 31.5% of the total electricity production [39]. The largest RoR plants are located along the major streams in the so-called Plateau region of Switzerland (the low elevation region); but similar to other Alpine regions, there are also numerous smaller and medium-sized RoR plants higher up in the mountains. In this study, we consider 21 RoR power plants that are shown in 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.

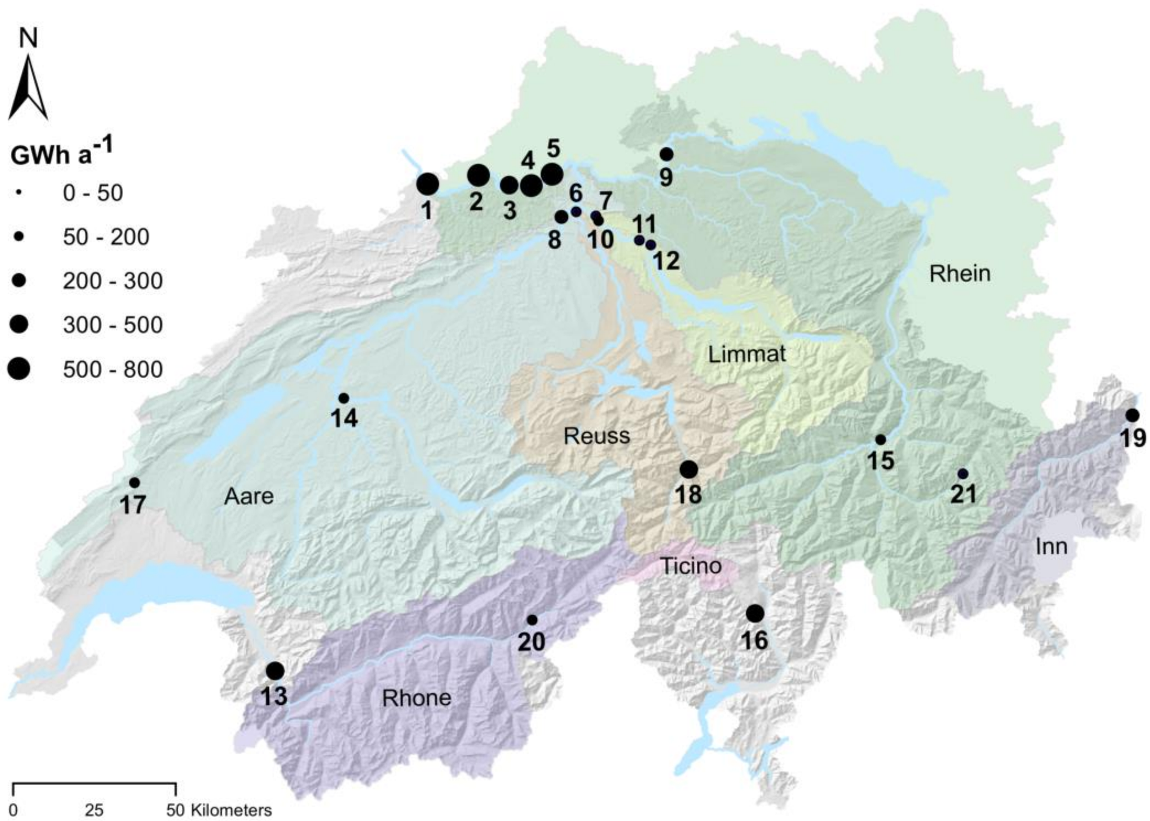


Figure 3. Location of the selected 21 RoR power plants in Switzerland. The size of the power plants corresponds to the annual production in GWh a^{-1}. The numbering (see Table 1) is arranged in ascending order according to the elevation [m a.s.l.] of the power plant's water intake. The colored areas 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; some plants have in addition a limited storage reservoir. Details for all power plants are in the provided data set [40].

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 the Power Plants name, the River it is located on, the Area and the mean Elevation of the catchment contributing to the streamflow, the presence of a water diversion, the installed power (P), the simulated power production for the reference period (E_{ref}), the power plants design discharge (Q_d) and the minimum flow to be provided for environmental flow requirements or fish passability (Q_e). More details on specific technical characteristics for each power plant are available in the provided data set [40].

Nr.	Power Plant	River	Area [km²]	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 small annual production (< 50 GWh a^{-1}), 12 plants with 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 to the estimation of RoR production potential is the estimation of the expected available streamflow volume, which is estimated based on the Flow Duration Curve (FDC); this is an inverse representation of the cumulative probability distribution of streamflow [41] (Figure 4) and classically used for RoR design [15,16,24,42]. 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 non-usable streamflow volume $V_{l,min}$, e.g. because of known water abstractions for irrigation or because of environmental flow requirements, i.e. water flows reserved for ecology purposes. 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 $V_{l,min}$ (Figure 4) and minus additional production loss $V_{l,max}$. $V_{l,max}$ results from the maximum streamflow Q_{max} during which the system still can be safely operated. Beyond Q_{max}, the power production system is shut down to prevent damages, e.g. by drift wood on the water intake. As can be seen in Figure 4, V_{exp} can thus be calculated as follows [15]:

$$V_{exp} = V_1 + V_2 = Q_d(\tau(Q_x) - \tau(Q_{max})) + \sum_{\tau(Q_x)}^{\tau(Q_{min})}(Q_d + Q_{min}), \quad (1)$$

