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Risks and opportunities for a Swiss hydroelectricity company in a changing climate

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Abstract. Anticipating and adapting to climate change impacts on water resources requires a detailed understanding of future hydroclimatic changes and of stakeholders' vulnerability to these changes. However, impact studies are often conducted at a spatial scale that is too coarse to capture the specificity of individual catchments, and, importantly, the changes they focus on are not necessarily the changes most critical to stakeholders. While recent studies have combined hydrological and electricity market modeling, they tend to aggregate all climate impacts by focusing solely on reservoir profitability. Here, we collaborated with Groupe E, a hydroelectricity company operating several reservoirs in the Swiss pre-Alps, and we co-produced hydroclimatic projections tailored to support the upcoming negotiations of their water concession renewal. We started by identifying the vulnerabilities of their activities to climate change; together, we then selected streamflow and electricity demand indices to characterize the associated risks and opportunities. We provided Groupe E with figures showing the projected impacts, which were refined over several meetings. The selected indices enabled us to assess a variety of impacts induced by changes in (i) the seasonal water volume distribution, (ii) low flows, (iii) high flows, and (iv) electricity demand. This enabled us to identify key opportunities (e.g., the future increase in reservoir inflow in winter, when electricity prices have historically been high) and risks (e.g., the expected increase in consecutive days of low flows in summer and fall which is likely to make it more difficult to meet residual flow requirements). We highlight that the hydrological opportunities and risks associated with reservoir management in a changing climate depend on a range of factors beyond those covered by traditional impact studies. This stakeholder-centered approach, which relies on identifying stakeholder's needs and using them to inform the production and visualization of impact projections, is transferable to other climate impact studies, in the field of water resources and beyond.

1 Introduction

Hydropower is the most widely used renewable energy resource across the globe (Schaefli, 2015). Given this global importance, there is a growing need to support the adaptation of hydropower facilities and operations to changes induced by climate change. This need is particularly strong in mountainous catchments, which are the major source of streamflow for hydropower production and are particularly sensitive to climate change (Schaefli et al., 2007; Zierl and Bugmann, 2005). Electricity companies across Switzerland are renewing and renegotiating their water concessions, transforming their existing infrastructure, and considering investments in new regions and sectors (Barry et al., 2015; SWV, 2012). However, in the vast majority of these cases, tailored analyses of climate change impacts are not used (Tonka, 2015).

To anticipate climate change impacts on hydropower production and to develop adaptation strategies, it is essential

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to account for end-user vulnerabilities and hydroclimatic changes at the local scale (Schaefli, 2015). Currently, the majority of studies that perform a climate change impact analysis focus on either the effect of climate change on the seasonal cycle or on extreme events (Addor et al., 2014; Etter et al., 2017; Finger et al., 2012; FOEN, 2012; Hänggi and Weingartner, 2012; Köplin et al., 2014; Lopez et al., 2009; Vano et al., 2010) but rarely on a combination of both. Furthermore, until recently, changes in streamflow (water supply) were typically analyzed in isolation and were usually not combined with projections of future electricity demand (Gaudard et al., 2013). In recent studies (Anghileri et al., 2018; Gaudard et al., 2018b; Savelsberg et al., 2018), the modeling of the electricity market has been combined with hydrological simulations to project potential revenue under climate change. These studies contribute to bridging the gap between economists and hydrologists and account for the interconnected nature of water and electricity, which is fundamental for sustainable hydropower development. However, their focus is still on the seasonal cycle (see Savelsberg et al., 2018, for a detailed overview of recent research on the impact of climate change on hydropower). The focus on particular streamflow indices is often determined by what climate and hydrological modelers perceive as most adequate and relevant (an approach commonly referred to as "top-down"). However, this does not necessarily correspond to the needs of the stakeholders in charge of designing adaptation strategies. Top-down studies typically provide an overview of the impacts of climate change on hydrological resources; however, for stakeholders to assess the future profitability of their operations, more specific and local information is often needed (Vano et al., 2018). Given the potential consequences and costs associated with climate change impacts, it is essential to reduce the risk of maladaptation, which can result from misunderstanding end-users' vulnerabilities to climate change or from ill-designed projections (Broderick et al., 2019). Robust adaptation measures that provide benefits under a range of climate change scenarios are especially valuable, as they reduce the risk of maladaptation. Prioritizing stakeholder involvement early on enables them to expose their concerns regarding climate change and to establish which potential future changes should be assessed as priorities. This stakeholder-centered approach is often referred to as "bottom-up" (Wilby and Dessai, 2010; Addor et al., 2015).

Here, we present a case study relying on a stakeholder-centered approach for creating hydrological and climatological projections tailored to support climate change adaptation and water concession negotiations. We collaborated with a Swiss electricity company that manages and has shares in several hydropower reservoirs in Switzerland. This project started with meetings with representatives from the company, thereby involving them in the design of the study from the beginning. We relied on their expertise and asked them to identify which hydroclimatic changes their hydropower operations are most vulnerable to and to indicate change thresholds beyond which their activities would be significantly impacted. These meetings enabled us to pinpoint vulnerabilities of the company's operations to climate change and to select hydrological and electricity demand indices to characterize the associated risks. The representatives stated that they expect the following to be considered during concession negotiations (i) the development of the electricity market and competitors, (ii) the projected supply of water resources, (iii) the changes in electricity demand, and (iv) the costs associated with adhering to new environmental standards. This study focuses on the estimation of future water resources (point ii) and provides preliminary insights into future electricity demand (point iii). Hence, over the course of this study, we addressed the following research questions:

1. Climate change impacts on water resources are already broadly described by the scientific literature and in reports published by public entities (e.g., environmental agencies). While this broad-scale information is available to hydroelectricity companies, is it adequate to support their negotiations for concession renewal?

2. Future climate change impacts are uncertain and are typically communicated using an ensemble of simulations. How well do stakeholders incorporate this uncertainty into their decision-making process on adaption strategies?

3. Future reservoir profitability depends on a wide range of economic and environmental factors. How can projections focused on the availability of water resources be leveraged in the negotiation process of a concession, and what are their limitations?

This paper is organized as follows: TS1Sect. 2 introduces the electricity company, the hydropower installations considered for this project, and describes the indices and associated thresholds selected by the electricity managers. Section 3 describes the observational and modeled data as well as the modeling framework employed to carry out hydrological (water supply) and climatological (electricity demand) projections. Section 4 presents the projected changes in the indices chosen by the electricity managers. Section 5 discusses the implications of these changes for future hydropower operations and possible future extensions of this study. In Sect. 6, we summarize our results and draw conclusions regarding the use of stakeholder-centered approaches in climate change impact analyses.

2 Project scope and identification of vulnerabilities to climate change

2.1 Hydropower company and study catchments

For this study, we interacted with two Groupe E electricity managers and helped them to assess future climate

Please note the remarks at the end of the manuscript.

change impacts. Groupe E is headquartered in Granges-Paccot in the canton of Fribourg in Switzerland. Considering all of Groupe E's installations and purchases from the electricity market, the company distributes an average of TS2 2451 GWh yr^{-1} to nearly 400 000 inhabitants and companies. The company's electricity generation fleet consists of 6 dams and 10 power stations. The installations are mainly located either directly along the Sarine River or on one of its tributaries (also on the Doubs, Wysswasser and the Binna River). Groupe E produces TS3 1329 GWh of electricity yearly, which is approximately TS4 35 % of the electricity that they distribute. The remaining TS5 65 % is balanced by purchasing and trading on the electricity market.

This study focuses on the inflow into two of Groupe E's reservoirs: (i) the Vernex (Rossinière) dam – Montbovon power station and (ii) the Montsalvens dam – Broc power station (Fig. 1). The catchments of Montsalvens and Vernex dams have areas of 172.7 and 398.5 km^2, respectively (Table 1). The Vernex and Montsalvens installations are situated upstream of several other installations belonging to Groupe E, which turbinate water from the Sarine River along its lower reach. Given the placement of the Montsalvens and Vernex installations, their future functionality and security are crucial for Groupe E. We explored the future inflow into these two reservoirs in order to support adaptation to climate change and, in particular, the negotiation of a new water concession for the two installations, as discussed in Sect. 2.2. Groupe E is familiar with the ensembles and uncertainties associated with hydrological simulations, as they use ensembles of short-term hydrological forecasts for their daily operations. Groupe E was very transparent throughout this collaboration; however, Groupe E's future strategies are confidential and cannot be fully disclosed in this paper.

2.2 Negotiations of the water concessions

In Switzerland, the sovereignty of public waters is assigned to the cantonal or local/municipal authorities, which can grant the right to use water for electricity production to a hydropower company via a lease known as a concession (Mauch and Reynard, 2004). Most dams in Switzerland were built between 1945 and 1970, and water concessions were then typically granted for a maximum of 80 years. Therefore, many electricity managers are currently faced with challenges spurred on by the cessation of their water concessions (SWV, 2012). Lac du Vernex is a reservoir with concession agreements with the cantons of Vaud and Fribourg that are both due to end in 2052. Lac de Montsalvens is a reservoir located in the canton of Fribourg and has a concession agreement with the canton of Fribourg ending in the year 2076. Typically, the submission for renewal is due 15 years in advance (i.e., the submission for renewal is due in 2037 for Vernex and 2061 for Montsalvens). Given the liberalization of the Swiss electricity market, new competitors are entering previously closed markets. Therefore, some hydropower companies may consider the early renewal of their concessions (decades in advance) to ensure their production portfolio and to position themselves securely in the market. Projections of climate change on relevant streamflow indices offer electricity companies insight into their resource availability in the future, and they also help them gauge the flexibility of future operations.

