

Journal: Hydrology Earth System Sciences

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

Authors: Kirsti Hakala, Nans Addor, Thibault Gobbe, Johann Ruffieux, Jan Seibert

Dear Prof. Dr. Markus Hrachowitz, Prof. Dr. Franco Romerio, and Anonymous Reviewer,

We thank the associate editor and our two reviewers for their insightful comments and for lending their perspective to our study. To address the comments shared by Prof. Dr. Hrachowitz and the anonymous reviewer, we reframed our scientific questions so that they are now more testable and of more general relevance. We bolstered our discussion of the limitations of our study to address the requests of the second reviewer, Prof. Dr. Romerio. We also reduced the number of times we mentioned of Groupe E so that our main messages can be more broadly received by our readers. Our detailed response to the reviewers' and editor's comments are included on the following pages, with our responses shown in [blue](#). We believe that the incorporated feedback has helped us fine-tune and improve our manuscript. We hereby resubmit the revised version of our manuscript for publication in Hydrology Earth System Sciences.

On behalf of all co-authors-

Sincerely,

Kirsti Hakala

Comments from the Editor (Prof. Dr. Markus Hrachowitz)

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As you have seen the two reviewers highly appreciate your contribution. I agree with this assessment and I think that your manuscript does have the potential to become an important reference. However, the reviewers also raise a few relevant concerns and provide several excellent suggestions to strengthen the manuscript. From my perspective the most relevant point is the framing of the manuscript as stressed by reviewer #1. While the analysis presented does indeed fall within the scope of HESS, the study comes too much across as a technical report. I understand that it is a thin line between what you are trying to do and technical reports. Yet, I feel the manuscript needs to be a bit more balanced towards science aspects. This could be relatively easily done by sharpening the science question, the research hypotheses to be tested and the discussion of the scientific context.

We agree with this comment and have subsequently reformulated our research questions on lines 76-85 (line numbers correspond to when track changes are turned off). The research questions now read:

1. Climate change impacts on water resources are already broadly described by the scientific literature and 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 reservoir concession, and what are their limitations?

Our discussion section addresses each of our research questions: RQ 1 = Section 5.1 (& 5.4 discusses limitations), RQ 2 = Section 5.2, and RQ 3 = Section 5.3.

It may also be very valuable to discuss the limitations inherent in the assumptions taken and their (potential) effects on the results/interpretation in more detail as requested by reviewer #2.

We appreciate the insight that Prof. Dr. Franco Remerio offered. We expanded our discussion of our limitations within Section 5.4 (please see lines 593 – 604, which now reads, “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. This study nevertheless 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.”

In order to make our contributions clear, lines 83-87 state, “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) changes in electricity demand, and (iv) costs associated with adhering to new environmental standards. This study focuses on the

estimation of future water resources (point ii) and provides preliminary insight into future electricity demand (point iii).” This was already mentioned in the previous version of this manuscript, but we moved this text to a more prominent location to avoid confusion.

We also reigned in our text where we make assumptions about future economic principles and user behavior and point out that we are assuming a continuity between past and present. For example, lines 415-417 read, “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.”

Now while I also understand that Groupe E thankfully made their data and knowledge available to allow a bottom-up approach here, Groupe E will also benefit from this study. In that sense, I believe the repeated explicit mentioning of Groupe E does not do service to this manuscript. The work would benefit from less emphasis on the name of the industry partner and a more generic presentation of the work.

We agree and have reduced the number of times that we specifically mention Groupe E throughout the manuscript. Direct references to Groupe E still occur where necessary, but overall we focused on broadening our main points so that they can be received by a wider audience.

Comments from Reviewer #1 (Anonymous)

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This study presents a case study focused on estimation of future changes in the streamflow and energy demand for two catchments in Switzerland. The main objective is to explore and evaluate the future inflows to two reservoirs used for hydropower production in order to support adaptation to climate change, and in particular, the negotiation of a new water concession.

The manuscript is clearly written and has a good structure, however I missed some more specific formulation of the scientific context and contribution. The link between science and engineering practice is interesting, but I wonder to what extent is the presented material in line with the scope of HESS. In its current form, the manuscript reads as a technical report and case study and does not provide clear formulations and demonstrations of the novel scientific contribution. If this is not a key requirement for publication in HESS (I’m a bit confused by reading the current scope of HESS) then I recommend to publish it, if not a substantial revision improving the formulation/ demonstration of novel scientific contribution is needed.

Thank you again for this comment – this feedback inspired us to restructure our research questions so that they are more testable. In addition, we incorporated this concept into our discussion section, which we believe helped focus our text on more scientific aspects. This point was also reiterated by the editor – please see our response to Prof. Dr. Markus Hrachowitz for a more elaborate response.

It will be very interesting to see some more quantitative assessment of the steps used in the workflow (e.g. definition, evaluation of vulnerabilities) and how do those reduce the uncertainty (e.g. how did the multiple rounds of feedbacks quantitatively impact the projections and reduce the associated risks).

Currently, Section 2.3 explains how our interactions with stakeholders resulted in a selection of indices and thresholds that allowed us to evaluate their vulnerabilities under climate change. The first paragraph of Section 5.3 describes how a stakeholder-centered approach influenced how we visualized uncertainty in our figures. We included additional text on lines 237-241 to explain how this approach influenced our selection of climate models, given the focus of this project on hydrological changes relevant for hydropower operations.

Comments from Reviewer #2 (Prof. Dr. Franco Romerio)

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The article “Risks and opportunities for a Swiss hydropower company in a changing climate” addresses relevant questions of scientific and practical nature. It can be published after a careful revision. The main added value is given by the definition of a set of hydrological indices related to the Group E’s vulnerability (well summarized in table 2). Of significance are the seasonal changes in inflow distribution. On this basis, the risks and opportunities for the operator are estimated. However, there are some drawbacks that should be considered by the authors, that I summarize below.

The analysis focuses on water inflows and energy demand, but doesn’t take into consideration other important characteristics of the energy turnaround and the opening of the power market to competition. Furthermore, as recognized by the authors, the analysis of the electricity demand is limited to the climate drivers. For instance, the authors point out “Under climate change, as flexibility decreases and energy demand likely increases due to heat waves [...], Groupe E stated that they would consider acquiring new sources of energy production to compensate for this loss.” However, Groupe E forgets that very likely its customers will install solar panels and perhaps batteries for the storage of electricity at home. Its market will therefore change quite deeply. I understand that the authors can’t develop this issue, which has not been studied. But they can’t ignore it; on the contrary, they should emphasize it. Several times, the authors take as granted higher energy (in fact, electricity) prices in winter, “given that the winter period usually corresponds to higher energy prices”. No doubt that this is a quite realistic scenario. But the problem is very complex and the future evolution of the market in Europe and Switzerland presents many uncertainties, as shown by a quite large literature. Some scenarios are not so favorable to hydropower. In any case, it is risky to assume a continuity between past and future.

We agree with your statements concerning the limitations of our study, namely that an economic study of the future value of water was not carried out. We recognize that there is room for expansion of this work, and indeed this is something that we are hoping will inspire other researchers and end-users. We have expanded Section 5.4, which points out the limitations of our study and the need to incorporate economic principles as a next step. We also reigned in our text where we make assumptions about future economic principles and user behavior and point out that we are assuming a continuity between past and present. For example, lines 415-417 read, “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.”

Also, please see our reformulated conclusions section, which has been tempered by this point.

Despite the limitation of our study, we still believe that this study is timely and useful. Our conclusions section states the following on lines 656-662, “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. Yet, as Tonka (2015) notes, 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.”

*\*Tonka, L., Hydropower license renewal and environmental protection policies: a comparison between Switzerland and the USA. Regional Environmental Change 15, 539-548 (2015) doi:10.1007/s10113-014-0598-8*

The authors state: “The figures we provide will help Groupe E determine the value of water in the future and the price they are willing to pay for the renewal of their concessions.” I agree, but on two conditions: it must be recognized that an economic study of the value of water has not been carried out; one must be aware that only two drivers have been taken into consideration: water flows and energy demand.

We agree entirely, and we have moved our statements regarding this to a more prominent location – the introduction. Lines 83-87 read, “The representatives stated that they expect the following to be considered during concession negotiations (i) the development of the energy market and competitors, (ii) the projected supply of water resources, (iii) changes in energy demand, and (iv) costs associated with adhering to new environmental standards. This study focuses on the estimation of future water resources (point ii) and providing preliminary insights into future energy demand (point iii).”

The collaboration with group E is the basis of this article. It produced interesting results. Group E must be thanked for its transparency. But my feeling is that the authors rely too much on the company’s expertise. It looks like that ultimately it belongs to the company to decide if the authors’ analyses are relevant or not. The authors should be a little more critical.

We agree and therefore expanded our discussions based on existing literature rather than solely relying on Groupe E to validate the usefulness of this study. Regarding our discussion of the future of electricity demand, please see the completely reformatted Section 5.1.4. Our discussion of changes to water volume and how this relates to hypothetical water fee systems is located in the last paragraph of Section 5.1.1 on lines 430-444, and is tempered by your 2018 paper\* with Ludovic Gaudard.

*\*Gaudard, L., Voegeli, G. and Romerio, F.: Hydropower investment profitability under different water fee systems., 2018a.*

Moreover, the company’s judgments depend on its strategy, which is not presented in the article.

Although Groupe E has been very transparent with us, their future strategies are not meant to be made public. Specific language about their future investments was purposely removed from the manuscript. This point is addressed on lines 141-142 which now states, “Groupe E was very transparent throughout this collaboration, however Groupe E’s future strategies are confidential and cannot be fully disclosed in this paper.

The authors state: “This study illustrates the benefits of involving stakeholders in hydropower climate change impact studies”. In fact, only one stakeholder was involved in this study, i.e. a power company. It would have been more interesting to highlight the perception of different stakeholders (public bodies,

environmental organizations, local communities, etc.) on these issues, as well as their convergences and divergences.

We agree that the inclusion of more stakeholders, public bodies, and environmental organizations would be an exciting and valuable way to move forward. It is not within the scope of this current project to include these additional complexities to the study. Lines 613-617 now state, “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, electricity market traders would help to support concession negotiations and to foster the sustainable development of hydropower.”

The authors stress the importance of their results in the context of the negotiations of the concessions renewal, residual flows and water fees. However, in order to develop a strategy, one has to understand the point of view of the main stakeholders involved. For instance, I imagine that the Groupe E’s request that “residual flow requirements should not increase or find a middle ground given the future behavior of low flows entering their reservoirs”, will be challenged by stakeholders primarily concerned by environmental issues.