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

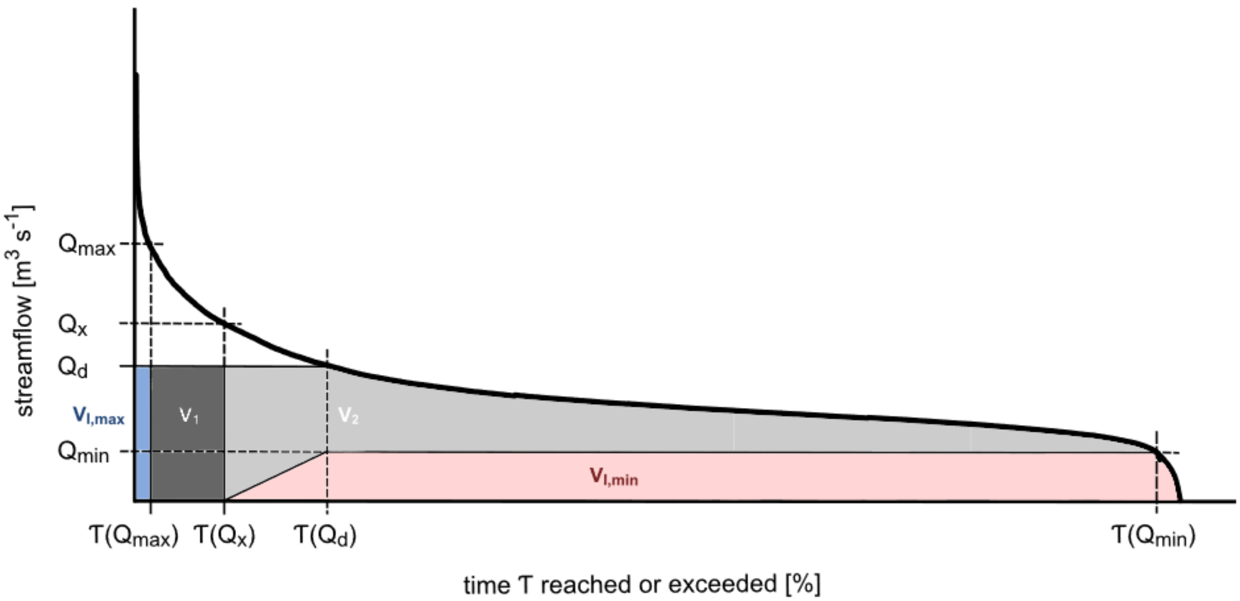


Figure 4. Illustration of the estimation of the hydrologic production potential based on the Flow Duration Curve (FDC), characterised by the parameters Q_{max} [m^3 s^{-1}], Q_d [m^3 s^{-1}] and Q_{min} [m^3 s^{-1}]. $\tau(Q_x)$ [%] designates the duration during which the streamflow reaches Q_d+Q_{min}, 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 data base. Q_{min} values must be collected from hydropower concessions, i.e. the plant-specific water use contracts. Q_{max} values are difficult to know in practice since these values are not formally fixed; they are ignored in this study (which results in $T(Q_{max})$=1 day). The resulting error can be assumed to be small. The FDCs (i.e. the streamflow distribution) are obtained here by ranking the entire time series, available from daily streamflow simulations (Section 2.2.1). FDCs for winter are obtained by considering the daily streamflow values for October to March and those for summer for April to September.

2.4.2 Calculation of RoR power production

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

$$P = Q_d H \varphi \eta g, \quad (2)$$

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}] 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}] (Equation 3);

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

F [kg m^{-2} s^{-2}] is a simplified overall efficiency. The specific efficiency η of a hydropower plant depends on several factors, e.g. on the runner, the turbine type, generator capacity or friction loss in the penstock [21,22]. We consider η to be constant here, but it is in principle time-variant, depending in particular also on the actual discharge through each turbine (if there are several). We make here the assumption that the machinery of all RoR plants allows hydropower 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 thus reads as

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

which theoretically is between 0.7 and 0.9 [43]. For RoR power plants, η [-] is usually somewhat higher than for storage power plants, because the penstocks are mostly shorter and thus the loss due to friction is lower.

Actual RoR power production at a given time step *t, E'(t)* [MWh] 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 expected production *E.* This expected production *E* is obtained by replacing *V(t)* in the above equation by V_{exp} from Equation 1:

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

This formulation makes the assumption that the turbines are fully operational whenever there is water to produce.

The production loss arising from an imposed minimum environmental flow (Figure 4) is obtained 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 since it would require replacing the turbines). This theoretical optimised design discharge is obtained here as the one that corresponds to the 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.

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

The required data to estimate E, E_e and E_{opt} are obtained as follows: installed power P and design discharge Q_d are obtained from WASTA (Section 2.2.2), the hydraulic head H [m] is obtained from the HydroGIS dataset (Section 2.2.2), Q_{min} (underlying V_{exp}) from detailed personal enquiry and streamflow (underlying V_{exp}) from hydrologic simulations (Section 2.2.1). WASTA also provides estimates of expected annual production. This data is used to optimise η and thus F in case there are any major discrepancies (see full data set in the Supplementary Data [40]).

2.4.3 Uncertainty quantification

Uncertainties inherent in the hydro-climatic 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 with the climate model ensembles (Section 3.1). The uncertainties in this simulated production namely 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.

3 Results

3.1 Validation of the current RoR production

In a first step, the reference period simulations are compared to the expected production listed in the hydropower infrastructure data base (WASTA, see Section 2.2.2), on annual and seasonal level. The estimated production considers environmental flow requirements and infrastructure characteristics for the 21 Run-of-River (RoR) power plants in this study. The estimated total mean annual production of all 21 RoR power plants of the reference period (5895.2 GWh a^{-1}) agrees well with WASTA data (5782.5 GWh a^{-1}); winter production (Oct-Mar) tends to be slightly overestimated (Δ +192.7 GWh w^{-1}) and summer production (Apr-Sep) tends to be slightly underestimated (Δ -43.3 GWh s^{-1}) (Figure 5). Given the good validation results, we do not further analyze production uncertainties arising from the simplified production model. Details on streamflow validation are available in the Supplementary Information (SI, Table SI2, Figure SI2).

