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Impacts of hot-dry conditions on hydropower production in Switzerland

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Abstract

Hydropower plays a significant role in the transition towards a low-carbon power system, being a renewable energy source that can complement solar and wind power, which are highly intermittent. However, hydropower is itself dependent on local weather conditions and climate variability. Moreover, extreme climate conditions, such as hot-dry compound events, can have a major impact on hydropower production (HP). Here, we examine the impacts of hot-dry conditions on HP under current and future climate scenarios in Switzerland, a country where hydropower provides the biggest share (60%) of the total electricity production. Overall, our results point out that the impacts of hot-dry conditions on HP are case-specific. We found that hot-dry compound conditions during the warmer months negatively impact HP in power plants with little or no water storage capacity (run-of-river schemes). On the contrary, schemes with large, seasonal accumulation lakes and significant glacier resources will continue to be able to produce high amounts of HP during hot-dry conditions in summer, which is an important result for Alpine hydropower.

1. Introduction

Hydropower production (HP) plays a key role in the transition to clean energy: it is one of the largest sources of renewable electricity production around the world (Cronin *et al* 2018), and it can be stored in large amounts (Fry *et al* 2022). In Switzerland, hydropower generates more than 60% of the total electricity, with nuclear power the next highest contributor, accounting for 30% (SFOE 2022a). The Swiss Energy Strategy 2050 aims to gradually phase out nuclear power between 2019 and 2035, and increase the installed capacity of renewable energy sources (Weiss *et al* 2021). Once nuclear power is phased-out, weather and climate-driven variability in renewable energy production and their spatio-temporal complementarity will become an increasing concern (François *et al* 2014).

Modeling HP for run-of-river (RoR) power plants, where there is little water storage, is straightforward, as production closely follows discharge patterns (Schaefli *et al* 2019, Wechsler *et al* 2022). It is more challenging to model HP for complex hydropower schemes that include large storage lakes, i.e. reservoirs, where electricity production depends on specific local management operations driven by water availability, electricity prices, and potentially additional considerations, such as flood management (Gaudard *et al* 2018). Existing approaches to model HP usually rely on physical models that require the specification of technical parameters unique to each power plant (e.g. number of turbines, turbine type, hydraulic head), which are typically not publicly available (Turner and Voisin 2022); hydropower plant characteristics and electricity production information are considered strategic for companies. Ho *et al*

(2020) argue that novel statistical and machine learning (ML) models have the potential to circumvent these challenges, learning information from observed data without any predetermined technical parameters. Thus, this study adopts hybrid forecasting (see Slater *et al* (2022) for a review) and combines traditional hydrological modelling approaches with ML and other proxies to estimate a target variable (here energy production).

On the other hand, since HP is dependent on local weather conditions, power schemes that are highly hydro-dominated, like in Switzerland, might be exposed to prolonged droughts (Brunner *et al* 2019c, Muelchi *et al* 2022). For example, the presence of heatwaves increases evapotranspiration, reducing water available to the discharge. Such weather and climate extreme conditions might not only cause water shortages, but might additionally lead to electricity demand peaks (Turner *et al* 2019, 2022). The combination of warm and dry conditions, often referred to as hot-dry compound events (Zscheischler *et al* 2017), has received attention from the scientific community because of associated environmental impacts and substantial socio-economic losses (e.g. Bevacqua *et al* 2022). The consequences of hot-dry compound events on the power system include reduced electricity grid reliability, due to peak electricity demand driven by cooling (Turner and Voisin 2022).

Due to this weather dependence, HP will be very sensitive to climate change (e.g. Cronin *et al* 2018, Turner *et al* 2019, Turner and Voisin 2022). In particular, HP in the Alpine region is strongly influenced by precipitation and snow and glacier melt (Schaefli *et al* 2007), and there is thus increasing concern about the effects of climate change on Swiss HP (Gaudard *et al* 2018, Schaefli *et al* 2019). Several studies have reported an earlier onset of snow melt in spring, and a reduction of the summer discharge due to glacier retreat and dry conditions (Schaefli *et al* 2007, 2019, Fatichi *et al* 2015, Muelchi *et al* 2021). Simultaneously hot and dry events are also expected to occur with an increased frequency under future climate conditions (Ridder *et al* 2022), which may further amplify the adverse impacts of individual extreme weather events on energy demand and power systems (Raymond *et al* 2020, Zscheischler *et al* 2020).

In this study, we examine the impacts of hot-dry compound events on HP in Switzerland, and study how these impacts are expected to change as a result of climate change. This is achieved using the following steps: (i) we first use state-of-the-art ML methods to reconstruct long-term time series of HP; (ii) a probabilistic approach is then used to study how HP reacts to hot and dry weather conditions under current climate conditions; (iii) finally, the ML models are fed with future climate projections and future discharge to obtain projections of HP over the coming century, allowing us to study not only how HP might change as a result of climate change, but also how the impact of hot and dry weather conditions on this production might evolve in the future. While this study focuses on Switzerland, our approach outlines avenues for future research to assess the impacts of compound weather extreme events on HP in a wider European and alpine context.

2. Materials and methodology

2.1. Data

Time series of Swiss HP are extracted from the European Network of Transmission System Operators (TSO) for Electricity (ENTSO-E) Transparency Platform (ENTSOE 2019), an online data platform for the European electricity system that provides data for 42 TSOs, including the Swiss TSO, Swissgrid (Hofmann *et al* 2022). This data is only available from 2015 onward. We select Swiss HP plants with a minimum of 5 years worth of data between 2016 and 2021; this ensures sufficient data is available to train and validate our ML model. We aggregate the hourly HP time series provided by ENTSO-E to a daily resolution, which matches the time resolution of the hydro-meteorological variables considered in this study.

The selected set of Swiss HP plants includes one RoR power plant (Rheinfelden along the Rhein river) and five accumulation HP plants distributed across the Alps, with installed capacities >200 MW (see figure 1 and table S1 in the supporting information, SI). Two of them, Mauvoisin and Emosson, belong to the largest seasonal storage schemes of Switzerland (see reservoir sizes and associated storage-to-inflow ratios in table S1), designed to collect ice and snow melt water inflow during spring and summer, to be released during winter (Schaefli *et al* 2019, Felix *et al* 2020). The Blenio scheme, with the reservoir Luzzone, has roughly half of the storage volume of Mauvoisin or Emosson but a larger catchment with a comparatively small glacierized area, i.e. it has less capacity to seasonally shift HP (tables S1 and S2). The schemes Leventina and Electra-Massa have a relatively small accumulation reservoir (compared to the catchment area feeding it) and can store water on a weekly scale only.

