

CHALLENGES IN EVALUATING PRESENT AND FUTURE WATER RESOURCES FOR MULTI-PURPOSE USE IN A SMALL ALPINE CATCHMENT

François, Mettra¹, Emilie Neveu
Institute of Energy and Environment, School of Engineering, HES-SO Valais-Wallis
Rue de l'Industrie 23, Sion, 1950, Switzerland
francois.mettra@hevs.ch, emilie.neveu@hevs.ch

KEY WORDS

Water management, climate change, hydrological modeling, model calibration, discharge estimation.

ABSTRACT

Switzerland, known as the "water tower of Europe," provides essential water resources to its neighboring countries through its river systems. While the main Alpine region is not currently experiencing significant water scarcity at the scale of large river basins, future challenges are expected due to glacier retreat, increasing water demand across various economic sectors, and growing pressure from neighboring countries, compounded by the effects of climate change. Moreover, water scarcity is already occurring locally during dry years. In this context, it is crucial to assess water resources for multiple uses, considering synergies and conflicts between them. A key aspect is the evaluation of available water resources—both the portion allocable to specific and total uses. However, direct monitoring of these resources remains limited, particularly at the scale of Alpine users such as villages, high-altitude reservoirs, ski resorts, and small mountain catchments. To address this gap, a multi-method approach was applied, integrating sparse water usage data from municipalities, climate data, and hydrological modeling to evaluate current water resources in the Sionne catchment (Valais). This approach enabled the estimation of monthly water availability for a specific year, and a more accurate calibration of the hydrological model. Additionally, regional climate and hydrologic scenarios, combined with our small-scale calibrated model, were used to project future water resources. The adopted methodology provides insights into water availability, identifying climate trends and potentially worsening future droughts. These findings highlight future challenges in water resource assessment and support informed decision-making in water management.

1. INTRODUCTION

Switzerland, due to its central position in Europe and its climatic conditions (enhanced orographic precipitation, winter and spring snow accumulation, and long-term water storage in glaciers), is known as the "water tower of Europe". While local communities can temporarily face drought impacts, at a larger scale, water scarcity was not yet really experienced in Switzerland in recent decades. However, with increasing water demand, inside and outside of Switzerland, and the effects of climate change, droughts are expected to occur more frequently, potentially concerning large areas [1]. In Valais, also considered as the "water tower of Switzerland", notably due to its glaciers representing still 10% of the surface area in 2024, the central Valais is paradoxically one of the driest regions of Switzerland. In addition, Valais is relatively densely populated and well-industrialized for a mountain region, including large, irrigated areas for agriculture, leading to widespread withdrawals for a variety of usages, even in small high Alpine catchments. Major storages and diversions by hydropower infrastructures have been accounted in hydrological modelling for flood predictions [2], [3] and water management [4] with an increasing interest with the emergence of multipurpose projects [5], [6]. However, other types of withdrawals, as they are much smaller than fluxes managed by hydropower, are generally not considered in regional hydrological modelling [4], [7] although those hydrological models are used to manage those same withdrawals. This could be a significant methodological bias, especially in small Alpine catchments where local communities rely on local water resources.

¹ Corresponding author

This study uses the case of the Sionne catchment in central Valais, Switzerland, which represent well the challenges in water management of the region. One of the objectives is to determine water resources in the whole catchment but also on this upper sub-catchment, known as Vallon de la Sionne, where crucial withdrawals for Arbaz municipality are undertaken (for drinking water of Arbaz, Grimsuat, and Sion and for irrigation of Arbaz and Grimsuat). However, the upper sub-catchment is ungauged, which complexifies water resources estimations, whereas the Swiss Federal Office for the Environment (FOEN) measures the water discharge of the Sionne River in Sion at its outlet close to its confluence with the Rhône River.

A second objective is to account for water withdrawals and inter-catchment transfers, which can be relatively large in small, Alpine, and well-human-occupied areas, like those often found in Switzerland. Those water fluxes are generally not accounted for by classic hydrological studies [7], however often aiming to determine natural resources. Brunner et al. [4] estimated water demand and supply at a regional scale for Switzerland to assess present and future water scarcity. However, their focus was on the final water consumption and not on the water withdrawn from catchments and rivers, which is always significantly larger than the final water consumption. Moreover, water demand can vary at the local scale, and regional estimations have only been done annually or sometimes at the seasonal scale, generally due to the sparse and low temporal resolution of historical records on water withdrawals, production, and consumption [8]. In addition, in Valais, the presence of the traditional irrigation systems, *les bisses*, leads to important water transfers between catchments and rivers, which have to be taken into account when assessing water resources ([9], [10], [11]).

Finally, our last objective is to look at dry years, as it is well known that the average climatic and hydrologic trend might not represent the drought trend. To do so, hydrological modelling and analysis at a year scale, rather than at climatic scale, is needed.

In this paper, the following research questions are addressed:

- Is it feasible to account for water withdrawals and inter-catchment transfers at sufficiently high temporal resolution, and does it improve the calibration and the overall hydrological modelling on small Alpine catchments? Does it pose a serious bias in water management modelling to not account for those water fluxes?
- Can sparse or low temporal resolution data of water withdrawals permit a partial validation of hydrological models on an ungauged sub-catchment?
- In addition to hydrologic trends, what are the future water resources of specific dry years or seasons? Are they comparable to reference drought, like the 2022 drought?

2. METHODS

The general concept in this paper is to quantify the amount of water that can be shared among various uses by estimating natural water resources. To do so, we have estimated the water discharge of the Sionne River at two locations from measured discharges and the partially known water usages. A hydrological model calibrated with these natural discharge estimations could then give the future natural resources using climate change scenarios.

2.1 Study site

2.1.1 Sionne catchment

The study site includes the small Alpine catchment of the Sionne River, a right-bank tributary of the upper Rhône River in Valais, Switzerland (**Figure 1**). This nival-regime river originates at around 2080 meters altitude, at the top of the Sionne Valley, between two exposed geological units [12]. It flows through the slopes of Arbaz, Savièse, and Grimsuat before crossing the city of Sion over a course of 11 kilometers, eventually joining the Rhône at 490 m asl. The river's average discharge is 0.425 m³/s at the Swiss Federal Office for the Environment (FOEN) hydrological station in Sion (497 meters altitude) over the 2007–2023 period. The Sionne catchment, covering an area of 27.2 km², is located in a karstic zone [13]. The neighboring catchments are the Lienne catchment to the east and the Morge catchment to the west. Four municipalities, Savièse, Arbaz, Grimsuat, and Sion share parts of the catchment area. Water is mainly used for drinking water, irrigation, and hydropower, and transfers with surrounding catchments are significant.

