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*

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

Abstract

Run-of-river (RoR) hydropower is essential in Alpine energy production and highly sensitive to climate change, due to no or limited water storage capacity. Here, we estimate climate change impact on 21 RoR plants in Switzerland, where 60% of the annual electricity is produced by hydropower (30% by RoR). This is one of the first comprehensive, simulation-based studies on climate change impacts on Alpine RoR production, including effects of environmental flow requirements and technical production potential. We simulate three future periods under three emission scenarios (RCP2.6, RCP4.5, RCP8.5). The results show an increase of winter and a decrease of summer production, which in conjunction leads to an annual decrease. The simulated impacts strongly depend on the elevation and the plant-specific characteristics. A key result is that the climate induced reduction is not linearly related to the underlying streamflow reduction, but is modulated by environmental flow requirements, the design discharge and streamflow projections. Stronger impacts are expected if climate change affects streamflow in the range that is usable for production. This result is transferable to RoR production in similar settings and should be considered in future assessments. Future work could in particular focus on further technical optimisation potential, considering detailed operational data.

1 Introduction

Hydropower is the key renewable in electricity production around the world [1–3]. The average capacity factor of run-of-river (RoR) power plants of selected European countries (AUT, FR, DE, PRT, ESP, CH) is around 40% and thus significantly higher than that of storage power plants (~15%) and pumped storage power plants (~10%) [4]. RoR exists in lowlands as well as in mountains. In the context of climate change and in Alpine countries, where climate change is particularly strong, there was a very high focus on accumulation production, because the significant changes of snow and glacier. But there are very few studies on RoR [5–11] and say that despite the majority of decreasing streamflows, annual production can increase.

In Switzerland, 576 RoR plants (>300 kW) produce about 21.3 TWh a^{-1}, 31.5% of the total electricity production [12]. An efficient RoR power plant uses either a large streamflow, a high hydraulic head or preferably, both. For RoR power plants the gross hydraulic head [m] refers to the usable gradient and corresponds to the difference between the water level at the intake and the tailwater level [13]. The net head corrects the gross head by the loss in height that occurs due to friction. This means that this value shows great heterogeneity depending on the infrastructure, especially the penstock(s). Furthermore, the RoR production depends on the plants infrastructure characteristics. RoR power plants are characterised by a steady production without or limited storage capacity and thus typically carry baseload. In case of a diversion power plant, a certain amount of streamflow must be guaranteed to the river to satisfy further interests, such as irrigation, water supply, ecosystem demand, fish passage or sediment transport and is defined as environmental flow [14–16]. At RoR power plants without diversion, a certain part is used for fish passability. The efficiency of a power plant depends on the interaction of the mechanics, such as the hydraulic structure (head loss, penstock, design discharge), the hydraulic machines (runner, turbine) and the electrical material (variable speed, rotating inertia, generator capacity) [17,18]. The efficiency of converting mechanical energy into electrical energy is 70% to 90% and is often defined as an average of 85% [19]. The efficiency of a power plant varies with the changing streamflow and the hydraulic head.

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 earlier RoR power plants was based on the immediate demand, e.g. of a nearby factory. Therefore, the amount of water used for production was in line with the expected installed power. The largest RoR plants are located along the major rivers in the Central Plateau; but there are also numerous smaller and medium-sized RoR plants high up in the Alps. In the meantime, the technology has become more efficient and the requirements regarding environmental flows have become stricter (Water Protection Act [20]). Despite the advantages such as low volatility [5], a low carbon footprint and low toxic impact [18,21], RoR power production has a strong impact on fluvial ecosystems [22,23]. From today's point of view, the goal should be to optimise the existing plants, considering the actual environmental flow requirements.

In addition, climate change modifies the annual hydrological pattern: a slight decrease in mean annual streamflow and a pronounced seasonal shift with less streamflow in summer and more streamflow in winter [6,24–28]. In this study, we want to show how RoR production could change in the future, considering the three aspects, climate change, environmental flow requirements and optimisations (expansions), using the example of 21 representative RoR plants. In particular, we ask, to what extent the targeted production increases as well as the increased environmental flow requirements harmonise with the climate-induced changes in production. To answer this question, it is not sufficient to consider the hydrological changes, but requires a consideration of environmental flow requirements and the infrastructure characteristics of each individual hydropower plant. Due to large geographical differences, it is therefore possible to examine the different impacts in relatively small areas under the same institutional framework conditions. To examine direct climate change impacts, we focus on the RoR power plants, as these have no or limited storage capacity, and are less influenced by market considerations [10,29,30].

2 Material and methods

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

2.1 Data sets

The analysis of Swiss run-of-river (RoR) power production is based on four data sets: (i) the CH2018 meteorological climate scenarios [31], (ii) the corresponding streamflow scenarios [32], (iii) the Swiss hydropower production statistics [33] and (iv) the Swiss HP infrastructure georeferenced database called HydroGIS [34].

2.1.1 Climate change scenarios CH2018

We use the transient Swiss Climate Change Scenarios CH2018 [31], which are based on the EURO-CORDEX dataset [35]. The CH2018 climate scenarios are based on climate model simulations and subsequent statistical downscaling with the quantile mapping approach [31]. A total of 39 climate change scenarios are available here, 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 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 Material: Table S1). The used meteorological variables are temperature, precipitation, relative humidity, global radiation and near-surface wind. 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).

2.1.2 Hydrological scenarios

Daily streamflow scenarios corresponding to the 39 climate change scenarios are available from the work of Brunner et al. [36]. The simulations used here are based on the hydrological model PREVAH (PREcipitation streamflow EVApotranspiration HRU related Model [37]), which has been largely used for climate change impact studies in Switzerland [32] and has previously been calibrated for diverse water resources applications in Switzerland [24,26,38] (Supplementary Material: Figure S1 & Table S2).

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 (for details, see Supplementary Material: Section 1.3). 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. 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 [39] and with regards to the representation of glaciers and their length evolution [28].

2.1.3 Hydropower production characteristics

Two data sets are available to characterise the Swiss hydropower infrastructure: i) the hydropower plants database WASTA [33], 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 [34], 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 related to 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 powerhouse, the difference in height 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 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 [20]) but are adapted for each production location in the water use contracts. These requirements have been obtained directly from the hydropower producers for the purpose of this study.

2.2 Selected case studies

We selected 21 run-of-river (RoR) power plants in Switzerland to analyse how climate change, the environmental flow requirements and the adjustment of the design discharge affect the annual and seasonal production. The 21 RoR power plants represent different infrastructure characteristics (in terms of installed turbines types and power), different catchment elevations, streamflow regimes and climatological regions (Figure 5). Furthermore, some RoR power plants are located directly on the considered stream, others divert the water; some plants have in addition a small storage resevoir (see Supplementary Data [40]). Some of these RoR power plants are located along the same river to show differences between sequential plants. 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 here meaning 5 small plants (annual production < 50 GWh a^{-1}), 11 medium-sized plants (annual production between 50 and 500 GWh a^{-1}) and 4 large plants (annual production > 500 GWh a^{-1}).

Details for all power plants are in the provided Supplementary Material (Table S2), including a link to the actual and future streamflow regimes.

2.3 Method

2.3.1 General change assessment framework

The analysis framework of our study is based on the comparison of the current hydropower production to future production under climate change and to future production resulting i) from rigorous application of current environmental flow requirements and ii) from an optimisation of the design discharge of the installed turbines. Given that we do not have exact observations of actual hydropower 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 (but not accounting for real-time turbine operations or shut-downs).