The Rheinfelden RoR power plant is a border power plant (Switzerland and Germany) and is owned by two power plant companies (SFOE 2022a). The data reported in the ENTSO-E database corresponds only to the Swiss ownership share, which amounts to 50% of the total production. It is worth mentioning that most of the selected storage power plants (Mauvoisin, Leventina, Blenio, Emosson) connect multiple hydrological catchment via penstocks comprise several powerhouses. Table S1 provides information about the power plants obtained from SFOE (2022a) and includes further characteristics such as catchment elevation, area and glacier cover,

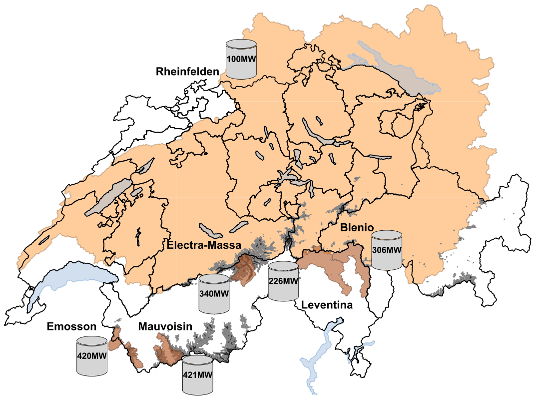

Figure 1. Map with the catchments (brown = reservoir power plants; orange = RoR power plant) corresponding to the selected hydropower plants according to the spatial database on Swiss hydropower plants developed by Balmer (2012) (see table S1 for further information). The filled grey shades illustrate the glacier coverage. Black lines represent the Cantonal borders.

obtained from the database developed by Balmer (2012) and SFOE (2022b).

Daily precipitation and temperature data stem from the daily gridded products RhiresD and TabsD from MeteoSwiss, with a resolution of 1 km × 1 km (MeteoSwiss 2017, 2019). The temperature and precipitation times series corresponding to all grid cells within a given HP plant catchment were averaged to obtain a single representative precipitation and temperature time series per catchment figure 1. Daily simulated inflow to each of the HP plants was obtained from the hydrological model PREVAH (Viviroli *et al* 2009), a conceptual, process-oriented hydrological model that has been largely used for hydrological and climate change impact studies in Switzerland (e.g. Köplin *et al* 2014, Brunner *et al* 2019a, 2019c). The model runs on a 500 m × 500 m grid and provides surface and subsurface discharge per grid cell without considering any human water use infrastructure (Viviroli *et al* 2009). The discharge data used here resulted from the work of other authors and correspond to 307 medium-sized catchments in Switzerland (Zappa and Brunner 2019, Brunner *et al* 2019a). The use of modeled discharge was preferred over observed discharge because we do not have observed data on natural inflow into the HP plants, and to make current and future data more comparable, avoiding a discrepancy between model training and its use in prediction.

Thus, the discharge data used here correspond to the catchments according to the PREVAH subdivision as shown in previous work (Brunner *et al* 2019a, 2019c) (see figure S1), except for Mauvoisin, for which a reconfiguration of PREVAH sub-catchments running on 200 m × 200 m grid for the Mauvoisin power plant has been done (with corresponding new simulations) to better represent the catchment elevation and glacier coverage (table S1). For Rheinfelden, only the Swiss part of the catchment is considered (table S1). For Blenio and Leventina, the simulated discharge from the PREVAH catchments that did not exactly correspond to the HP sub-catchments presented in figure 1 was scaled to the actual sub-catchment area.

To assess changes in future HP, we used the output of ten climate model chains available from the Swiss Climate Change Scenarios CH2018 (CH2018 2018, Fischer *et al* 2022). The CH2018 scenarios are based on EURO-CORDEX simulations for three representative concentration pathways (RCPs); the corresponding temperature and precipitation time series were obtained by statistically downscaling via quantile mapping (CH2018 2018). Such a quantile mapping technique also applies a bias-correction that accounts for potential biases at the model grid scale (CH2018 2018). Thus, future projections of temperature and precipitation were extracted from the CH2018 climate scenarios provided by the Swiss National Centre for Climate Services (CH2018 2018). Corresponding future discharge simulations were also available from PREVAH, forced with the same CH2018 scenarios (CH2018-hydro). The future glacier extents have been computed by Zekollari *et al* (2019) and their temporal evolution has been accounted for in the hydrological simulations. The selected ten model chains correspond to the ones previously used by Brunner *et al* (2019b). Further information about model chains considered in this study can be found in table S3.

We reconstructed historical HP time series for a 41 yr period covering 1981–2021. To assess the impact of climate change, we define two overlapping 41 yr periods in the mid-21st century (2030–2070) and in the end of the 21st century (2059–2099).

2.2. Methodology

The workflow of our analysis is summarized in figure 2. The components of this workflow are described in this section. We first discuss how we reconstruct long-term time series of historical and future HP, and we then provide details on the probabilistic model that is used to examine the effects of hot-dry conditions.

2.2.1. HP: ML set-up

Firstly, we use ML techniques to model HP as a function of discharge. Discharge is one of the most relevant variables for HP, and is particularly relevant in our case since the simulated discharge runs have been driven by precipitation and temperature, among other variables (Viviroli *et al* 2009). Thus, the discharge data already contains meteorological information that is expected to have an influence on HP.

Given that the electricity production at day *d* is usually highly influenced by preceding hydrometeorological conditions, our ML models include