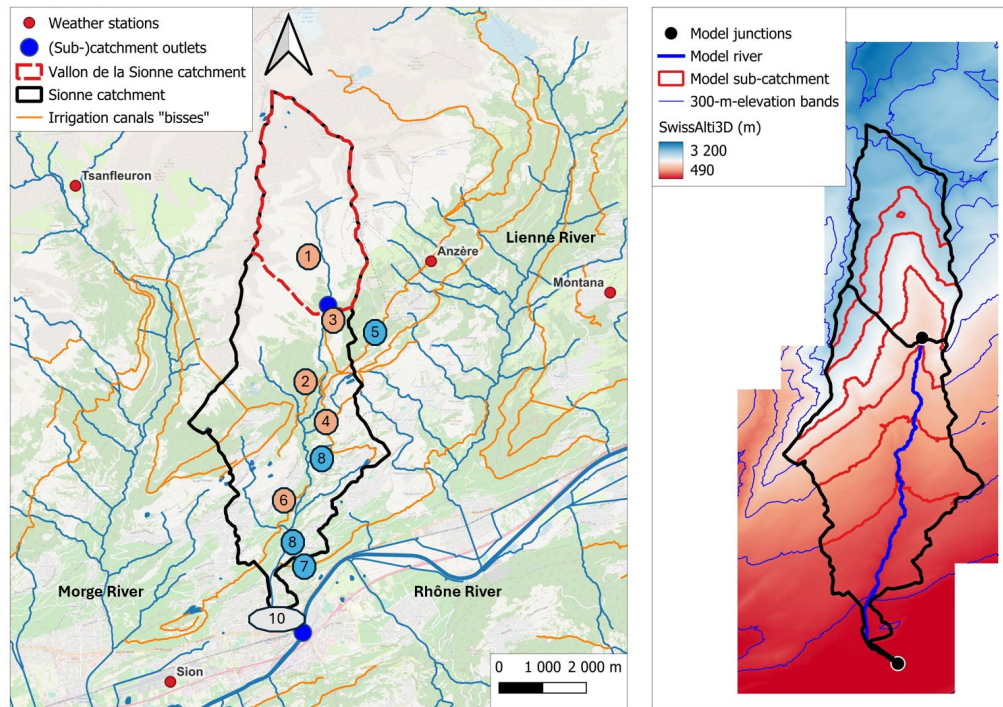


Figure 1: Maps of the study site (left) and the river, junctions, and sub-catchments used to model the hydrology of the Sionne catchment with RS Minerve software (right). Numbers refer to the list of water fluxes considered in this study (see **Table 1**): red ones are withdrawals from the Sionne River and blue ones are inputs to the Sionne River.

2.1.2 Climate and hydrology

The Sionne catchment exhibits a strong altitudinal gradient in precipitation, ranging from 583 mm in Sion to approximately 2000 mm on the highest ridges at around 2800 m asl (1991–2020 climate norms from MeteoSwiss). In 2021, a relatively wet year, Sion (483 m asl, airport site) recorded 695.7 mm of precipitation, while Montana (1424 m asl) received 1003.7 mm.

The upper part of the catchment contains numerous ravines, which remain dry most of the time. These ravines become active only during snowmelt or intense rainfall events (e.g., summer thunderstorms), which can cause a significant but temporary increase in the Sionne's flow, even during dry periods. Groundwater resources are substantial, with numerous used springs distributed throughout the catchment. Notable sources include the Sionne spring at around 2100 m, the springs in the Comba area at approximately 1650 m, the Évouettes spring group between 1500 and 1600 m, isolated springs near the localities of Vermenala, Deylon, and Incron (between 1500 and 1900 m), and *La Fille* springs, located between the Drahin and the Sionne, at elevations ranging from 1050 to 1200 m. The Sionne catchment is known to be located on karstic terrain within the Wildhorn nappe [14]. However, the hydrogeology of the Sionne catchment, particularly that of its source, remains one of the least studied in the region, partly because the Sionne spring is not exploited. However, the hydrogeology of the other springs, captured by the municipality of Arbaz, was studied by Coupy [12]. Two types of aquifers supply those captured springs: shallow aquifers (debris deposits) and deeper karst aquifers. *La Fille* springs are also located in a karstic environment, but their water supply appears to remain local.

2.1.3 Water context in the region

In Switzerland, the northern Alpine ridge, where the upper part of the Sionne catchment is situated, acts as a climatic barrier for northwestern and northern synoptic weather flows. The majority of the precipitation falls on this ridge, and, due to the Foehn effect, central Valais (the Rhône Valley), including the lower part of the Sionne catchment, receives a small amount of precipitation [15]. Moreover, evapotranspiration is high, leading to a high water deficit during the summer period from April to September in Sion in the valley at 483 m asl and a less high deficit from May to September in Montana at 1424 m asl [16]. Central Valais is therefore not well suited for agricultural crops [17]. At a year scale, water balance was approximately at equilibrium in Sion in the period 1981-2000, then significantly negative (see Figure 1), which could be the result of climate change. Note the two low extreme values in 2003 and 2022.

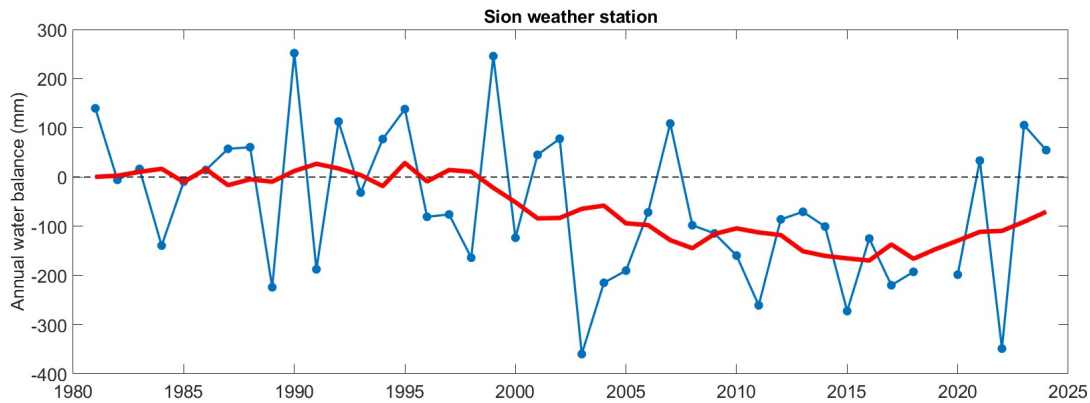


Figure 2: Annual water balance at the Sion weather station operated by MeteoSwiss. The red line shows the 10-year moving average.

Since the 11th century (or earlier), traditional irrigation systems, called *bisses* in Valais, have transferred water from high mountain rivers, most often from glacial rivers, to the dry regions of the central Valais. Nowadays, those *bisses* are still widely maintained and used for irrigation and other secondary purposes, like tourism, implying large withdrawals from Alpine rivers and water transfers from one catchment to another. As *bisses* use is still traditional, water fluxes in those irrigation systems are poorly quantified, which makes the evaluation of water resources and transfers difficult.

On our study site, two *bisses*, *Sion* and *Clavau*, bring water from the Lienne River catchment to the Sionne River. *Bisse de Sion* aims to only transfer water from the Lienne catchment to the Sionne River, whereas *bisse de Clavau* is used to irrigate vineyards. As water continuously runs in the *bisses* from spring to autumn, it is estimated that they transfer 75% of the water to the receiving river, accounting for irrigation consumption and leaks. Three main *bisses* withdraw water from the Sionne River: *Bitaille*, *Grimisuat*, and *Lentine*. Much of this water is used for irrigation or leaves the catchment. Note that *Bisse de Bitaille* withdraws water from the upper sub-catchment, Vallon de la Sionne, all year round.

