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Journal of Hydrology: Regional Studies 44 (2022) 101241

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Vulnerability of water resource management to climate change: Application to a Pyrenean valley

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ARTICLE INFO

Keywords:
Water resource management
Climate change
Bottom-up approach
Adaptation and mitigation
Hydropower
Irrigation
Environmental flow

ABSTRACT

Study region: The Aure Valley in the French Pyrenees.
Study focus: This study applies a bottom-up framework for assessing water management vulnerability in terms of hydropower production, environmental regulations, and reservoir storage management by integrating the sensitivity, the management metrics with the participation of stakeholders, and the exposure of the water system. The hydrological model GR6J-CEMANEIGE is implemented to simulate the management metrics in the study region. The sensitivity of management metrics to climate change is investigated by comparing simulation results under current climate conditions and under perturbed climate series. Results are demonstrated with response surfaces, which are overlaid with the predefined thresholds of management metrics. The thresholds help identifying climate conditions that are critical for water management. Plausible climate change pathways are displayed on the response surfaces to assess the probability of critical conditions.
New hydrological insights for the region: Results show that annual hydropower production is mostly vulnerable to future drier conditions. Environmental metrics are sensitive to both precipitation and temperature changes while the current policy render the low-flow management less susceptible to risks. Reservoir storage management is found to be extremely sensitive to temperature increase that induces an earlier snowmelt. Although downstream water use is less vulnerable to climate change even under a high greenhouse gases emissions scenario, more intense water competition among stakeholders could be foreseen. Corresponding adaptation actions are proposed to reduce the vulnerability.

1. Introduction

Snow-dominated mountains, frequently referred to as natural water towers, provide essential surface water resource that are of great importance for ecosystems and human society water use (Barnett et al., 2005; Viviroli et al., 2011; Immerzeel et al., 2019). Water in these mountains is stored as snowpack or glacier in the cold season and melts in the warm season to naturally sustain low flows. However, climate change significantly impacts the snow accumulation-melting patterns, thus altering hydrological regimes and propagating to water resource management, e.g., hydropower generation, agricultural practices, and respect of environmental rules (e.g., Farinotti et al., 2019; Qin et al., 2020; Pepin et al., 2015). In particular, the Pyrenees mountain range is an important source of water for regions in Southwestern Europe (e.g., Andorra, France, and Spain) while it is considerably vulnerable to climate change (García-Ruiz et al., 2011; Morán-Tejeda et al., 2017; Amblar-Francés et al., 2020).

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https://doi.org/10.1016/j.ejrh.2022.101241
Received 31 January 2022; Received in revised form 28 April 2022; Accepted 11 October 2022
Available online 3 November 2022

The Pyrenees constitute a transition band from Atlantic to Mediterranean climate conditions, which is recognized as a "hotspot" influenced by climate change (e.g., Chauveau et al., 2013; Fayad et al., 2017; Spinoni et al., 2017; Tuel and Eltahir, 2020). As such, investigating the impact of climate change on Pyrenean water resource and management is a continuous concern.

The most recent climate change study focusing on the Pyrenees (Amblar-Francés et al., 2020) with a high spatial resolution (5 km × 5 km) indicated a marked warming in the Pyrenees as temperature continues to increase under three Representative Concentration Pathways (RCPs: RCP 4.5, RCP 6.0, and RCP 8.5) while precipitation changes were not clear due to model uncertainty and spatial heterogeneity. Concerning Pyrenean water resource changes, numerous studies have reported a general decrease in terms of snowpack or river flows from in situ observations (e.g., Morán-Tejeda et al., 2012; Sánchez-Chóliz and Sarasa, 2015; Buendia et al., 2015; López-Moreno et al., 2020) and climate change impact projections (e.g., López-Moreno et al., 2009, 2011; Morán-Tejeda et al., 2014, 2017; Dayon et al., 2018; Haro-Monteagudo et al., 2020). Specifically, snow processes as the dominant factor in the hydrological regimes in the Pyrenees are extremely sensitive to changes in temperature, precipitation, and solar radiation (e.g., López-Moreno et al., 2008b, 2012; Alonso-González et al., 2020). In addition to the major physical drivers (e.g., latitude, elevation, and slope and aspect) that results in different sensitivity of snowpack to warming climate, López-Moreno et al. (2017) further concluded that the Pyrenees is among the most sensitive Mediterranean climate mountains of the world. Water availability in the Pyrenees is thus questioned by climate change.