During concession negotiations, the authorities granting the water rights and electricity managers will agree upon the duration of the contract and the terms of the water fee (i.e., the price to be paid by the electricity company to the owner of the water rights). The water fee is determined based on the gross capacity of the hydropower plant and elevation differential (head) as well as the amount of water that can be used for electricity production under particular hydrological conditions as defined in the concession (Betz et al., 2019). A key aspect in the negotiations of a water concession are new environmental regulations that hydropower companies must now comply with, such as new residual water flow requirements. Environmental impacts on the ecosystem were not a primary concern in the early stages of hydropower in Switzerland (Tonka, 2015). However, it is now well understood that hydropower systems impact the natural connectivity, temperature, and dynamics of rivers and, therefore, have substantial impacts on the downstream ecosystem (e.g., fish habitat). Swiss environmental regulations are listed within the Water Protection Act (Gewässerschutzgesetz), which sets the rules for residual water flow; it defines residual flow as the amount of water that must remain in a river after water withdrawals. Cantonal requirements are currently being strengthened to increase the amount of residual flow required to remain in streams, which reduces the amount of water for hydropower production (as discussed further in Sect. 5.1.2).

2.3 Vulnerabilities to climate change and the selection of indices and thresholds

Our discussions with Groupe E representatives enabled us to identify three main types of vulnerabilities: (i) water volume vulnerabilities (will seasonal changes in inflow distribution impact the reservoir profitability, given that electricity prices have historically been highest in winter as electricity demand is relatively higher during this season?), (ii) low-flow vulnerabilities (will low-flow situations become more frequent and make it more challenging to guarantee a residual discharge?), and (iii) high-flow vulnerabilities (will high-flow situations become more frequent and how may they be used for profit?). To address these vulnerabilities, streamflow indices were selected in collaboration with electricity managers. Corresponding thresholds were also chosen, whose exceedance would significantly impact Groupe E's production activities and profit. These hydrological indices and their relevance for hydropower operations are summarized in Table 2. While future changes in the mean monthly streamflow cycle have been well explored (Addor et al., 2014; Smi-

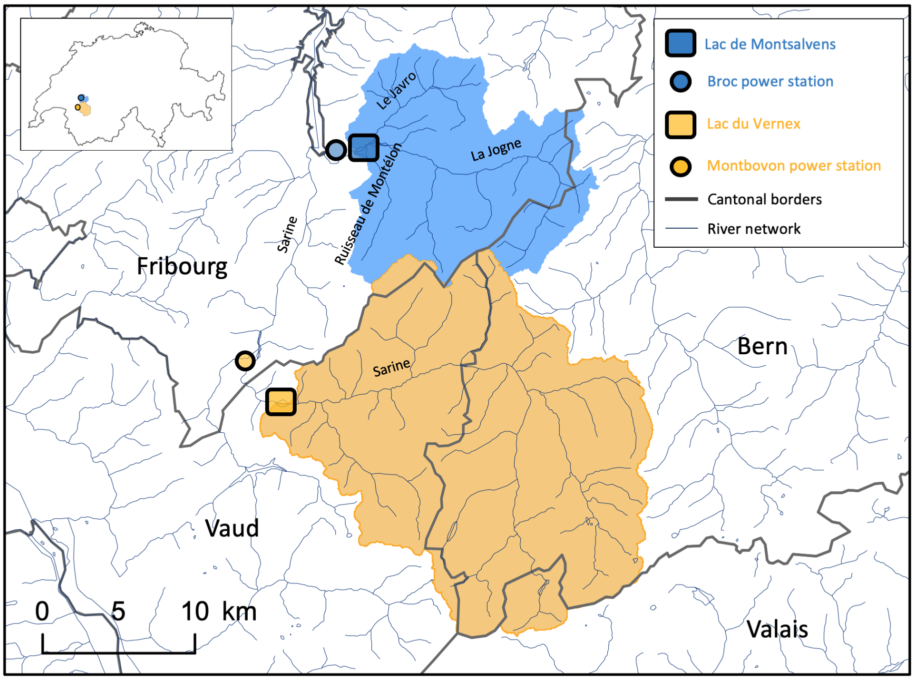


Figure 1. Map of the two study catchments: Montsalvens (blue) and Vernex (orange). The river network is shown in blue (dataset provided by the Swiss Federal Office for the Environment; FOEN); the cantons are labeled, and the dark gray lines depict the cantonal boundaries. The major river tributaries to the reservoirs are also labeled. The inset shows the location of the catchments within Switzerland.

Table 1. Main characteristics of the two study catchments, including catchment area, elevation, glacier coverage, karst percentage, forest cover, and energy production. Data for this table were derived from multiple sources: the area and mean elevation of the catchment were provided by Groupe E and were confirmed during delineation for modeling purposes, glacier coverage was estimated using satellite imagery from Google, karst hydrogeology was estimated using a dataset provided by Bitterli et al. (2004), and mean energy production was provided by the Swiss Federal Office of Energy (SFOE).

Reservoir, dam	Area (km^2)	Mean elevation (m)	Glacier coverage (%)	Karst hydrogeology (%)	Mean energy production ($MWh\,yr^{-1}$)
Montsalvens, Broc	172.7	1386	0	35	71 567
Vernex, Montbovon	398.5	1639	< 1	15	59 422

atek et al., 2012; Vicuna and Dracup, 2007; Zierl and Bugmann, 2005), studies focusing on changes in other streamflow characteristics, such as extremes (Köplin et al., 2014), are less common. Groupe E representatives stated that although changes in the long-term mean monthly cycle are crucial, additional hydrological indices are necessary to inform their concession negotiations and adaptation efforts.

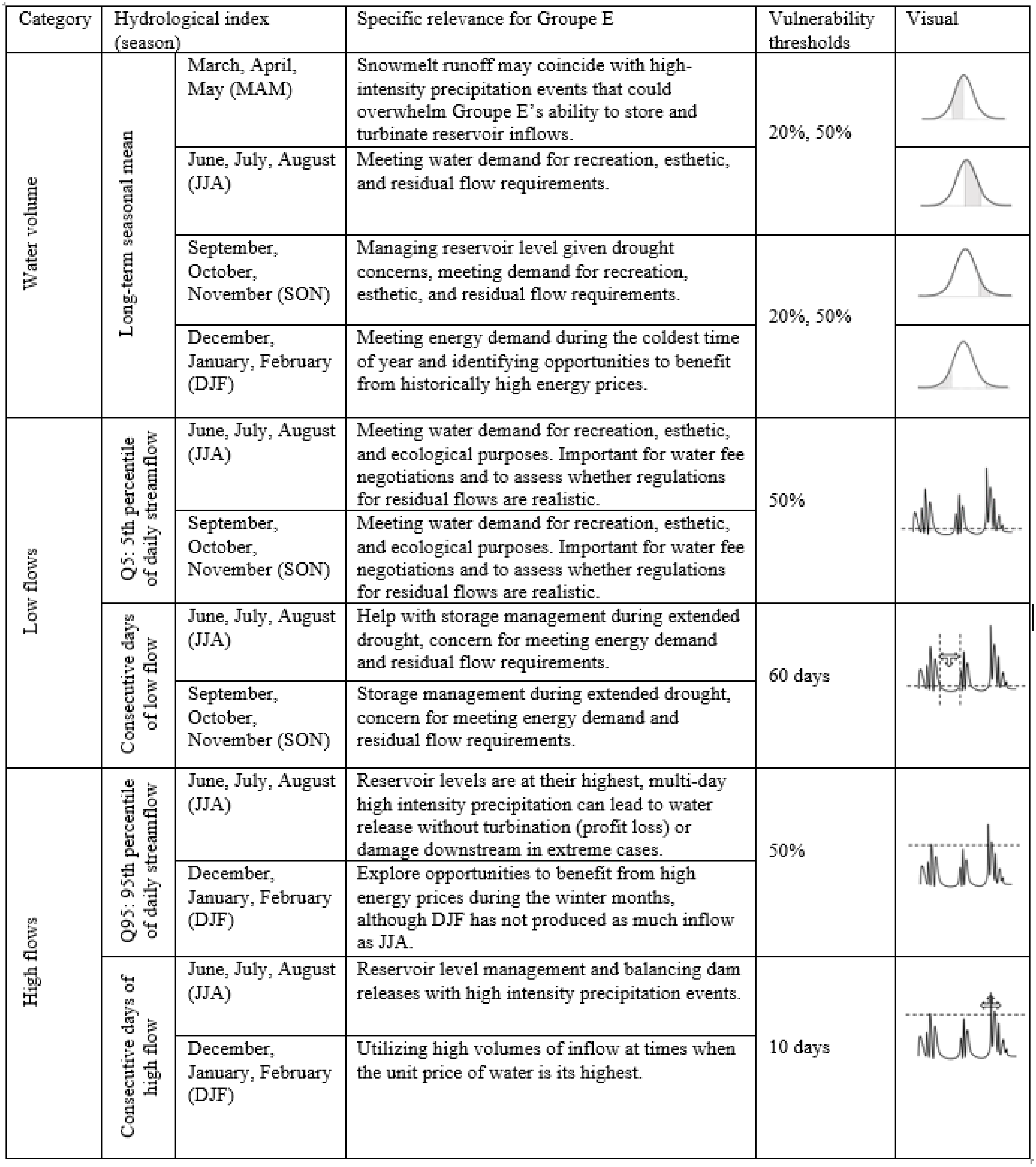
Aside from hydrological indices, Groupe E also requested an assessment of the rain versus snow contribution to runoff so that they can gain insight into their seasonal-scale operations. Historically, the Vernex and Montsalvens reservoirs reach their highest level in May after the spring runoff. The onset of the convective storm season is also around May/June. Thus, the coincidence of meltwater and high-intensity precipitation events can lead to excess storm flow entering the reservoirs; this excess water must be released without turbination, resulting in a profit loss and possible damage downstream. We used a hydrological model to characterize the respective contribution of rain and snowmelt to discharge (see Sect. 3.3.1).