Accordingly, we compare current hydrological production potential to the future potential, impacted by climate change, environmental flow requirements or modified design discharge, using a reference period (T_{ref}: 1981-2010) and three future periods (T_1: 2020–2049, T_2: 2045–2074, T_3: 2070–2099).

Climate change-induced 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.

2.3.2 Quantification of usable water volume

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 1) and classically used for RoR design [8,15,42,43]. 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 1) 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 1, V_{exp} can thus be calculated as follows [43]:

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

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

Figure 1

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 FDC (i.e. the streamflow distribution) are obtained here by ranking the entire time series, available from daily simulations with PREVAH model (in the set up as described in the work of Brunner et al. [28]). FDCs for winter are obtained by considering the daily streamflow values for October to March and for summer for April to September.

2.3.3 Calaculation 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, 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 is the design discharge for 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);

$$F = \varphi \eta \, g \quad (3)$$

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 [17,18]. 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 stable efficiency.

The actual value of F is unknown; it can be estimated from Equation 2 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):

$$F = \frac{P}{Q_d \, H} \quad (4)$$

The corresponding specific efficiency η thus reads as

$$\eta = \frac{P}{Q_d \, H \, \varphi}, \quad (5)$$

which theoretically is between 0.7 and 0.9 [19]. 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 are 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 hours T [h]

$$E'(t) = Q(t) H F \tau(t) = V(t) H F \tag{6}$$

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 (see Figure 1) is obtained as:

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

We also quantify the annual production that could be obtained by replacing the old turbines by turbines with higher design discharge Q_d with an optimised design discharge value Q_{opt} [m^3 s^{-1}] that corresponds to the river 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} 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 can be determined with WASTA (Section 2.1.3), the hydraulic head *H* [m] is obtained from the HydroGIS dataset (Section 2.1.3), Q_{min} (underlying V_{exp}) from detailed personal enquiry and streamflow (underlying V_{exp}) from hydrologic simulations (Section 2.1.2). 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]).

3 Results

3.1 Validation of the current RoR production

In a first step, the reference period simulations are compared with the expected production listed in the hydropower infrastructure data base (WASTA, see Section 2.1.3), on annual and seasonal level. The estimated production considers environmental flow requirements and infrastructure characteristics for the 21 RoR power plant in this study. The estimated mean annual production of all 21 RoR power plants (5895.2 GWh a^{-1}) of the reference period agree fairly well with WASTA (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) slightly underestimated (Δ -43.3 GWh s^{-1}) (Figure 2). Details on streamflow validation are available in the Supplementary Material (Table S2, Figure S2).

Figure 2

3.2 Change in RoR production

RoR power production impacts of climate change, 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 3, left); the Glaris, Davos power plant, shows only minor changes in streamflow, but an increase in annual production (Figure 3, right).

Figure 3

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 4).

Figure 4

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

Considering all 21 RoR power plants, the future mean annual production is slightly decreasing over the century under the given climate projections (Figure 5). Exceptions are the high-elevation power plants, which are strongly influenced by snow and ice melt processes.

The total production loss due to environmental flow requirements for the 21 RoR power plants is estimated to 207 GWh a^{-1}, 3.5% of the annual production. 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 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 5

The annual changes in production due to climate change range between 0% and -7% (Table 1). An annual loss of 7% corresponds to the electricity consumption of around 82'500 households in Switzerland (~5000 kWh a^{-1}). The projected decrease is more pronounced for later time periods and in the absence of climate mitigation measures. The climate-induced decrease is of a similar order of magnitude as 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 1. Annual RoR power production and projected change 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%

3.3 Overall change in seasonal RoR power production

Future winter (Oct-Mar) mean RoR power production is increasing over the century (Figure 6 left). The increases are most pronounced in the mountains, 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 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 can only 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 climate change range between +2% and +9% (Table 2; left). The projected increase is more pronounced with time and missing climate mitigation measures (RCP8.5). The climate-induced increase is in a similar order of magnitude as 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 climate change (Figure 6 right). 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 the Alpine region. The changes in summer RoR production due to climate change range between -2% and -21% (Table 2; right). The projected decrease is more pronounced with time and missing climate mitigation measures. The climate-induced decrease in summer is of a larger order of magnitude as 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 6

Table 2. Winter (left) and summer (right) RoR power production and projected change 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.

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

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

3.4 Key-signatures for change in RoR power production

A correlation analysis with selected catchment characteristics (Figure 7) revealed that elevation [m a.s.l.] is an important signature influencing future RoR production. There is a distinct positive correlation between the mean catchment elevation (ØElevation) and the climatically induced production changes (T_1, T_2, T_3 for the emission scenario RCP8.5). In the smaller catchments considered in this study, currently less RoR power is produced (E T_{ref}), but the production is characterised by more diversions and higher hydraulic head (H [m]). Although the hydraulic head shows a strong correlation with the change in production, this is rather a consequence of the catchment elevation, because power plants in the Alpine region are rather designed for high heads, whereas in the lowlands for large water volumes. The correlations of the production scenarios of the three emission scenarios (RCP2.6, RCP4.5, RCP8.5) with the other variables show no clear differences. Therefore, only the emission scenario RCP8.5 is presented for the three periods T_1: 2020-2049, T_2: 2045-2074, T_3: 2070-2099. Corresponding data for RCP2.6 and RCP4.5 are in the Supplementary Data [40]. There is no significant correlation between the production loss due to environmental flow requirements (E_e) and the climate induced production changes T_1, T_2, T_3 for the emission scenario RCP8.5. On the other hand, the production increase potential due to optimising the design discharge (E_{opt}) tends to be located in small and higher catchments and shows a positive correlation with the climate induced production changes; power plants with an higher design discharge are more affected by negative production changes. The seasonal analysis shows that the mean catchment elevation correlates stronger with the changes (T_1, T_2, T_3 for the emission scenario RCP8.5) in winter production (Figure 7 left) than summer production (Figure 7 right).

Figure 7

In winter, the loss due to environmental flow requirements (E_e) are more likely to be located in the higher elevations, where a stronger increase in production is predicted. There is no significant correlation between the production scenarios and the optimised design discharge (E_{opt}) because full capacity in winter is usually not reached. In summer, there is a positive correlation between the climate-induced changes in production and the loss due to environmental flow requirements (E_e), which again fall on the Alpine region; however, the summer half-year is less affected by the production reductions through environmental flow requirements (E_e). Optimising the design discharge (E_{opt}) is more important for the summer half-year and mainly affects the power plants in higher elevations.

4 Discussion

This study estimates to what extent Swiss run-of-river (RoR) power production will be affected by climate change. Due to the steep gradients, the Swiss Alps are particularly affected by climate change, which strongly 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 climate change impacts. An optimisation of the design discharge can only be achieved in combination with replacement of the turbine or the runner.

The joint analysis of the three variables climate change, 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 hydrology does not necessarily mean a linear change in production [6,44] and, taken a step further, a change in production does not necessarily mean a linear change in financial revenue [10,29,30].

The available national-scale data sets 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 parameters that are relevant for production impacts. 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. RoR power plants with a relatively small design discharge (Q_d) are less affected by climate change.

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 run-of-river power plant data.

The present study confirms the climate change trends of previous streamflow studies in the Alps [2,8–10], i.e. increased winter production and decreased annual production. The projections presented here include mean annual and seasonal production over 30 years, but do not address interannual changes.