Our aim was to give Groupe E a first insight into the impacts of climate change on the inflow entering their reservoir and into possible changes in energy demand based on air temperature. It is true that Groupe E will likely face challenges from stakeholders during the renegotiation process. We therefore developed our text further to reflect the need for future research that incorporates the viewpoints and concerns of all main stakeholders (please our response to your previous point above). We also tempered our language where possible – for instance our discussion of low flows in Section 5.1.2 has been updated. Lines 458-462 now read, “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 should not increase, which is likely to be challenged by stakeholders primarily concerned by environmental issues.”

# Risks and opportunities for a Swiss ~~hydropower~~ 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, ~~climate change~~ impact studies are often conducted at a spatial scale that is too coarse to capture the specificity of individual catchments, and ~~more~~ 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, ~~and thereby provide limited insights into climate change adaptation.~~ Here, we collaborated with Groupe E, a ~~hydropower~~ hydroelectricity company operating several reservoirs in the Swiss pre-Alps, and ~~we co-worked with them to produce~~ hydroclimatic projections tailored to support their upcoming negotiations of their water concession renewal negotiations. We started by identifying the vulnerabilities of their activities to climate change and then, together, ~~we chose selected~~ streamflow and ~~electricity demand~~energy indices to characterize the associated risks and opportunities. We provided Groupe E with figures showing the projected ~~climate change~~ impacts, which were refined over several meetings. The selected indices enabled us to ~~simultaneously~~ assess a variety of impacts induced by changes ~~on~~ in i) the seasonal water volume distribution, ii) low flows, iii) high flows; and iv) ~~electricity~~energy demand. ~~This enabled us~~ We were hence able to identify key opportunities (e.g., the future increase of reservoir inflow in winter, when electricity prices ~~are~~ have historically been high) and risks (e.g., the expected increase of consecutive days of low flows in summer and fall, ~~which~~ is likely to make it more difficult to meet residual flow requirements). ~~This study~~ We highlights 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. ~~We also illustrate the importance of identifying stakeholder needs and using them to inform the production of climate impact projections.~~ This stakeholder-centered approach, which relies on identifying stakeholder's

needs and using them to inform the production and visualization of impact projections. Our user-centered approach is transferable to other climate-impact modeling studies, in the field of water resources and beyond.

## 35 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).

40 Electricity energy companies across Switzerland are renewing and renegotiating their water concessions, transforming their existing infrastructure, and considering investments in new regions and energy 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 to  
45 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 a combination of both. Furthermore, until recently, runoff quantities changes in streamflow (water supply) are often typically analyzed in isolation and not are usually not  
50 combined with climate projections of future (electricity energy demand) related to hydropower management (Gaudard et al., 2013). However, in recent studies (Anghileri et al., 2018; Gaudard et al., 2018b; Savelsberg et al., 2018), modeling of the electricity market was combined with hydrological simulations for climate change to project potential revenue changes. These studies contribute to bridging the gap between economists and hydrologists and account for the interconnected nature of water and electricity energy, which is fundamental for sustainable hydropower development. Yet, similarly to the  
55 previously mentioned papers, their focus is still on the seasonal cycle (see A detailed overview of recent research on the impact of climate change on hydropower is provided by Savelsberg et al., (2018) for a detailed overview of recent research on the impact of climate change on hydropower). The focus on particular runoff streamflow quantities indices is often determined by what climate and hydrological modelers perceive as most adequate and relevant (an approach commonly referred to as “top-down”); see e.g. summarized by see Wilby, Robert L.; Dessai 2010). However, this  
60 does not necessarily correspond to the needs of decision-makers in charge of designing adaptation strategies. Top-down studies typically provide an overview of the impacts of climate change on hydrological resources, yet, for decision makers decision-makers 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 addressing and climate preparing for climate change impacts, it is essential to reduce the risk of maladaptation, which can it is essential to minimize the risk of



65 ~~maladaptation (i.e. inappropriate reaction to a threat) resulting from a misunderstanding of 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, ~~given as they reduce the the reduced chance for risk of~~  
maladaptation ~~risk~~. Prioritizing stakeholder involvement early on ~~(i.e. following a so-called “bottom-up” approach)~~ enables  
70 ~~the m stakeholders~~ to expose their concerns regarding climate change and to establish which potential future changes should  
be assessed in priority. ~~This stakeholder-centered approach is often referred to as “bottom-up” (Wilby, Robert L.; Dessai~~  
~~2010; Addor et al., 2015). This leads to adaptation strategies, which are both autonomous (i.e., can be performed~~  
~~implemented locally; IPCC 2008) but also dynamic and multi-sectoral (e.g., evolving while considering uncertainties related~~  
~~to modeling, economic, and social aspects; IPCC, 2012).~~

75 Here, we present a case study relying on a ~~stakeholder-centered bottom-up~~ approach for creating hydrological and  
climatological projections tailored to support ~~hydropower~~ climate change adaptation ~~and water concession negotiations~~. We  
collaborated with ~~Groupe E~~, a Swiss electricity company that manages and has shares in several hydropower reservoirs in  
Switzerland. This project started with meetings with ~~Groupe E managers 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  
80 hydroclimatic changes ~~their business their hydropower operations are~~ is most vulnerable to and to indicate change thresholds  
beyond which their activities would be significantly impacted. These meetings enabled us to pinpoint vulnerabilities of  
~~Groupe E the company's~~ operations to climate change and to select hydrological indices and ~~electricity energy~~ demand  
indices to characterize the associated risks. ~~During concession negotiations, the representatives stated that they expect the~~  
~~following would is expected to be considered during concession negotiations (i) the development of the electricity market and~~  
85 ~~competitors, (ii) the projected supply of water resources, (iii) changes in electricity demand, and (iv) costs associated with~~  
~~adhering to new environmental standards. This study focuses on the estimation of future water resources (point ii) and~~  
~~providing preliminary insights into future electricity demand (point iii). Furthermore, the figures showing our simulations~~  
~~were subjected to multiple rounds of feedback with Groupe E, and were tuned to enable Groupe E to discern future~~  
~~opportunities and risks related to their operations.~~ Hence, over the course of this study, we addressed the following research  
90 questions:

- 95 ~~1. While future reservoir profitability depends on a wide range of economic factors, this analysis is focused on the~~  
~~availability of water resources. How can this be leveraged in the negotiation process of a reservoir concession, and~~  
~~what are its limitations?~~
- ~~1. What are the vulnerabilities of Groupe E's operations to climate change? the and the communication of the results,~~  
~~on the basis of close interactions with stakeholders~~

100 ~~2.1. How will inflows to Groupe E's reservoirs be altered by climate change? Climate change impacts on water resources are already broadly described within by the scientific literature and reports published by public entities (e.g., environmental agencies). While this broad-scale information is available to hydroelectricity managers/companies, however the question is whether this is it adequate to support their negotiations for concession renewal and climate change adaptation strategies?~~

105 ~~2. Future climate change impacts are uncertain and are typically communicated using an ensemble of simulations. What are the most considerable risks and opportunities induced by climate change and how may Groupe E adapt to these changes? How can well do stakeholders incorporate this uncertainty into their decision-making process on adaption strategies the results of a climate change impact assessment be communicated given the use of ensemble outputs/simulations (representing uncertainty in the modeling chain)?~~

110 ~~While future reservoir profitability depends on a wide range of economic and environmental factors. How can projections this analysis is focused on the availability of water resources. How can this be leveraged in the negotiation process of a reservoir concession, and what are their limitations?~~

3.

4. ~~While reservoir economical, this is focussed the availibility off. How can it be leveraged in reservoirs~~

115 This paper is organized in the following way: Section 2 introduces the ~~Groupe E~~ electricity company, the hydropower installations considered for this project, and it describes the indices and associated thresholds selected by ~~Groupe E~~ the electricity managers. Section 3 describes the observational and modelled data as well as the modeling framework employed to carry out hydrological (water supply) and climatological (electricity energy demand) projections. Section 4 presents the projected changes of in the indices chosen by ~~Groupe E~~ the electricity managers. Section 5 discusses the implications of these changes for ~~Groupe E's~~ future hydropower operations, and discusses possible future extensions of this study. In section 120 ~~Section~~ 6, we summarize our results and draw conclusions regarding the use of stakeholder-centered bottom-up approaches in climate change impact analyses.

## 2 Project scope and identification of ~~Groupe E's~~ vulnerabilities to climate change

### 2.1 Hydropower company and study catchments

125 For this study, we interacted with two Groupe E electricity energy managers and provided helped them to assess future climate change impacts them with projections of the inflow entering two of their reservoirs. 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 energy market, the company distributes an average of 2451 GWh/year to nearly 400,000 inhabitants. The company's electricity generation fleet consists of 6 dams and 10 power stations. The installations are located either directly along the Sarine River or on one of its tributaries. Groupe E produces 1329 GWh of energy yearly, which is approximately

130 35% of the energy that they distribute. The remaining 65% is balanced by purchasing and trading on the electricityenergy 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 (Figure 1). The catchments of Montsalvens and Vernex have areas  
135 of 172.7 and 398.5 km<sup>2</sup>, respectively (Table 1). The Vernex and Montsalvens installations are situated upstream of several other installations belonging to Groupe E, which turbine 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 Section 2.4.12. Groupe E is familiar with  
140 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 the entirety of this collaboration, however it should be noted that Groupe E's future strategies are confidential and cannot be fully disclosed in this paper.~~

## 2.2 Negotiations of the water concessions

145 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 energy-electricity managers are currently faced with challenges spurred on by the ending of their water concessions (SWV, 2012). Lac du Vernex is a reservoir with concession agreements with the  
150 cantons of Vaud and Fribourg, which both 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 in order to ensure their  
155 production portfolio and to position themselves securely in the market. Projections of climate change on relevant streamflow indices offer Groupe E electricity companies insight into their resource availability in the future, and also help them gauge the flexibility of future operations. ~~Therefore, Groupe E and other hydropower companies are currently interested in obtaining projections of future impacts of climate change, although the renewal of their concession is in theory only due in a few decades.~~

160 ~~During concession negotiations, Groupe E representatives stated that the following would be considered (i) the development of the energy market and competitors, (ii) the projected supply of water resources, (iii) changes in energy demand, and (iv)~~

costs associated with adhering to new environmental standards. This study focuses on the estimation of future water resources (point ii) and providing preliminary insights into future energy demand (point iii). During concession negotiations, the respective water right granting authorities and Groupe E the electricity company will agree upon the duration of the contract and the terms of the water fee (i.e., the price to be paid by Groupe E to the owner of the water right). 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 now must 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, and 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 (discussed further in Section 5.1.2).