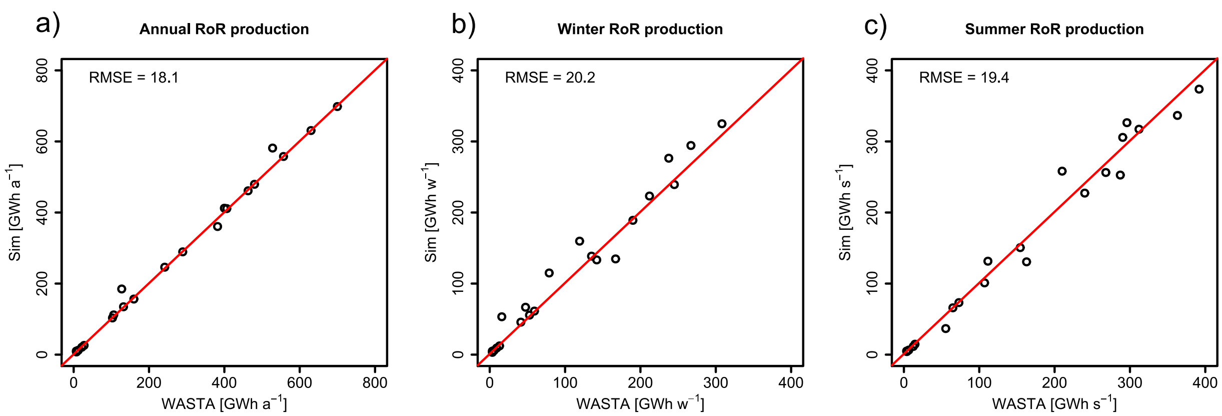


Figure 5. Comparison of the mean simulated production with production reported in WASTA for the 21 RoR plants: a) annual production, b) winter production (Oct-Mar) and c) summer production (Apr-Sep).

3.2 Change in RoR power production

3.2.1 Case study of two RoR power plants

RoR power production impacts of climate change (CC), environmental flow requirements and optimised design discharge is calculated with the Flow Duration Curve (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 [40]. 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 6, a); the Glaris, Davos power plant, shows only minor changes in streamflow, but an increase in annual production (Figure 6, b).

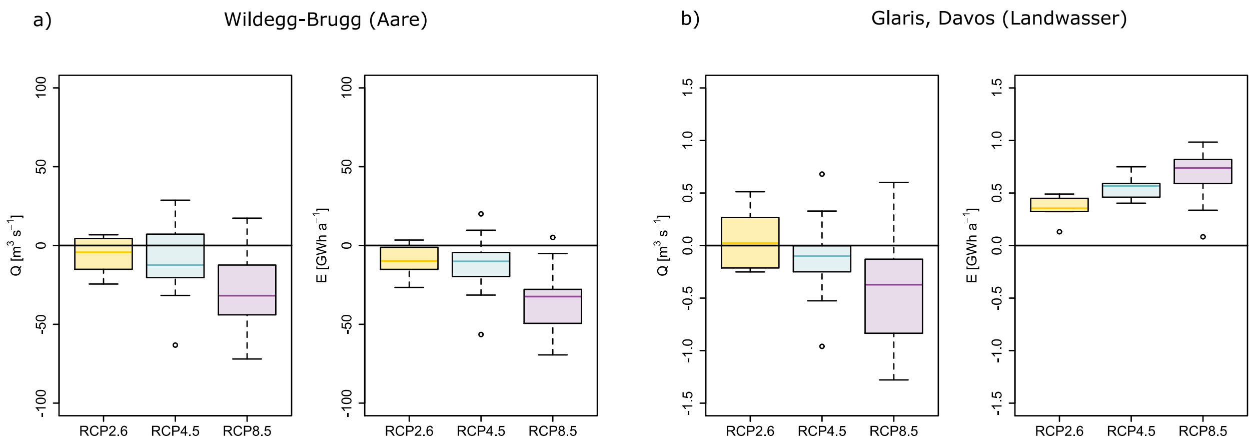


Figure 6. Simulated changes in the mean annual streamflow (Q) and mean production (E) at the a) Wildegg-Brugg power plant and b) at the Glaris, Davos power plant for the end of the century (2070-2099). The black line indicates the median value of the reference period (1981-2010). The yellow (RCP2.6),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

This difference is caused by the infrastructure characteristics of the power plant. If the changes in streamflow are in the range that can be used for hydropower 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).

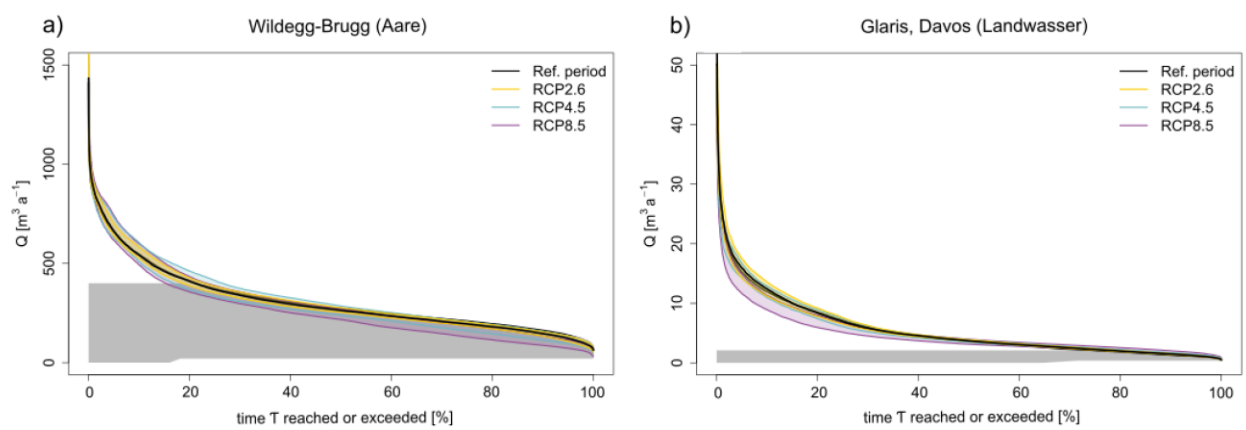


Figure 7. Flow Duration Curves (FDCs) for the power plants a) Wildegg-Brugg and b) Glaris, Davos. The black line represents the reference period (1981–2010), the grey shaded area represents the expected available streamflow (V_{exp}), and the areas bounded by yellow (RCP2.6), blue (RCP4.5) and purple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

The production loss due to environmental flow requirements (E_e) for these two RoR power plants is estimated at 17.5 GWh a^{-1}, i.e. -6% at the Wildegg-Brugg power plant and 0.5 GWh a^{-1}, i.e. -6% of the annual production at the Glaris, Davos power plant. The potential for increasing production by optimising the design discharge (E_{opt}), by corresponding it to the streamflow that is exceeded 20% of the time, amounts to 2.5 GWh a^{-1}, i.e. 1% at the Wildegg-Brugg power plant, and 9.8 GWh a^{-1}, i.e. 128% of the annual production at the Glaris, Davos power plant (see Supplementary Data [40]).