Finally, it is worth pointing out that we included a single environmental aspect of hydropower production, which is environmental flows. 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 [15,22,23,45]. Future work could potentially investigate such additional aspects, which are already present in the current Swiss and European legislation. This could ultimatively further contribute to weigh the balance economic, societal and environmental interests for RoR development.

5 Conclusions

Our study represents one of the first comprehensive analysis of climate change impacts on run-of-river (RoR) hydropower production in an Alpine context. The simulated climate change impacts show that RoR power plants at higher elevations (i.e. fed by higher elevation catchments, thus currently receiving more snowfall) are more affected by climate change than lower elevation plants. Comparing the results for the three emission scenarios (RCP2.6, RCP4.5, RCP8.5) and three future time periods furthermore underlines that the changes intensify with time and with missing climate mitigation measures.

For the 21 RoR power plants in this study, we anticipate, for the end of the century, a minor change of about -2% to -7% (depending on the emissions scenario) in mean annual production; the seasonal redistribution is more pronounced, with more winter production (+4% to +9%) and less summer production (-2% to -22%). Our results clearly show that future RoR production does not depend linearly on the changes in streamflow and, accordingly, no linear change in revenue can be expected. The magnitude of hydropower production change mainly depends on the mean catchment elevation.

In addition, environmental flow requirements and increase potential through optimising the design discharge are decisive on the future RoR production, as clearly illustrated in this work through the analysis of series of RoR plants located along the same river. The estimated annual production loss due to environmental flow requirements equal on average 3.5% of the simulated production during the reference period (1981-2010), with above average loss during winter and for small and medium-sized RoR power plants and with diversion. The production increase potential due to the optimisation of the design discharge is estimated 8% on average. The increase potential is, in addition, for most plants higher in the summer than in the winter, because in winter, full capacity is hardly ever reached, especially for small and medium-size power plants. Both the loss due to environmental flow requirements and the increase potential are evident especially in smaller and medium-sized RoR power plants at higher elevations and with diversion.

The presented analysis of current environmental flow requirements loss and of gains through design discharge optimisation underlines that the potential changes are of a similar order of magnitude as annual production changes due to climate change impacts. 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.

Acknowledgements

The authors gratefully acknowledge funding from the Swiss Innovation Agency Innosuisse through the Swiss Competence Centre for Energy Research - Supply of Electricity (SCCER-SoE). The HydroGIS database was provided by M. Balmer and WASTA is updated annually by the Swiss Federal Office of Energy and made publicly available. The latest climate change scenarios were produced and made available by MeteoSwiss, which were then translated into hydrological future scenarios in the frame of the FOEN (Federal Office of the Environment) program Hydro-CH2018 [32].

6 Reference

[1] D.E.H.J. Gernaat, P.W. Bogaart, D.P.V. Vuuren, H. Biemans, R. Niessink, High-resolution assessment of global technical and economic hydropower potential, Nat. Energy. 2 (2017) 821–828. https://doi.org/10.1038/s41560-017-0006-y.

[2] B. Schaefli, P. Manso, M. Fischer, M. Huss, D. Farinotti, The role of glacier retreat for Swiss hydropower production, Renew. Energy. 132 (2019) 615–627. https://doi.org/10.1016/j.renene.2018.07.104.

[3] IHA, Hydropower Status Report 2020, Int. Hydropower Assoc. (2020) 1–83. https://www.hydropower.org/sites/default/files/publications-docs/2019_hydropower_status_report_0.pdf.

[4] IEA, Hydropower Special Market Report - Analysis and forecast to 2030, 2021.

[5] B. François, M. Borga, S. Anquetin, J.D. Creutin, K. Engeland, A.C. Favre, B. Hingray, M.H. Ramos, D. Raynaud, B. Renard, E. Sauquet, J.F. Sauterleute, J.P. Vidal, G. Warland, Integrating hydropower and intermittent climate-related renewable energies: A call for hydrology, Hydrol. Process. 28 (2014) 5465–5468. https://doi.org/10.1002/hyp.10274.

[6] G.S. Mohor, D.A. Rodriguez, J. Tomasella, J.L. Siqueira Júnior, Exploratory analyses for the assessment of climate change impacts on the energy production in an Amazon run-of-river hydropower plant, J. Hydrol. Reg. Stud. 4 (2015) 41–59. https://doi.org/10.1016/j.ejrh.2015.04.003.

[7] P. Manso, B. Schaefli, A. Schleiss, Adaptation of Swiss hydropower infrastructure to meet future electricity needs, Proceedings of Hydro 2015-Advancing policy and practice, Bordeaux, 2015.

[8] T. Wagner, M. Themeßl, A. Schüppel, A. Gobiet, H. Stigler, S. Birk, Impacts of climate change on stream flow and hydro power generation in the Alpine region, Environ. Earth Sci. 76 (2017). https://doi.org/10.1007/s12665-016-6318-6.

[9] B. François, B. Hingray, M. Borga, D. Zoccatelli, C. Brown, J.D. Creutin, Impact of climate change on combined solar and run-of-river power in Northern Italy, Energies. 11 (2018) 1–22. https://doi.org/10.3390/en11020290.

[10] J. Savelsberg, M. Schillinger, I. Schlecht, H. Weigt, The impact of climate change on Swiss hydropower, Sustain. 10 (2018) 23. https://doi.org/10.3390/su10072541.

[11] T. Wechsler, M. Stähli, Climate change impact on Swiss hydropower production: Synthesis Report, SCCER-SoE. (2019) 28.

[12] Bundesamt für Energie (BFE), SCHWEIZERISCHE ELEKTRIZITÄTS? STATISTIK 2019, Statista. (2020). https://de.statista.com/statistik/daten/studie/291824/umfrage/anzahl-der-elektrowaermepumpen-in-der-schweiz/.

[13] R.S.W. Röthlisberger, Der Wasserzins – die wichtigste Abgabe auf der Wasserkraftnutzung in der Schweiz, Serie Wass, Bern, 2002. http://sig_derwasserzins--02.pdf.

[14] D. Anderson, H. Moggridge, P. Warren, J. Shucksmith, The impacts of “run-of-river” hydropower on the physical and ecological condition of rivers, Water Environ. J. 29

(2015) 268–276. https://doi.org/10.1111/wej.12101.

[15] A. Kuriqi, A.N. Pinheiro, A. Sordo-Ward, L. Garrote, Flow regime aspects in determining environmental flows and maximising energy production at run-of-river hydropower plants, Appl. Energy. 256 (2019). https://doi.org/10.1016/j.apenergy.2019.113980.

[16] M.D. Bejarano, A. Sordo-Ward, I. Gabriel-Martin, L. Garrote, Tradeoff between economic and environmental costs and benefits of hydropower production at run-of-river-diversion schemes under different environmental flows scenarios, J. Hydrol. 572 (2019) 790–804. https://doi.org/10.1016/j.jhydrol.2019.03.048.

[17] S. Basso, G. Botter, Streamflow variability and optimal capacity of run-of-river hydropower plants, Water Resour. Res. 48 (2012) 1–13. https://doi.org/10.1029/2012WR012017.

[18] V. Yildiz, J.A. Vrugt, A toolbox for the optimal design of run-of-river hydropower plants, Environ. Model. Softw. 111 (2019) 134–152. https://doi.org/10.1016/j.envsoft.2018.08.018.

[19] F. Laufer, S. Grötzinger, M. Peter, A. Schmutz, Ausbaupotential der Wasserkraft, 2004. https://www.newsd.admin.ch/newsd/message/attachments/2663.pdf.