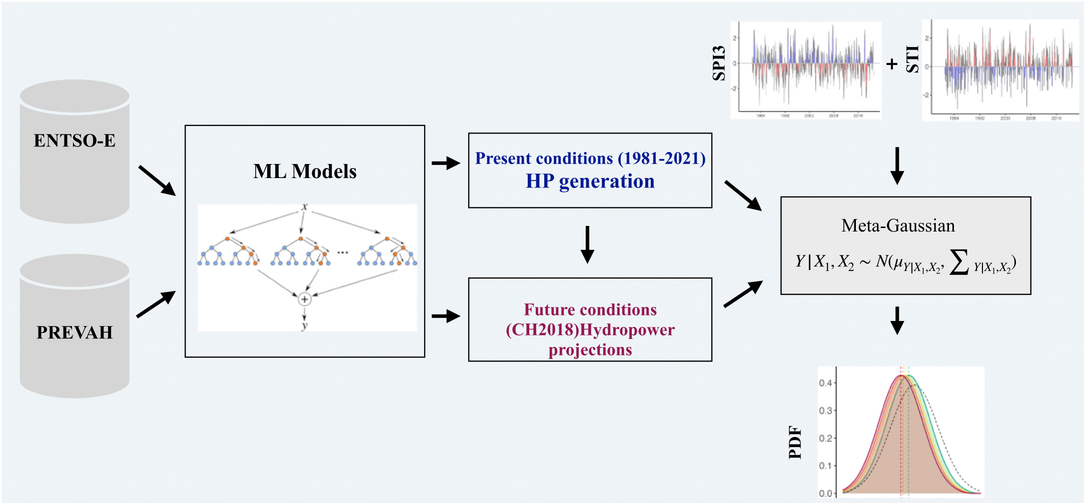

Figure 2. Methodological framework developed to reconstruct long-term time series of HP, later used to assess the impact of hot-dry compound events through a probabilistic modelling approach.

moving-averages for the discharge over the previous weeks (i.e. 7, 15, and 30 days). We believe that using only discharge to reconstruct HP is a reasonable choice and sufficient to reconstruct HP because (i) the actual discharge (Q) is the dominant driver of HP (Schaefli *et al* 2019) and (ii) potential temperature effects on HP demand (Tilov *et al* 2020) are indirectly also included in Q, which strongly depends on temperature. In addition, the day of the year was included as a predictor, as a proxy for human factors that influence HP (e.g. management operations). We do not include the day of the week as a predictor, which implies that our model cannot reproduce within-week production variability. This is not critical since the probabilistic analysis of production extremes is based on monthly aggregates (see below).

Note that the ML models assume an invariant relationship between the target variable and the predictors over time: in our case, this means that the effect of discharge on HP is the same now as in the future. This is reasonable because (i) for RoR, the production simply depends on discharge; the relationship can evolve if there is a strong shift of the discharge regime, with much more frequent peaks above the turbine capacity; (ii) for accumulation production, the production pattern depends on the relative storage volume compared to the total annual inflow (for seasonal storage plants) or compared to the weakly inflow for the short-term storage plant (e.g. Electra Massa). For all considered accumulation plants, the annual inflow exceeds the storage volume under past and future discharge regimes (see table S4). Accordingly, no fundamentally new production pattern will arise related to discharge (new patterns related to the electricity demand or infrastructure are of course possible). It is important to note that the ML model nevertheless accounts for future glacier retreat because the input variable, discharge, stems from a hydrological model that explicitly takes into account glacier retreat (CH2018 2018, Brunner *et al* 2019a, Muelchi *et al* 2022).

Four statistical and ML algorithms were tested for modeling HP: (i) linear regression; (ii) random forest regression (RF); (iii) an artificial neural network; and (iv) long short-term memory, a type of recurrent neural network. In our tests, the RF outperformed the other models (figure S2), and therefore, the results presented here are based on HP obtained from a RF model. A separate RF model was trained for each HP plant. We used 5-fold cross-validation on a rolling basis to evaluate model performance, i.e. the model is trained and validated using one year, and then assessed out-of-sample using the remaining 4 years. This is repeated for each year, allowing us to consider anomalous warm or dry years during the training stage, and permitting the use of all available data to evaluate the models. Detailed information about the selected ML method can be found in the supporting information. Note that the time period indeed spans some of the hottest years on record as mentioned by MeteoSwiss: 'The years 2015 to 2022 were the warmest since measurements began, with 2020, 2019 and 2016 being the current record holders' (MeteoSwiss 2023). However, the record also includes the wet and colder summer 2021.

2.2.2. Probabilistic modeling

Our probabilistic approach is based on widely-used climate indices that quantify standardized departures from fitted probability distribution functions. Specifically, we identify hot-dry conditions using the Standardized Precipitation Index (SPI) (McKee *et al* 1993) and the Standardized Temperature Index (STI) (Zscheischler *et al* 2014). We use a 1 month timescale for computing the STI and a 3 month time scale for the SPI to account for the preceding seasonal precipitation conditions. Compound hot-dry conditions are then defined as concurrent low SPI values, below or equal to a certain threshold t_P, and high STI values, above or equal to a threshold t_T.

The probabilistic response of HP to hot-dry compound conditions can be quantified based on the conditional distribution of HP given certain values of the SPI or STI. Multivariate methods, such as copulas (Nelsen 2006), are commonly employed to construct multivariate probability distributions (e.g. Ribeiro *et al* 2019, Zscheischler *et al* 2020). Similar to previous studies (e.g. Feng *et al* 2019, Hao *et al* 2021, Wu and Jiang 2022), we use a trivariate Gaussian distribution (i.e. a meta-Gaussian model) to model the joint distribution of HP, SPI, and STI (Hao *et al* 2016). To do so, we first aggregate daily HP into monthly values, which are subsequently transformed into a Standardized Hydropower Production Index (referred to as the SHPI) based on the normal quantile transformation (Bogner *et al* 2012, Allen and Otero 2022). This step is necessary because normal random variables are required for the probabilistic model. We then use the SHPI to examine the HP response to hot-dry conditions.

The trivariate Gaussian model is defined as follows. Let Y denote the (unknown) SHPI at a given time and location, and let X_P and X_T denote the corresponding SPI and STI values. Then, the conditional distribution of Y given X_P and X_T is:

$$Y|X_P,X_T \sim \mathcal{N}(\mu_{Y|X_P,X_T}, \Sigma_{Y|X_P,X_T}), \quad (1)$$

where $\mu_{Y|X_P,X_T}$ is the conditional mean of Y given X_P and X_T, and $\Sigma_{Y|X_P,X_T}$ is the conditional variance (Wilks 2011). These terms can be estimated as follows Wilks (2011), Hao *et al* (2016), Feng *et al* (2019):

$$\mu_{Y|X_P,X_T} = \mu_Y + \Sigma_{YX}\Sigma_{XX}^{-1}(X - \mu_X), \quad (2)$$

$$\Sigma_{Y|X_P,X_T} = \Sigma_{YY} - \Sigma_{YX}\Sigma_{XX}^{-1}\Sigma_{XY}, \quad (3)$$

where μ_X is the mean of the random vector $X = (X_P, X_T)^\top$, Σ_{XX} is the covariance matrix of X, μ_Y is the mean of the random variable Y, Σ_{YY} is the variance of Y, Σ_{YX} is a (row) vector containing the covariances between Y and X, and $\Sigma_{XY} = \Sigma_{YX}^\top$, with $\rightarrow p$ denoting the vector transpose.