3.2.2 Spatial analysis of 21 RoR power plants

Considering all 21 RoR power plants, the future mean annual production is slightly decreasing 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 to 207 GWh a^{-1}, 3.5% of the annual production (see Supplementary Data [40]). 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).

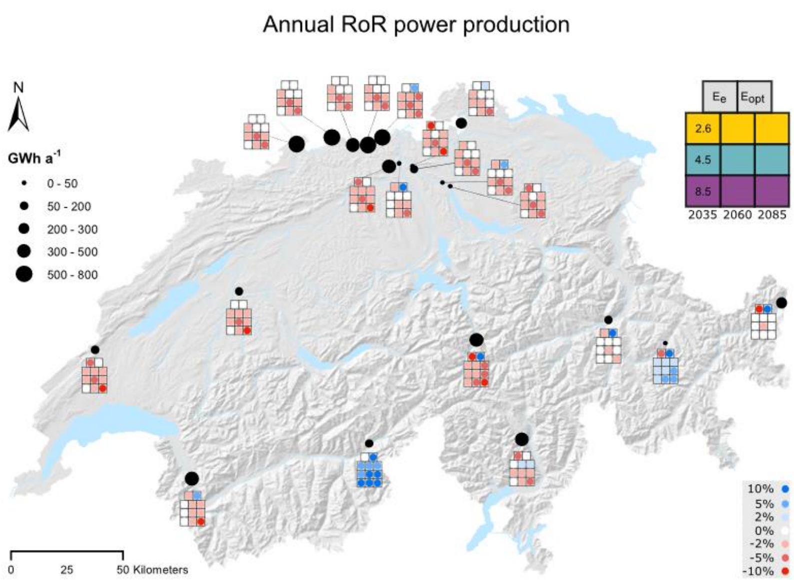


Figure 8. Simulated production changes of the 21 RoR power plants; the size of the power plants represents the annual production in GWh a^{-1}, the colored dots represent the loss due to environmental flow requirements (E_e), the increase potential due to the optimsation of the design discharge (E_{opt}) 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 emission scenarios RCP2.6 (yellow), RCP4.5 (blue) and RCP8.5 (purple).

The annual changes in production due to CC range between 0% and -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 climate mitigation measures. The CC-induced decrease is of a similar order of magnitude to the production loss due to environmental flow requirements (E_e -3.5%) and the increase potential due to the optimsation of the design discharge (E_{opt} +8%).

Table 2. Simulated change of annual RoR power production for the periods (T_1: 2020-2049, T_2: 2045-2074, 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 power production

Future winter (Oct-Mar) mean RoR power production is increasing over the century (Figure 9). The increases are most pronounced in high elevations, due to the shift from solid to more liquid precipitation, which increases the streamflow during the winter (since less water is stored in the snowpack). On the other hand, the production loss due to environmental flow requirements (E_e) in the winter half-year are slightly higher than the annual average at -4.5% (E_e 115 GWh w^{-1}). The optimisation of the design discharge (E_{opt}) can cause an increase of 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 usually not reached. The winter changes in RoR production due to CC range between +2% and +9% (Table 3; a). The projected increase is more pronounced with time and missing climate mitigation measures (RCP8.5). The CC-induced increase is in a similar order of magnitude to the production loss due to environmental flow requirements (E_e -4.5%) and the increase potential due to the optimise of design discharge (E_{opt} 2.5%). However, our results show that the increasing winter production cannot outweigh the negative change in annual production, as winter production only accounts for 43% of the total annual production.

In summer (Apr-Sep), RoR production declines under CC (Figure 9; b). The absence of climate mitigation and the progressing time make a large difference. The loss due to environmental flow requirements are -2.5% (E_e 91 GWh s^{-1}) and therefore less during the summer. Optimising the design discharge would result in a production increase of 12% (E_{opt} 404 GWh s^{-1}). The increase potential tends to lie more in high elevations. The changes in summer RoR production due to CC range between -2% and -21% (Table 3; b). The projected decrease is more pronounced with time and missing climate mitigation measures. The CC-induced decrease in summer is of a larger order of magnitude to the production loss due to environmental flow requirements (E_e -2.5%) and the increase potential due to optimising the design discharge (E_{opt} 12%).

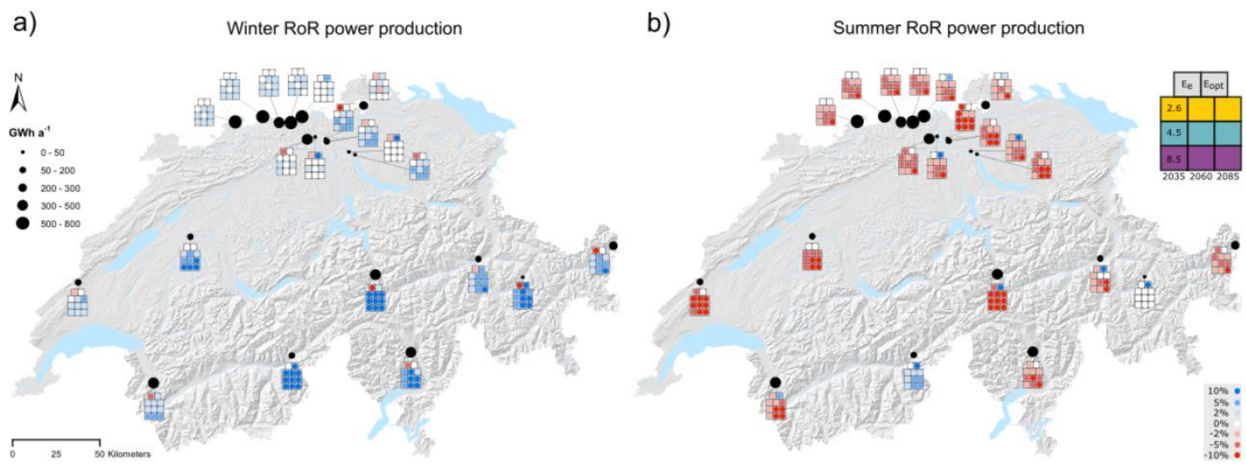


Figure 9. As Figure 8 but for a) winter (Oct-Mar) and b) summer (Apr-Sep).