[20] GSchG, Bundesgesetz über den Schutz der Gewässer (Gewässerschutzgesetz GSchG), 1991 (2011) 1–34. https://fedlex.data.admin.ch/filestore/fedlex.data.admin.ch/eli/cc/1992/1860_1860_1860/20150908/de/pdf-a/fedlex-data-admin-ch-eli-cc-1992-1860_1860_1860-20150908-de-pdf-a.pdf.

[21] C. Bauer, S. Hirschberg, Y. Bäuerle, S. Biollaz, B.C. Calbry-Muzyka, T. Heck, M. Lehnert, A. Meier, H.-M. Prasser, W. Schenler, K. Treyer, F. Vogel, H.C. Wieckert, X. Zhang, M. Zimmermann, V. Burg, G. Bowman, M. Erni, M. Saar, M.Q. Tran, Potentials , costs and environmental assessment of electricity generation, Bern, 2017. https://www.psi.ch/lea/HomeEN/Final-Report-BFE-Project.pdf.

[22] C. Gabbud, S.N. Lane, Ecosystem impacts of Alpine water intakes for hydropower: the challenge of sediment management, Wiley Interdiscip. Rev. Water. 3 (2016) 41–61. https://doi.org/10.1002/wat2.1124.

[23] A. Kuriqi, A.N. Pinheiro, A. Sordo-Ward, M.D. Bejarano, L. Garrote, Ecological impacts of run-of-river hydropower plants—Current status and future prospects on the brink of energy transition, Renew. Sustain. Energy Rev. 142 (2021) 17. https://doi.org/10.1016/j.rser.2021.110833.

[24] L. Bernhard, M. Zappa, Schlussbericht CCHydrologie: Teilprojekt WHH-CH-Hydro. Natürlicher Wasserhaushalt der Schweiz und ihre bedeutendsten Grosseinzugsgebiete, Bern, 2009. https://www.bafu.admin.ch/bafu/de/home/suche.html#Klimawandel Schnee Regen Eis Alpen.

[25] J.S. Nans Addor, Ole Rössler, Nina Köplin, Matthias Huss, Rolf Weingartner, regimes of Swiss catchments, Water Resour. Res. 50 (2014) 7541–7562. https://doi.org/10.1002/2014WR015549.Received.

[26] N. Köplin, B. Schädler, D. Viviroli, R. Weingartner, Seasonality and magnitude of floods in Switzerland under future climate change, Hydrol. Process. 28 (2014) 2567–2578. https://doi.org/10.1002/hyp.9757.

[27] D. Vázquez-Tarrío, M. Tal, B. Camenen, H. Piégay, Effects of continuous embankments and successive run-of-the-river dams on bedload transport capacities along the Rhône River, France, Sci. Total Environ. 658 (2019) 1375–1389. https://doi.org/10.1016/j.scitotenv.2018.12.109.

[28] M.I. Brunner, A. Björnsen Gurung, M. Zappa, H. Zekollari, D. Farinotti, M. Stähli, Present and future water scarcity in Switzerland: Potential for alleviation through reservoirs and lakes, Sci. Total Environ. 666 (2019) 1033–1047. https://doi.org/10.1016/j.scitotenv.2019.02.169.

[29] A. Ranzani, M. Bonato, E.R. Patro, L. Gaudard, C. De Michele, Hydropower future: Between climate change, renewable deployment, carbon and fuel prices, Water (Switzerland). 10 (2018) 1–17. https://doi.org/10.3390/w10091197.

[30] M. Cassagnole, M.-H. Ramos, I. Zalachori, G. Thirel, R. Garçon, J. Gailhard, T. Ouillon, Impact of the quality of hydrological forecasts on the managementand revenue of hydroelectric reservoirs – a conceptual approach, Hydrol. Earth Syst. Sci. Discuss. (2020) 1–36. https://doi.org/10.5194/hess-2020-410.

[31] CH2018, CH2018 - Climate Scenarios for Switzerland. Techincal Report, Zurich, 2018.

[32] BAFU, Hydro-CH2018: Auswirkungen des Klimawandels auf die Schweizer Gewässer, Bundesamt für Umwelt (BAFU), Bern, 2021. https://doi.org/http://www.biodiversity.ch/publications/hotspot/documents/WEBhotspot16.2007_DT.pdf.

[33] WASTA, Statistik der Wasserkraftanlagen der Schweiz (WASTA), (2019) 1–5.

[34] M. Balmer, Nachhaltigkeitsbezogene Typologisierung der schweizerischen Wasserkraftanlagen - GIS-basierte Clusteranalyse und Anwendung in einem Erfahrungskurvenmodell, ETHZ, Zürich, 2012.

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

[36] M.I. Brunner, M. Zappa, M. Stähli, Scale matters: Effects of temporal and spatial data resolution on water scarcity assessments, Adv. Water Resour. 123 (2019) 134–144. https://doi.org/10.1016/j.advwatres.2018.11.013.

[37] D. Viviroli, M. Zappa, J. Gurtz, R. Weingartner, An introduction to the hydrological modelling system PREVAH and its pre- and post-processing-tools, Environ. Model. Softw. 24 (2009) 1209–1222. https://doi.org/10.1016/j.envsoft.2009.04.001.

[38] M.J.R. Speich, L. Bernhard, A.J. Teuling, M. Zappa, Application of bivariate mapping for hydrological classification and analysis of temporal change and scale effects in Switzerland, J. Hydrol. 523 (2015) 804–821. https://doi.org/10.1016/j.jhydrol.2015.01.086.

[39] D. Freudiger, I. Kohn, J. Seibert, K. Stahl, M. Weiler, Snow redistribution for the hydrological modeling of alpine catchments, Wiley Interdiscip. Rev. Water. 4 (2017)

e1232. https://doi.org/10.1002/wat2.1232.

[40] T. Wechsler, RoRCC, (2021) 5. https://doi.org/10.16904/envidat.259.

[41] R.M. Vogel, N.M. Fennessey, FLOW DURATION CURVES II : A REVIEW OF APPLICATIONS IN WATER RESOURCES PLANNING ' proverb " one picture is worth a thousand words " are used to summarize the results of detailed and ly , streamfiow duration curves have been used in sparse . This is the fir, Water Resour. Bull. 31 (1995) 1029–1039.

[42] I.K. Westerberg, J.L. Guerrero, P.M. Younger, K.J. Beven, J. Seibert, S. Halldin, J.E. Freer, C.Y. Xu, Calibration of hydrological models using flow-duration curves, Hydrol. Earth Syst. Sci. 15 (2011) 2205–2227. https://doi.org/10.5194/hess-15-2205-2011.

[43] P. Hänggi, R. Weingartner, Variations in Discharge Volumes for Hydropower Generation in Switzerland, Water Resour. Manag. 26 (2012) 1231–1252. https://doi.org/10.1007/s11269-011-9956-1.

[44] B. François, M. Borga, S. Anquetin, J.D. Creutin, K. Engeland, A.C. Favre, B. Hingray, M.H. Ramos, D. Raynaud, B. Renard, E. Sauquet, J.F. Sauterleute, J.P. Vidal, G. Warland, Integrating hydropower and intermittent climate-related renewable energies: A call for hydrology, Hydrol. Process. 28 (2014) 5465–5468. https://doi.org/10.1002/hyp.10274.

[45] L. Gorla, P. Perona, On quantifying ecologically sustainable flow releases in a diverted river reach, J. Hydrol. 489 (2013) 98–107. https://doi.org/10.1016/j.jhydrol.2013.02.043.