### **2.3 Vulnerabilities to climate change and 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 energy prices have historically been highest in winter since electricity demand is relatively greater 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 specifically address these vulnerabilities, streamflow indices were selected together with Groupe E electricity managers. Corresponding thresholds were also chosen, along with thresholds whose exceedance would significantly impact Groupe E's production activities and profit. These hydrological indices and their relevance for Groupe E hydropower operations are summarized in Table 2. While future changes in the mean monthly streamflow cycle have been well explored (Addor et al., 2014; Smiatek 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 around May/June as well. The

coincidence of meltwater and high intensity precipitation events can therefore lead to excess stormflow entering the reservoirs, which 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 Section 3.3.1).

200 Finally, two indices were chosen by Groupe E to gain insights into future [electricityenergy](#) 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 Eq. (1) and (2):

$$H_{DD} = \max \sum (T_h - \theta_t, 0) , \quad (1)$$

$$C_{DD} = \max \sum (\theta_t - T_c, 0) , \quad (2)$$

205 where  $\theta_t$  is the air temperature retrieved from climate projections (Sections 3.2.2 and 3.2.3). The thresholds  $T_h = 13^\circ\text{C}$  and  $T_c = 18.3^\circ\text{C}$  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 Zurich and Geneva, given that these areas comprise of typical  
210 Groupe E [electricityenergy](#) consumers. Results for Geneva are shown below and results for Zurich can be found in the Supplementary Materials-S8.

### 3 Data and methods for impact modeling

#### 3.1 Modeling framework

To assess future changes in the streamflow and [electricityenergy](#) demand indices introduced above, we relied on the following model chain. We combined two greenhouse gas emission scenarios (see Section 3.2.1), eleven regional climate  
215 models forced by general circulation models (GCM-RCMs; see Section 3.2.2), two GCM-RCM [post-post](#)-processing methods (see Section 3.2.4) and one hydrological model to simulate inflow entering the two reservoirs (Figure 1). The hydrological model was calibrated using three objective functions and ten optimized parameter sets were generated per objective function and per calibration period (see Section 3.3.3). This modeling framework follows the procedure outlined in Hakala et al., (2019). It enabled us to assess uncertainties in the projected discharge and to provide Groupe E with a  
220 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

225 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. RCPs 4.5 and 8.5 were selected for this study. RCP 4.5 corresponds to an intermediate emission trajectory, where greenhouse gas (GHG) emissions peak around 2040 and then generally stabilize. In contrast, RCP 8.5 assumes that GHG emissions will continue to increase throughout the 21st century (Meinshausen et al., 2011).

### 3.2.2 Observational and GCM-RCM data

230 Observational meteorological data were retrieved from the 2 km MeteoSwiss gridded datasets of TabsD (Frei, 2014) and RhiresD (Frei and Schär, 1998; Schwarb, 2000). The daily reservoir inflow was estimated by Groupe E for the period of 2008-2018 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° resolution, but only 0.11° data was used  
235  
240 given the size of the catchments investigated in this study. Overall, the exclusion of some GCM-RCMs due to their poor hydrological performance results in a tailored modeling setup that prioritizes 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  
245 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 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 ~12.5 km), nine grid cells at least partially overlapped with the Vernex catchment and four grid cells overlapped with the Montsalvens  
250 catchment.

### 3.2.4 Bias correction

The GCM-RCM simulated temperature (T) and precipitation (P) time series were bias corrected using a nonparametric 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-  
255 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-day calendar, observational data were converted to a 360-day calendar before bias correction and the hydrological model was run using this calendar. The ‘qmap’ package in R (Gudmundsson, 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  
260 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, so 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

265 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 version HBV-Light (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  
270 the reader to Seibert and Vis, (2012). For the remainder of the manuscript, we use the term HBV when referring to the version HBV-Light.

### 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  
275 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  
280 factor was applied to the observed discharge to re-scale 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 2008-2018, where P represents precipitation



falling within the catchment, E stands for actual evaporation, Q represents the inflow reported to enter the Montsalvens reservoir, and  $\Delta S$  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. This method therefore 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 ~~was-were~~ based on three different objective functions, namely the Lindström measure (Lindström et al., 1997), Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), and Kling-Gupta efficiency (Gupta et al., 2009). Two separate periods were used for calibration and validation: 01-10-2008 to 30-09-2013 and 01-10-2013 to 31-08-2018. For each combination of objective function and time period, ten 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 (above 0.75 NSE 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,  $Q_{\text{obs}}$  and  $Q_{\text{ref}}$  stem from different time periods, as Group E records only cover the period 2008-2018. Given this mismatch in time periods, we began by comparing the monthly precipitation of the  $Q_{\text{obs}}$  and  $Q_{\text{ref}}$  time periods (Supplementary Materials-S1). The period 1980-2009 ( $Q_{\text{ref}}$  period) experienced a wetter climate than 2008-2018 ( $Q_{\text{obs}}$  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 (Figure 2a). Bias-correction leads to a significant reduction of these biases, and ~~in fact, it~~ was necessary ~~here~~ to capture ~~the behavior of the~~ -indices required by Group E (Figure 2a to 2h). 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 of 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



315 uncertainty. As ~~Groupe E~~ 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 (mm/day) is shown on the left-hand axis, and the discharge (m<sup>3</sup>/day) is displayed on the right-hand  
axis. The former allows for a comparison between catchments, whereas the latter is more useful for ~~energy managers, such~~  
~~as Groupe E, electricity managers~~ when operations primarily are looked at in terms of volumes.

320 Overall, when using bias-corrected climate simulations, HBV satisfactorily captures the annual discharge cycle (Figure 2a),  
the respective contribution of snow and rain to streamflow (Figure 2b) as well as Q5 and Q95 during the seasons of interest  
(Figures 2c and 2d). In contrast, HBV tends to overestimate both the duration of periods below Q5 and above Q95 (Figure 2e  
and 2f). It is however, important to note that HBV was not specifically calibrated against the hydrological indices mentioned  
325 in Table 1, and so it is not surprising if  $Q_{obs}$  and  $Q_{ref}$  deviate when compared across these indices. 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 ~~for Groupe E~~. A  
comparison of the  $Q_{obs}$  and  $Q_{ref}$  inflow time series (Supplementary Materials-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).

### 330 3.5 Projections of climate change impacts

Since the performance of the modeling chain was considered to be satisfactory over the reference period, all parameter sets  
generated in Section 3.3.3 were used to simulate projections for the periods of 2020-2049, 2045-2074, and 2070-2099. Our  
modeling chain comprised of: two emission scenarios (RCP4.5 and RCP8.5), eleven EURO-CORDEX GCM-RCMs, two  
post-processing methods (raw and quantile mapping), one hydrological model (HBV), three objective functions for the  
335 hydrological model (Lindström measure, Nash-Sutcliffe efficiency, Kling-Gupta efficiency), along with ten optimized  
parameter sets per objective function, and two calibration periods. This lead 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, ~~as it is~~  
~~the most interesting for Group E~~, 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 Supplementary  
340 Materials. 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.

## 4 Results

This section presents the changes in streamflow and electricity demand indices projected by our modelling chain. The implications of these changes for future reservoir operations and profitability are discussed in Section 5-1.

### 4.1 Projected changes in ~~Water-water~~ volume

Figure 3a compares historical (1980-2009) and future (2070-2099) annual distribution of inflow entering the Vernex reservoir for RCP 8.5. ~~Changes in Winter-winter~~ (DJF) discharge ~~are~~ shown to widely exceed the +20% and +50% thresholds specified by Groupe E. Meanwhile, 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 RCP 8.5, the Vernex reservoir ~~will-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 M m<sup>3</sup>/day (likely range: -4.52 to +2.54 likely range) under RCP 8.5 and -0.24 M m<sup>3</sup>/day (likely range: -2.9768 to +2.35487 likely range) under RCP 4.5. Similarly, the inflow entering the Montsalvens reservoir is expected to~~will~~ experience an average decrease of -0.724 M m<sup>3</sup>/day (-2.19 to +0.81 likely range) under RCP 8.5 and -0.18 M m<sup>3</sup>/day (-1.61 to + 1.08 likely range) under RCP 4.5.

The shift in the annual distribution of inflow entering ~~Groupe E's~~the reservoirs is primarily caused by changes in the form of precipitation contributing to inflow (Figure 4). 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 ~~will-is shown to~~ decrease its respective contribution to inflow over the summer. The shift in spring runoff and the reduction of rainfall contribution to inflow results in a reduction of inflow entering ~~Groupe E's~~the reservoirs (Figures 3b, S4). Over the 21st century, winters are expected to~~will~~ 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 of snowfall contribution (Supplementary Materials-S5).

### 4.2 Projected changes in ~~Low-low~~ flows

Q<sub>qm</sub> simulations of low flows (Q5) for JJA and SON strongly decrease under RCP 8.5, with the majority of the ensemble indicating a decrease greater than the -50% threshold (Figure 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 (Supplementary Materials-S6).

375 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 to 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 (Figure 2e). The  
380 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 (Supplementary Materials-S7).

#### 4.3 Projected changes in High-high flows

385 The magnitude of high flows (Q95) is expected to decrease in JJA under RCP 8.5 (Figure 5b). However, the median and the  
majority of ensemble members are within the 50% threshold interval ~~designated by Groupe E~~. In contrast, for winter,  $Q_{qm}$   
simulations show a significant increase, far exceeding the +50% threshold ~~specified by Groupe E~~. Inflows entering the  
Montsalvens reservoir exhibit similar behavior over both seasons (Supplementary Materials-S6).

390 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 ten-day threshold. Results for Montsalvens indicate similar but less pronounced changes  
(Supplementary Materials-S7).

#### 4.4 Projected changes in temperature-based indices ~~Energy~~ ~~Electricity demand~~

395 Figure 7a shows that the number of HDD ~~is expected to~~ ~~will~~ decrease over the winter months under the influence of climate  
change, whereas the summer months experience no change given that 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 given that these months are too cold to invoke cooling within the household of a typical ~~Groupe~~  
~~Electricity~~ customer. Projections ~~of for~~ the Canton of Zurich show a general agreement with the magnitude and distribution  
of change (Supplementary Materials-S8).