Finally, two indices were chosen by Groupe E to gain insights into future electricity demand: cooling degree days (C_{DD}) and heating degree days (H_{DD}). They were computed following the method presented in Gaudard et al. (2013) and are solely based on air temperature as shown in Eqs. (1) and (2):

$$H_{\mathrm{DD}} = \max(\mathrm{Th} - \theta t,\, 0), \tag{1}$$

$$C_{\mathrm{DD}} = \max(\theta t - \mathrm{Tc}, 0) \tag{2}$$

Table 2. Hydrological indices selected after discussions with Groupe E representatives. The relevance of each index for Groupe E's operations is explained, and the vulnerability thresholds for each index are provided. Relative changes exceeding these thresholds would have a significant impact on Groupe E's operations. In cases where two thresholds are provided, the exceedance of the lower threshold represents a significant impact and the upper threshold represents a critical impact. Visual aids for each index are also provided in the far-right column.TS6



Category	Hydrological index (season)		Specific relevance for Groupe E	Vulnerability thresholds	Visual
Water volume	Long-term seasonal mean	March, April, May (MAM)	Snowmelt runoff may coincide with high-intensity precipitation events that could overwhelm Groupe E's ability to store and turbinate reservoir inflows.	20%, 50%	
		June, July, August (JJA)	Meeting water demand for recreation, esthetic, and residual flow requirements.		
		September, October, November (SON)	Managing reservoir level given drought concerns, meeting demand for recreation, esthetic, and residual flow requirements.	20%, 50%	
		December, January, February (DJF)	Meeting energy demand during the coldest time of year and identifying opportunities to benefit from historically high energy prices.		
Low flows	Q5: 5th percentile of daily streamflow	June, July, August (JJA)	Meeting water demand for recreation, esthetic, and ecological purposes. Important for water fee negotiations and to assess whether regulations for residual flows are realistic.	50%	
		September, October, November (SON)	Meeting water demand for recreation, esthetic, and ecological purposes. Important for water fee negotiations and to assess whether regulations for residual flows are realistic.		
	Consecutive days of low flow	June, July, August (JJA)	Help with storage management during extended drought, concern for meeting energy demand and residual flow requirements.	60 days	
		September, October, November (SON)	Storage management during extended drought, concern for meeting energy demand and residual flow requirements.		
High flows	Q95: 95th percentile of daily streamflow	June, July, August (JJA)	Reservoir levels are at their highest, multi-day high intensity precipitation can lead to water release without turbination (profit loss) or damage downstream in extreme cases.	50%	
		December, January, February (DJF)	Explore opportunities to benefit from high energy prices during the winter months, although DJF has not produced as much inflow as JJA.		
	Consecutive days of high flow	June, July, August (JJA)	Reservoir level management and balancing dam releases with high intensity precipitation events.	10 days	
		December, January, February (DJF)	Utilizing high volumes of inflow at times when the unit price of water is its highest.		

Here, θt is the air temperature retrieved from climate projections (Sects. 3.2.2 and 3.2.3). The thresholds Th = 13 °C and Tc = 18.3 °C were provided by Groupe E and correspond to the threshold values used in Gaudard et al. (2013). They represent the air temperatures that, when reached, cause consumers to turn on either cooling or heating in their homes. C_{DD} and H_{DD} were calculated for the cities (canton boundaries) of Zürich and Geneva, given that these areas are comprised of typical Groupe E electricity consumers. Results for Geneva are shown below, and results for Zürich can be found in Fig. S8 in the Supplement.

3 Data and methods for impact modeling

3.1 Modeling framework

To assess future changes in the streamflow and electricity demand indices introduced above, we relied on the following model chain. We combined 2 greenhouse gas emission scenarios (see Sect. 3.2.1), 11 regional climate models forced by general circulation models (GCM-RCMs; see Sect. 3.2.2), 2 GCM-RCM post-processing methods (see Sect. 3.2.4), and 1 hydrological model to simulate inflow entering the two reservoirs (Fig. 1). The hydrological model was calibrated using 3 objective functions, and 10 optimized parameter sets were generated per objective function and per calibration period (see Sect. 3.3.3). This modeling framework follows the procedure outlined in Hakala et al. (2020). It enabled us to assess uncertainties in the projected discharge and to provide Groupe E with a projected likely range for each index under future climate. The following subsections describe the steps of our modeling chain in greater detail.

3.2 Climate data and preparation

3.2.1 Emission scenarios

Representative concentration pathways (RCPs) are scenarios describing possible futures for the evolution of Earth's atmospheric composition and, as such, provide boundary conditions for climate models. RCP4.5 and RCP8.5 were selected for this study. RCP4.5 corresponds to an intermediate emission trajectory, where greenhouse gas (GHG) emissions peak around 2040 and then generally stabilize. In contrast, RCP8.5 assumes that GHG emissions will continue to increase throughout the 21st century (Meinshausen et al., 2011).

3.2.2 Observational and GCM-RCM data

Observational meteorological data were retrieved from the 2 km MeteoSwiss TabsD (Frei, 2014) and RhiresD (Frei and Schär, 1998; Schwarb, 2000) gridded datasets. The daily reservoir inflow was estimated by Groupe E for the period from 2008 to 2018 by solving the water balance based on variations of the reservoir level, the volume of water turbinated for hydropower production, and estimated losses due to evaporation from the reservoir (reservoir losses to the groundwater were neglected). GCM-RCM temperature and precipitation data were retrieved from the Coordinated Regional Downscaling Experiment for Europe (EURO-CORDEX; http://www.euro-cordex.net/, see Table 3). GCM-RCM model selection followed the methodology described in Hakala et al. (2018), which entails selecting models based on their hydrological performance over the historical period. Furthermore, we excluded models generating snow towers because of the influence that cooler temperatures associated with the snow towers may have on the climate change signal (Frei et al., 2018; Hakala et al., 2018; Zubler et al., 2016). EURO-CORDEX provides simulations at both 0.44° and 0.11° resolutions, but only 0.11° data were used given the size of the catchments investigated in this study. Overall, the exclusion of some GCM-RCMs due to their poor hydrological performance resulted in a tailored modeling setup that prioritized end-user decision-making.

3.2.3 Data extraction

To extract temperature and precipitation from the gridded datasets, an area-weighted method, as shown in Hakala et al. (2018), was used. As a first step, the grid cells of the meteorological data were overlaid with the shapefile of a given catchment. Once the data from the overlapping grid cells were extracted, a weight factor was applied to each grid-cell time series based on the percentage of the catchment area overlapped by the grid cell, resulting in a single catchment-mean time series. This area-weighted methodology was used to extract temperature and precipitation data from both the EURO-CORDEX and MeteoSwiss datasets. In the case of the EURO-CORDEX dataset (horizontal grid spacing of $\sim$ 12.5 km), nine grid cells at least partially overlapped with the Vernex catchment and four grid cells overlapped with the Montsalvens catchment.

3.2.4 Bias correction

The GCM-RCM simulated temperature (T) and precipitation (P) time series were bias corrected using a non-parametric quantile transformation of seasonal distributions. The cumulative distribution functions (CDFs) were determined individually for the different seasons – December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON) – for both the observed (MeteoSwiss) and simulated (EURO-CORDEX) T and P time series. For GCM-RCMs with a non-leap-year calendar (Table 3), T and P were converted to a Gregorian calendar prior to bias correction. For GCM-RCMs with a 360 d calendar, observational data were converted to a 360 d calendar before bias correction, and the hydrological model was run using this calendar. The "qmap" package in R (Gudmunds-

Table 3. Overview of the 11 EURO-CORDEX GCM-RCM combinations used in this study. Some models were removed from the ensemble due to either snow tower issues or irregularities in the discharge simulations. The models that were removed are denoted using italic font.

No.	GCM	RCM	Calendar	Notes
1	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	Gregorian	
2	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	Gregorian	
3	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	360	
4	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	Gregorian	
	ICHEC-EC-EARTH	*DMI-HIRHAM5*	*Gregorian*	*R-ST*
	NCC-NorESM1-M	*DMI-HIRHAM5*	*Gregorian*	*R-ST*
	IPSL-IPSL-CM5A-MR	*IPSL-INERIS-WRF331F*	*Gregorian*	*R-D*
	ICHEC-EC-EARTH	*KNMI-RACMO22E*	*Gregorian*	*R-ST*
	ICHEC-EC-EARTH	*KNMI-RACMO22E*	*360*	*R-ST*
5	MOHC-HadGEM2-ES	KNMI-RACMO22E	Gregorian	
6	MPI-M-MPI-ESM-LR	MPI-CSC-REMO2009	Gregorian	
7	CNRM-CERFACS-CNRM-CM5	SMHI-RCA4	Gregorian	
8	ICHEC-EC-EARTH	SMHI-RCA4	Gregorian	
9	IPSL-IPSL-CM5A-MR	SMHI-RCA4	Non-leap year	C
10	MOHC-HadGEM2-ES	SMHI-RCA4	360	
11	MPI-M-MPI-ESM-LR	SMHI-RCA4	Gregorian	

(R-ST) refers to models removed due to snow towers in the GCM-RCM model output.
(R-D) refers to models removed due to irregularities in the mean monthly distribution of discharge when simulations were forced with this GCM-RCM.
(C) denotes that the calendar was converted from non-leap year to proleptic Gregorian.

son, 2016; Gudmundsson et al., 2012) was used to match the CDF of the simulated data to that of the observed data. Specifically, a transfer function was generated to match each raw GCM-RCM P and T percentile to the associated P and T percentile of the MeteoSwiss data. The biases in the raw GCM-RCM simulations were assumed to be stationary over time; thus, the same transfer functions were used to correct the projections of T and P.