2.2 Data collection

Data were collected from different sources. Water withdrawal and usage were available from the concerned municipalities. It includes quantitative data and estimations. Interviews with municipal officials and technicians responsible for the water network were carried out to be able to estimate all water fluxes linked with the Sionne River. Cantonal inventories were also used. Environmental data primarily comes from federal services, notably the FOEN, MeteoSwiss, and the NCCS.

2.2.1 Water withdrawal and usage data

Captured discharges from the springs were usually not directly measured. Withdrawals were estimated indirectly using measurements available in water networks. Those measurements do not exactly represent the available spring resources because during high flow periods water cannot be entirely captured by the infrastructure. Moreover, the available data were not validated and not corrected. However, it represents well the withdrawal, i.e. the part of the water that does not feed the Sionne River. Several other fluxes are not measured in the Sionne catchment, as water is captured in the Sionne River at several locations via the *bisses* and used for irrigation, which represents large water volumes. Those unmeasured fluxes are roughly estimated from indications given by the users, local stakeholders, and the respective water rights determined originally for each *bisse*.

2.2.2 Geospatial data

Basic geospatial hydrological data were freely available from the FOEN (main catchment limit, river network). We used the SwissAlti3D product, a 2-m-resolution elevation model, from SwissTopo (the Swiss Federal Office of Topography) to build the hydrological model and compute the altitudinal statistics.

2.2.3 Meteorological data

Hourly meteorological data, corrected and validated, were freely collected from the MeteoSwiss portal IDAWEB. It includes two main weather stations (Sion and Montana) to calibrate the model (because they have a long historical record, and they are present in climate change scenario CH2018) and two other pluviometric stations (Anzère and Tsanfleuron) to compute the altitudinal precipitation gradient in 2021.

2.2.4 Historic hydrological data

Hydrological data at the outlet of the catchment, corrected and validated, were collected from FOEN. 5-minute and hourly average discharge was available from 2006 until 2024.

2.2.5 CH2018: Swiss Climate Change Scenarios

CH2018 is the name of the last update of the climate change scenarios of the Swiss National Centre for Climate Change (NCCS). Those scenarios are based on the EURO-CORDEX ensemble of regional climate simulations [18]. CH2018 consists of 68 simulation chains (combinations of global climate models and regional climate models) with either an original spatial resolution of 12.5 km or 50 km, spanning the 3 Representative Concentration Pathways (RCPs) scenarios, RCP 2.6, RCP 4.5, and RCP 8.5. The available data at Montana and Sion weather stations is bias-adjusted and downscaled daily series of meteorological variables from 1981 to 2099 [14]. In the present study, hourly data temporally downscaled from CH2018 data by Michel et al. [19], [20] are used.

Recently, the NCCS developed a climate model ensemble sub-selection for impact studies to facilitate the use of the climate scenarios [21], [22]. It permits selecting 3 simulation chains (T1, T2, and T3) that represent the full simulation ensemble for one type of impact: one simulation representing the median ensemble and two other simulations two terciles relative to this specific impact. In the present study, the concerned thematic is the future availability of water resources; thus, we choose the three simulations that represent well the impact of drought.

The 1981–2010 period serves as the reference period for the CH2018 simulations. This reference is simulated for each of the 68 simulation chains. These simulations accurately reflect the climate measurements of the 1981–2010 period, which were used for bias correction. However, they do not reproduce the actual chronology of observed events, as they are based on past climate simulations rather than historical weather data. For example, exceptionally hot or dry years may not be represented exactly or at the same time, though the 30-year statistics are preserved. In this study, the reference hydrological simulation uses historical weather data to be able to analyze specific dry years, like 2003 or 2022, against future dry years.

2.2.6 Hydro-CH2018: hydrological scenarios

To quantify current and future water resources using a method that is easily reproducible in other Swiss catchments, the Hydro-CH2018 scenarios were used [1]. These scenarios are themselves based on the CH2018 climate scenarios [23]. The relevant Hydro-CH2018 data for this study consists of gridded (raster) data from hydrological modeling of Swiss catchments between 1981 and 2099. These data were produced by WSL [24] and are available through the NCCS website (gridded Hydro-CH2018 dataset). The data represents the streamflow generated at each grid point (500 m x 500 m), including surface runoff and subsurface flow that reaches the surface. They were derived from hydrological modeling using the PREVAH model [25], [26], which was calibrated and validated for Swiss conditions [27], [28], [29], [30].

These gridded data are available for four 30-year climatic periods (1981–2010, 2020–2049, 2045–2074, and 2070–2099) and three greenhouse gas emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5). They provide both annual and monthly values for each period and scenario. We use here the mean value of the available RCP 8.5 climate simulations for the period 2070–2099. In practice, the gridded data are integrated into a Geographic Information System (GIS) and aggregated over the relevant catchments to estimate the volume of available water resources. Indeed, the sum of the streamflow values from each grid point within a catchment corresponds to the discharge at the outlet of that catchment [24] and can be easily evaluated on any catchment in Switzerland. These simulation data have been commonly used in Switzerland, for example, to investigate potential water shortages from the national scale down to fine spatial scales of 30 km² [4]. Gonin [31] also successfully used these data to estimate water resources on the left bank of the Val de Bagnes in Valais on catchments of 0.1 to 2 km².

2.3 Natural river discharge reconstruction

One of the objectives of this study is to determine the present water resources in the Sionne River. Compared to 35.6 Mm³ falling as precipitation over the catchment in 2021, the known withdrawals in the catchment of about eight Mm³ and transfers towards the Sionne from the Lienne catchment (east of the Sionne) of three Mm³ are significant. A water transfer exists between the Morge catchment (west of the Sionne) and the Sionne catchment; however, the volume is relatively small, and it is entirely used by the Grimsuat municipality in irrigation (no return to the Sionne). This flux is then not considered in this study as it does not influence the Sionne River. Moreover, the seasonal variations of the precipitation, withdrawals, and transfers are important, which underlines the necessity of reconstructing the natural discharge to work on the natural resources available in the catchment and prevent, for instance, considering the unknown usages when modelling future resources. We aim to estimate natural resources, i.e. to reconstruct the natural discharge of the Sionne River without its present human influence and to model natural water resources available given future climatic scenarios.