To study the impact of hot-dry conditions on HP, we consider the probability of obtaining lower than average HP (i.e. SHPI < 0) given that a hot-dry event has occurred. This probability, $P(Y < 0|X_P < t_P, X_T > t_T)$, can readily be obtained from the model in equation (1). If the HP is independent of the SPI and STI, the above probability will equal 0.5 for all t_P and t_T; a higher probability of HP being lower than average indicates that hot-dry conditions have a negative effect on HP, whereas a lower probability suggests hot-dry conditions positively affect HP. As our interest focuses on the HP to compound hot-dry events, the probabilistic analysis is limited to the warmer months, April–September.

3. Results

3.1. Reconstruction of historical electricity production

After validating and selecting the best ML model (see SI), we reconstruct long time series of electricity production for each power plant, which are subsequently used to assess the impacts of hot-dry conditions on HP. As illustrated in figure 3, the models capture observed monthly HP as well as year-to-year variability well (figures S2 and S3). Similar model performance is also observed out-of-sample.

All the hydropower schemes produce more electricity over the summer half year (April to September) than over the winter half year (on average, the winter production in Switzerland amounts to 43% of annual HP) (for Energy 2022). Important differences in HP between the schemes with the smallest and the largest reservoirs can be observed in figure 3. For the RoR scheme with no reservoir, Rheinfelden, the production is relatively constant, limited by the installed capacity. For Electra-Massa, which has a high glacier cover but a small reservoir, the monthly production pattern follows closely the discharge pattern, but largely limited in summer by the installed capacity. For all other schemes, the management operations have the common objective of shifting part of the available water from summer (when inflow in mountainous areas is highest) to winter (when demand is highest) (Anghileri *et al* 2018, Felix *et al* 2020, Kosch *et al* 2021), in addition individual entrepreneurial considerations including long term production contracts and short-term production operations during peak demand (Ranzani *et al* 2018). The production of each scheme is thus influenced by the discharge regime, the reservoir size, the installed capacity and economic considerations. For the two schemes with small to intermediate reservoirs (compared to inflow, i.e. Leventina, Blenio), monthly HP follows largely the monthly discharge variations (limited by installed capacity in summer), with some carry-over effects visible for Blenio. For the schemes with the largest reservoirs (Mauvoisin and Emosson), HP is strongly shifted from summer to winter. For Mauvoisin, the production has a peak in summer because the reservoir size is limited and decreases thereafter along with discharge, to remain relatively constant in winter as a result of the carry-over effect of the reservoir.

3.2. HP under climate change

The projected HP for the mid-century (2030–2070) and the end-of-century (2059–2099) periods suggest

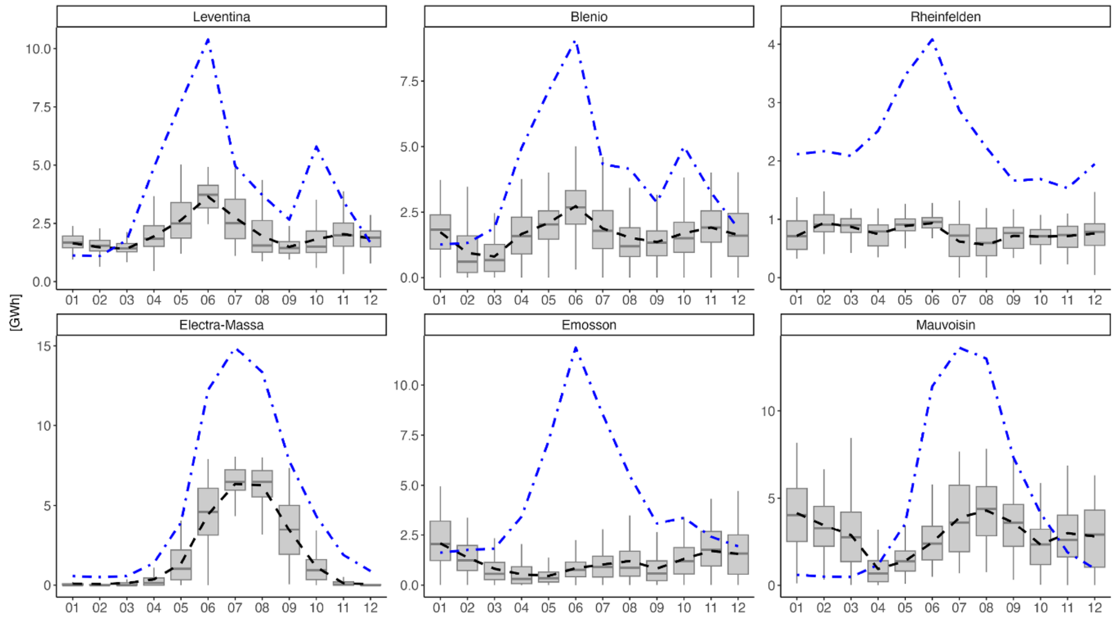

Figure 3. Boxplots with monthly modeled HP for the training period 2016–2021. Black dashed lines indicate the observed HP obtained from ENTSO-E. Monthly discharge (mm/day) is represented by dashed blue lines (same *y*-axis but different unit).

a decrease in summer HP under the three climate scenarios, RCP2.6, RCP4.5, and RCP8.5, for the scheme with no reservoir (RoR power plant Rheinfelden) and for the ones with small to intermediate reservoirs but little glacier-cover, i.e. Blenio and Leventina (figures 4 and 5). This summer decrease comes with a slight increase in winter production.

For the scheme with a high elevation catchment but with a small reservoir, Electra-Massa, summer production is slightly shifted to an earlier period and winter production increases slightly, which corresponds exactly to the projected changes in the discharge regime changes (see SI for further details about the CH2018 climate projections). For the schemes with the largest seasonal reservoirs and high elevation catchments, i.e. Mauvoisin and Emosson, the projections suggest little change in summer HP (except the same shift for Mauvoisin as for Electra-Massa) for the mid-of-century period (figure 4, but for Mauvoisin it can be noticed a decreasing summer production by the end of the century (figure 5. Also for those schemes, the projections suggest a decrease in winter production, despite the projected increase in winter discharge at high elevations. This pattern stems from the fact that our ML model necessarily reproduces the current relationship between reservoir inflow and management strategies.