3.3 Hydrological data and model

3.3.1 Hydrological model

The bucket-type Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Bergström, 1976; Lindström et al., 1997) was used to simulate streamflow entering the two reservoirs. For this project, we used the HBV-Light version (Seibert and Vis, 2012). HBV is a semi-distributed model that uses four routines (snow, soil, response, and routing routines) and relies on elevation bands to account for changes in T and P with elevation within a catchment. HBV requires temperature, precipitation, and potential evaporation time series as input. For a more detailed description of the separate routines, we refer the reader to Seibert and Vis (2012). For the remainder of the paper, we use the term HBV when referring to the HBV-Light version.

3.3.2 Adjustment of discharge data

When initially analyzing the discharge data provided by Groupe E in combination with MeteoSwiss observational meteorological data, we noticed that precipitation was too small to explain the discharge flowing into the Montsalvens reservoir. Based on water balance calculations informed by karst hydrogeological information (Bitterli et al., 2004) and actual evaporation estimates (Menzel et al., 1999), it was assumed that karst was responsible for the larger than expected discharge. The Montsalvens and Vernex catchments are located in a transitional region between the Alps and the Swiss Plateau. As pointed out by Fan, (2019), a catchment is more likely to be an open or "leaky" system when positioned at either the high or low end of a steep regional topographic and climate gradient, which is the case here. Therefore, a correction factor was applied to the observed discharge to rescale it to match the expected mean discharge. The factor was calculated following the water balance equation $P = E + (f \cdot Q) + \Delta S$ for the period from 2008 to 2018, where P represents precipitation falling within the catchment; E stands for actual evaporation; Q represents the inflow reported to enter the Montsalvens reservoir; and ΔS stands for change in storage, which was considered negligible in this case. By applying the factor f (0.79) to the discharge time series, we were able to close the water balance equation. Therefore, this method assumes that 21 % of the total inflow entering the Montsalvens reservoir is groundwater entering through the karst system. Karst hydrogeology did not appear to have a discernible effect on discharge for the Vernex catchment.

3.3.3 Calibration and validation

Calibration and validation of HBV were based on three different objective functions, namely the Lindström measure (Lindström et al., 1997), the Nash–Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), and the Kling–Gupta efficiency (Gupta et al., 2009). Two separate periods were used for calibration and validation: 1 October 2008 to 30 September 2013 and 1 October 2013 to 31 August 2018. For each combination of objective function and time period, 10 independent parameter sets were generated. HBV was calibrated using a genetic algorithm and Powell optimization (Seibert, 2000) method (10 000 model runs for the genetic algorithm and an additional 1000 runs for the Powell optimization). Using multiple objective functions and calibration periods enabled us to account for parameter uncertainty and to generate an ensemble of equally likely realities (Brigode et al., 2013; Coron et al., 2012; Klemeš, 1986). Both catchments achieved reasonable calibration and validation scores (an NSE of 0.75 or higher for all objective functions and periods). Therefore, all parameter sets were carried forward in the modeling chain.

3.4 Evaluation of the modeling chain over the reference period

Prior to creating projections, we analyzed our modeling chain performance over a reference period. Figure 2 provides a comparison between $(\text{variable})_{\text{obs}}$ and $(\text{variable})_{\text{ref}}$ for each hydrological index and climate change impact index. The ref subscript indicates that the index was computed using HBV simulations driven by observed atmospheric forcing. In the case of the hydrological indices, Q_{obs} and Q_{ref} stem from different time periods, as Group E records only cover the period from 2008 to 2018. Given this mismatch in time periods, we began by comparing the monthly precipitation of the Q_{obs} and Q_{ref} time periods (Supplement Fig. S1). The period from 1980 to 2009 (Q_{ref} period) experienced a wetter climate than the period from 2008 to 2018 (Q_{obs} period).

Figure 2 shows that hydrological simulations driven by raw climate simulations present severe biases. For instance, the mean monthly inflow is vastly overestimated by raw data from April through December (Fig. 2a). Bias correction leads to a significant reduction in these biases, and it was necessary to capture the indices required by Group E (Fig. 2a–h). Figure 2g shows that the application of bias correction is successful at reducing the ensemble spread of $H_{\text{DD raw}}$ (yellow shaded area), resulting in $H_{\text{DD qm}}$ (purple shaded area). $H_{\text{DD qm}}$ can be seen to fit well with $H_{\text{DD ref}}$ for the entirety of the annual cycle. Figure 2h also shows a reduction in the $C_{\text{DD raw}}$ ensemble spread (yellow shaded area) due to the application of quantile mapping ($C_{\text{DD qm}}$; purple shaded area), with August retaining a relatively high level of uncertainty. As concession negotiations require more finely tuned projections than what can be delivered by raw simulations, we excluded simulations generated using raw GCM-RCM data from the results section so that the focus can be on future changes and not on the effects of the bias correction. Figures displaying hydrological variables utilize two y axes where specific discharge ($\text{mm}\,\text{d}^{-1}$) is shown on the left-hand axis, and discharge ($\text{m}^3\,\text{d}^{-1}$) is displayed on the right-hand axis. The former allows for a comparison between catchments, whereas the latter is more useful for electricity managers when operations are primarily looked at in terms of volumes.

Overall, when using bias-corrected climate simulations, HBV satisfactorily captures the annual discharge cycle (Fig. 2a), the respective contribution of snow and rain to streamflow (Fig. 2b), and Q5 and Q95 during the seasons of interest (Fig. 2c, d). In contrast, HBV tends to overestimate both the duration of periods below Q5 and above Q95 (Fig. 2e, f). It is, however, important to note that HBV was not specifically calibrated against the hydrological indices mentioned in Table 1; thus, it is not surprising if Q_{obs} and Q_{ref} deviate when compared across these indices. TS7 Pool et al. (2017) showed that HBV tends to underestimate streamflow characteristics related to mean and high-flow conditions and generally overestimates low-flow conditions. For this study, it is the relative change that is most important. A comparison of the Q_{obs} and Q_{ref} inflow time series (Fig. S2), plotted over their shared period (2008–2010), shows that HBV generally underestimates low flows, which is consistent with the results shown in Pool et al. (2017).

3.5 Projections of climate change impacts

As the performance of the modeling chain was considered to be satisfactory over the reference period, all parameter sets generated in Sect. 3.3.3 were used to simulate projections for the periods from 2020 to 2049, from 2045 to 2074, and from 2070 to 2099. Our modeling chain was comprised of 2 emission scenarios (RCP4.5 and RCP8.5), 11 EURO-CORDEX GCM-RCMs, 2 post-processing methods (raw and quantile mapping), 1 hydrological model (HBV), 3 objective functions for the hydrological model (Lindström measure, Nash–Sutcliffe efficiency, and Kling–Gupta efficiency), and 10 optimized parameter sets per objective function and 2 calibration periods. This led to a total of 1320 bias-corrected simulations for each future period and basin. Below, we focus on the comparison between 1980–2009 and 2070–2099 under RCP8.5 and on the Vernex catchment. The results and figures for all periods, RCP4.5, and both catchments were provided to Groupe E, and the end-of-century results for Montsalvens can be found in the Supplement. The projected streamflow indices were not compared to observed discharge data, because such a comparison could be misleading due to the mismatch in time periods and the inclusion of hydrological model uncertainty. Instead, the projections were compared to simulations for the reference period based on bias-corrected GCM-RCM simulations.

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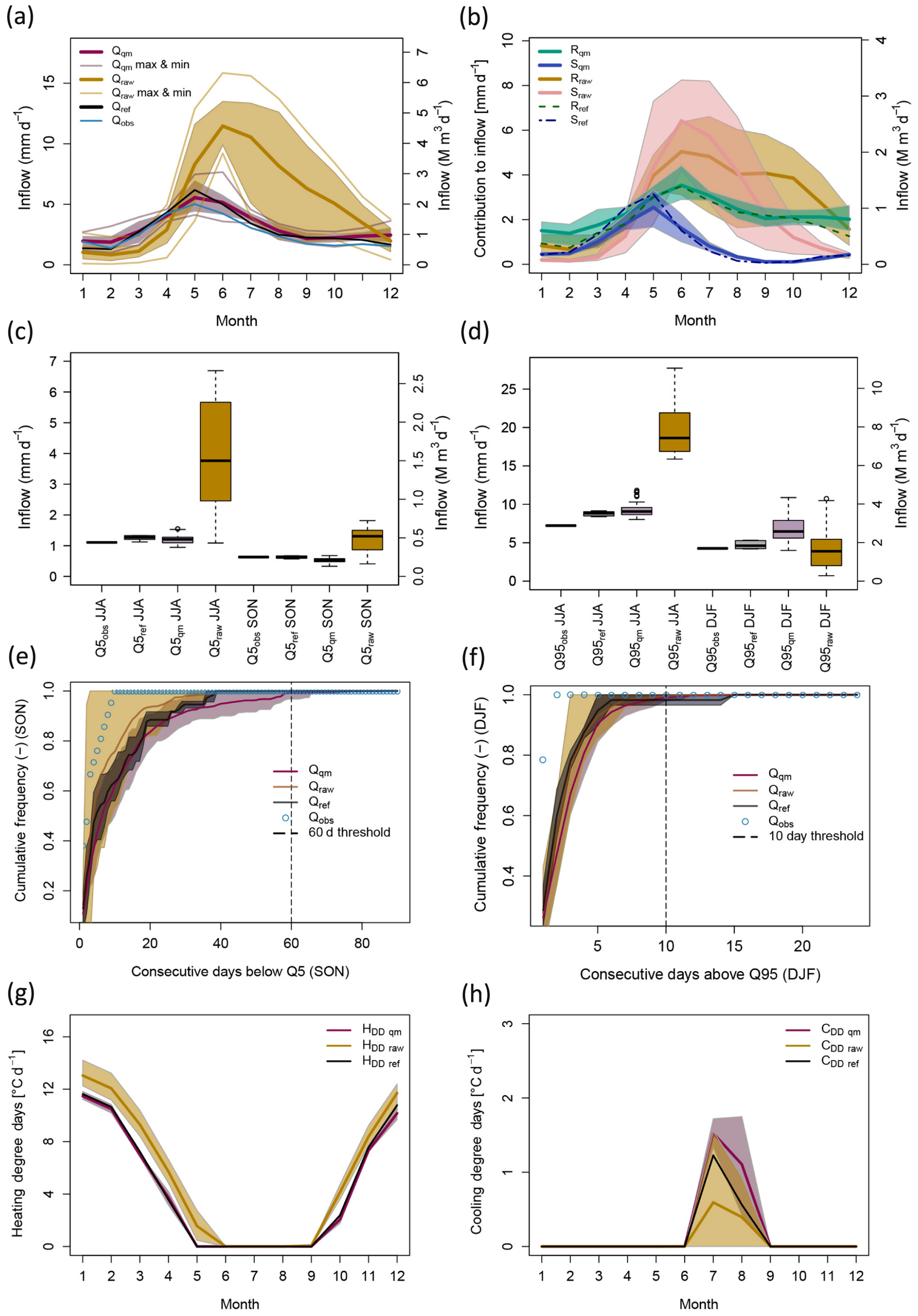