	Water fluxes	Description	Data availability	Data temporal resolution	Type of data	Type of flux relative to the Sionne River
1	Arbaz springs	Inflow drinking water reservoir	14.02.2012 to 23.10.2024	daily	flowmeter	Withdrawal – Vallon de la Sionne
		To hydropower Arbaz	01.01.2021 to 31.12.2021	daily	flowmeter	Withdrawal – Vallon de la Sionne
		Bypass to lake (Arbaz)	01.01.2021 to 31.12.2021	daily	flowmeter	Withdrawal – Vallon de la Sionne
2	Springs of La Fille		01.01.2021 to 31.12.2024	daily	flowmeter	Withdrawal – downstream Sionne
3	Bisse de Bitailla		2021	monthly	estimation	Withdrawal – Vallon de la Sionne
4	Bisse de Grimsuat		2021	monthly	estimation	Withdrawal – downstream Sionne
5	Bisse de Sion	From the Lienne River	2021	monthly	estimation	Input – downstream Sionne
6	Bisse de Lentine		2021	monthly	estimation	Withdrawal – downstream Sionne
7	Bisse de Clavau	From the Lienne River	2021	monthly	estimation	Input – downstream Sionne
8	Tsamaraude stream		2021	monthly	estimation	Input – downstream Sionne
9	Hydropower station	Unused drinking water	01.01.2021 to 31.12.2021	daily	estimation	Input – downstream Sionne
10	Hydrologic station	From drinking water network	19.10.2006	5-min-average	rating curve	outlet flow

Table 1: List of data available from different sources in the catchment and used to compute the reconstructed natural discharge. The periods of availability and the type of data are given. The numbers in the first column identify where those withdrawals, transfers, and measurements are located in the map of **Figure 1**.

The natural water discharge of the Sionne River in Sion is reconstructed from measurements at the hydrological station (main outlet of the Sionne catchment in Sion) and the withdrawals used by municipalities for different usage like irrigation, drinking water, and hydropower impacting the whole catchment and also the upper sub-catchment *Vallon de la Sionne*. This natural discharge estimation will be used to calibrate the hydrological model, which computes the natural discharge from climatic variables. **Table 1** shows a summary of the different withdrawals from the Sionne River by the concerned municipalities and the transfers (inputs) to the Sionne River from the Lienne catchment or water returns from the withdrawals. It is supposed that all water used for irrigation is used locally or by evapotranspiration and does not partly return to the Sionne River. We note that a large part of the water flowing in the *bisses* is simply transferred as the irrigated parcels along

its way do not use all the water. In addition, our discharge reconstruction assumes 25% of loss along the *bisses*. This represents the main uncertainty in the reconstructed natural discharge.

2.4 Hydrological modelling

The hydrological modelling is conducted using the RS Minerve software. Significant GIS preparatory work is needed.

2.4.1 RS Minerve and SOCONT model

To study water resources in the catchment, we use the semi-distributed conceptual hydrological model SOCONT implemented in RS Minerve software [32]. The SOCONT model is widely used in Alpine environments and was developed and used in Switzerland [33], [34]. It combines a snow model (Snow-SD), an infiltration model (GR3), and a runoff model (SWMM). The catchment is decomposed into 2 zones: the upper part, the Vallon de la Sionne, and its lowest part. Each zone is cut into 300m elevation bands to represent the high altitudinal gradient of precipitation. The water computed at the outlet of the upper zone is routed via a river object in RS Minerve to the main catchment outlet using the kinematic wave model available in RS Minerve. The built-in formula of Oudin [35] was used, which depends on the latitude (46°) and temperature computed for each altitudinal model band.

2.4.2 GIS analysis

The Sionne catchment is divided into two main sub-catchments. The outlet of the upper sub-catchment is chosen as the location of several withdrawals at the downstream part of the *Vallon de la Sionne*, where water is taken from several springs for drinking water and from the Sionne by the *bisse de Bitaille*, mainly for irrigation. Each sub-catchment is divided into altitudinal bands of 300 m using the 2-m-resolution elevation model SwissAlti3D.

2.4.3 Parameter calibration and model validation

Parameter calibration is done manually with visual inspection because the discharge reconstruction used for the calibration is based on data of different time resolution and precision. The predicted natural discharge may not accurately reflect peak flow at the hourly and daily scales, but weekly and monthly volumes should be accurately estimated. For this reason, the model's performance and validation are done on aggregated data at a monthly scale, which is also the scale of importance for water resources management. This prevents the use of the automatic calibration that is offered in RS Minerve. For each band, the SOCONT parameters were adjusted to simulate the 2021 discharge estimation. Less effort was made to simulate well flood peaks, which are often brief and have little bearing on the annual water balance, in favor of matching water volume and accurately depicting well low flow circumstances.

Further, a complementary validation was conducted with the entire time series of the measured discharge (the natural discharge was not reconstructed for other years than 2021). Although withdrawal and transfer water fluxes are not available for other years than 2021, simulated discharge is expected to be higher, particularly during the winter season and in spring, similar to 2021. Water flows in *bisses* usually do not change much from year to year, but spring water withdrawals might vary significantly with climate, usages (drinking water or hydropower), and other operations (work or maintenance).

2.4.3 Future changes

The calibrated model is used to estimate future water resources using CH2018 data. Water scarcity is assessed considering the present water withdrawals and consumptions. Simulations of 30-year climatic periods were started 32 months before the start of the analysis, matching the start of a hydrological year, i.e. in October 1992 and in October 2067 for the reference periods 1995-2024 and 2070-2099, respectively. The reference simulations (on the reference period) use observations (at Sion and Montana weather stations) instead of the synthetic data from CH2018, which permit comparing critical dry years, like 2003 and 2022, with future dry years. That is why the most recent period, 1995-2024, was chosen as the reference period, which differs from the CH2018 and Hydro-CH2018 datasets.

3. RESULTS

3.1 Precipitations

3.1.1 Altitudinal precipitation gradient

The altitudinal precipitation gradient in 2021 was computed using pluviometric data from the four weather stations. Annual precipitations as a function of the elevation are shown in **Figure 3**. For the lower catchment, the altitudinal gradient is about 30 mm/100 m and reaches about 160 mm/100 m on the upper catchment. Those gradients are coherent with those estimated in the region using older data [10], although the gradient in the upper catchment is larger in our 2023 data (including more recent weather station on a reduced area). Those two different gradient estimates are used as a modeling parameter of the model bands. Values of 30 mm/100 m and 160 mm/100 m are allocated for model bands below 1500 m asl and above 1500 m asl, respectively.

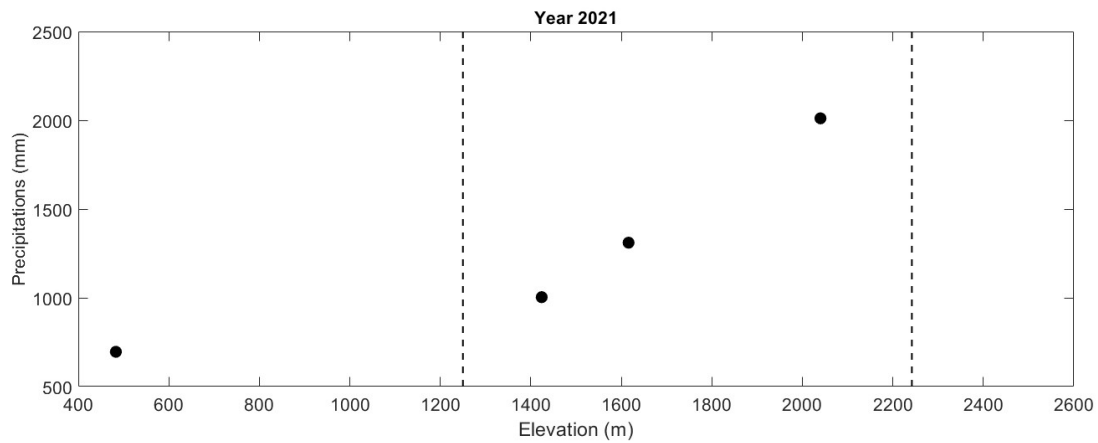


Figure 3: Precipitation measured in 2021 by the MeteoSwiss weather stations located near the Sionne catchment: Sion, Montana, Anzère, and Tsanfleuron (listed in order of increasing altitude). The vertical lines indicate the average elevation of the two Sionne sub-catchments studied here.