[46] M. Bernhard, Luzi; Zappa, Schlussbericht: CCHydrologie: Teilprojekt WHH- CH-Hydro: Natürlicher Wasserhaushalt der Schweiz und ihrer bedeutendsten Grosseinzugsgebiete, Birmensdorf, 2012.

[47] HADES, Hydrological scenarios (Hydro-CH2018), (2021). https://hydromapscc.ch/#en/8/46.832/8.190/bl_hds--l02_standorte$0/NULL.

[48] J. Gurtz, A. Baltensweiler, H. Lang, Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins, Hydrol. Process. 13 (1999) 2751–2768. https://doi.org/10.1002/(SICI)1099-1085(19991215)13:17<2751::AID-HYP897>3.0.CO;2-O.

[49] S. Zappa, M; Bernhard, L; Fundel, F; Jörg-Hess, Vorhersage und Szenarien von Schnee- und Wasserressourcen im Alpenraum. In Forum Für Wissen: Alpine Schnee- Und Wasserressourcen Gestern, Heute, Morgen, Birmensdorf, 2012.

[50] P. Schattan, M. Zappa, H. Lischke, L. Bernhard, E. Thürig, B. Diekkrüger, An approach for transient consideration of forest change in hydrological impact studies, IAHS-AISH Proc. Reports. 359 (2013) 311–319.

[51] D. Viviroli, H. Mittelbach, J. Gurtz, R. Weingartner, Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland - Part II: Parameter regionalisation and flood estimation results, J. Hydrol. 377 (2009) 208–225. https://doi.org/10.1016/j.jhydrol.2009.08.022.

[52] D. Viviroli, M. Zappa, J. Schwanbeck, J. Gurtz, R. Weingartner, Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland - Part I: Modelling framework and calibration results, J. Hydrol. 377 (2009) 191–207. https://doi.org/10.1016/j.jhydrol.2009.08.023.

[53] N. Köplin, D. Viviroli, B. Schädler, R. Weingartner, How does climate change affect mesoscale catchments in Switzerland? - A framework for a comprehensive assessment, Adv. Geosci. 27 (2010) 111–119. https://doi.org/10.5194/adgeo-27-111-2010.

[54] RGI_Consortium, Randolph Glacier Inventory –A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, (2017). https://doi.org/https://doi.org/10.7265/N5-RGI-60.

[55] M. Huss, R. Hock, A new model for global glacier change and sea-level rise, Front. Earth Sci. 3 (2015) 1–22. https://doi.org/10.3389/feart.2015.00054.

[56] H. Zekollari, M. Huss, D. Farinotti, Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble, Cryosphere. 13 (2019) 1125–1146. https://doi.org/10.5194/tc-13-1125-2019.

[57] DHI, River Network Editor. In MIKE 11 - River Modelling Unlimited, 2004.

[58] T. Wechsler, M. Zappa, A. Inderwildi, in publication: Projektbericht: Auswirkungen Klimaszenarien CH2018 auf Alpenrandseen, Bern, 2021.

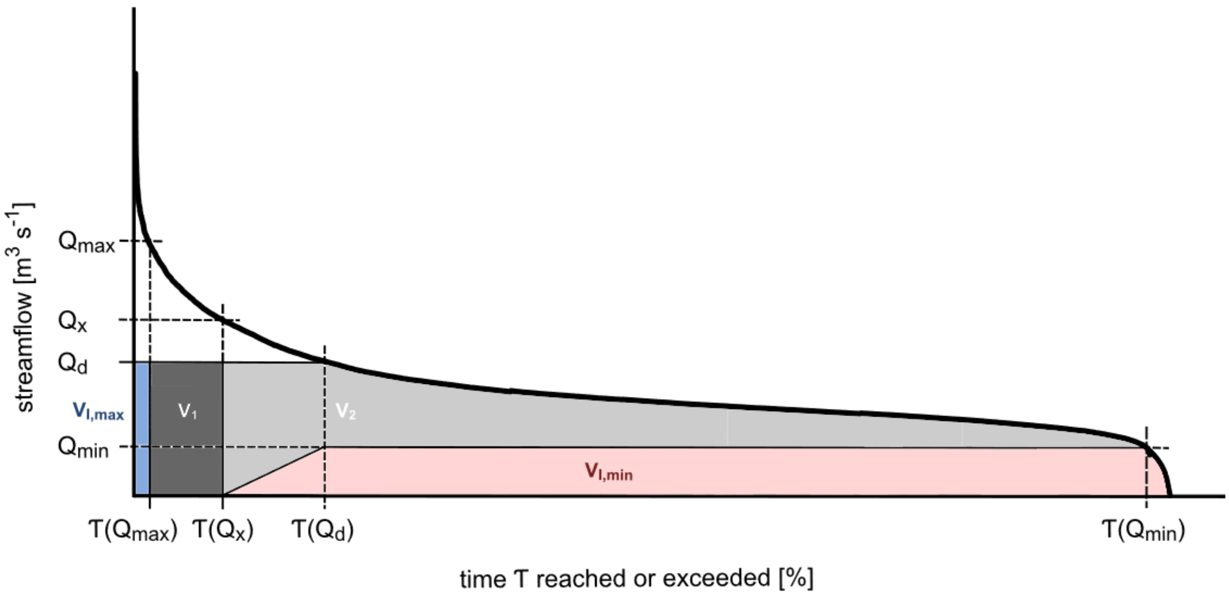

Figure 1. Illustration of the estimation of the hydrologic production potential based on the flow duration curve (FDC), characterized by the parameters Q_{max} [m^3 s^{-1}], Q_d [m^3 s^{-1}] and Q_{min} [m^3 s^{-1}]. $\tau(Q_x)$ [%] designates the duration during which the streamflow reaches Q_d+Q_{min}, 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}.

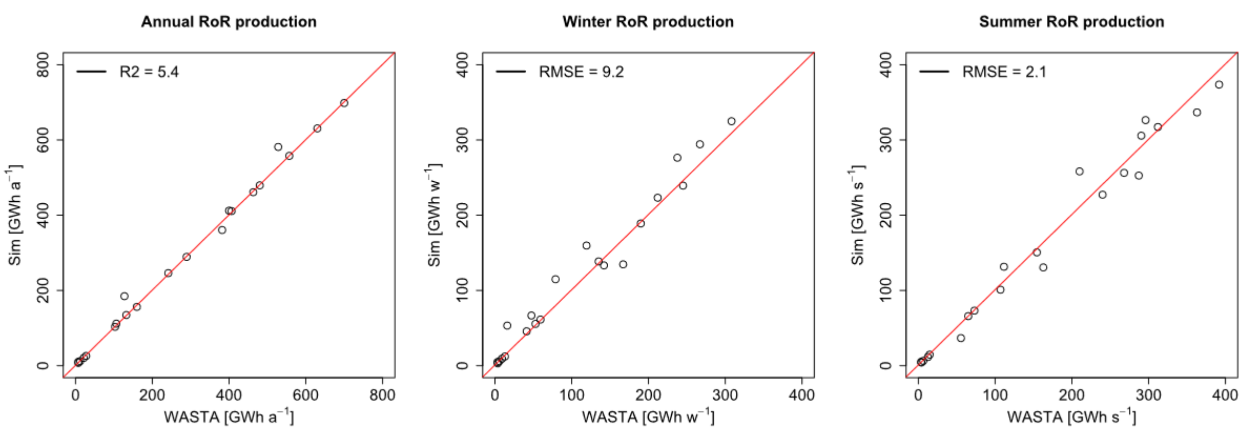

Figure 2. The comparison of the mean simulated annual, winter and summer production of the selected 21 RoR power plants (1981-2010) with the production reported in WASTA.