Changes in HP are site-specific (Gaudard *et al* 2018). Wechsler *et al* (2022) quantified the change of HP of Swiss RoR power plants based on projected discharge statistics and some technical information on the analyzed plants. They find a general increase in winter production during the mid and end-of-century periods ($\sim$ 5%) and a decrease in summer production, resulting in little change to the annual production by mid-century, but a decrease by the end of the century. Mountain regions are particularly sensitive to climate change, as glacier retreat strongly affects HP (Schaefli *et al* 2007, 2019). Previous studies analysing the potential changes in future HP in Alpine catchments suggested that HP will likely be substantially affected by climate change. Some studies (e.g. Schaefli *et al* 2007, Finger *et al* 2012, Fatichi *et al* 2015) pointed out that future melt and rainfall-discharge are projected to increase during the spring months and to decline in summer, leading to an enhanced variability in the reservoirs inflow. In particular, Fatichi *et al* (2015) quantified the effect of climate change in the upper Rhone basin in the Alpine region and suggested that reservoirs receiving a large fraction of water from glacier-covered catchments might be unable to reach the same levels of water in late summer and autumn, which calls for a modification in the current management strategies.

It must be noted that when projecting future HP there exist an overall uncertainty associated with climate change projections (Gaudard *et al* 2018, Muelchi *et al* 2022) (further details can be found in the supporting information and figures S5–S7). Differences are noticeable in the cases of Leventina or Blenio when the modeling chain show more discrepancies when comparing with the reference period (see figure S5). Nevertheless, our findings are consistent with these studies, although our results clearly show distinct climate change impact patterns for each of the analyzed HP plants, which results from the range of hydropower plants analyzed here, including RoR power plants, small and seasonal reservoir-based storage power plants.

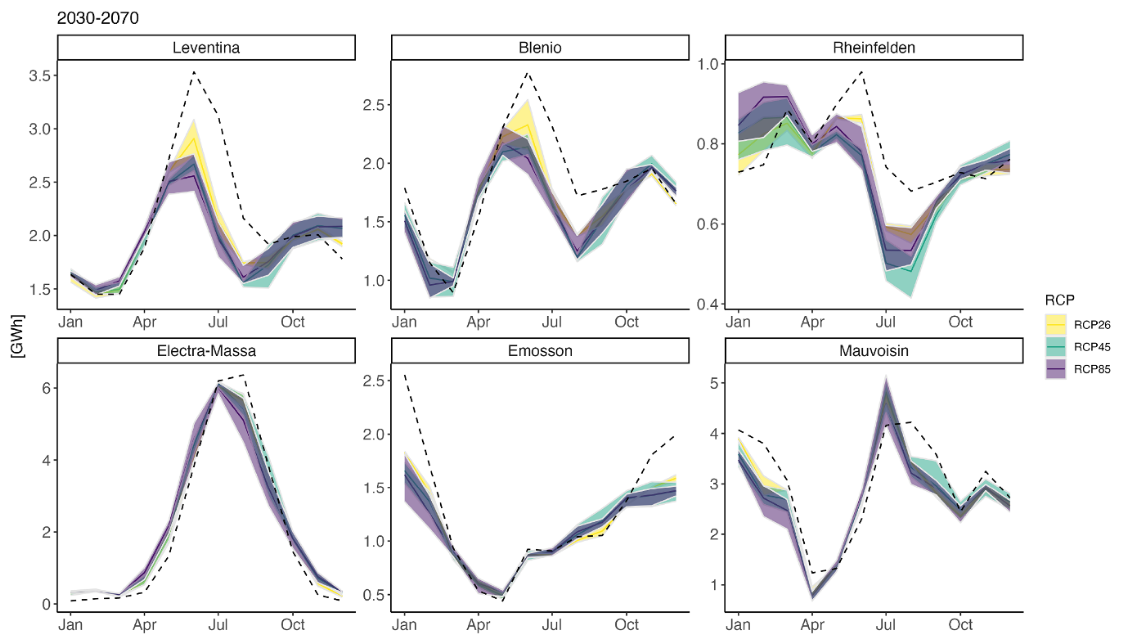

Figure 4. Projected monthly HP for the mid-of-century period (2030–2070). Solid lines represent the multi-model median and shadings indicate the model spread within an emission scenario. The black dashed line shows the control simulations for the reference period 1981–2021.

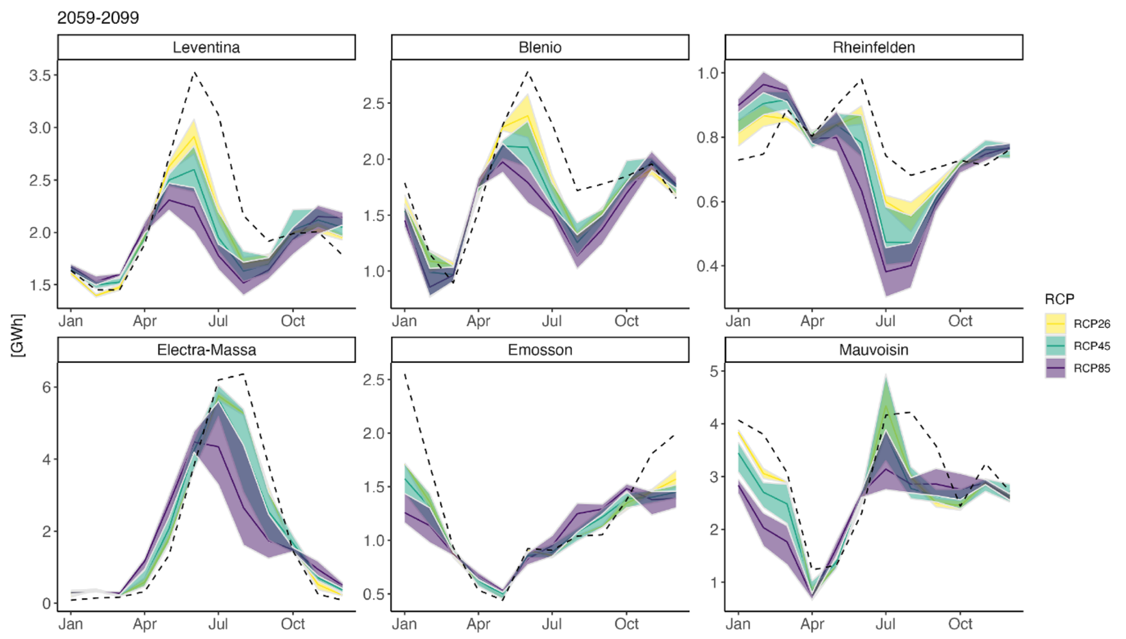

Figure 5. Projected monthly HP for the end-of-century period (2059–2099). Solid lines represent the multi-model median and shadings indicate the model spread within an emission scenario. The black dashed line shows the control simulations for the reference period 1981–2021.