Figure 2. The performance of the calibration of HBV and the bias correction treatment are shown for each index for the Vernex catchment **(a–f)** and the canton of Geneva **(g, h)**. When observational data were not available, only the bias correction performance is shown **(g, h)**. All simulated data cover the period from 1 January 1980 to 31 December 2009, except for Q_{obs} data which span the period from 1 October 2008 to 31 August 2018. Panels **(a)**, **(b)**, **(g)**, and **(h)** depict long-term monthly means.

4 Results

This section presents the changes in streamflow and electricity demand indices projected by our modeling chain. The implications of these changes for future reservoir operations and profitability are discussed in Sect. 5.

4.1 Projected changes in water volume

Figure 3a compares the historical (1980–2009) and future (2070–2099) annual distribution of inflow entering the Vernex reservoir for RCP8.5. Changes in winter (DJF) discharge are shown to widely exceed the +20 % and +50 % thresholds specified by Groupe E. Meanwhile, the summer (JJA) discharge decrease is expected to be around the −50 % threshold (ensemble mean). Groupe E asked for the long-term mean monthly discharge cycle to be visualized by showing the volume difference between future (2070–2099) and historical (1980–2009) conditions. Figure 3b was requested so that the total amount of water gained/lost can be directly considered during concession negotiations. Under RCP8.5, the Vernex reservoir should experience more inflow between December and March but less inflow from May to October. By the end of the century, the expected average change in inflow for the Vernex reservoir is $-1.11\,\mathrm{M\,m^3\,d^{-1}}$ (likely range from −4.52 to +2.54) under RCP8.5 and $-0.24\,\mathrm{M\,m^3\,d^{-1}}$ (likely range from −2.97 to +2.35) under RCP4.5. Similarly, the inflow entering the Montsalvens reservoir is expected to experience an average decrease of $-0.72\,\mathrm{M\,m^3\,d^{-1}}$ (likely range from −2.19 to +0.81) under RCP8.5 and $-0.18\,\mathrm{M\,m^3\,d^{-1}}$ (likely range from −1.61 to +1.08) under RCP4.5.

The shift in the annual distribution of inflow entering the reservoirs is primarily caused by changes in the form of precipitation contributing to inflow (Fig. 4). The peak annual contribution to inflow from snowpack is expected to decrease by more than half and to occur earlier in the year, shifting from May to April. Spring runoff derived from snowpack will likely be a less reliable source of inflow in the future. Meanwhile, rain is shown to decrease its respective contribution to inflow over the summer. The shift in spring runoff and the reduction in the rainfall contribution to inflow results in a reduction in inflow entering the reservoirs (Figs. 3b, S4). Over the 21st century, winters are expected to see an increasing rain contribution to inflow and a reduced contribution from both rain and snow from May until November. The Montsalvens catchment is expected to experience a similar regime change in the future, with an even more pronounced reduction in snowfall contribution (Fig. S5).

4.2 Projected changes in low flows

Q_qm simulations of low flows (Q5) for JJA and SON strongly decrease under RCP8.5, with the majority of the ensemble indicating a decrease greater than the −50 % threshold (Fig. 5a). The spread of the ensemble for both seasons is relatively small in absolute terms. Projections for the inflow entering the Montsalvens reservoir indicate similar changes, with Q5 dropping below the −50 % threshold for JJA and the median of the SON ensemble lying close to the −50 % threshold (Fig. S6).

The frequency of consecutive days below Q5 is expected to increase under the influence of climate change in SON. Figure 6a demonstrates this concept by showing the cumulative distribution functions (CDFs) of the consecutive days below Q5 for the Vernex catchment over the SON season. The robust nature of the change compared with historical simulations demonstrates that there is high confidence that there will be more days below Q5 over the SON season in the future, although it should be noted that Q_qm data initially overestimated the CDFs of consecutive days below Q5 (Fig. 2e). The results for the Montsalvens reservoir agree with the changes shown for the Vernex reservoir, with a slightly less pronounced difference between the historical and future periods. For the Montsalvens catchment, there are relatively fewer extended periods of low flow (Fig. S7).

4.3 Projected changes in high flows

The magnitude of high flows (Q95) is expected to decrease in JJA under RCP8.5 (Fig. 5b). However, the median and the majority of ensemble members are within the 50 % threshold interval. In contrast, for winter, Q_qm simulations show a significant increase, far exceeding the +50 % threshold. Inflows entering the Montsalvens reservoir exhibit similar behavior over both seasons (Fig. S6).

More extended periods of consecutive days above Q95 are projected in DJF under the influence of climate change. The CDFs of the future simulations show a significant increase in the length of consecutive high-flow periods, including periods longer than the stipulated 10 d threshold. Results for Montsalvens indicate similar but less pronounced changes (Fig. S7).

4.4 Projected changes in temperature-based indices

Figure 7a shows that the number of H_DD is expected to decrease over the winter months under the influence of climate change, whereas the summer months experience no change as this time of year is already too hot to invoke heating within a household. Figure 7b shows that C_DD will likely increase for the months between May and October. The winter months show no change as these months are too cold to invoke cooling within the household of a typical electricity customer. Projections for the canton of Zürich show a general agreement with the magnitude and distribution of change (Fig. S8).

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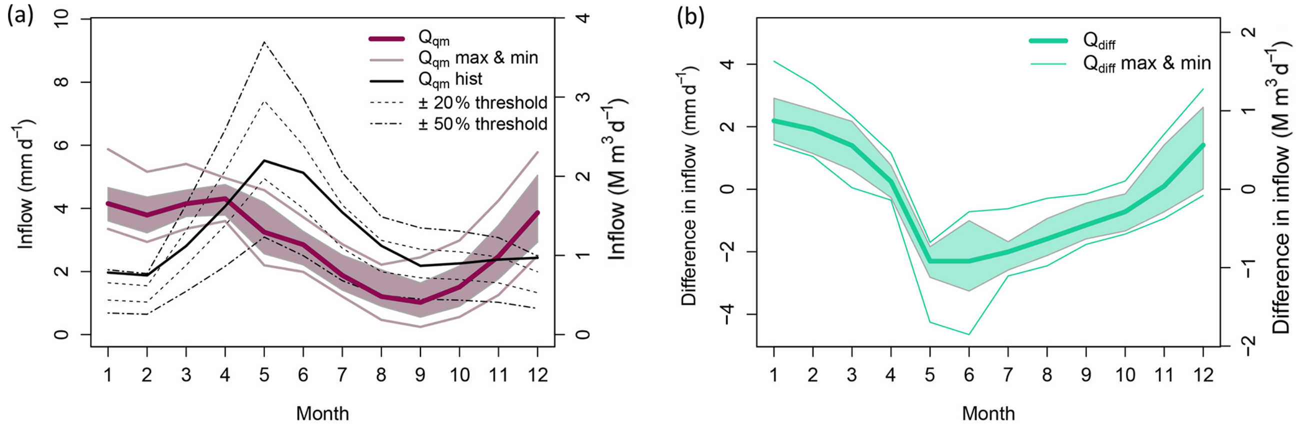


Figure 3. (a) Long-term mean monthly inflow entering the Vernex reservoir for 1980–2009 (Q_{qm} hist) and for 2070–2099 (Q_{qm}, RCP8.5). The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two-thirds of the 660TS8 simulations. The two thresholds are based on the mean of the simulations forced by observed climate data (Q_{ref} over the period from 1980 to 2009). **(b)** Long-term mean monthly change in inflow (2070–2099 with respect to 1980–2009) for the Vernex catchment.