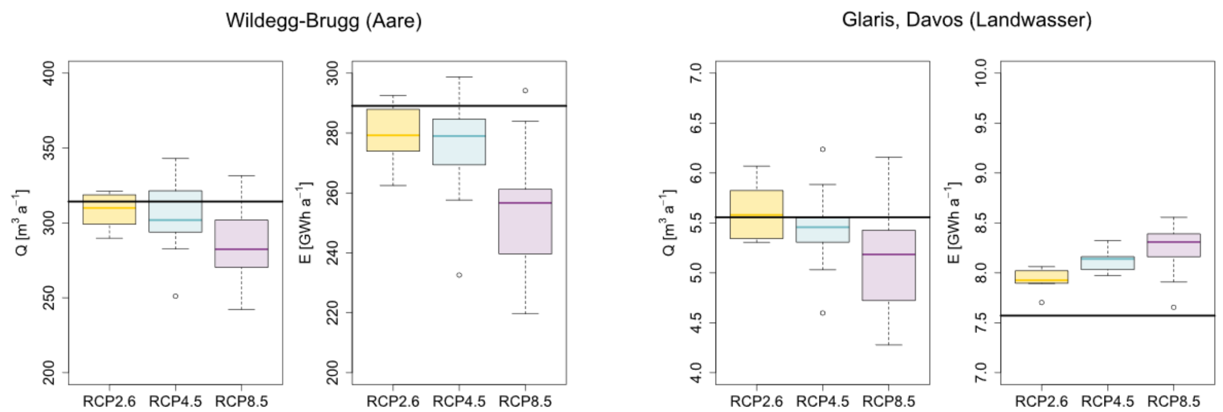

Figure 3. The estimated changes in the annual mean discharge (Q) and mean production (E) at the Wildegg-Brugg power plant (Aare; left) and at the Glaris, Davos power plant (Landwasser; right) for the end of the century (2070-2099). The black line indicates the median value of the reference period (1981-2010). 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.

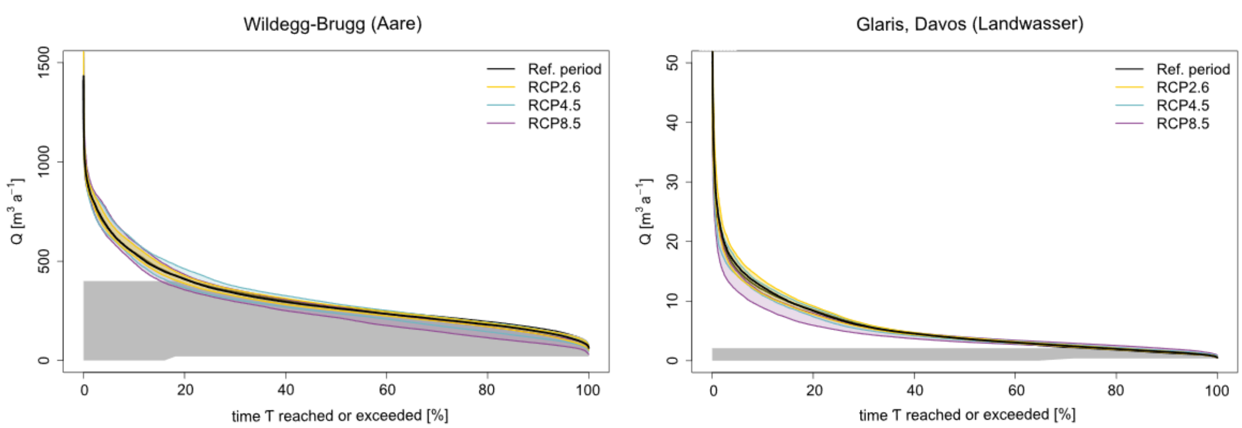

Figure 4. Flow Duration Curves (FDCs) for the RoR power plants Wildegg-Brugg (left) and Glaris, Davos (Landwasser; right). The black line represents the reference period (1981–2010), the grey shaded area represents the expected available streamflow (V_{exp}), and the areas bounded by yellow, blue and purple curves represent the range of FDCs for the projected model ensembles within the three emission scenarios RCP2.6, RCP4.5 and RCP8.5, respectively, for the end of the century.