### 5.1 Implications of the projected changes for ~~Climate risks and opportunities and possible adaptation strategies~~Impacts of climate change on hydropower operations

The projected changes in streamflow are summarized in Figure 8 along with the critical thresholds selected by Groupe E. ~~Here we discuss the implications of these changes for hydropower operations are discussed below as well as and how they~~  
 405 ~~how these expected changes could be leveraged to during be leveraged in the negotiation of the process of a water~~  
~~concession.~~  
concession.

#### 5.1.1 Water volume

~~Of the selected indices, Groupe E stated that a seasonal breakdown of changes to water volume are the most important~~  
 410 ~~indices for their operations.~~ Some changes in the seasonal inflow distribution represent new opportunities ~~for Groupe E.~~  
 Over the winter period, the inflow into Lac du Vernex is expected to ~~will experience an average increase by of +90% under~~  
 RCP 8.5 (Figures 8a & b) and by +63% under RCP 4.5 (ensemble mean). ~~Inflow into Lac de Montsalvens will is expected to~~  
~~increase by experience an average increase of +89% under RCP 8.5 and +61% increase under RCP 4.5 (ensemble mean).~~  
 Hydropower will likely remain an important supplier source of electricity in the winter given the low yield of photovoltaics  
 415 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 ~~electricityenergy~~ 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 ~~to the winter,~~ the regime changes in the summer and fall are expected to lead to new challenges for Groupe E.  
 420 Over the summer period, the Lac du Vernex will is expected to experience an average decrease of -51% under RCP 8.5  
 (Figures 8a & b) and -30% under RCP 4.5 (ensemble mean). Lac de Montsalvens will is likely to experience an average  
 decrease of -49% under RCP 8.5 and -28% decrease under RCP 4.5. The reduction of summer inflow can be linked to the  
 snowpack shrinkage over the coming century and the simultaneous reduction of total precipitation over the summer months  
 (Figure 4). Köplin et al., (2014) showed that when snow accumulation is important to a catchment hydrological regime  
 425 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 ~~for it to be used~~ to offset droughts in the  
 summer period. Adjusting the size of their reservoirs is currently not a viable option and therefore it was not ~~necessary to~~  
~~adjust the size of the reservoir explored by during our modeling experimentsexercises.~~

Given a decrease in inflow over the summer, and a likely possible increase in ~~electricityenergy~~ demand for cooling (Figure  
 7b), ~~Groupe E may need to consider increasing their investmentingsan investment into in other energy sectorsenergy~~  
 430 ~~sources may be considered,~~ such as photovoltaics, ~~which with peak production during the longer summer days, correlates~~  
sources may be considered,

nicely to the relatively longer daylight hours in summer. ~~Furthermore, Groupe E stated that i~~In addition to other market conditions and legal requirements, ~~they could potentially~~may use ~~these projections of changes in water volume~~is information to negotiate a lower cost for their water fee, ~~which as the fee~~ is in part determined based on the amount of water that can be used for electricity production ~~under particular hydrological conditions.~~ ~~However, the water fee framework is subject to re-review in 2024 (Betz et al., 2019).~~ ~~For an~~An impact comparison of the different water fee systems on Swiss hydropower, ~~see was performed by~~ Gaudard et al., (2018a). ~~Within their study they compared different water fee frameworks including a (i) no-fee system, (ii) fixed-fee system, (iii) semi-flexible or fixed and variable fee system, and a (iv) profit-based imposition system. The current water fee framework follows a fixed-fee system. The authors discuss that under a fixed system, the water fee tends to flatten the differences between the lowest and highest financial years. The hydropower sector is vulnerable in this system, which provides no flexibility and instead imposes a fee based on theoretical power. In contrast, a profit-based system is shown to 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~~will reduce drastically ~~compared to historical values~~, with the majority of ensemble members ~~predicting a change~~ exceeding the -50% threshold in JJA and SON (Figure ~~8a-8c & bd~~). In addition, ~~droughts periods of low flow are expected to~~will increasingly extend beyond Groupe E's 60-day threshold in JJA and SON (Figure ~~8a-8c & bd~~). ~~These~~ ~~Groupe E stated that these changes would be~~ 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 ~~water managers~~hydropower operators to turbine when electricity prices are optimal. ~~Under climate change, as flexibility decreases and energy demand likely increases due to heat waves (Section 5.1.4), Groupe E stated that they would consider acquiring new sources of energy production to compensate for this loss.~~

Cantonal requirements are currently being strengthened to reduce environmental impacts. One of the cantonal measures include increasing the amount of residual flow for environmental reasons (e.g. flora, fauna, and sediment transport are affected by very low flows). ~~However, the result~~s of this study ~~demonstrate~~ shows that the water carried by low flows ~~will~~ is expected to substantially decrease over the coming decades and the duration of low flow conditions will ~~likely~~ increase. ~~Hence, Therefore, during concession negotiations, minimum flow requirements are~~ likely to be a delicate topic during ~~concession negotiations, as~~ Groupe E may request that residual flow requirements should not increase, ~~which is likely to be challenged by stakeholders primarily concerned by environmental issues.~~ ~~or find a middle ground given the future behavior of low flows entering their reservoirs.~~

### 5.1.3 High flows

465 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% (Figure 8d) and exceed the ten-day threshold ~~specified by Groupe E~~ (Figure 6b). An increase of high flows entering the reservoirs during the winter period, when ~~electricity~~energy 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~~energy market. ~~Groupe E stated that this increase is generally seen as a positive outcome for their operations given that energy prices are usually highest during the winter.~~ The hydrological shift from slow, snow-dominated processes to more variable, rainfall-driven processes will require ~~Groupe E to a flexible adapt the management of their reservoirs 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). ~~This would require Groupe E To generate more revenue, the extra inflow would have to be captured and turbinated the inflow at optimal times or at pre-arranged prices. Conversely, projections show a decrease in high flows in the summer (Figure 8c), which indicates a reduced risk of water loss due to spillovers.~~ 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 (Figure 8c), which indicates a reduced risk of water loss due to spillovers.~~

### 5.1.4 ~~Electricity~~Energy demand

~~Our analysis using temperature indices suggests that Groupe E will need to supply their consumer's increasing electricity~~energy demand during ~~in the summer and fall seasons will increase~~ (Figure 7b), which will be ~~difficult to satisfy using~~ challenging if only inflow entering their reservoirs is considered (which is expected to decrease). Ownership in other ~~electricity~~energy sectors may help offset losses directly associated with hydropower production. The Swiss Energy Strategy 2050 stipulates that the energy deficit left from the decommissioning of nuclear ~~power plants~~energy should be partially replaced ~~compensated~~ with an increase in hydropower production. However, Switzerland has almost reached its maximum capacity for hydropower production, and projections of future ~~electricity~~energy mix show that renewables (e.g. wind and photovoltaics) will need to play a significant role in supplementing the energy deficit left by the phase out of nuclear ~~power~~energy (Redondo and Van Vliet, 2015).

To adapt to climate change, ~~Electricity~~ ~~electricity~~hydropower~~electricity~~ companies that hope to adapt to climate change cannot base their strategies on water availability (~~supply~~) alone, ~~they also need to estimate future electricity demand~~ (Gaudard et al., 2013; Savelsberg et al., 2018). ~~Storage hydropower plants have the ability to release water and generate~~

495 ~~energy in response to electricity prices in order to create revenue (Savelsberg et al., 2018).~~ This motivated the selection of  
the ~~electricity~~energy demand indices ~~that was chosen~~ for this study. ~~Although such~~ a temperature-based electricity demand  
approach is inherently limited, it is a sensible way to initiate the discussion on future changes in climate, electricity market  
and electricity consumption behaviors. Our analysis using temperature indices suggests that electricity demand in summer  
and fall may increase (Figure 7b), which will be difficult to satisfy using only inflow entering the reservoirs (as it is expected  
500 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 with an increase in hydropower production. Yet, 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 phase out of nuclear power (Redondo and Van Vliet, 2015).

505 ~~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)Savelsberg et al., 2018).~~ A flexible operation mode could allow Groupe E to  
capitalize on peak prices, as  
510 ~~Although a temperature-based electricity~~energy demand approach is inherently limited, alternative projections of how the  
electricity market will develop over time are highly uncertain and only a limited amount of research has been done to assess  
the impact of energy and economic policies on future hydropower (Anghileri et al., 2018). Nonetheless, if operations can be  
adapted to an expected increase in electricity prices are expected to become more volatile volatility ~~(due to the increased  
contribution of renewable energy sources into the electricity market (Anghileri et al., 2018)), a more flexible operating  
strategy could allow Groupe E to capitalize on peak prices (see Section 5.4 for further discussion).~~ However, water right  
515 regulations in some countries limit the ability of hydropower operations to change their mode of operation ~~deal with  
variability (e.g. the water right would have to be re-negotiated if to enable the plant operators wants to update the design of  
their installation (Gaudard et al., 2016)). More flexibility (e.g. duration of contract, installation design and capacity, low flow  
requirements) could be incorporated into the water concession since, at present, the vested rights within a concession cannot  
undergo important changes once agreed upon. The flexibility of concessions is discussed by (Gaudard, (2015) who argues  
520 that ~~ich endorses the idea that concessions should last 40 years rather than 80 years, and points out that the more the  
concession is flexible, the more it gains in value.~~~~

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

525 ~~Following a bottom-up approach and i~~nvolving stakeholders in the modeling and figure design provided key benefits and  
insights (Addor et al., 2015) ~~(Wilby and Dessai 2010; Addor et al., 2015).~~ It revealed, for instance, that the indices ~~often~~  
chosen by impact modelers are not necessarily well-suited to support decision-making. Although ~~these~~ standard indices, such  
as the long-term mean monthly distribution of inflow are useful, ~~interacting with Groupe E made clear that,~~ given the  
complexity of ~~their decision-making~~the concession re-negotiation process, a ~~singular~~single index or non-tailored indices are



of limited use. ~~Instead, indices need to be chosen. It is therefore important to bridge the gap between the global-scale climate change phenomenon, and what is actually felt on concerns and vulnerabilities at the regional to local level.~~ This ~~for instance~~

530 led to the selection of a less common index, consecutive days of low flows, which enabled us to explore a critical vulnerability for hydropower operations often overlooked by top-down impact studies. The importance of tailored projections ~~and indices~~ is especially apparent when ~~the projections presented here are~~ compared to ~~the~~ existing literature on climate change impacts on hydropower production ~~in Switzerland~~. The ~~expected~~ mean monthly inflow changes ~~that for~~ the Vernex and Montsalvens catchments ~~will experience~~ are most comparable to projections ~~shown~~ for the nearby Emme catchment simulated by (Addor et al., (2014). But 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. ~~the cold biases surrounding~~