3.3. HP changes under hot-dry conditions

Here, we examine the probabilistic response of HP to compound hot-dry conditions during the historical period (1981–2021). For this, we estimate the conditional distribution of HP for certain combinations of hot-dry conditions, corresponding to different thresholds of the SPI and STI: namely, extreme ($t_P = -1.9$, $t_T = 1.9$), severe ($t_P = -1.6$, $t_T = 1.6$), moderate ($t_P = -1.3$, $t_T = 1.3$) and mild ($t_P = -0.8$, $t_T = 0.8$) conditions.

The response of HP to hot-dry conditions differs across the sites (figure 6). In the RoR power plant Rheinfelden and for the schemes with the small to intermediate reservoirs, Leventina and Blenio, the conditional mean of the SHPI is negative for all severity levels, indicating a negative impact of compound

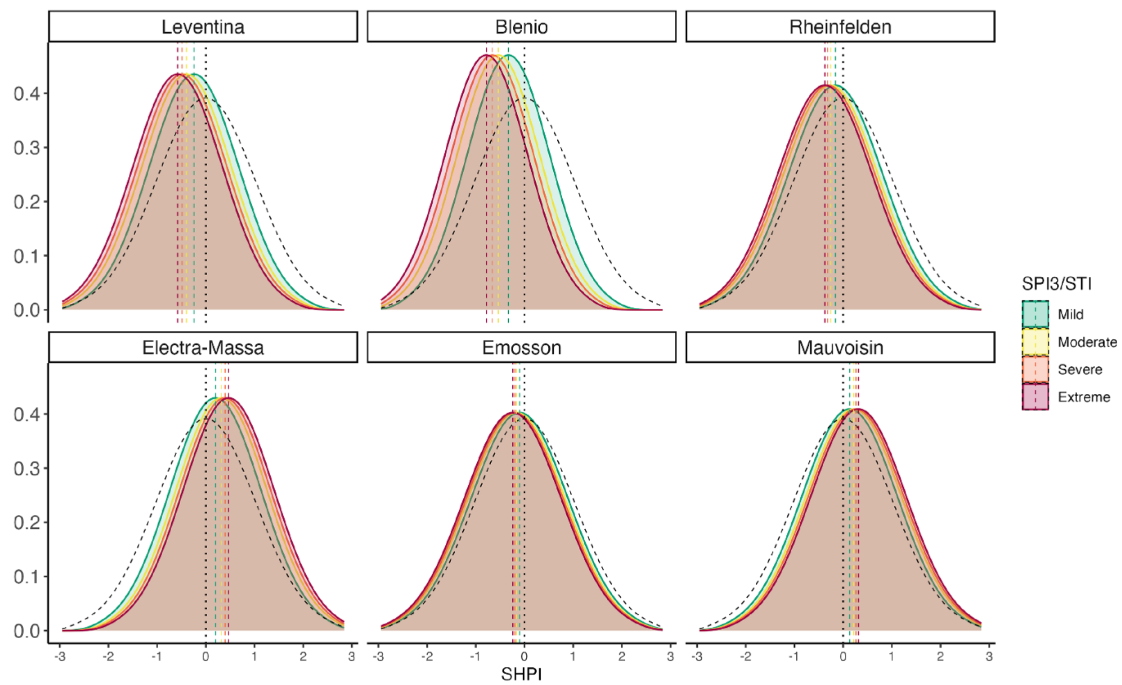

Figure 6. The conditional PDF of the SHPI given the three hot-dry compound conditions for each HP plant under present climate conditions (1981–2021). The conditional mean μ is indicated by the vertical dashed lines. The black dashed line represents the standard normal.

hot-dry conditions on HP. The probability density function (PDF) of the SHPI gradually shifts to the left as the severity of the hot-dry event increases, suggesting a greater reduction of HP with more extreme meteorological conditions, due to the stronger sensitivity of RoR power plants to climate conditions (Wechsler *et al* 2019). A negative impact of hot-dry conditions can also be observed for Emosson, which, while belonging to the category of large storage reservoirs, has little glacier coverage (compared to Mauvoisin and Electra-Massa, see table S2). In this case, the PDF shows a slight shift to more negative SHPI values as the hot-dry conditions become more severe (figure 6).

The response of HP is very different for Mauvoisin and Electra-Massa, which both have considerable glacier melt inflow, with a positive response of HP to hot-dry conditions (i.e. the conditional PDF of SHPI shifts to the right). This positive response of HP can be explained by the high relative glacier coverage of the catchments feeding these HP plants and the corresponding large amount of water from ice melt during the summer months (Zappa and Kan 2007).

To further investigate HP during hot-dry compound conditions, we examine the conditional probabilities of below-average HP (SHPI < 0) given various combinations of SPI and STI values (figure 7). Consistent with the strong shift of conditional means to negative values depicted in figure 6, the highest conditional probability values are found for the Blenio power plant, where below-average HP becomes more likely as the severity of hot-dry conditions increases. For Leventina, the conditional probability is less sensitive to the STI than to the SPI, as visible from the absence of conditional probability increase with STI in figure 7. This indicates that the HP is mostly driven by the SPI (i.e. drought conditions). Similar to Blenio, Rheinfelden and Emosson show an increasing conditional probability as both SPI and STI become more extreme, though the conditional probability values are lower than for Blenio and Leventina. An opposite response is found for the high glacier-cover schemes Mauvoisin and Electra-Massa, where the low conditional probabilities (< 0.5) indicate a slight positive effect of hot-dry conditions on HP. Both schemes show a similar pattern of decreasing conditional probabilities as a function of STI increase and no sensitivity to SPI. This is related to the high share of glacier melt inflow, which explains the positive response of HP for these schemes under warmer temperatures, based on two mechanisms: on one hand, large summer inflow can lead to a surplus of water that cannot be stored locally and thus leads to more HP (for the smaller reservoir of Electra-Massa, but also for Mauvoisin). On the other hand, in particular the Mauvoisin scheme with a large storage can increase its HP during hot-dry summers to fill in the lack of HP from the lower elevation schemes.