Table 3. Simulated change in a) winter (Oct-Mar) and b) summer (Apr-Sep) RoR power production for the periods (T_1: 2020-2049, T_2: 2045-2074, 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 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 out of the 21 plants, design discharge optimization could lead to a production increase of between 1% and 149% (average of the 11 plants 45% increase; the total increase corresponds to 8% of the current production); for 6 of them, this could compensate the loss due to environmental flow requirements. For 5 of them, design discharge optimisation could compensate expected CC-induced loss under the most extreme scenario (RCP8.5) by the end of the century.

3.3 Key explanatory variables for change in RoR power production

To gain further insights into what might explain the observed changes in RoR production, we analyze the correlations (linear and rank correlations) between the simulated production changes and i) underlying streamflow changes on one hand and ii) the technical plant characteristics on the other hand. The production impacts related to the different scenarios and time periods are strongly correlated to each other (lowest linear correlation of 0.78), accordingly we show here only the results for RCP8.5. Corresponding data for RCP2.6 and RCP4.5 are in the Supplementary Data [40].

Changes in streamflow do not show a linear relationship with CC-induced changes in production (Figure 11; c); production changes are rather modulated by the currently used range of streamflows (modulated by environmental flow requirements and design discharge) and by how this range is affected by CC.

A correlation analysis with selected plant characteristics (Figure 10) reveals that mean catchment elevation [m a.s.l.] is an important variable influencing future RoR power production changes. There is a distinct positive correlation (>0.68) between the mean catchment elevation (ØElevation) and the climatically induced production changes (T_2, T_3 for the emission scenario RCP8.5). The highest plants show a production increase under all scenarios and for all time periods; with one exception (see full results Table in Supplementary Data [40]), 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 hydropower 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).

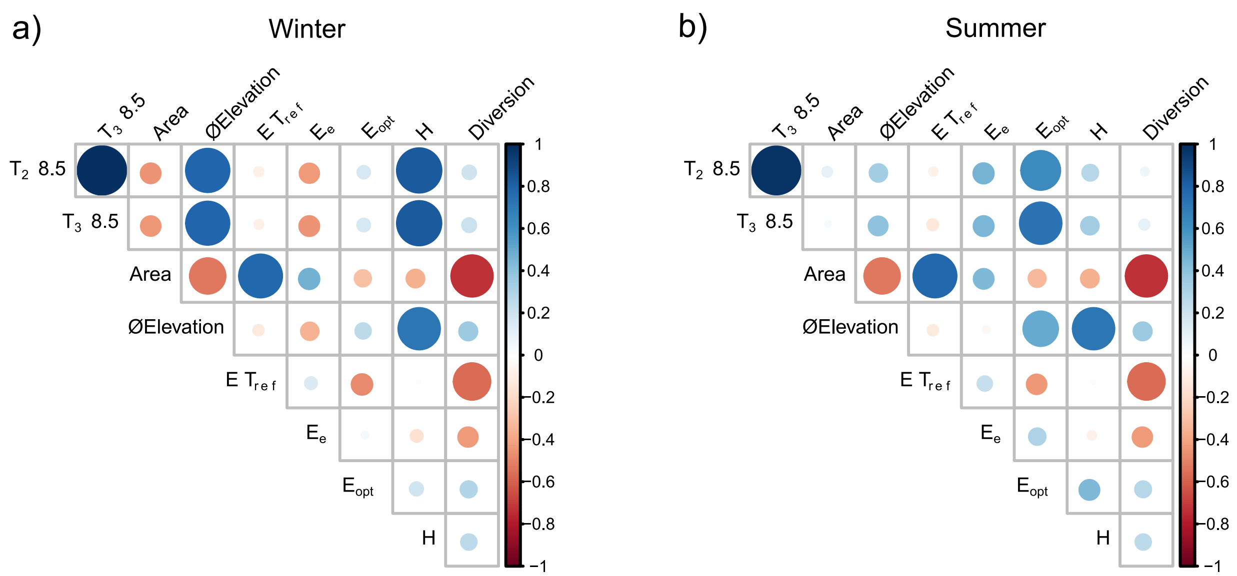


Figure 10. Correlation matrix for a) winter (Oct-Mar) and b) summer (Apr-Sep) Run-of-River (RoR) power production: the simulated production changes of the emission scenario RCP8.5 for the two future periods: T_2/2060 [%] and

T_3/2085 [%], catchment Area [km^2], mean Elevation of the catchment [m a.s.l.], the mean annual production of the reference period (E T_{ref} [GWh a^{-1}]), the loss due to environmental flow requirements (E_e [%]), the increase potential due to optimsing the design discharge (E_{opt} [%]), the hydraulic head H [m] and if streamflow is diverted (Diversion [Yes;No]). The blue dots indicate a positive, the red dots a negative correlation. The larger the dots are, the stronger the correlation is.

This relationship between mean catchment elevation and CC production changes potentially results from several explaining factors referring to i) infrastructure characteristics: higher elevation plants have higher hydraulic heads, they have smaller catchments, i.e. less average streamflow and smaller design discharge; and ii) hydrologic regime: high elevation plants show a regime with marked differences between summer and winter streamflow.

There is, in addition, 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 high are most likely to see a production decrease (Figure 11; a). This is explained by the fact that if this usable streamflow volume range is high, the projected streamflow decreases will more directly translate into production decreases.