540 Groupe E managers expressed that our collaboration enabled them to ~~see-envision~~ the impacts of climate change at the local level ~~and, in a way that allows them~~ to ~~envision-prepare for~~ the impacts they may experience ~~on a daily basis~~ as ~~energy electricity~~ managers. Groupe E is interested in similar studies for other catchments and they ~~mentioned that they would are~~ considering ~~investing an investment~~ in ~~new-additional~~ hydrological projections ~~in the future as models develop over time~~.  
545 Importantly, they stressed ~~the importance of that it is useful to having access toe inflow the~~ projections ~~as early as possible in~~ order to begin the process of climate change adaptation and to prepare for critical conversations prior to official negotiations. They stated that, ~~compared to generic information they have access to,~~ this collaboration made the climate change phenomenon ~~much~~ more real and that, ~~compared to generic information they have access to,~~ the figures we co-produced provided ~~d~~ them with a ~~particularly~~ clear picture of the likely impacts of climate change on their ~~hydropower~~ activities. This  
550 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

~~The design of all the visuals presented in this study was informed by Groupe E. A decision-analytic summary figure was created based on Figure 2 in and was proposed initially to Groupe E. This type of figure uses two axes to represent 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, this type of visual is limited as it is too simple to display the numerous considerations influencing the concession renewal. Instead, Figure 5 in Broderick et al., (2019) was used as a basis for Figure 8 to succinctly visualize changes in a series of key indices in relation to thresholds prescribed by the Groupe E. A summary table of the main opportunities and adaptation options was also provided to Groupe E (Table 4).~~



Characterizing and visualizing projections uncertainty ~~also~~ played a central role during this project, as ~~Groupe E~~ hydropower managers must negotiate their water concessions despite an abundance of uncertainty. ~~Our meetings with electricity managers reaffirmed the notion that uncertainty information is of great value to decision makers (Gaudard et al., 2016). We hence made sure to~~ At the onset of the project, we made sure to understand how Groupe E interprets uncertainty bands intervals associated with the inflow projections ~~of their water resources~~. Uncertainties associated with model calibration ~~(parameteric uncertainty) and validation~~ and multi-model ensembles (structural uncertainty) were already familiar to Groupe E because they routinely utilize ensemble of these streamflow forecasts methods and ~~incorporate account for these these~~ uncertainties into their day-to-day operations. ~~They recognize the value of accounting for uncertainties, in particular as this helps to prevent maladaptation, as deterministic projections convey an unjustified impression of certainty.~~ Groupe E explained that they consciously consider the width of uncertainty bands compared to the mean change in order to render assess the robustness of changes confidence in the figure. For instance, Figure 5a shows the magnitude of Q5 over the JJA and SON seasons between the historical (1980-2009) and future period (2070-2099). The spread of the projections is reflected by the width of the boxplots. Figure 5a shows a clear change between historical and future low flows, where all future ensemble members exceeded 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. show results from~~ For instance, a decision-analytic summary figure was created based on Figure 2 in Brown et al., (2012) and was proposed initially 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 is type of visual is limited as it is too simple to display the numerous considerations influencing the concession renewal. Instead, Figure 5 in Broderick et al., (2019) was used as a basis for Figure 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 and were not used for further analysis (see Table 3). Models which 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. These changes are important but they only partially determine the profitability of the two reservoirs. However, this study does not account for the uncertainties related to the development of the European or Swiss electricity market. We did not explicitly model the electricity market. Instead we used a simple method to estimate future electricity demand is solely based on air temperature, which is a simplification of a very complex system. The challenge of concession negotiations has many challenging facets and although hydrological changes are important, they only partially determine the profitability of hydropower operations. In this study, we did not explicitly model the uncertainties related to the development of the European or Swiss electricity market. However, this study nevertheless 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 thus provides a more informed basis useful for their concession negotiations.

There is now a need to complement this analysis with a more economical analysis, focused on the future electricity energy demand and on the evolution of the electricity energy market. A collaboration between hydrological climate change climate impact modeling and energy-economic modeling (e.g. Anghileri et al., (2018); Savelsberg et al., (2018)) seems to be the practical natural next step, e.g. Anghileri et al., (2018); Savelsberg et al., (2018). However, these studies tend often to aggregate all climate change impacts by focusing solely on the profitability of the reservoir, and they tend to consider only changes in the seasonal cycle. In contrast, this study shows how linking stakeholder vulnerabilities to changes in individual indices offers an approachable means to discuss evaluate adaptation measures compared to a lumped profit/loss figure. New research projects would benefit from involving a wider range of all relevant stakeholders in the creation of projections relevant for concession renewal. A collaboration between hydrologists, economists, and relevant stakeholders such as (e.g. cantonal authorities, environmental interest groups, hydropower operations specialists, electricity market traders) would help to ensure the incorporation of all necessary components into a modeling framework to support concession negotiations and to foster the sustainable development of hydropower.

Additional streamflow indices would be useful to Groupe E, in particular related to magnitude and duration of flooding. Future work could expand the hydrological indices to include rare and potentially damaging flooding events. The indices and thresholds chosen by Groupe E should not be interpreted as universally appropriate 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

625 characterization of sources of uncertainty not considered in this study, such as hydrological model uncertainty and natural variability.

## 6 Conclusions

630 This study ~~illustrates~~ demonstrates the benefits of involving stakeholders early in ~~hydropower~~ climate change impact studies, ~~whereby decision making was given top priority~~. This project went beyond a usual climate change impact assessment by ~~addressing the specific needs and concerns of decision makers~~ stakeholders, ~~while~~ This approach is essential given that most ~~hydrological climate change~~ hydroclimatic impact studies ~~analyze explore streamflow changes runoff quantities~~ in isolation ~~but and~~ rarely address ~~issues their implications for~~ of 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~~. ~~This project was designed to provide guidance Groupe E regarding their adaptation efforts to climate change and to support the negotiations of their water concession~~. We ~~asked~~ worked with representatives from a hydroelectricity company ~~Groupe E representative, and~~ sand ~~asked them~~ to describe their main vulnerabilities to hydroclimatic variations, and together, we selected hydrological and ~~electricity~~ energy demand indices to characterize future impacts. ~~This enabled us to identify key opportunities and risks that are relevant to the concession negotiation process and climate change adaptation strategies~~.

640 ~~The figures we provide will help Groupe E determine the~~ Our ~~These results provide~~ enabled us to identify a first estimate of the likely key challenges and opportunities for the electricity company's hydropower operations under climate change, value of water in the future and ~~and~~ we ~~to provide tailored guidance on the price they are for~~ the upcoming actions that could be taken as well as stipulations that could be included ~~willing to pay for the renewal of their~~ within the updated operating framework (agreed upon within the water concession negotiatons) ~~concessions~~. Our ~~results~~ projections indicate a significant increase of inflow over the winter period when ~~electricity~~ energy prices have historically been at their highest. ~~Alternatively~~ In contrast, a reduction of summer inflows is expected and will ~~present~~ represent a challenge, ~~new risks for Groupe E, given~~ the possible ~~an~~ increase in ~~electricity~~ energy demand for cooling as a result of higher temperature ~~due to temperature increase~~ ing temperatures. Our projections of low flows provide a basis to support the ~~from which Groupe E~~ the electricity company may ~~negotiation of~~ new ~~for residual flow~~ updated residual flow requirements ~~to remain the same or only slightly increase~~. High flows ~~The projected increase of high flows over the winter period could~~ represent an opportunity if this water can be ~~captured and~~ turbined at optimal times or at pre-arranged prices, leading to ~~overspills~~ opportunity for Groupe over the winter, given that the winter period usually corresponds to higher energy prices ~~volume~~. In order to generate profit, Groupe E will need to consider new ways in which to store and turbine these higher inflows. The involvement of Groupe E representatives ~~stakeholders~~ early on in the project was vital towards ensuring that results and figures of this study were directly useful for their concession negotiations and ~~to~~ provide insights into how their operations are likely to be impacted by climate change.

660 This case study demonstrates how projections of future climate change impacts on water resources can be tailored to support the negotiations for the re-licensure of water concessions. Study is timely as many electricity managers are currently faced with re-negotiating their water concessions in ~~light~~<sup>the context</sup> of climate change and an uncertain electricity market. Yet, as for instance Tonka (2015) notes, ~~that~~ there has been a 'striking lack of attention paid to climate change impacts on water resources availability in relicensure procedures' ~~in the USA and studies on this topic have only recently been conducted in Switzerland.~~ 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 ~~this assessment~~ provides guidance for other climate change projects that strive to follow a ~~stakeholder-centered bottom-up~~ approach and deliver projections ~~that are~~ useful for decision-making.

665 The environmental regulations that are agreed upon during the concession negotiations usually cannot be altered during the duration of the concession. 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 this assessment provides guidance for other climate change projects that strive to follow a bottom up approach and deliver projections that are directly useful for decision-making.

670 **Authors contribution:**

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 manuscript occurred primarily between KH and NA.

675 **Competing interests:**

The authors declare that they have no conflict of interest.

**Acknowledgements:**

This study was supported by the Swiss National Science Foundation via the grants 200020\_156606 and P400P2\_180791. The authors thank Marc Vis for support related to the HBV model. We also thank Prof. Dr. Hannes Weigt for providing  
680 useful insights into the Swiss water fee framework. We acknowledge the Federal Office of Meteorology and Climatology MeteoSwiss and the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) for the atmospheric and climate modeled data, respectively.

**Supplementary Materials:**

685 Supplementary materials for this article ~~include the are located as an attachment at the end~~ projections of the Montsalvens reservoir and the additional time periods analyzed (the time peirods of: 2020-2049, 2045-2074, and 2070-2099 were analyzed, but given length considerations, only projections covering 2070-2099 are included within the manuscript). In addition, the following materials are available online for those who wish to carry out their own hydrological climate change impact analysis: (i) download of HBV hydrological model can be accessed: <https://www.geo.uzh.ch/en/units/h2k/Services/HBV-Model.html>, (ii) we refer the reader to Hakala et al., (2019), which is an  
690 encyclopedia chapter which introduces the steps of a hydrological climate change impact assessment.