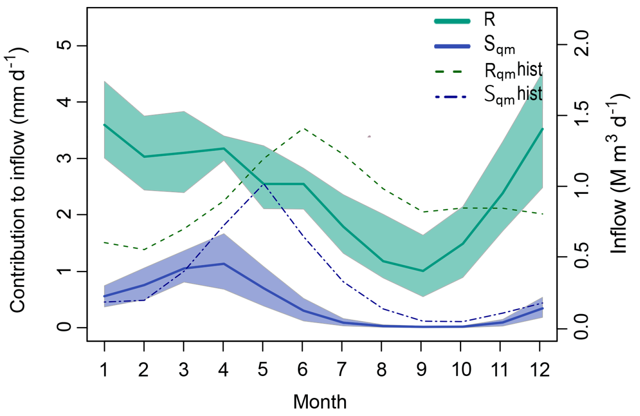


Figure 4. Mean monthly contribution of rain (R, green) versus snow (S, blue) to inflow entering the Vernex reservoir. Two periods are compared: 1980–2009 (R_{qm} and S_{qm} hist) and 2070–2099 (R_{qm} and S_{qm}). All projections shown are simulations under RCP8.5. The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two-thirds of the 660 simulations. The dashed lines indicate the mean of the reference simulations.

5 Discussion

5.1 Implications of the projected changes for hydropower operations

The projected changes in streamflow are summarized in Fig. 8 along with the critical thresholds selected by Groupe E. Here, we discuss the implications of these changes for hydropower operations and how they can be used as leverage during the negotiation of the water concession.

5.1.1 Water volume

Some changes in the seasonal inflow distribution represent new opportunities. Over the winter period, the inflow into Lac du Vernex is expected to increase by 90 % under RCP8.5 (Fig. 8a, b) and by 63 % under RCP4.5 (ensemble mean). Inflow into Lac de Montsalvens is expected to increase by 89 % under RCP8.5 and by 61 % under RCP4.5 (ensemble mean). Hydropower has the potential to remain an important source of electricity in the winter given the low yield of photovoltaics during the short winter days and the unpredictability and contentious politics of wind power (Kienast et al., 2017). Therefore, these changes could allow Groupe E to capitalize on generally higher electricity prices in winter (assuming that electricity prices remain higher in winter than in summer), resulting in a potential increase in profits for this season.

In contrast, regime changes in the summer and fall are expected to lead to new challenges for Groupe E. Over the summer period, Lac du Vernex is expected to experience an average decrease of −51 % under RCP8.5 (Fig. 8a, b) and −30 % under RCP4.5 (ensemble mean); Lac de Montsalvens is likely to experience an average decrease of −49 % under RCP8.5 and −28 % under RCP4.5. The reduction in summer inflow can be linked to the snowpack shrinkage over the coming century and the simultaneous reduction in total precipitation over the summer months (Fig. 4). Köplin et al. (2014) showed that when snow accumulation is important to a catchment hydrological regime during the historical period, the anticipated changes in seasonality are most pronounced. Groupe E stated that the Vernex and Montsalvens reservoirs are too small to store water over the winter period in order to offset droughts in the summer period. Adjusting the size of their reservoirs is currently not a viable option; therefore, it was not explored by our modeling experiments.

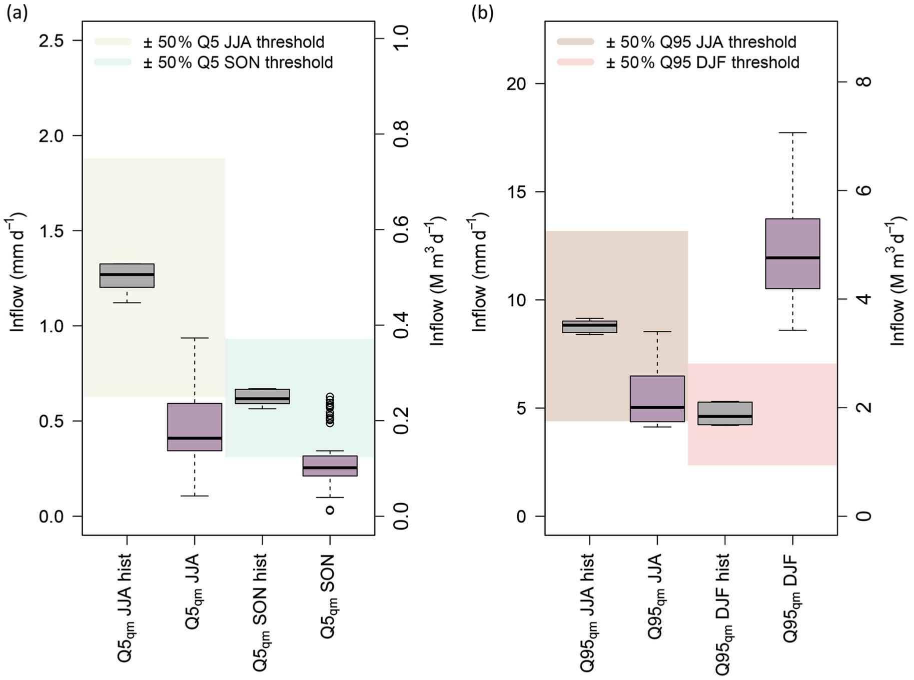


Figure 5. (a) Boxplots showing low-flow (Q5) and **(b)** high-flow (Q95) indices, where the historical period (gray boxplots; 1980–2009) is compared to the future period (purple boxes; 2070–2099) for inflows entering the Vernex reservoir. All projections shown are for RCP8.5. For each index, an associated ±50 % threshold is designated by the shaded area. These thresholds are based on the mean of simulations when forced by observed climate data (Q_{ref}) over the period from 1980 to 2009.

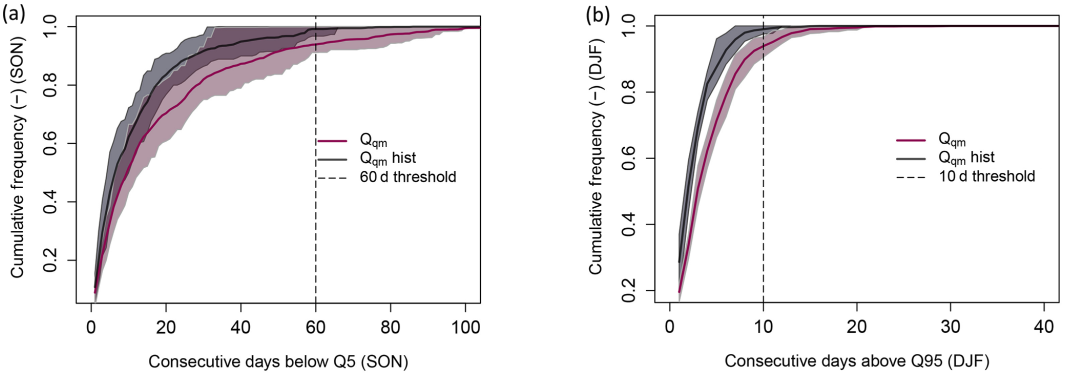


Figure 6. Cumulative distribution functions (CDFs) are shown, where the historical period (1980–2009; gray) is compared to the future period (2070–2099; purple) for the Vernex catchment. **(a)** CDFs for consecutive days below Q5 are shown for the SON season, and a 60 d threshold is indicated by the black dashed line. **(b)** CDFs of the consecutive days above Q95 are shown for the season of DJF, and a 10 d threshold is shown by the black dashed line. Instances where the simulations exceed their associated threshold represent a level of change that is of interest to Groupe E. The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two-thirds of the 660 TS9 simulations.

Given a decrease in inflow over the summer and a possible increase in electricity demand for cooling (Fig. 7b), an investment in other energy sources may be considered, such as photovoltaics which have their peak production during the longer summer days. In addition to other market conditions and legal requirements, hydropower energy providers may use these projections of changes in water volume to negotiate a lower cost for their water fee, as the fee is partially determined based on the amount of water that can be used for electricity production. An impact comparison of the different water fee systems on Swiss hydropower was performed by Gaudard et al. (2018a). Within their study, they compared different water fee frameworks including a (i) no-fee system, (ii) a fixed-fee system, (iii) a semiflexible or fixed and variable fee system, and a (iv) profit-based imposition system. The current water fee framework follows a fixed-fee system.

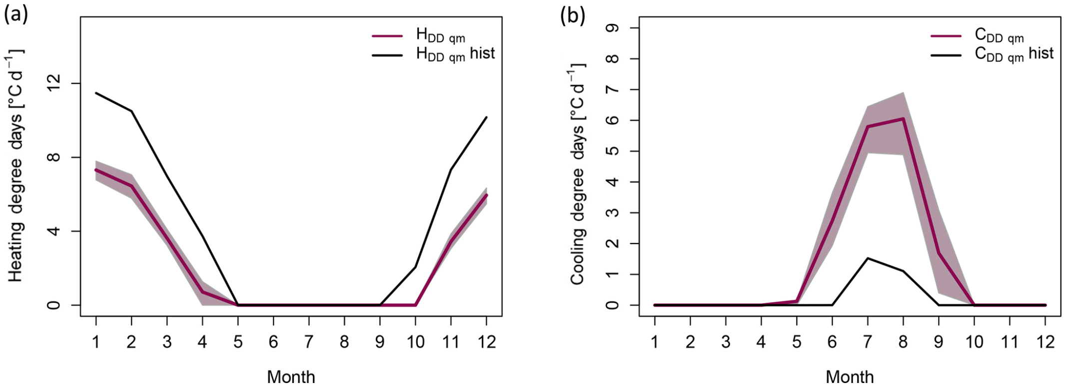


Figure 7. Mean monthly **(a)** H_{DD} and **(b)** C_{DD} for the canton of Geneva. The mean of the historical simulations (1980–2009; gray) are compared to the future simulations under the influence of RCP8.5 climate change scenario (2070–2099; purple). The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two-thirds of the 660TS10 simulations. Groupe E prescribed thresholds of 13 and 18.3 °C to compute H_{DD} and C_{DD}, respectively.

The authors discuss that the water fee tends to flatten the differences between the lowest and highest financial years under a fixed system. The hydropower sector is vulnerable in such a system, which provides no flexibility and instead imposes a fee based on theoretical power. In contrast, a profit-based system is shown to increase the financial robustness of the hydropower sector. The water fee framework is subject to re-review in 2024 (Betz et al., 2019).