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

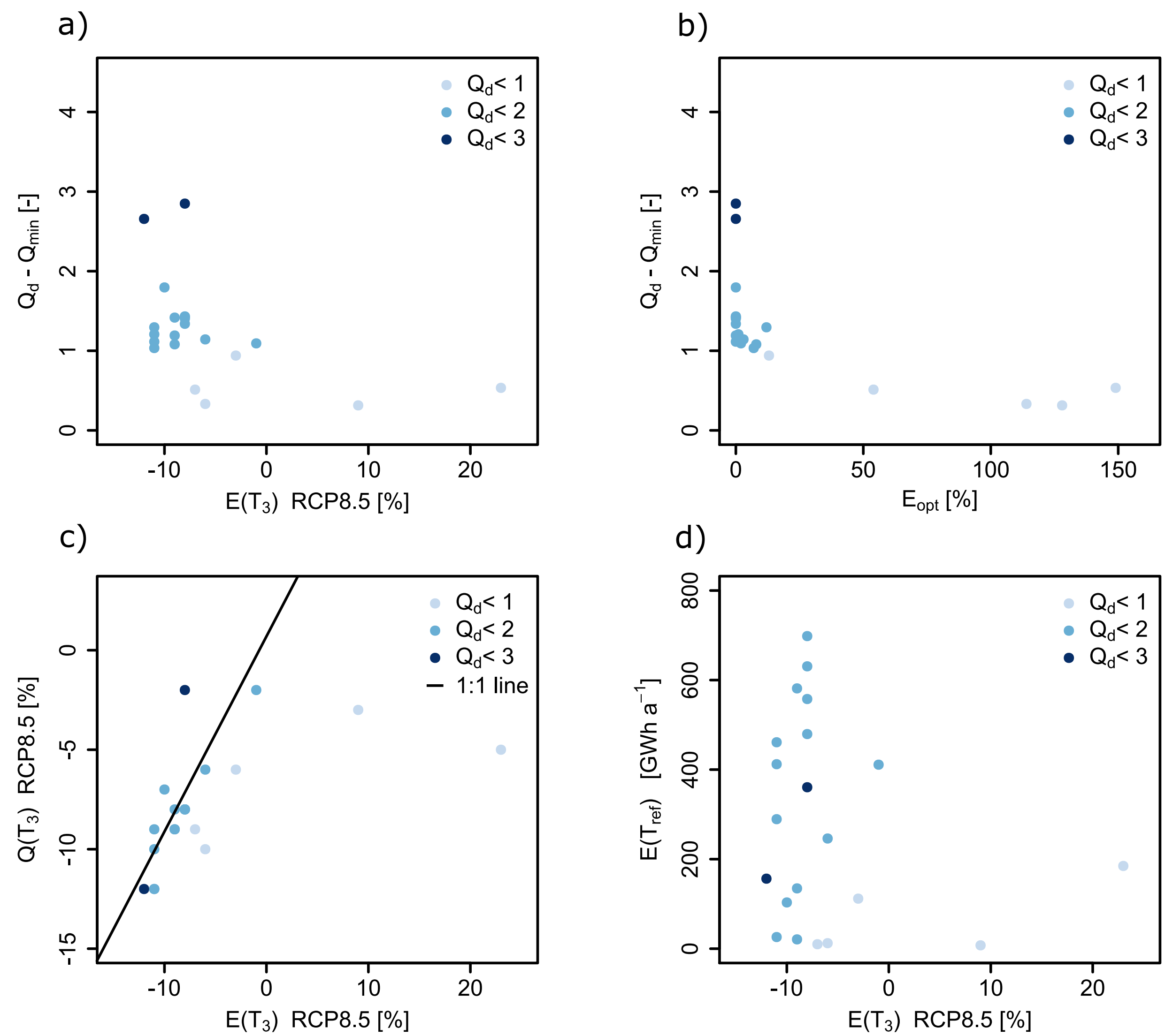


Figure 11. Negative spearman correlation between a) future (T_3 under the emission scenario RCP8.5) annual production changes and the range [-] of usable streamflow volume (the difference between normalised design discharge Q_d and normalised environmental flow Q_{min}) and b) between the production increase potential [%] and the range [-] of usable streamflow volume. And a comparison of c) streamflow changes [%] and production changes [%] (T_3, RCP8.5) complemented with a linear line and d) the annual production [GWh a^{-1}] during the reference period (T_{ref}) compared to the projected production changes [%] by the end of the century (T_3, RCP8.5). The colors of the dots represent the normalised (by the mean streamflow) design discharge (Q_d) of the 21 RoR power plants; the darker the dot, the more streamflow is used for production.

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 highest optimisation potential are those that currently have a low usable streamflow range (small difference between normalised Q_d and normalised environmental flow Q_{min}) (Figure 11; b). These power plants (Q_d<1) show a non-linear relationship between streamflow changes and production changes; two of them show an increase in production despite decreasing streamflow (Figure 11; c). These are predominantly smaller and medium-sized RoR power plants (Figure 11; d).

At a seasonal scale, we see some additional patterns: In winter, the loss due to environmental flow requirements are more likely to be located in higher elevation plants with diversion, where a stronger increase in winter production is predicted (see Figure 9 or Table in Supplementary Data [40]). The summer half-year is less affected by production reductions through environmental flow requirements, whereas optimising the design discharge (E_{opt}) is more important in summer and mainly affects the power plants in higher elevations (see Figure 9 or Table in Supplementary Data [40]).

4 Discussion

This study estimates to what extent Run-of-River (RoR) power production will be affected by climate change (CC). Due to the steep gradients, the Alps are particularly affected by CC, which in particularly affects RoR power plants due to no or limited storage. Because the study area is limited to Switzerland, the institutional framework conditions are comparable, which is particularly 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. An 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 of previous streamflow studies in the Alps [2,15,16,25–27], i.e. slightly decreased annual production, but increased winter production, the most critical period for electricity demand matching. The projections presented here include mean annual and seasonal production over 30 years, but do not address interannual changes. In comparison with the study by Savelsberg et al. [25], who compared individual years with future periods and found an increase of 4% in Swiss mean annual RoR production, we compare the future periods with the entire reference period (T_{ref}: 1981-2010), which leads to a decrease in RoR annual production of up to 7%. The novelty of this study is the consideration of the specific infrastructure characteristics of the power plants. Although the CC-induced decreases in annual electricity production are of the similar order of magnitude to the studies on Alpine RoR power production by Wagner et al. [16] and Totschnig et al. [27], the simulation-based joint analysis of the three variables CC, environmental flow requirements and the optimisation of the design discharge allows for the first time to compare 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 the design discharge also shows that a change in streamflow does not mean a linear change in production [14,44] and, taken a step further, a change in production does not mean a linear change in financial revenue [11,25,45].