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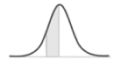
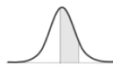
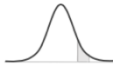
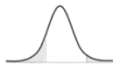
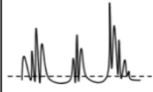
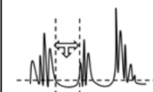
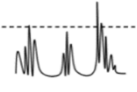
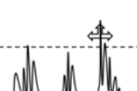
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**Table 1: Main characteristics of the two study catchments including catchment area, elevation, glacier coverage, karst percentage, forest cover, and energy production. Data for this table were derived from multiple sources: area and mean elevation of the catchment was provided by Groupe E and 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 <sup>2</sup> ]	Mean elevation [m a.s.l.]	Glacier coverage [%]	Karst hydrogeology [%]	Mean energy production [MWh/year]
Montsalvens- Broc	172.7	1386	0	35	71 567
Vernex- Montbovon	398.5	1639	<1	15	59 422

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**Table 2: Hydrological indices selected after discussions with representatives of Groupe E. The relevance of each index for Groupe E's operations is explained, and 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.**

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 turbine 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.		

**Table 3: Overview of the eleven 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 which have been removed are denoted by light gray text and italicized font.**

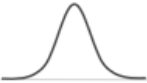
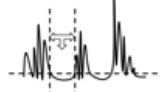
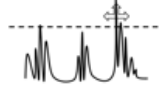


No	GCM	RCM	Calendar	Notes
1	CNRM-CERFACS-CNRM-CM5	CLMcom-CCLM4-8-17	Gregorian	
2	ICHEC-EC-EARTH	CLMcom-CCLM4-8-17	Gregorian	
3	MOHC-HadGEM2-ES	CLMcom-CCLM4-8-17	360	
4	MPI-M-MPI-ESM-LR	CLMcom-CCLM4-8-17	Gregorian	
	<i>ICHEC-EC-EARTH</i>	<i>DMI-HIRHAM5</i>	<i>Gregorian</i>	<i>R-ST</i>
	<i>NCC-NorESM1-M</i>	<i>DMI-HIRHAM5</i>	<i>Gregorian</i>	<i>R-ST</i>
	<i>IPSL-IPSL-CM5A-MR</i>	<i>IPSL-INNERIS-WRF331F</i>	<i>Gregorian</i>	<i>R-D</i>
	<i>ICHEC-EC-EARTH</i>	<i>KNMI-RACMO22E</i>	<i>Gregorian</i>	<i>R-ST</i>
	<i>ICHEC-EC-EARTH</i>	<i>KNMI-RACMO22E</i>	360	<i>R-ST</i>
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	C
10	MOHC-HadGEM2-ES	SMHI-RCA4	360	
11	MPI-M-MPI-ESM-LR	SMHI-RCA4	Gregorian	

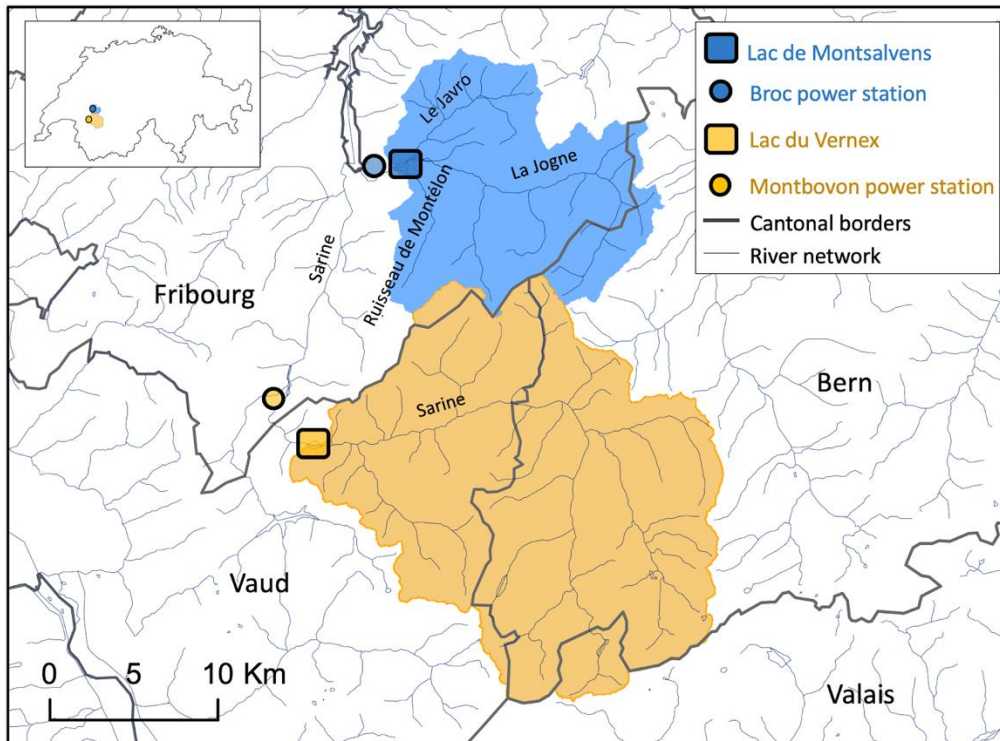
(R-ST): Removed due to snow towers in GCM-RCM model output

(R-D): Removed due to irregularities in the mean monthly distribution of discharge when simulations when forced by this GCM-RCM

(C): Calendar converted from non-leap year to proleptic Gregorian

**Table 4: The major opportunities and risks for Groupe E's hydropower operations diagrammed in relation to the hydrological and climatological considerations for concession renewal.**

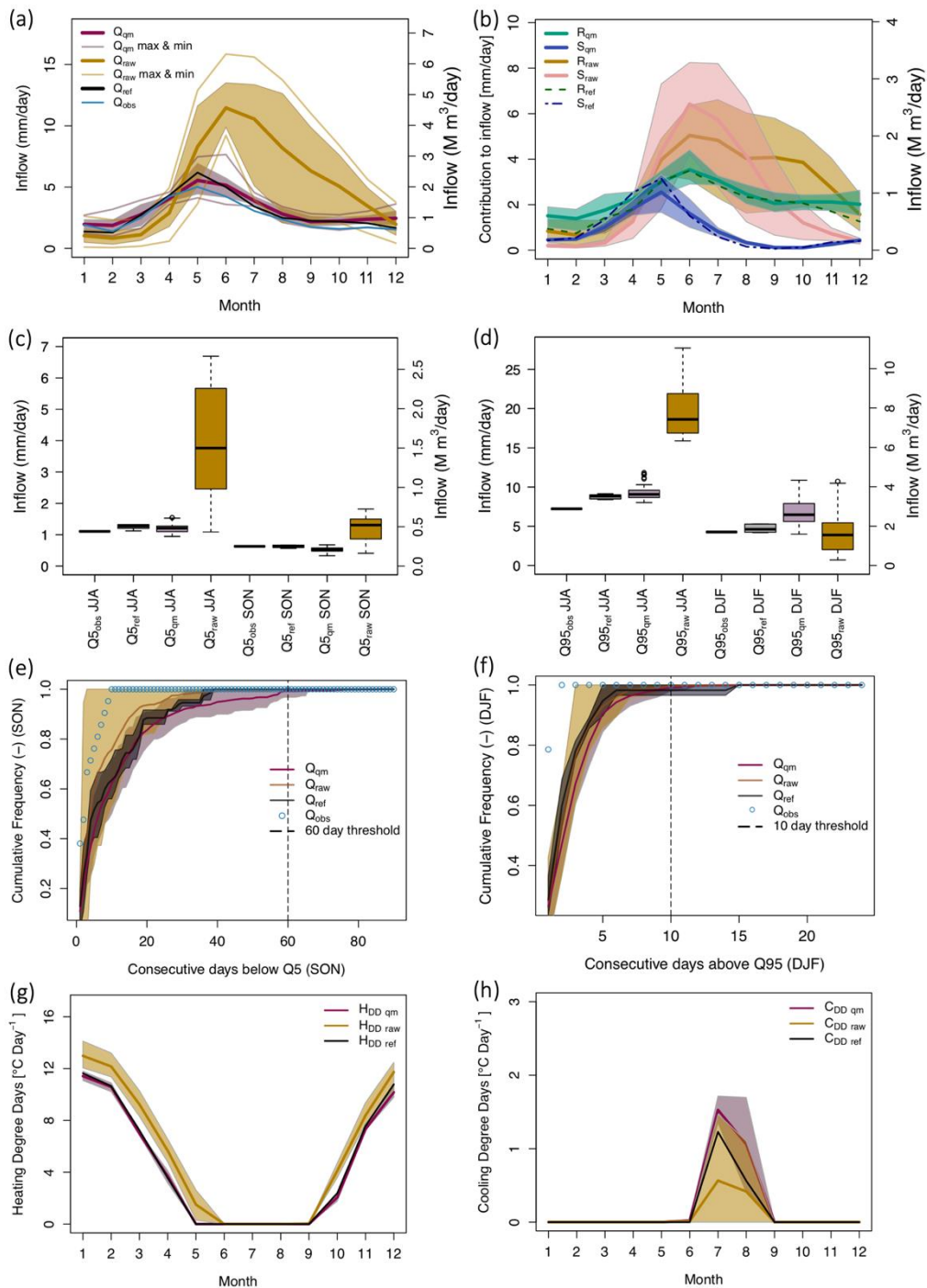
Vulnerability	Decrease in inflow and changes in its seasonal distribution	Increase in the duration of low flows while simultaneously less water is carried by low flows	Increase in the intensity and duration of high flows	Changes in the contribution of snowmelt to inflow in the spring, when reservoirs approach their annual maximum	Decrease in electricity demand over winter and increase in electricity demand over summer
Indes	<ul style="list-style-type: none"> <li>Seasonal means</li> </ul> 	<ul style="list-style-type: none"> <li>Q5</li> <li>Consecutive days below Q5</li> </ul> 	<ul style="list-style-type: none"> <li>Q95</li> <li>Consecutive days above Q95</li> </ul> 	<ul style="list-style-type: none"> <li>Rain versus snow contribution to runoff</li> </ul> 	<ul style="list-style-type: none"> <li>HDD</li> <li>CDD</li> </ul> 
Likely projected changes	<ul style="list-style-type: none"> <li>Increase in long-term mean inflow over the winter</li> <li>Decrease in long-term mean inflow over summer and fall</li> </ul>	<ul style="list-style-type: none"> <li>Reduction of the magnitude of water carried by Q5 by 50% over the summer and fall seasons</li> <li>The duration of low flows below Q5 will likely increase</li> </ul>	<ul style="list-style-type: none"> <li>The duration of high flows above Q95 will likely increase over the winter</li> <li>Decrease in summer high flows</li> </ul>	<ul style="list-style-type: none"> <li>Peak contribution of snow melt to inflow will likely shift from May to April</li> <li>Rain will increase its contribution to inflow during the winter</li> </ul>	<ul style="list-style-type: none"> <li>Decrease in demand for energy over the winter</li> <li>Increase in demand for energy over the summer and fall</li> </ul>
Opportunity – adaptation option	<p>Electricity prices have traditionally been at their highest during winter. Hydropower operations could be adapted so that they can capture and turbine the expected increase of inflow over winter.</p> <p>Summer flows are expected to be less reliable for energy supply. A more diverse energy mix could offset this change.</p>	<p>The projected increase in the duration of low flows and simultaneous reduction of water carried by these low flows needs to be accounted for when negotiating residual flow requirements during the concession renewal negotiations. The water fee framework should also consider the expected reduction of flow.</p>	<p>If captured, the increase of high flows over winter could be turbinated when energy prices are typically at their highest (or locked in at a high price).</p> <p>Summer high flows cannot be relied upon to offset drought. A diverse energy mix could be used to help meet consumer needs.</p>	<p>As spring runoff derived from snowpack becomes less reliable, it may be useful to increase the reservoir's ability to capture and store high intensity rain events. Bolstering forecasting systems could help utilize high intensity rain events in spring and prevent the risk of spillover as the reservoir level is approaching its annual maximum (late spring).</p>	<p>Flexibility could be incorporated into the concession agreement (e.g. duration of contract, installation design and capacity, low flow requirements), to allow hydropower the ability to fill gaps when possible. Simultaneously, the increasing role of renewables in the market could be considered, along with the intermittency of their production.</p>