5.1.2 Low flows

Low flows will require special attention in the coming decades, as the magnitude of Q5 is likely to reduce drastically, with the majority of ensemble members predicting a change exceeding the −50 % threshold in JJA and SON (Fig. 8c, d). In addition, periods of low flow are expected to increasingly extend beyond Groupe E's 60 d threshold in JJA and SON (Fig. 8c, d). These changes are likely to influence the negotiated terms of the water fee. The decrease in production over a long period of time has a significant effect on the flexibility of production. Flexibility is a significant component of a storage hydropower plant's profitability, as it enables hydropower operators to turbinate when electricity prices are optimal.

Cantonal requirements are currently being strengthened to reduce environmental impacts. One of the cantonal measures includes increasing the amount of residual flow for environmental reasons (e.g., flora, fauna, and sediment transport are affected by very low flows). This study shows that the water carried by low flows is expected to substantially decrease over the coming decades, and the duration of low-flow conditions will likely increase. Hence, minimum flow requirements are likely to be a delicate topic during concession negotiations, as Groupe E may request that residual flow requirements do not increase, which is likely to be challenged by stakeholders that are primarily concerned with environmental issues.

5.1.3 High flows

Opportunities are present over the winter period, as the average high inflows to the Vernex and Montsalvens reservoirs are projected to increase by more than 50 % (Fig. 8d) and exceed the 10 d threshold (Fig. 6b). An increase in high flows entering the reservoirs during the winter period, when electricity prices are highest, would allow Groupe E to better satisfy demand using their own production, rather than supplementing their supply by trading/purchasing on the electricity market. The hydrological shift from slow, snow-dominated processes to more variable, rainfall-driven processes will require a flexible operating framework so that these quick inflows can lead to increased profit, rather than spillover. Storage power plants are already being utilized to their full extent during peak price hours, so additional inflows in winter and early spring will be utilized in hours of lower prices (Savelsberg et al., 2018). To generate more revenue, the extra inflow would have to be captured and turbinated at optimal times or at prearranged prices. Groupe E could consider investing in their existing short-term forecasting and trading unit in order to improve their forecasts of high-flow events. As Groupe E can decide when to sell its electricity (anytime between the next hour to the next 3 years), a balance between best price and risk management needs to be found. Conversely, projections show a decrease in high flows in the summer (Fig. 8c), which indicates a reduced risk of water loss due to spillover events.

5.1.4 Electricity demand

To adapt to climate change, hydroelectricity companies cannot base their strategies on water availability alone, they also need to estimate future electricity demand (Gaudard et al.,

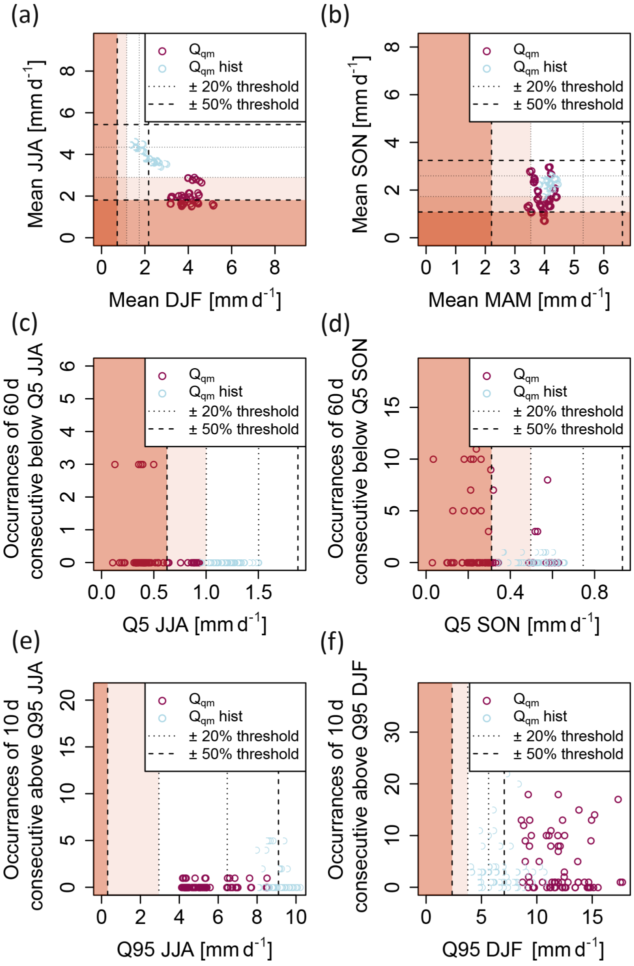


Figure 8. Situations leading to the greatest stress on Groupe E's operations are depicted by the comparisons of low-flow, high-flow, and seasonal-flow indices for the Vernex catchment. Two time periods are compared in the left and right columns: **(a–c)** 1980–2009 and **(d–f)** 2070–2099. Panels **(d–f)** show simulations under the influence of RCP8.5. Panels **(a)** and **(b)** depict seasonal flows: mean winter flow (DJF) versus mean summer flow (JJA). Panels **(c)** and **(d)** depict low flows: Q5 summer flows (JJA) versus the occurrence of consecutive days below Q5. Panels **(e)** and **(f)** depict high flows: Q95 winter flows (DJF) versus the occurrence of consecutive days above Q95. For all plots, two thresholds, which were provided by Groupe E, are included: ±20 % and ±50 %. Shading from white to progressively darker red tones indicates the lowest (white) to highest (dark red) levels of stress placed on Groupe E's operations based on the relationship between the indices.

2013; Savelsberg et al., 2018). This motivated the selection of the electricity demand indices for this study. Although a temperature-based electricity demand approach is inherently limited, it is a sensible way to initiate the discussion on future changes in climate, the electricity market, and electricity consumption behaviors. Our analysis using temperature indices suggests that electricity demand in summer and fall may increase (Fig. 7b), which will be difficult to satisfy using only inflow entering the reservoirs (as it is expected to decrease over these seasons), implying that ownership in other electricity sectors may be needed to respond to future electricity demand. The Swiss Energy Strategy 2050 stipulates that the deficit left from the decommissioning of nuclear power plants should be partially compensated for by an increase in hydropower production. However, as Switzerland has almost reached its maximum capacity for hydropower production, renewables (e.g., wind and photovoltaics) are expected to play a significant role in supplementing the deficit left by the phaseout of nuclear power (Redondo and Van Vliet, 2015).

Storage hydropower plants have the ability to release water and generate energy in response to electricity prices in order to create revenue (Savelsberg et al., 2018). A flexible operation mode could allow Groupe E to capitalize on peak prices, as electricity prices are expected to become more volatile due to the increased contribution of renewable energy sources to the electricity market (Anghileri et al., 2018). However, regulations regarding water rights in some countries limit the ability of hydropower operations to change their mode of operation (e.g., the water rights would have to be renegotiated to enable the plant operators to update the design of their installation; Gaudard et al., 2016). More flexibility (e.g., the duration of the contract, the installation design and capacity, and low-flow requirements) could be incorporated into the water concession, as the vested rights within a concession cannot currently undergo important changes once agreed upon. The flexibility of concessions is discussed by Gaudard (2015), who argues that concessions should last 40 years rather than 80 years; the abovementioned study also points out that the more flexible the concession, the more it gains in value.

5.2 Benefits of developing tailored projections by following a stakeholder-centered approach

Involving stakeholders in the modeling and figure design provided key benefits and insights (Addor et al., 2015). It revealed, for instance, that the indices chosen by impact modelers are not necessarily well suited to support decision-making. Although standard indices, such as the long-term mean monthly distribution of inflow, are useful, given the complexity of the concession renegotiation process, a single index or non-tailored indices are of limited use. Instead, indices need to be chosen to bridge the gap between the global-scale climate change phenomenon and concerns and vulnerabilities at the regional to local level. This, for instance, led to the selection of a less common index – consecutive days of low flows – which enabled us to explore a critical vulnerability of hydropower operations that is often overlooked by top-down impact studies. The importance of tailored projections is especially apparent when compared to the existing literature on climate change impacts on hydropower production in Switzerland. The expected mean monthly inflow changes for the Vernex and Montsalvens catchments are most comparable to projections for the nearby Emme catchment simulated by Addor et al. (2014). However, given the local-scale information needed for hydropower management and concession negotiation, indices beyond the long-term mean monthly cycle are needed. Finger et al. (2012) produced hydrological projections for the Saas Fee region in Switzerland, but these are not directly useable by Groupe E, as the hydrological indices they analyzed are not specific enough for concession negotiations nor is the alpine region they cover expected to respond in the same way to climate change as region of Groupe E's catchments.

Groupe E managers expressed that our collaboration enabled them to envision the impacts of climate change at the local level and to prepare for the impacts they may experience as electricity managers. Groupe E is interested in similar studies for other catchments, and they are considering an investment in additional hydrological projections in the future. They stressed the importance of having access to inflow projections in order to begin the process of climate change adaptation and to prepare for critical conversations prior to official negotiations. They stated that, compared with the generic information they have access to, this collaboration made the climate change phenomenon more real and that the figures we co-produced provided them with a clear picture of the likely impacts of climate change on their activities. This highlights the benefits of the direct inclusion of stakeholders to anticipate and efficiently prepare for future climate change impacts.