The available national-scale data sets [30,31] provide a solid database 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 and which both (head and streamflow) influence the operating point of the turbines and the conversion efficiency. The added value of considering the specific infrastructure characteristics compared to previous studies is that the loss due to the environmental flow requirements and technical increase potential by an adjusted design discharge can be analysed. Production reductions due to environmental flow requirements are higher 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 the 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 the same design discharge shows a large spread between the studied hydropower plants. This stems for the considerable differences in the design and construction standards underlying for the different plants. The chosen optimised design discharge, corresponding to the streamflow that is reached or exceeded 20% of the time, does not represent any agreed-on reference design value, but this heuristic choice shows the potentially important hydropower 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 work should focus on further technical optimisation potential, considering operational RoR power plant data.

Finally, it is worth pointing out that we included a single environmental aspect of hydropower production, which is the minimum flow. With regard to the future of RoR power production, many other environmental aspects are relevant, including sediment or fish connectivity or the problem of streamflow variability for ecosystem function [24,46–48]. Future work could potentially investigate such additional aspects, which are already present in the current Swiss [49] and

European legislation [50]. This could ultimately further contribute to weigh the socio-economic and environmental interests for 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 foresees not only a minimum flow, it also states that the flow regime should allow a good ecological river status [51]; in the Swiss legal framework, the streamflow value Q_{347} (95% percentile) serves as a reference for the determination of the minimum flow [38]. These differences in the legal frameworks need to be considered before transferring results to other settings.

5 Conclusions

Our study of 21 hydropower plants in Switzerland represents one of the first comprehensive analysis of climate change (CC) impacts on Run-of-River (RoR) hydropower production in an Alpine context. The simulated CC impacts show, for the end of the century, a minor change of about -2% to -7% (depending on the emissions scenario) in mean annual production. 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; below 1900 m a.s.l. mean catchment elevation, the plants show an elevation-dependent decrease of production. Comparing the results for three emission scenarios (RCP2.6, RCP4.5, RCP8.5) and three future time periods furthermore underlines that the production changes intensify with time and with missing climate mitigation measures.

The seasonal results show that the decrease of annual production results from a generalised increase of winter production (+4% to +9%) and less 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 optimization could lead to a production increase for 11 of the 21 plants and thereby compensate production loss from CC impact for about half of those plants under all scenarios; the optimization can however compensate the loss due to environmental flow for 6 plants only. The increase potential is for most plants higher in summer than in winter, which is the most critical period for renewable electricity production.

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

- Winter RoR production, which is the most critical period for electricity demand matching, will increase under future climate; production increase potential by optimizing the design discharge is limited during this period, the potential is about 7 times smaller than in summer.
- Future RoR production does not depend linearly on projected changes in streamflow; production changes are rather modulated by the currently used range of streamflows (modulated by environmental streamflow requirements and design discharge) and by how this range is affected by CC. Whereas, if the usable streamflow volume range is high, the changes in streamflow will more directly translate into 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 hydropower development, especially in light of ongoing efforts to increase the share of renewable energy production.

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1 Supplementary Information

1.1 Climate change scenarios CH2018

Table SI1. 39 climate model ensembles used are based on the CH2018 climate scenarios [29]*. The combination of TEAM (responsible institute), RCM (Regional Climate Model), GCM (General Circulation Models), RES (spatial resolution) and RCP ("Representative Concentration Pathway" = emission scenario). The colours correspond to the three RCPs (RCP2.6, RCP4.5, RCP8.5).*

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					

1.2 Model calibration

Table SI2. Results of the calibration and verification by Bernhard and Zappa [52] *and Speich et al.* [36] *of the hydrological modelled discharge at selected stations (s. Figure SI1) for the calibration period (1984-1996) and verification periods (1980-1983 & 1997-2009). Nr. corresponds to the number in Figure SI1; Name of the discharge measurement station; NS (Nash criterion) [-]; NSL (Logarithmic Nash criterion) [-]; DV (Volume error) [%]. A link takes you to the web atlas* [53] *where the streamflow regimes and hydrological future projections are visualised.*

Nr.	Name		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	

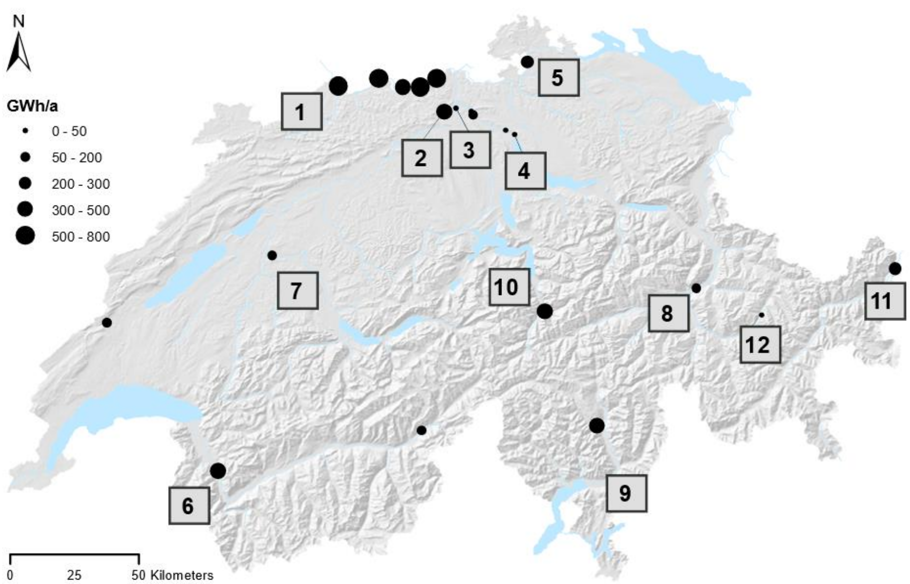

Figure SI1. 21 Swiss run-of-river power (RoR) plants considered in this study. The size of the power plants represents the annual production in GWh a^{-1}. The numbers correspond to the discharge measuring stations in Table SI2 that were used for calibration and validation.