3.4. Future HP under hot-dry conditions

The conditional means projected under the three emission scenarios indicate a major HP decline for the highest emission scenario (RCP8.5) for the RoR

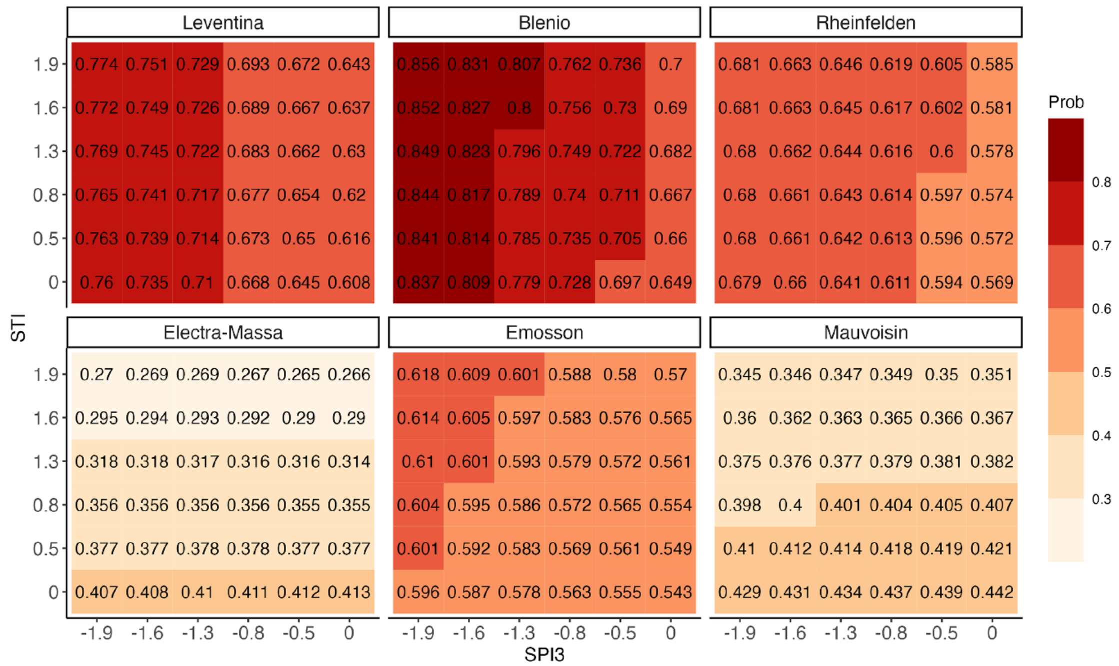

Figure 7. Conditional probabilities of below average HP (i.e. SHPI < 0) given different combination of SPI3 and STI that indicate several levels of compound hot-dry conditions. Low values of the conditional probability mean little impact, high values mean high probability of below average production.

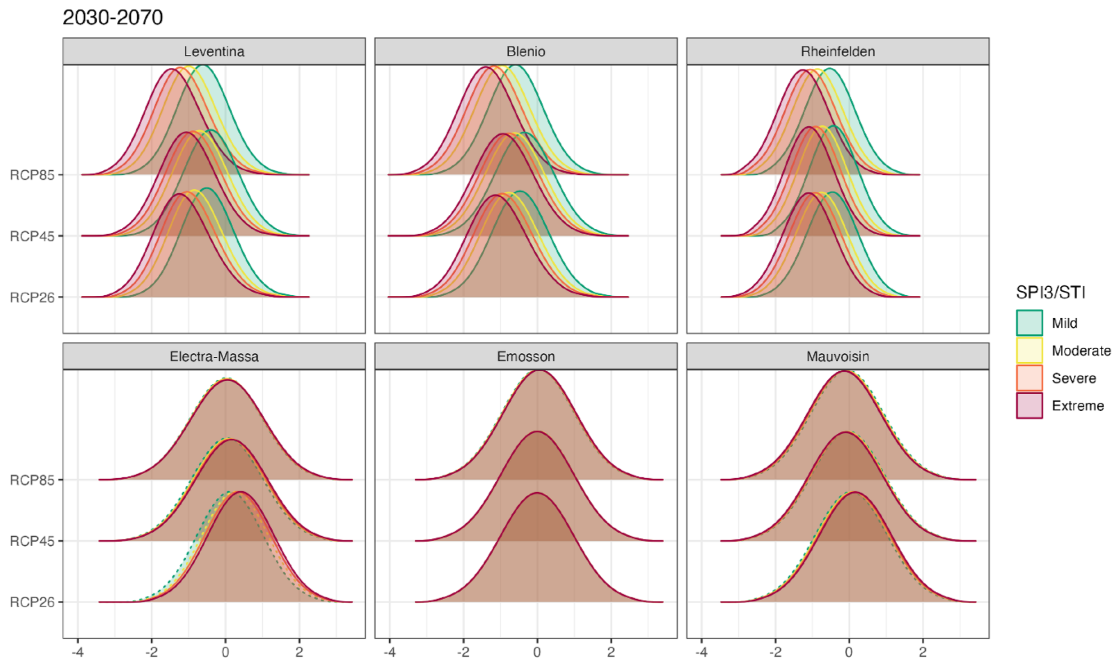

Figure 8. Projected changes in the conditional PDF of the SHPI by the mid-century period (2030–2070) under the emission scenarios given three hot-dry compound conditions for each hydropower plant. Solid lines indicate projected changes that are statistically significant at the 95% confidence level of a two-sided *t* test. Dashed lines indicate not statistically significant projected changes.

scheme and the schemes with small to intermediate reservoirs with catchments small glacier cover (i.e. Leventina and Blenio) (figure 8 top row). While the conditional PDFs corresponding to mild hot-dry conditions (i.e. SPI < -0.8, STI > 0.8) are very similar across the emission scenarios, there is a clear shift towards more negative SHPI values as the severity of the compound event and of the emission scenario increases. This shift is thus more noticeable for the highest emission scenario, RCP8.5. An opposite HP response to future hot-dry conditions is observed for all three schemes with high elevation catchments (figure 8 bottom row). The conditional means show little changes when compared with those of the power plants with lower elevation catchments. The PDFs are slightly shifted to the right (a positive HP response) as the severity of the hot-dry compound event increases. Similar patterns are found by the end of the century (2059–2099) (figure S8).