5.3 Visualizing climate change impact projections and their uncertainties to inform decision-making

Characterizing and visualizing projections uncertainty played a central role during this project, as hydropower managers must negotiate their water concessions despite an abundance of uncertainty (Gaudard et al., 2016). At the onset of the project, we made sure to understand how Groupe E interprets the uncertainty intervals associated with the inflow projections. Uncertainties associated with model calibration (parametric uncertainty) and multi-model ensembles (structural uncertainty) were already familiar to Groupe E, because they routinely utilize an ensemble of streamflow forecasts and account for these uncertainties in their day-to-day operations. Groupe E explained that they consciously consider the width of uncertainty bands compared to the mean change in order to assess the robustness of changes. For instance, Fig. 5a shows the magnitude of Q5 over the JJA and SON seasons between the historical (1980–2009) and future (2070–2099) periods. The spread of the projections is reflected by the width of the boxplots. Figures 5a shows a clear change between historical and future low flows, where all future ensemble members exceed the $-50\,\%$ threshold specified by Groupe E. This result represents a profit loss for Groupe E because there will likely be less water available for turbination, and, if turbinated, it will be at a lower efficiency. In other cases, when results are less definitive, Groupe E stated that the mean (or median) of the projections is most useful to them.

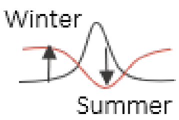
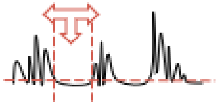
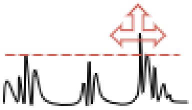
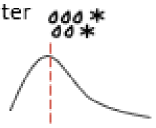
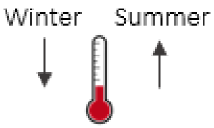
Our visuals were subject to multiple rounds of feedback, where different variables were compared and shown to Groupe E so that we were able to tell a meaningful story. For instance, a decision-analytic summary figure was created based on Fig. 2 in Brown et al. (2012) and was initially proposed to Groupe E. This type of figure uses two axes to show changes in two selected variables and indicates which decision is optimal for different regions of this two-dimensional space. Groupe E pointed out that, given their situation, the value of this type of visual is limited as it is too simple to display the numerous considerations influencing the concession renewal. Instead, Fig. 5 in Broderick et al. (2019) was used as a basis for Fig. 8 to succinctly visualize changes in a series of key indices in relation to the specified thresholds. A summary table of the main opportunities and adaptation options was also provided to Groupe E (Table 4). In addition, given this project's focus on hydrological changes relevant for hydropower operations, we selected climate models based on historical hydrological performance. Some climate models were found to generate unrealistic simulations of discharge or snow processes and were not used for further analysis (see Table 3). Models that produced unrealistic snow processes were excluded given that the cold biases associated with the unbridled snow accumulation may impact the climate change signal of the surrounding grid cells and, thus, provide unreliable projections of hydrological change.

5.4 Limitations and next steps

Concession negotiations have many facets and although hydrological changes are important, they only partially determine the profitability of hydropower operations. This study focused on hydroclimatic changes using a range of streamflow indices. We did not account for the uncertainties related to the development of the European or Swiss electricity market. Instead, we used a simple method to estimate future electricity demand solely based on air temperature. Nevertheless, this study points out that despite the uncertainties involved, quantifying the supply of future water resources and providing an estimate of changes to demand (based on changes to air temperature) improves the information currently available to electricity managers and is useful for their concession negotiations.

There is now a need to complement this analysis with a more economical analysis, focused on the future electricity demand and on the evolution of the electricity market. A collaboration between climate impact and energy–economic modeling (e.g., Anghileri et al., 2018; Savelsberg et al., 2018) seems to be the natural next step. Economical studies often aggregate all climate change impacts by focusing on the profitability of the reservoir and only consider changes in the seasonal cycle. In contrast, this study shows

Table 4. The major opportunities and risks for hydropower operations presented in relation to the hydrological and climatological considerations for concession renewal.

Vulnerability	Overall decrease in annual inflows and seasonal change in the distribution of inflow	Increase in the duration of low flows while simultaneously less water is carried by low flows	Seasonal change in the behaviour of high flows	Meltwater mixing with rain events while reservoir levels approach annual maximum	Electricity demand – decrease over winter and increase over summer
Index	• Seasonal means	• Q5 • Consecutive days below Q5	• Q95 • Consecutive days above Q95	• Rain versus snow contribution to runoff	• HDD • CDD
Change in index	Increase in long-term mean monthly inflow over winter Decrease in long-term mean monhtly inflow over summer and fall 	Reduction of the magnitude of water carried by Q5 by 50% over summer and fall Duration of low flows below Q5 will likely extend as long as 80-90 days consecutive 	Duration of high flows above Q95 will likely extend as long as 20 consecutive days over winter Likely decrease in summer high flows 	Peak annual contribution from snowpack will likely shift from May to April Rain will likely increase its contribution to inflow during the winter 	Likely decrease in demand for electricity over winter Likely increase in demand for electricity over summer and fall 
Opportunity – adaptation option	<u>Winter</u> • Increase in inflows when electricity prices have been historically high could result in profit <u>Summer</u> • Summer inflows more unreliable • Reduced inflows will likely make it harder to meet reservior level requirements	<u>Summer</u> • Less water & longer periods of low flows will likely make it harder to meet residual flow requirements • Negotiate new/flexible residual flow requirements as part of concession • These projections could provide a basis for price reduction for water fee	<u>Winter</u> • Increase in inflows when prices are historically high could result in profit <u>Summer</u> • High flows are likely to be unreliable to offset extended periods of low flows • Diversify electricity mix	<u>Spring</u> • Fast runoff when reservoir levels are high could make reservoir level management precarious <u>All seasons</u> • High-intensity events could be turned to profit if forecasted early – lock in trade/sale based on forecast & bolster forecast systems	<u>All seasons</u> • Future electricity demand is highly uncertain • Suggest flexible concession terms • A potential increase in dependency on renewables likely means intermittency in production, which could represent a challenge in meeting future demand

how linking stakeholder vulnerabilities to changes in individual indices offers an approachable means to evaluate adaptation measures compared with a lumped profit/loss figure. New research projects would benefit from involving a wider range of stakeholders. A collaboration between hydrologists, economists, and stakeholders, such as cantonal authorities, environmental interest groups, hydropower operations specialists, and electricity market traders, would help to support concession negotiations and foster the sustainable development of hydropower.

Additional streamflow indices would be useful to Groupe E, in particular those related to the magnitude and duration of flooding. Future work should include rare and potentially damaging flooding events. The indices and thresholds chosen by Groupe E should not be assumed to be adequate for all hydropower climate change adaptation studies. Instead, we advocate for stakeholder involvement early in future studies so that indices, modeling chains, and results can be tailored for decision-making. Finally, future work could also involve the characterization of sources of uncertainty not considered in this study, such as hydrological model uncertainty and natural variability.

6 Conclusions

This study demonstrates the benefits of involving stakeholders early in climate change impact studies. While most hydroclimatic impact studies explore streamflow changes in isolation and rarely address their implications for water management (Gaudard et al., 2013; Hänggi and Weingartner, 2012), this project went beyond a usual top-down analysis and addressed the specific needs and concerns of stakeholders. We worked with representatives from a hydroelectricity company, and we asked them to describe their main vulnerabilities to hydroclimatic variations; together, we then selected hydrological and electricity demand indices to characterize future impacts. These results enabled us to identify likely key challenges and opportunities for hydropower operations under climate change and to provide guidance on the upcoming water concession negotiations. Our projections indicate a significant increase in inflow over the winter period when electricity prices have historically been at their highest. In contrast, a reduction in summer inflows is expected and will represent a challenge, given the possible increase in electricity demand for cooling as a result of higher temperature. Our projections of low flows provide a basis to support the negotiation of new residual flow requirements. The projected increase in high flows over the winter period could represent an opportunity if this water can be captured and turbinated at optimal times or at prearranged prices. The involvement of stakeholders early on in the project was vital to ensuring that the results and figures of this study were directly useful for their concession negotiations and provide insights into how their operations are likely to be impacted by climate change.

This study is timely as many electricity managers are currently faced with renegotiating their water concessions in the context of climate change and an uncertain electricity market. However, studies such as Tonka (2015) note, there has been a "striking lack of attention paid to climate change impacts on water resources availability in relicensure procedures". We show that although many uncertainties exist, given the multi-decade length of a concession, it is crucial for climate change to be considered at the onset of concession negotiations. The analysis presented here is transferable to other water management entities and provides guidance for other climate change projects that strive to follow a stakeholder-centered approach and deliver projections useful for decision-making.

Code and data availability. EURO-CORDEX data can be accessed via different European data nodes and are available at https://www.hzg.de/ms/euro-cordex/060378/index.php.en (Earth System Grid Federation, 2019). The TabsD and RhiresD interpolated products used to create the historical reference climate time series are available from MeteoSwiss. The streamflow time series representing the inflow to the Lac de Montsalvens and Lac du Vernex was provided by Groupe E.

Supplement. The Supplement for this article includes the projections of the Montsalvens reservoir and the additional time periods analyzed (the time periods from 2020 to 2049, from 2045 to 2074, and from 2070 to 2099 were analyzed; however, given length considerations, only projections covering 2070–2099 are included within the paper). In addition, the following materials are available online for those who wish to carry out their own hydrological climate change impact analysis: (i) a download of HBV hydrological model (https://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html, last access: May 2020) and (ii) an encyclopedia chapter that introduces the steps of a hydrological climate change impact assessment (Hakala et al., 2020). The supplement related to this article is available online at: https://doi.org/10.5194/hess-24-1-2020-supplement. TS11

Author contributions. KH and NA designed this study based on previous exchanges between NA and Groupe E. KH refined the scope of the project with Groupe E over the course of several meetings. KH performed the climate change impact analysis, with oversight from NA and JS. Writing of the paper was led by KH with feedback from all coauthors; finalization of the paper primarily occurred between KH and NA.

Competing interests. The authors declare that they have no conflict of interest.

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