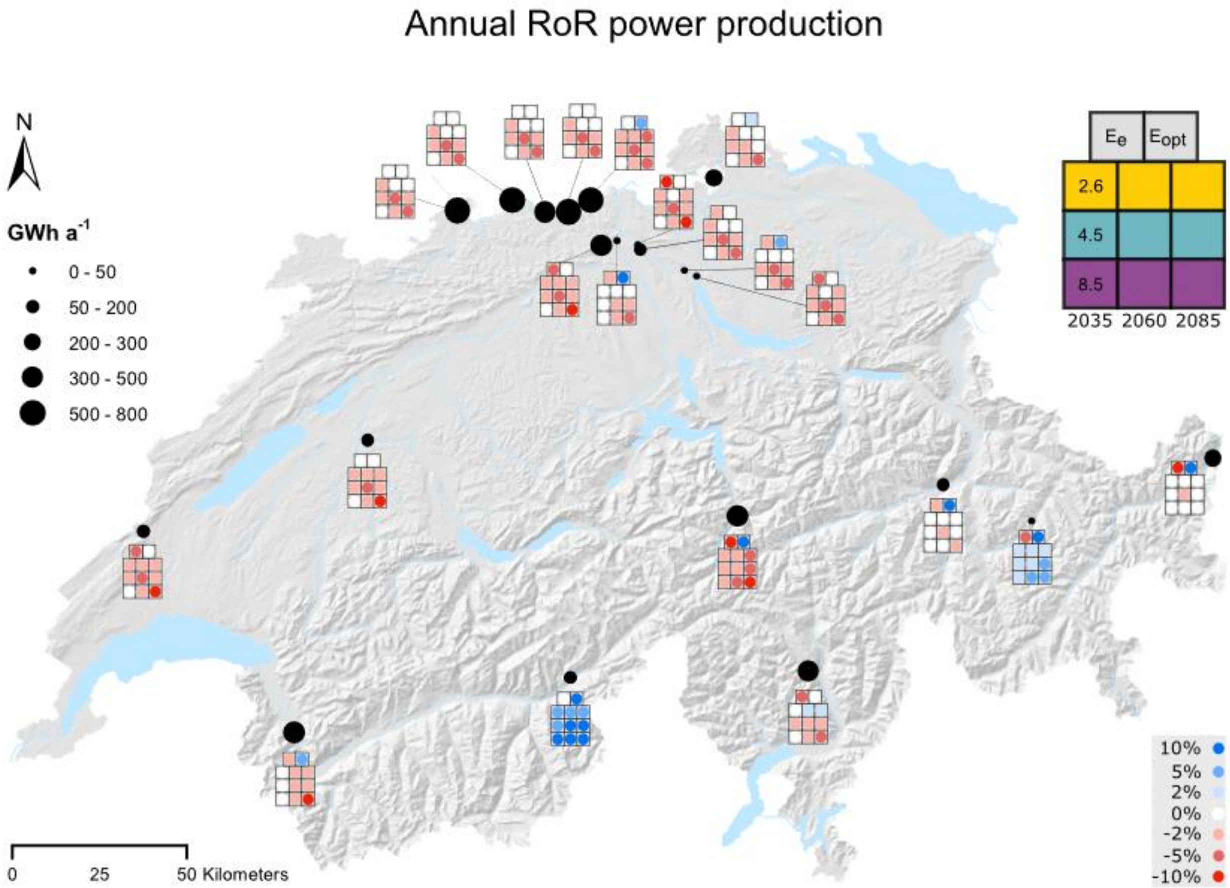

Figure 1. The 21 Swiss run-of-river power plants considered in this study. The size of the power plants represents the annual production in GWh a^{-1}. The colored dots represent the losses due to environmental flow requirements (E_e), the increase potential due to the optimsation of the design discharge (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). The calculations are based on the most recent Climate Change Scenarios CH2018 provided by MeteoSwiss (39 model ensembles; three emission scenarios: with concerted concerted mitigation efforts RCP2.6 (yellow), limited climate mitigation measures RCP4.5 (blue) and no climate mitigation measures RCP8.5 (purple) and a state-of-the-art hydrological model (PREVAH), assuming unchanged installed machinery and environmental flow requirements.

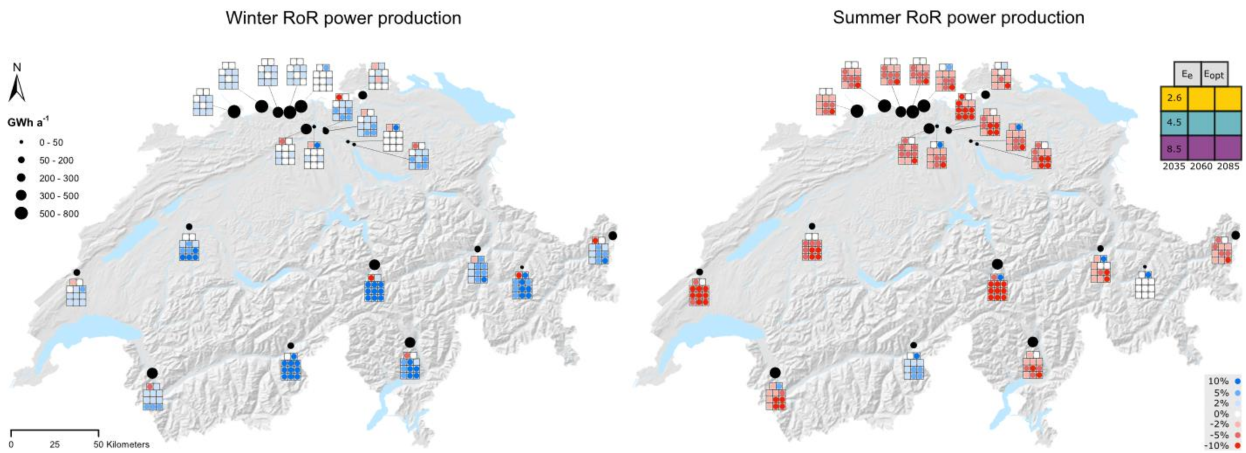

Figure 2. Expected changes in winter (left) and summer (right) production of 21 selected Swiss run-of-river power plants. The colored dots represent the losses due to environmental flow requirements (E_e), the increase potential due to the optimsation of the design discharge (E_{opt}) and the climate change impact for the periods 2035 (near future, 2020-2049), 2060 (mid-century, 2045–2074) and 2085 (end of century, 2070–2099). The calculations are based on the most recent Climate Change Scenarios CH2018 established by MeteoSwiss (39 model ensembles; three emission scenarios: with concerted mitigation efforts RCP2.6 (yellow), limited climate mitigation measures RCP4.5 (blue) and no climate mitigation measures RCP8.5 (purple) and a state-of-the-art hydrological model (PREVAH), assuming unchanged installed machinery and environmental flow requirements.

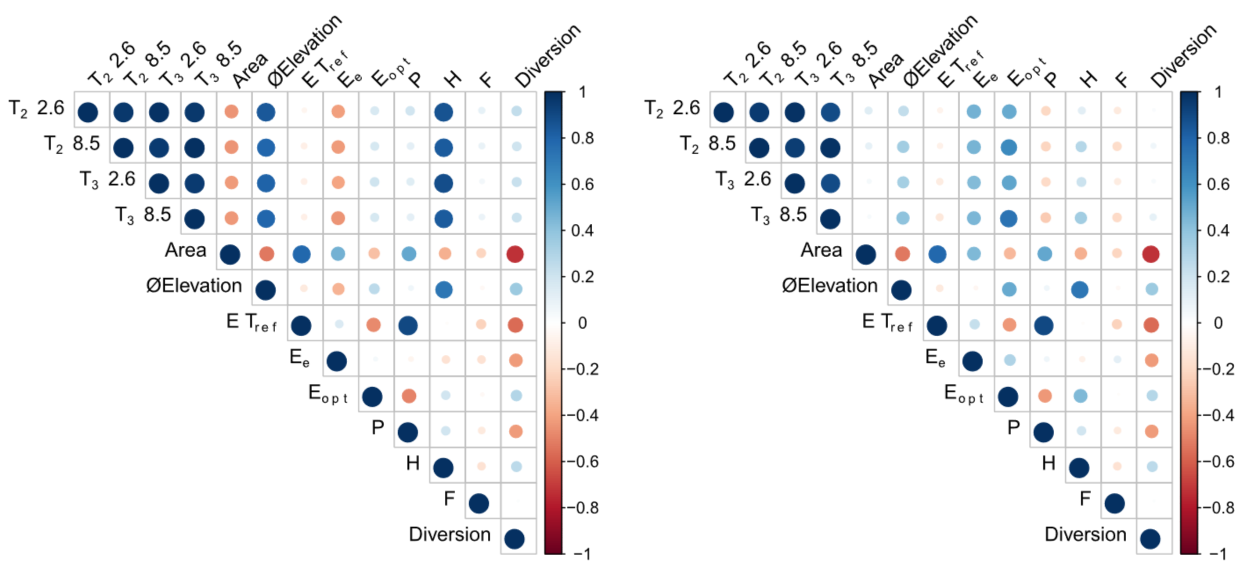

Figure 3. The correlation matrix for winter (left) and summer (right) RoR production: the production changes of the emission scenario RCP2.6 and RCP8.5 for the two time periods: 2060: T_2 2.6 [%] and T_2 8.5 [%]; 2085: T_3 2.6 [%] and T_3 8.5 [%], Catchment area [km^2], ØElevation of the catchment [m a.s.l.], the mean annual production of the reference period (1981-2010): E T_{ref} [GWh a^{-1}], the influence of environmental flow requirements: E_e [%], the increase potential due to the optimsation of the design discharge: E_{opt} [%], and the 4 dimensions of the power plants: P [MW], H [m], F [kg m^{-2} s^{-2}], Diversion [Yes;No]. The blue dots indicate a positive, the red dots a negative correlation. The larger the dots are, the more significant the correlation is.