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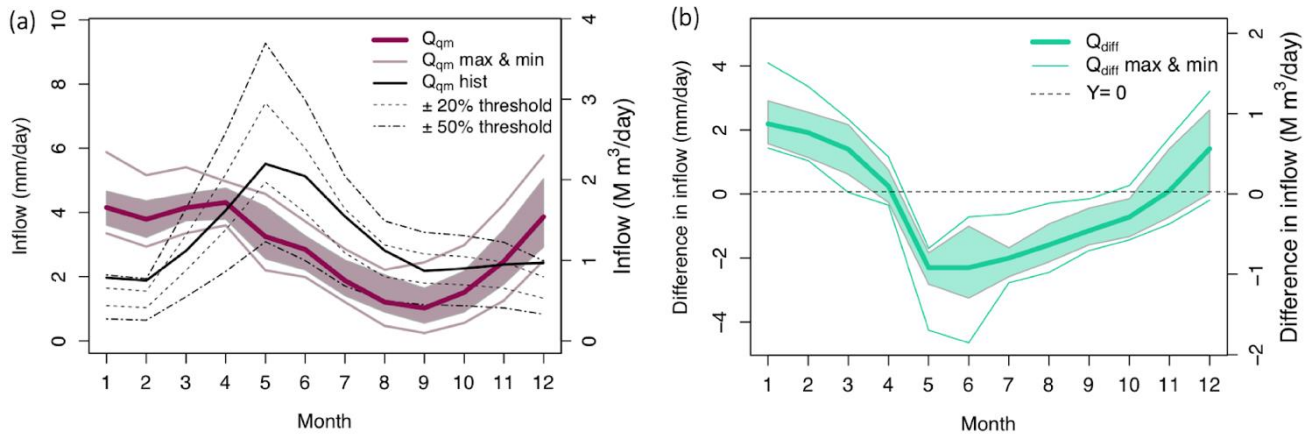
Figure 1: Map of the two study catchments Montsalvens (blue) and Vernex (orange). The river network is shown in blue (dataset provided by the Swiss Federal Office for the Environment, FOEN), the cantons are labeled and dark gray lines depict the cantonal boundaries. The major river tributaries to the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

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875 **Figure 2: Performances of calibration of HBV and bias correction treatment are shown for each index for the Vernex catchment. When observational data were not available, then only bias correction performance is shown (plots e and f). All simulated data cover the period of 01-01-1980 to 31-12-2009, except for  $Q_{obs}$  data which spans the period of 01-10-2008 to 31-08-2018. Plots a, b, g, h depict long-term monthly means.**

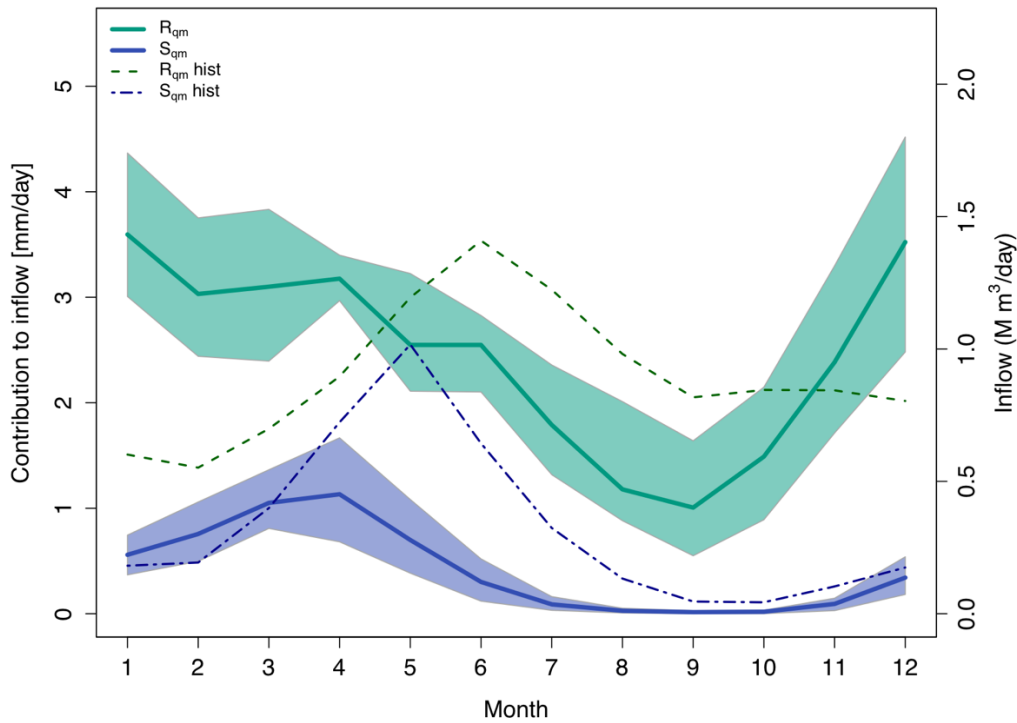




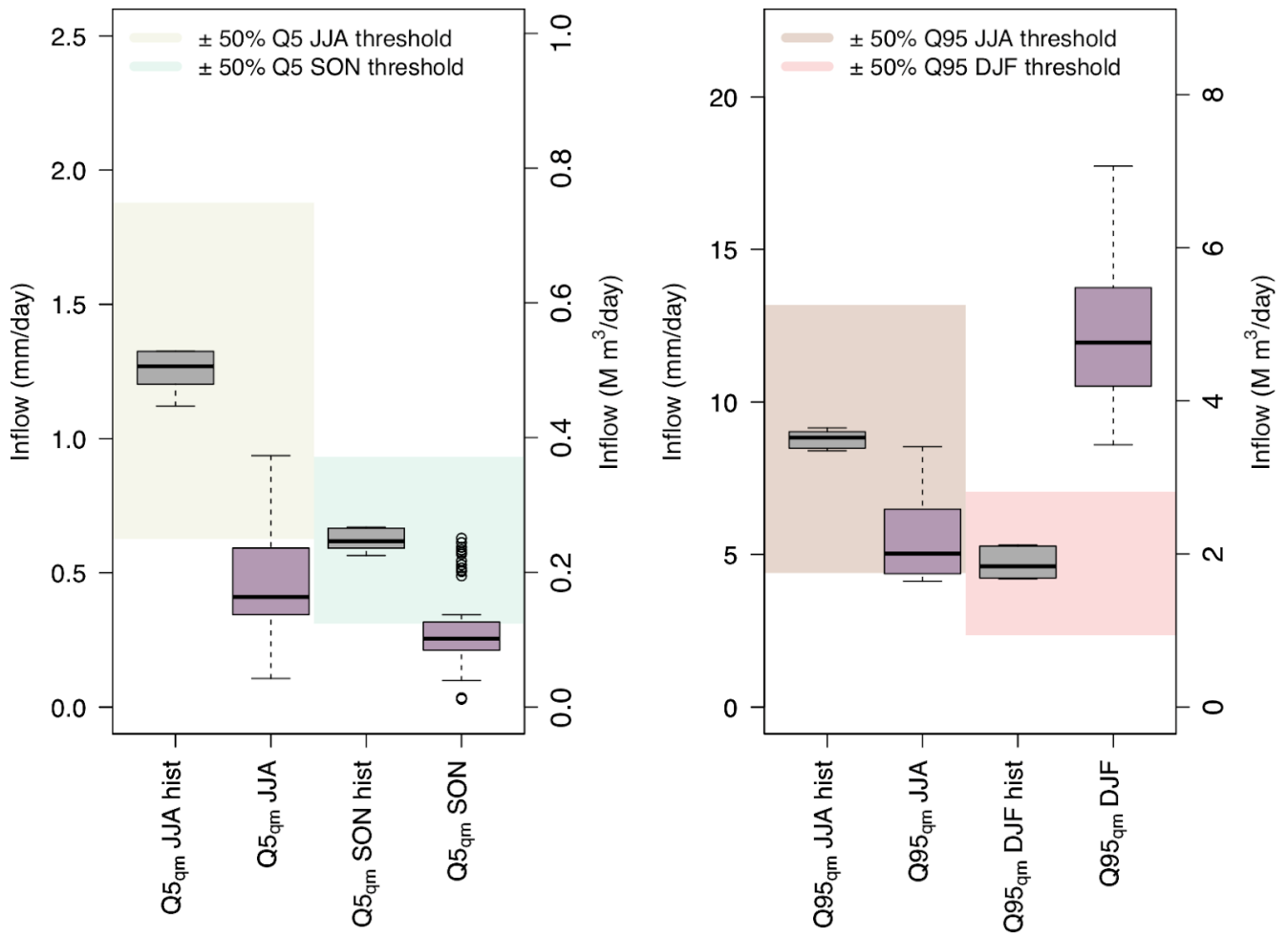
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**Figure 3: (a) Long-term mean monthly inflow entering the Vernex reservoir for 1980-2009 ( $Q_{qm}$  hist) and for 2070-2099 ( $Q_{qm}$ , RCP 8.5). The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two thirds of all 660 simulations. The two thresholds are based on the mean of the simulations forced by observed climate data ( $Q_{ret}$  over the period of 1980-2009). (b) Long-term mean monthly change in inflow (2070-2099 with respect to 1980-2009) for the Vernex catchment.**