1.3 Hydrological remiges

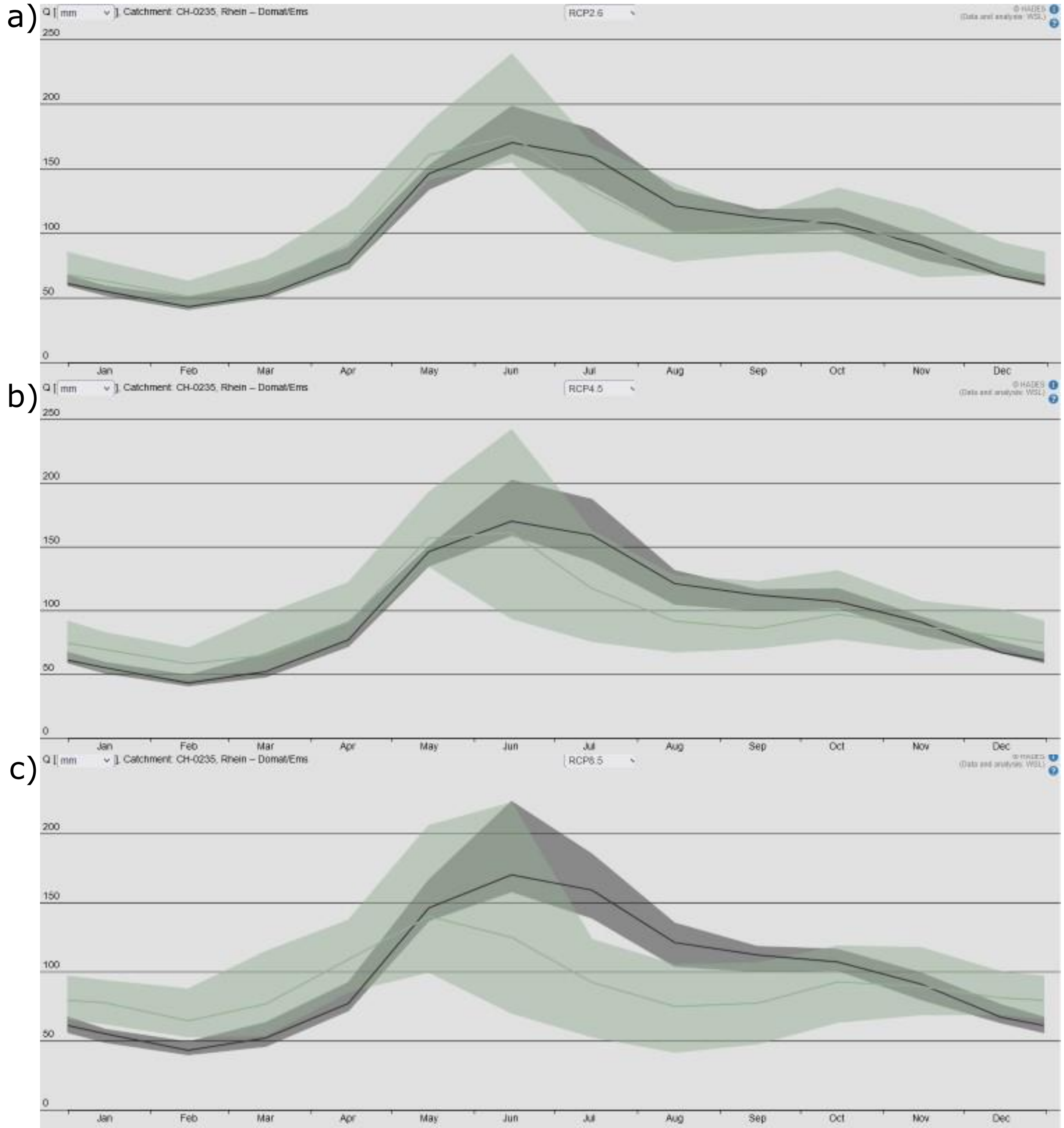

Figure SI2. Changes in mean monthly streamflow under the three emission scenarios a) RCP2.6, b) RCP4.5, and c) RCP8.5 by the end of the century (2070–2099, green) in comparison with the reference period of (1981–2010, black) at Domat Ems (Nr. 8 in Table SI2 and Figure SI1) shown on https://hydromapscc.ch.

1.4 Hydrological scenarios CH2018

PREVAH is a conceptual, process-oriented model [34], which has been continuously improved since its development [54]. As part of the CCHydro study [52], a spatially explicit version was created for PREVAH (grid version), with a resolution of 200 m × 200 m [20,36,55,56]. PREVAH consists of several model components covering the following hydrological processes [34]: 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 [6,36,52,57,58]. The DEM, land use data, glacier inventory and meteorological data are then inserted as inputs into the calibrated model [20]. The meteorological data are spatially interpolated by Inverse Distance Weighting (IDW) and a combination of IDW and Elevation Dependent Regression (EDR) [52,57]. Snow accumulation and melting in PREVAH are determined by temperature and global radiation [34]. Compared to early applications, the model version underlying the present scenarios has been improved with regards to the representation of snow accumulation at high elevations [37] and with regards to the representation of glaciers and their length evolution [20]. 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 lying areas where snowmelt is more likely. The glaciers are divided into short (< 1 km) and long glaciers (> 1 km) based on their lengths [59]. Future glacier extent for short glaciers is modelled with the Global Glacier Evolution Model (GloGEM) [60], for long glaciers with the newer and extended version of GloGEM (GloGEMflow) [61]. The simulated glacier lengths are finally converted to the model grid of PREVAH [20,61]. In addition to the mass balance due to freezing and thawing at the surface, it also considers the changes due to the flow of the glaciers. 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 [62] model was created to take lake regulation into account [63].