A Student's *t*-test was applied to determine whether the differences between the mean of the SHPI distribution in each emission scenario and the mean of the historical SHPI distribution were statistically significant. The *t*-test was applied to each scenario and to each severity of hot-dry compound conditions. For the schemes that show a decline in HP, the projected changes in the SHPI distributions were found statistically significant ($p < 0.05$) under future climate conditions for all severity levels of hot-dry compound conditions(figure 8 top row). For the schemes with high elevation catchments (figure 8 bottom row), the projected changes in the PDFs of the SHPI were found statistically significant under extreme hot-dry compound conditions.

4. Summary and discussion

A key challenge when analyzing HP is the limitation of data. In this paper, we used ML methods to reconstruct long time series of HP for a total of six HP plants (five reservoirs and one RoR) that are representative of the Swiss HP. The ML models used for the historical period (1981–2021) were then applied to future climate projections, resulting in estimates of HP under three future emission scenarios.

While ML algorithms have proven to be a suitable approach for HP modeling (e.g. Troccoli *et al* 2019, Falchetta *et al* 2020, Turner and Voisin 2022), some limitations must be acknowledged. ML models assume a stationary relationship between the target variable and the predictors, whereas electricity demand and management strategies are important factors for HP that are generally non-stationary, especially in the ongoing evolution towards a more renewable energy mix in Europe (European Climate Foundation 2010). A key factor driving current HP management decisions is ongoing glacier retreat, which is expected to impact HP throughout the 21 century (Schaefli *et al* 2019). While the discharge simulations used here to reconstruct HP do account for glacier retreat and corresponding melt water availability (Viviroli *et al* 2009, Brunner *et al* 2019a), our approach cannot account for other effects related to glacier retreat such as modification of prescribed environmental flows or production adaptation to evolving sediment inputs into water intakes and reservoirs (Boes and Hagmann 2022, Hauer *et al* 2018). Similarly to Ho *et al* (2020), we assume constant installed capacities; periods of maintenance or failure are not considered.

Moreover, when projecting future HP, we must bear in mind the overall uncertainty associated with climate projections (Gaudard *et al* 2018, Muelchi *et al* 2022), such as the post-processing and statistical downscaling of climate model outputs using quantile mapping (Maraun 2016, Sø rland *et al* 2020). By using the CH2018 Climate Change Scenarios, we accounted for part of this uncertainty through the use of different model chains.

Despite the above uncertainties, this first attempt to quantify the impact of hot-dry conditions on Alpine HP highlights the overall pattern of possible changes: (i) A decrease of HP under hot-dry compound conditions under present and future climate conditions for RoR power schemes and for schemes with small to intermediate accumulation reservoirs and without significant glacier cover in their catchments. (ii) An increase of HP under hot-dry compound conditions under present conditions for schemes with large reservoirs and a high glacier cover in the feeding catchments. For those schemes, this increase under future climate scenarios is projected to be insignificant except for the most extreme severity levels of hot-dry compound conditions.

It is noteworthy that we obtain these results for Mauvoisin and Electra-Massa despite the fact that future glacier cover is projected to decrease considerably for the catchments feeding these schemes (table S1), which is accounted for in the simulated discharge that we use as input in our RF models. This result suggests that future discharge, resulting from less glacier melt and from less snowmelt in summer is still sufficient to buffer hot-dry conditions, which is of key importance for HP management in Switzerland.

A possible limitation arises from the fact that our model cannot account for physical limitations related to the reservoir sizes and the installed capacity. The future inflow will most likely be much more concentrated in time during spring and early summer (see discharge pattern in figure 3), namely for Mauvoisin and Emosson. This concentration could potentially lead to an over-spill of the reservoirs.

5. Conclusions

We have utilized both ML and probabilistic models to analyze the impact of hot-dry conditions on Alpine HP. To the best of our knowledge, this is the first such assessment. The selected case studies from Switzerland cover the full range of Alpine HP schemes and are therefore also of interest to other

Alpine regions. The study fully benefited from an ensemble of state-of-the-art climate change simulations and corresponding glacier retreat and discharge scenarios.

Our results underline that the vulnerability of HP to climate change is case-specific. Simultaneously hot and dry conditions negatively affect HP during the warmer months for schemes with no or little water storage capacity and without significant glacier cover in the feeding catchments: Blenio, for example, showed a high conditional probability (> 0.8) that the average HP decreases during hot-dry compound events. For these schemes, the conditional probability of low HP under future climate scenarios statistically significant increase with respect to the historical period (1981–2021). An opposite result was found for schemes that currently have a high glacier cover in their feeding catchments: these HP schemes show the lowest conditional probabilities that average HP will be lower than average, which indicates a more positive response of HP to hot-dry events, despite declining glacier water resources. For these schemes, the future distribution of standardized HP under compound hot-dry conditions did not show considerable differences when compared with that obtained for the historical periods. These results suggest that the schemes with high elevation catchments will continue to be able produce high amounts of HP during hot-dry conditions in summer even in the future, which is an important result for Alpine HP. Moreover, within the current energy transition, scheduling the capability of HP will become challenging due to the growing share of renewable sources, particularly solar power that will lead to high production peaks during summer months.

While the results presented here focus on Switzerland, this approach can be indeed applied to other countries and world regions for which climate change impact projections on discharge are available. Hence, this modeling framework might be used in future research studies to better understand the impact of compound extreme events on HP in different regions and spatial scales. For example, our approach is applicable to most European countries for which a substantial amount of data has been collected from different sources (Troccoli *et al* 2019). As an outlook, it is worth noting that our modeling results suggest that continued high production during summer might come at the expense of winter production. Future work should therefore focus on how hot-dry summers influence winter HP.

Data and code availability statement

The code used for this study is available in: https://github.com/noeliaof/Hydro_Compound or https://zenodo.org/record/7932791#.ZGCG_-xBzLA. The data processed and used for this study can be found in https://doi.org/10.5281/zenodo.7934296. Note that the raw discharge data is also available via the EnviDat repository, https://www.envidat.ch/dataset/hydro-meteorological-simulations-1981-2018 for the historical period and https://www.envidat.ch/dataset/simulated-future-discharge-and-climatological-variables for the simulated future discharge. Similarly, the gridded meteorological data can be ordered from MeteoSwiss (www.meteoswiss.ch). Observed hydropower timeseries are publicity available at ENTSO-E: https://transparency.entsoe.eu/dashboard/show.

All data that support the findings of this study are included within the article (and any supplementary files).

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