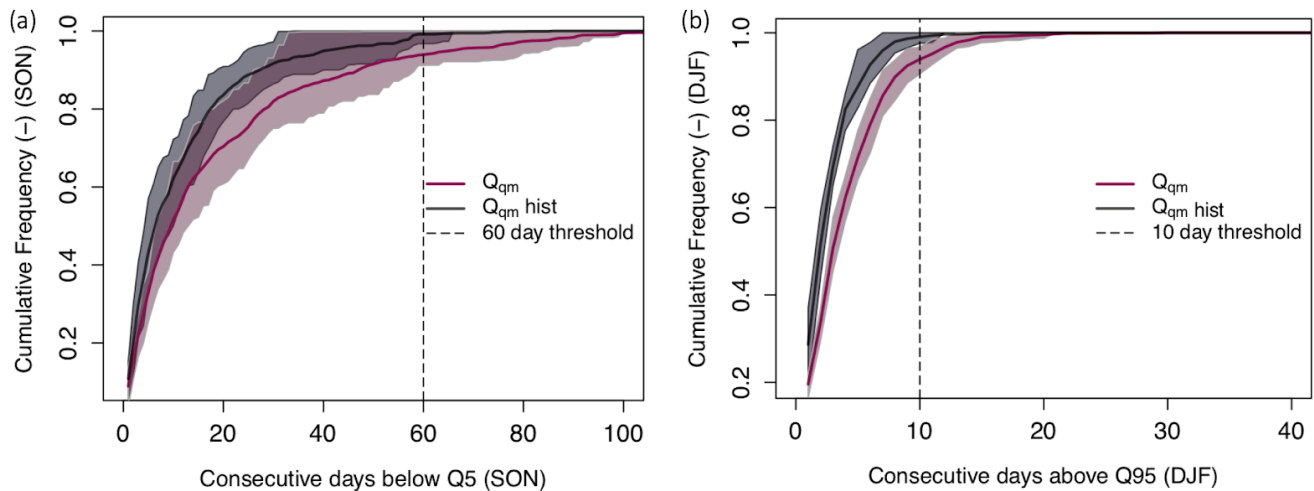


890 **Figure 4: Mean monthly contribution of rain (R, green) versus snow (S, blue) to inflow entering the Vernex reservoir. Two periods are compared: 1980-2009 ( $R_{qm}$  and  $S_{qm}$  hist) and 2070-2099 ( $R_{qm}$  &  $S_{qm}$ ). All projections shown are simulations under RCP 8.5. The mean (solid lines) and likely range (shaded areas) are shown, where the likely range represents two thirds of all 660 simulations. The dashed lines indicate the mean of the reference simulations.**



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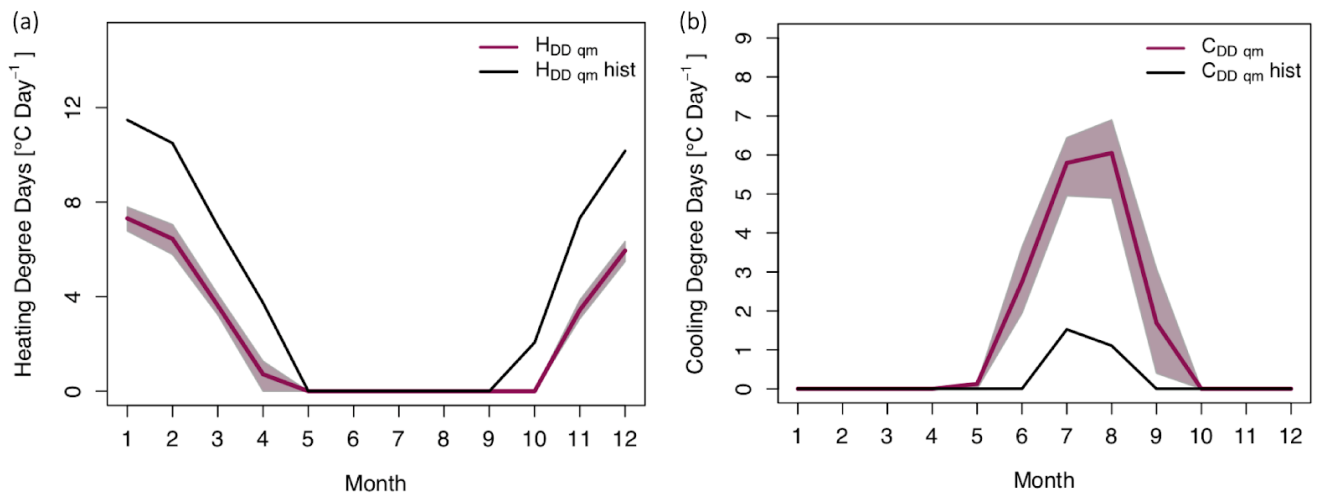
**Figure 5:** (a) Boxplots showing low flow (Q5) and (b) high flow (Q95) indices, where the historical period (gray boxplots; 1980-2009) is compared to the future period (purple boxes; 2070-2099) for inflows entering the Vernex reservoir. All projections shown are for RCP 8.5. For each index, an associated  $\pm 50\%$  threshold is designated by a shaded area. These thresholds are based on the mean of simulations when forced by observed climate data ( $Q_{ref}$ ) over the period of 1980-2009.



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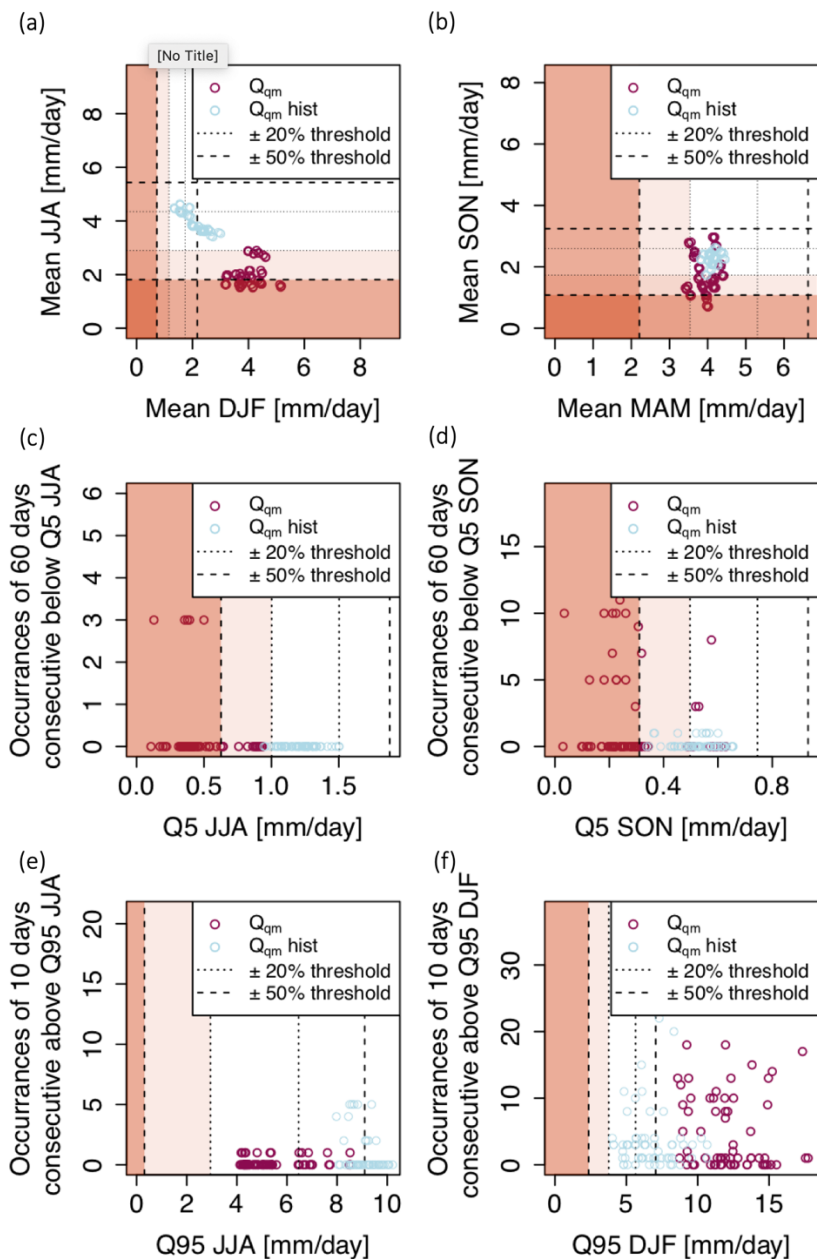
Figure 6: Cumulative distribution functions (CDFs) are shown, where the historical period (1980-2009; gray) is compared to the future period (2070-2099; purple) for the Vernex catchment. (a) CDFs for consecutive days below Q5 are shown for the SON season, and a 60-day threshold is indicated by a black dashed line. (b) CDFs of the consecutive days above Q95 are shown for the season of DJF, and a 10-day threshold is shown by a 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 all 660 simulations.



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**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 RCP 8.5 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 all 660 simulations. Group E prescribed thresholds of  $13^{\circ}\text{C}$  and  $18.3^{\circ}\text{C}$  to compute  $H_{DD}$  and  $C_{DD}$ , respectively.**

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920 **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 as left and right columns: (a-c) 1980-2009 and (d-f) 2070-2099. Plots (d-f) show simulations under the influence of RCP8.5. Plots (a) and (b) depict seasonal flows: mean winter flow (DJF) versus mean summer flow (JJA). Plots (c) and (d) depict low flows: Q5 summer flows (JJA) versus occurrences of consecutive days below Q5. Plots (e) and (f) depict high flows: Q95 winter flows (DJF) versus occurrences of consecutive days above Q95. For all plots, two thresholds are included:  $\pm 20$  and  $\pm 50$  %, which were provided by Groupe E. Shading from white to progressively darker red tones indicates the least (white) to greatest (dark red) levels of stress placed on Groupe E's operations based on the relationship between the indices.**

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