3.1.1 Precipitation volumes in the catchment

	Mean elevation (m)	Area (m ²)	Precipitation (mm)	Volume of precipitation (m ³)
Vallon de la Sionne	2 242	9 200 000	2 300	21 160 000
Sionne - downstream	1 250	18 200 000	900	16 380 000
Sionne - all	1 579	27 400 000	1 300	35 620 000

Table 2: Estimated precipitations over the Sionne catchment for the year 2021 and the corresponding volumes. The surface areas were calculated based on the topographic sub-catchments.

3.2 River discharge reconstruction

The analysis shows that the withdrawals are larger than the artificial inputs to the river through the whole year. This means that the discharge measured by the FOEN at the outlet of the Sionne catchment is annually an underestimation of available natural water resources. In **Figure 4**, the natural discharge estimation made at the hydrological station is always higher than the measured one in 2021. The absolute difference is small in summer due to a larger compensation from water from the Lienne watershed, notably via the *bisse de Sion* and the *bisse de Clavau*. However, this difference (absolute and relative) is large during the extended winter period (from October to April), with the natural estimate occasionally being twice the measured discharge, particularly in low-flow circumstances. This underlines the importance of making efforts to reconstruct this natural discharge to have better-representative data to calibrate hydrological models, at least for drought purposes.

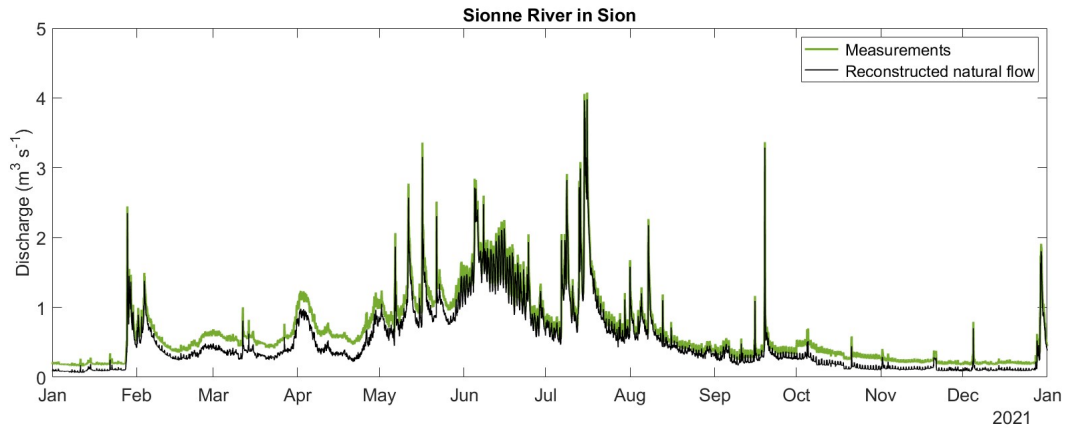


Figure 4: Determination of the natural water resources in the Sionne catchment: measured and reconstructed natural discharge of the Sionne River at the catchment outlet in 2021. The natural discharge represents the discharge that the river should have without human intervention on water fluxes.

3.3 Current resource evaluation

3.3.1 Model calibration

The calibration was undertaken with the reconstructed natural discharge at the outlet of the catchment (civil year of 2021; **Figure 4**). The simulation started 32 months before January 2021. Overall, the simulation done with the calibrated model generally represents correctly the 2021 reconstructed discharge (**Figure 5**). Flood peaks, winter and spring flows (January to April and November and December), and long periods of low flows are well simulated. The end of the snowmelt period in June and flood recessions from August to October are less well simulated. This leads in 2021 to a model overestimation of water volumes in August and October and an underestimation in June (**Figure 6**).

When calibrating the model, an excessive amount of water was present in the model. This might be due to the karst environment of the upper part of the catchment. Using the dedicated parameter on the altitudinal model bands corresponding to the karstic area, precipitation was removed from the model in order to address this issue. This fact might indicate a strong influence of the karst in this catchment, which should be investigated further to confirm our findings.

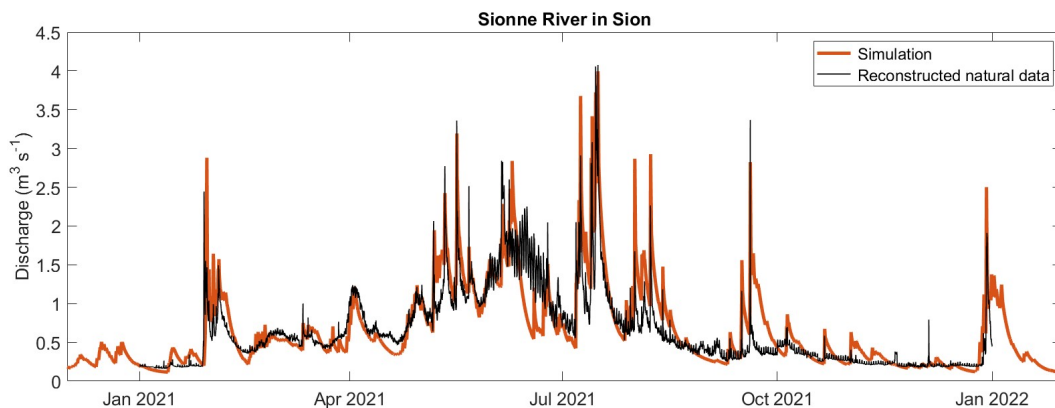


Figure 5: Simulated and reconstructed natural discharge of the Sionne River at the catchment outlet in 2021.

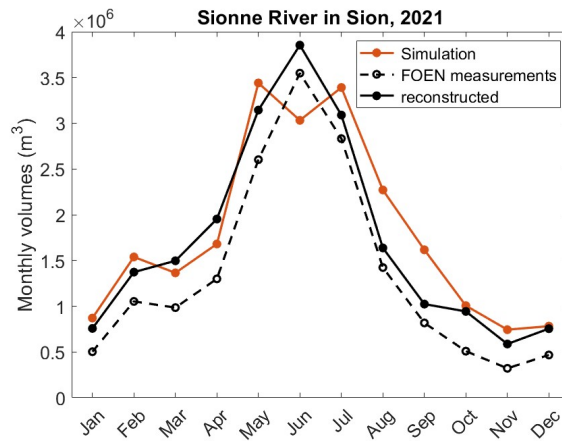


Figure 6: Monthly volumes computed from the time series of: (1) the simulation of the natural discharge with RS Minerve, (2) the FOEN measurements (influenced by human infrastructures), and (3) the reconstructed natural discharge.