1 Supplementary Material

1.1 Climate change scenarios CH2018

Table S1. The 39 climate model ensembles used are based on the CH2018 climate scenarios [31]*. 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
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

TEAM	RCM	GCM	RES	RCP
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 S2. Results of the calibration and verification by Bernhard and Zappa [45] *and Speich et al.* [38] *of the hydrological modelled discharge at selected stations (s. Figure S1) for the calibration period (1984-1996) and verification periods (1980-1983 & 1997-2009). Nr. corresponds to the number in Figure S1; Name of the discharge measurement station; NS (Nash criterion) [-]; NSL (Logarithmic Nash criterion) [-]; DV (Volume error) [%]. A link takes you to the web atlas* [46] *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	

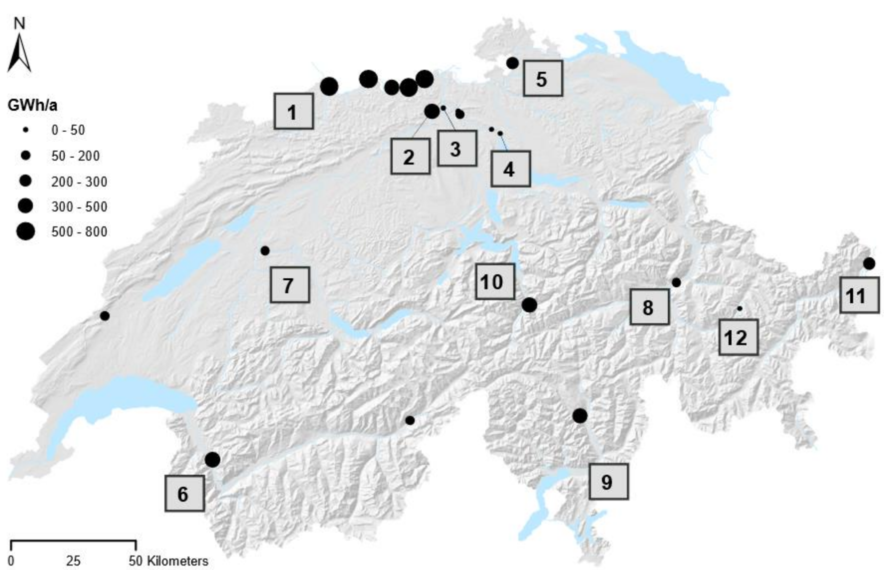

Figure S1. The 21 Swiss run-of-river power (RoR) plants considered in this study. The size of the power plants represents the annual production in GWh a^{-1}. The numbers correspond to the discharge measuring stations in Table S2 that were used for calibration and validation.

1.3 Hydrological remiges

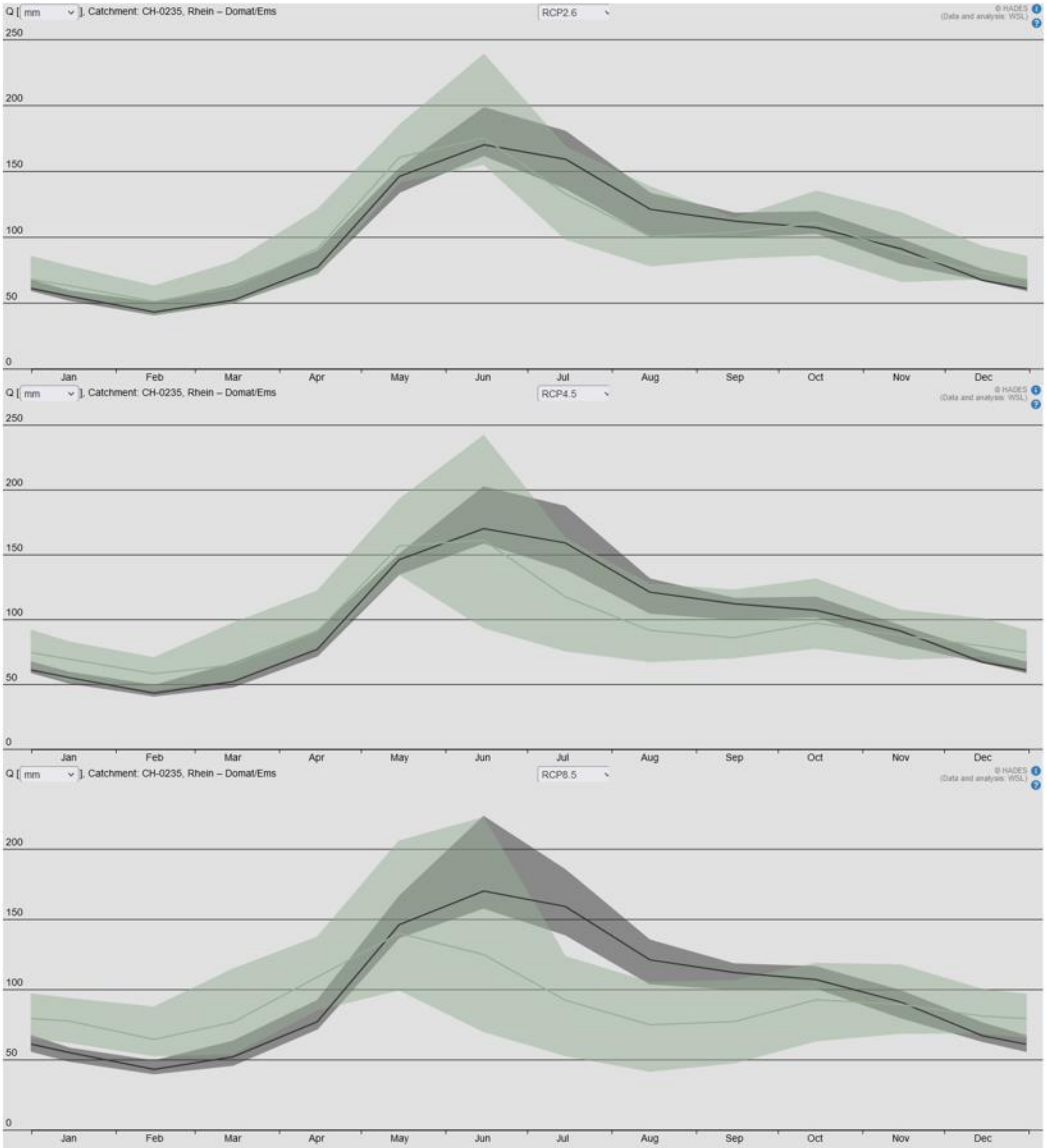

Figure S2. Changes in mean monthly streamflow under the three emission scenarios RCP2.6, RCP4.5, and RCP8.5 by the end of the century (2070–2099, green) in comparison with the reference period of (1981–2010, black) at Domat Ems (Nr. 8 in Table S2 and Figure S1) shown on https://hydromapscc.ch.

1.4 Hydrological scenarios CH2018

PREVAH is a conceptual, process-oriented model [37], which has been continuously improved since its development [47]. As part of the CCHydro study [45], a spatially explicit version was created for PREVAH (grid version), with a resolution of 200 m × 200 m [28,38,48,49]. PREVAH consists of several model components covering the following hydrological processes [37]: 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 [38,45,50–52]. The DEM, land use data, glacier inventory and meteorological data are then inserted as inputs into the calibrated model [28]. The meteorological data are spatially interpolated by Inverse Distance Weighting (IDW) and a combination of IDW and Elevation Dependent Regression (EDR) [45,50]. Snow accumulation and melting in PREVAH are determined by temperature and global radiation [37]. 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 [39] and with regards to the representation of glaciers and their length evolution [28]. 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 [53]. Future glacier extent for short glaciers is modelled with the Global Glacier Evolution Model (GloGEM) [54], for long glaciers with the newer and extended version of GloGEM (GloGEMflow) [55]. The simulated glacier lengths are finally converted to the model grid of PREVAH [28,55]. 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 [56] model was created to take lake regulation into account [57].