3.3.2 Validation of the hydrological simulations

Figure 7 and **Figure 8** present data that gives some elements of validation; however, no complete validation can be done because the reconstruction discharge could not be undertaken for other years than 2021. At *Vallon de la Sionne*, the river discharge is not measured, and a full discharge reconstruction was not possible. However, the withdrawals on the upper sub-catchment might be useful to partly evaluate the simulation. On **Figure 8** (right), the simulated data is almost always superior to the estimated withdrawals. During winter, the withdrawals are almost equal to the available resources, which is expected given the capacity of the water infrastructures. This partly validates the simulation for this upper sub-catchment.

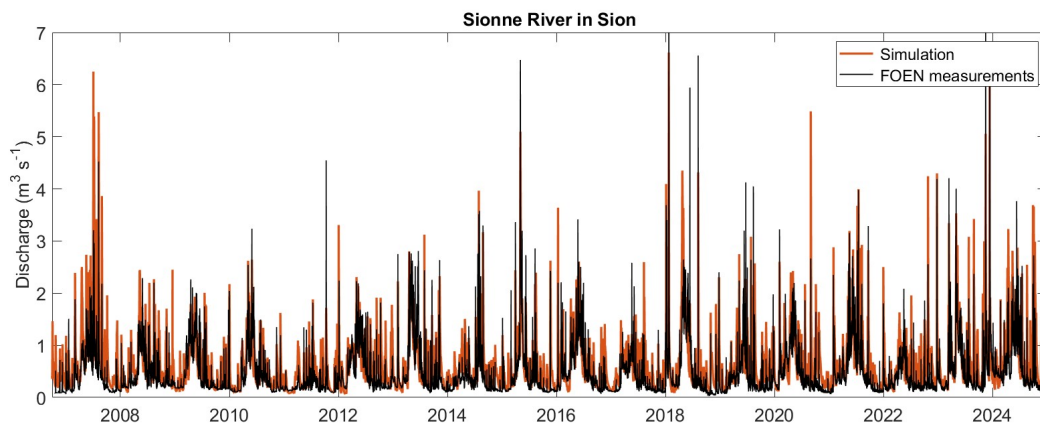


Figure 7: Simulated and measured (unadjusted FOEN data) discharge of the Sionne River at the catchment outlet during the period 2006-2024.

3.3.3 Current resource

The daily snowmelt amplitude of the natural discharge in Sion is relatively small, except in June, as seen for 2021 (**Figure 5**) and other years (not shown). Small daily peaks are linked to hydropower and drinking water consumption, both sharing the same water network. Sharp flood peaks from rainfall events occur all year round. Maximum base flow is at the end of spring in June in 2021 (wet year) and rather in May on average. Low flows occur from October to February (**Figure 6** and **Figure 8**).

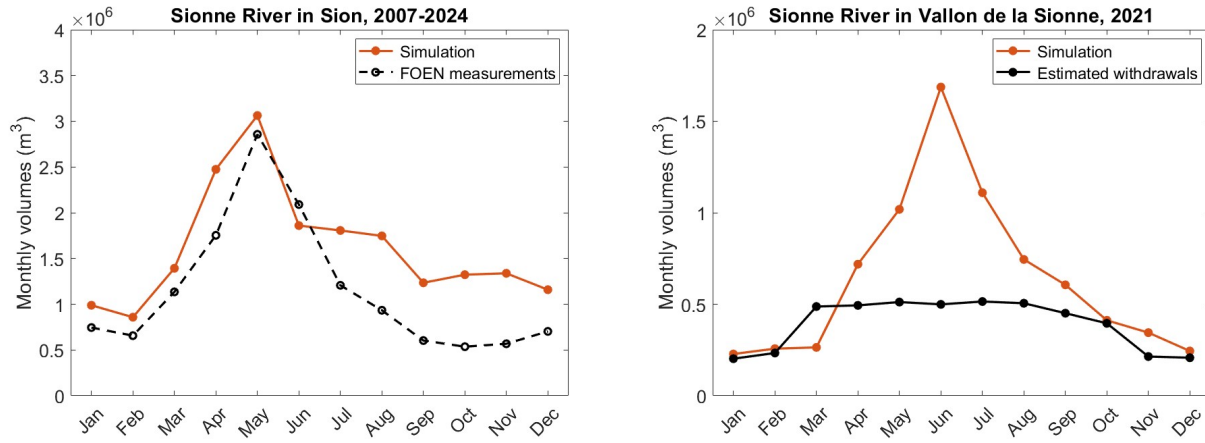


Figure 8: Monthly volumes of the simulation and available measurements and estimations to validate the model. Left: Sionne discharge measurements (uncorrected, unreconstructed) at the outlet of the catchment, which is expected to be lower than the simulated natural discharge (see section 3.2). Right: Simulated discharge in the upper catchment (Vallon de la Sionne) and estimation of the concerned withdrawals (*Bisse du Bitaila* and *Arbaz* springs).

3.4 Future resource evaluation

3.3.1 Future resource simulations

Figure 9 presents the three simulations, T1, T2, and T3 (RCP 8.5) for the period 2070-2099 and the reference simulation. For the three 2070-2099 simulations, monthly volumes increase significantly from November to February. For T2 and T3, the increase is large until April with a snowmelt peak in April instead of May, and a strong low-flow period appears in July and August and until October for T3. For *Vallon de la Sionne*, the changes seem to be less pronounced for the low flow period, with still a significant advance of the snowmelt peak flow meaning that water resources decrease quickly at the end of the spring.

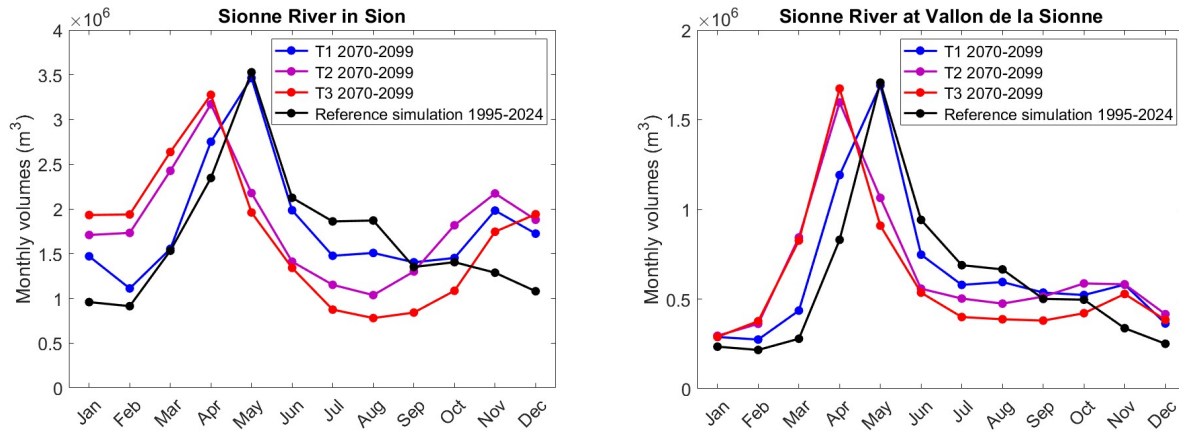


Figure 9: Simulated monthly volumes of the Sionne River in Sion (left) and *Vallon de la Sionne* (right), from RCP 8.5 scenario on 2070-2099 and observations on the reference period. The three simulations, T1, T2, and T3, represent the sub-ensemble (first and third terciles and average) of the CH-2018 for drought.

3.3.2 Comparison with Hydro-CH2018 data

Figure 11 presents the comparison of our simulations (the median simulation) with the Hydro-CH2018 datasets for *Vallon de la Sionne* and the main outlet in Sion. For both the reference period and the 2070-2099 period, Hydro-CH2018 simulations overestimate the discharge compared to our simulations. Note that the reference is not the same, although there is a 15-year overlap.

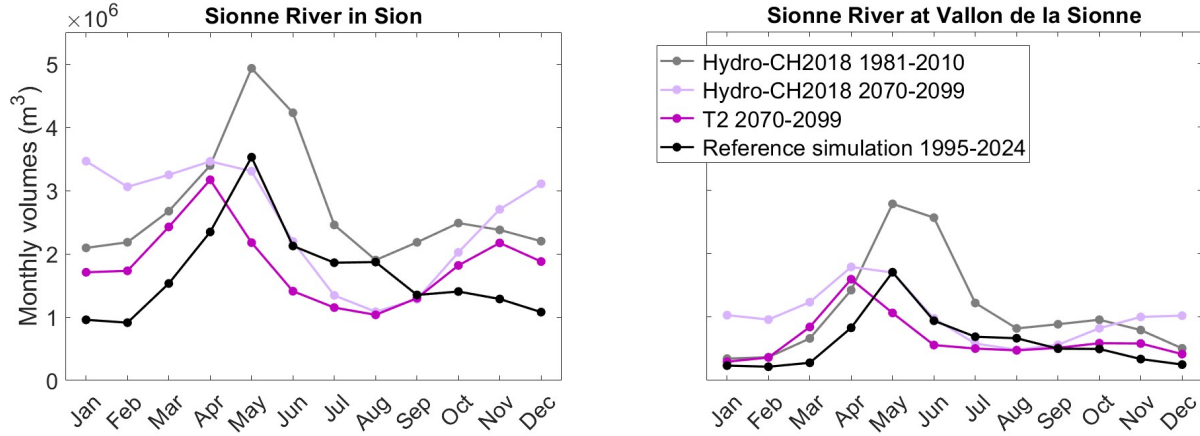


Figure 10: Comparison between the simulation of the present study and the analyzed Hydro-CH2018 data for RCP8.5 scenario. Left: at the outlet of the Sionne catchment. Right: on the upper sub-catchment (Vallon de la Sionne).

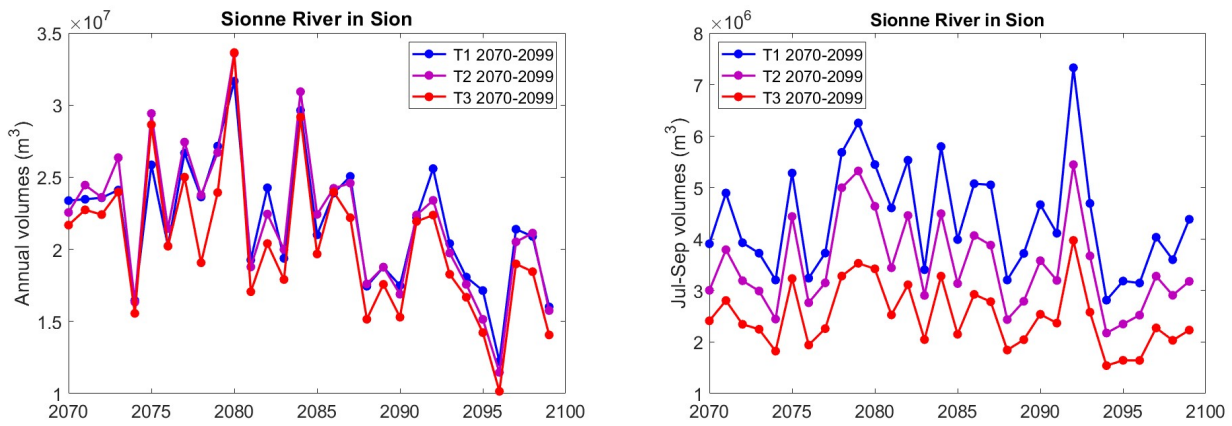


Figure 11: Time series of annual (left) and Jul-Sep volumes simulated on the 2070-2099 period for T1, T2, and T3 climate simulations.

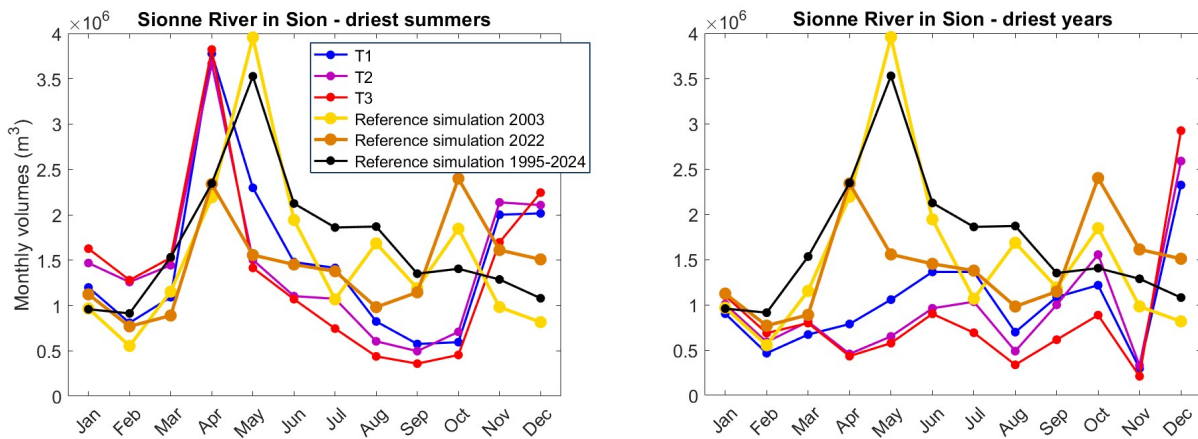


Figure 12: Simulated monthly volumes of the Sionne River in Sion of the driest summer (left) and year (right) from RCP 8.5 scenario on 2070-2099 and the past dry cases of 2003 and 2022.

3.3.3 Drought analysis

To improve our understanding of future challenges in water management, particularly in drought preparation, we look at historic drought years like 2003 and 2022 and compare them with potential future droughts from our simulation. Driest years and summer in 2070-2099 simulations were selected on the annual and Jul-Sep volumes, respectively, which are represented in **Figure 12**: 1994 and 1996 are respectively the driest summer and year. **Figure 13** shows those past and future dry years and summers along the reference simulation for

comparison. For the whole range of future simulations, the summer drought seems to be worse than 2022 and 2003, with low flow all year round for the dry year case. Interestingly, the case of the driest future summer occurs after a relatively high snowmelt peak flow (comparable to the reference simulation) and after a wet winter than the reference simulation. This shows that even wetter winters in the future might not prevent summer drought due to higher temperatures and stronger subsequent evapotranspiration.

4. DISCUSSION

The reconstruction of the natural Sionne discharge was based on known measurements and estimations through a quite exhaustive data collection. This has been made at the daily scale for fluxes linked to drinking water and at the monthly scale for other fluxes. We show that those withdrawal and transfer fluxes significantly influence the Sionne discharge, particularly at low flow, but some fluxes are still unknown or have large uncertainties. First, the rainwater captured by urbanized surfaces and transferred to the water treatment plant was not estimated. Second, discharges in the *bisses* are not measured, but they should approximately respect the water rights defined at their withdrawal intakes. Moreover, water is unintentionally lost along the course of the *bisses*. This could only be roughly estimated. Third, withdrawal measurements, when present, do not exactly represent the available natural water resources. Indeed, generally discharges of the water entering the drinking network for distribution management are measured, but not the discharges that are diverted before entering the network (for quality reasons, for maintenance of the network, or due to overflow). This is particularly the case for Arbaz springs because the infrastructures cannot capture all the spring water during the high flow period, and less for *La Fille* springs. Fourth, data used for the reconstruction has different formats, time resolution, purposes, and uncertainties. They have to be processed and homogenized. Notably, discharge estimations of the *bisse* are based on old water rights and what local people could tell us for 2021 (almost nothing is written). Usage data from municipalities are collected by civil years, whereas hydrological models usually run on hydrological years (October to September). All these constraints and limitations lead to significant complexities and uncertainties in reconstructing natural water resources. That is why we could only reconstruct one year of natural discharge, which is a strong limitation of our study, although the validation seems to confirm the relevance of the methodology.

The use of the reconstructed natural discharge to calibrate hydrological models seems essential from our case study, as the difference with the measured discharge is relatively large. Moreover, after calibration, the present, past, or future hydrological simulations represent strictly natural resources, not including bias due to any background usages, making it easier to evaluate, for instance, the scarcity in a second step. It shows that the reconstruction of the outlet discharge (adjustment or correction of the measured outlet discharge) is needed, especially for a correct drought assessment and model calibration respecting low flow. As those fluxes may vary from year to year, notably with varying weather conditions, each year has to be processed, and many small municipalities do not have the economic and human resources to provide the required data. At regional scales, withdrawals are significant, and their impact could increase in the future [4], which makes the estimations of the natural discharges essential, i.e. a correction of the measured discharges when upstream withdrawals are present. If the data used to determine the supply is impacted by the withdrawals without corrections, it presents a methodological incoherence. The case of water diversions for large-scale hydropower is well-studied, and its effect is often accounted for in hydrological studies [4]. However, traditional irrigation systems like the *bisses* have not received much attention in hydrological modelling. Overall, our approach, although difficult and time-consuming to undertake, should be more widely used to improve knowledge of local natural water resources.

It is well-known that the upper part of the Sionne catchment takes part of a wide karstic environment, but the origins of the Sionne spring waters were not well-studied. For instance, it is possible that under certain conditions (e.g., during high-flow periods), part of the water from the upper section of the topographic catchment flows toward the Lienne. Another key question is to what extent meltwater from the Wildhorn Glacier contributes to the Sionne spring. This issue is particularly important for future water resources, as the glacier is expected to disappear completely by the mid-21st century under a high greenhouse gas emission scenario (Huss & Fischer, 2016), which would reduce water availability, especially in late summer. Regarding this hydrogeological context, an effort could be made to improve our modelling by better defining hydrogeological sub-catchments and using, for instance, an HBV model with two groundwater reservoirs (instead of one for the SOCONT model).

Our reference simulation seems to reproduce well the discharge, although the period of reconstructed natural discharge should be increased to improve the calibration and validation. Interestingly, hydrological simulations of Muelchi et al. [7] particularly overestimate the measured Sionne discharge (used for the calibration) at low flow, which could be due to non-accounted water withdrawals and transfers. Could a hydrological model perform better undertaking a calibration on a short period while correcting data for withdrawals and transfers than using long time series, which do not well represent what the model is intended to simulate?

The difference between Hydro-CH2018 data (on the reference period as well on the 2070-2099 period for RCP8.5 scenario), which is large, is probably due to the fact that the karstic environment is not taken into account in Hydro-CH2018 for the area. Moreover, the aim of Hydro-CH2018 was to obtain a Swiss-wide simulation that cannot represent local particularities which are determinant on a such small Alpine catchment like the Sionne catchment. However, Hydro-CH2018 on the Sionne catchment is still valuable to address the evolution trend of the seasonal water availability, like early snowmelt peak, increase discharge in winter and longer and more pronounced drought in summer. The comparison with Hydro-CH2018 also highlights that the simple model developed in this study is efficient to simulate past, present and future water resources in a karst environment at the scale of months (and better than complex model, regionally calibrated, like PREVAH used for the concerned Hydro-CH2018 data).

Our simulations confirm the general trend predicted in unglacierized Swiss Alpine catchment about changing water resources for the period 2070-2099 in the RCP 8.5 scenario: increase of winter flows, early and smaller snowmelt peak flow, and longer and more intense summer drought [1]. At the season and year scale, it highlights that summer droughts could be more severe in this future climate scenario and that even wetter winter cannot compensate for the water deficit if drought conditions occur.

5. CONCLUSIONS

To undertake hydrologic modelling of future climatic scenario and determine subsequent future natural water resources, well-calibrated models are needed. Based on the study case of the Sionne catchment in Valais, Switzerland, where several types of water withdrawals and transfers occur, we look at the influence of accounting or not those water fluxes on hydrological model calibration and simulation. We show that those fluxes represent a relatively large proportion of the flow measured at the outlet of the catchment, up to 100% at low flow. This finding poses the question of serious calibration bias in local to regional scale hydrologic modelling if the widespread withdrawals inter-catchment transfers are not considered, particularly for drought management. Indeed, the modelling results might be used to manage the same water fluxes, not considered in the simulations. This proposed approach of accounting those types of water fluxes suggests that one year of reconstructed natural discharge could improve model calibrations and hydrologic simulations. We perform simulations of RCP 8.5 scenario with a simple conceptual model calibrated on this approach. Our results match the expected climatic trend for Swiss Alpine catchment. In addition, we perform simulations of the driest past and future cases and found that drought could severely worsen under climate change by the end of the century. Even after a wet winter, we could experience longer and more intense droughts than in 2022. Finally, we think that more work should be done on collecting local water withdrawal and transfer data that are currently mostly unknown: local municipalities should be supported in this task and regional framework should be developed in this direction.

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