Increasing efforts have also been made to understand the consequences of changes in hydrological processes on water resource management in the Pyrenees (e.g., Lhuissier et al., 2016). Agricultural irrigation is the leading consumptive use of water in downstream areas, for maize cropping in southern France, and wheat and barley cropping in northern Spain. Irrigation management is threatened by a decreasing water availability and an increasing water demand due to climate change (e.g., López-Moreno et al., 2008a; Majone et al., 2012; López-Moreno et al., 2014; Senthilkumar et al., 2015; Caubel et al., 2018). Haro-Monteagudo et al. (2020) investigated the largest irrigation system of Europe in the Spanish Pyrenees under climate change scenarios and showed that a decrease of available water for summer irrigation. Similar results are found for the Yesa reservoir in the Spanish Pyrenees with reduced water inflow from the upper basin and an earlier spring snow melt, which accounts for the limited water availability to meet the irrigation demand in summer (López-Moreno et al., 2014). Besides, the increasing water demand that could be attributed to increased crop evapotranspiration by warming climate and enlarged cropland is challenging water management for irrigation (López-Moreno et al., 2008a; Majone et al., 2012; Senthilkumar et al., 2015; Caubel et al., 2018). Regarding hydropower generation, Hendrickx and Sauquet (2013) developed a simplified hydropower reservoir management model based on dynamic programming to simulate dam operations in the Ariège River basin in the French Pyrenees. Results demonstrated that hydropower generation in winter is projected to decrease due to a reduced annual inflow and an earlier snow melt if reservoir operations remain unchanged. The management of other water provisioning services such as drinking water could also be considerably affected with less water yield and more sediment retention in the reservoirs (e.g., Bangash et al., 2013). The flood events in the Pyrenean regions are complex within both meteorological and hydrological processes while climate change is likely to impair flood control as snowmelt contributes to amplifying the flooding duration instead of triggering the events (e.g., García-Ruiz et al., 2011; Pino et al., 2016; Morán-Tejeda et al., 2019). Furthermore, the overall reduced water resource brings about intensive water competition, rendering water management rather challenging in the Pyrenees.

Given the adverse impact of climate change on Pyrenean water resources and water management, adaptation strategies are thus highlighted and a comprehensive assessment under climate change is fundamental to adaptation design. In general, the top-down and bottom-up approaches are two main frameworks to assess water resource and management under climate change. Typically, the top-down approach projects future climate under different emission scenarios by using global climate models (GCMs) whose outputs are downscaled to match regional spatio-temporal scales, and projections are then forced into an integrated water resource system model to compare with current system performance (e.g., Schaefli, 2015; Vidal et al., 2016). However, the top-down approach is reported to cascade uncertainty through the modelling chain and fails to testing more extreme climate change scenarios (Wilby and Dessai, 2010; Brown and Wilby, 2012). The alternative bottom-up approach shifts attention to assessing the system vulnerability to a wide range of scenarios generated by either parametric or stochastic perturbation of historical climate drivers. This approach is flexible and advantageous in identifying which climatic variables the system is sensitive to Culley et al. (2016). Several frameworks based on the bottom-up approach have been proposed in the literature, such as "Scenario Neutral" (e.g., Prudhomme et al., 2010; Sauquet et al., 2019), "Decision Scaling" (e.g., Brown et al., 2012; Ray et al., 2020), and "Robust Decision Making" (e.g., Lempert et al., 2006; Kasprzyk et al., 2013). The "Scenario Neutral" (SN) approach distinguishes from the others in leaving decision processes to the decision-maker (Prudhomme et al., 2015). Prudhomme et al. (2010) suggested that the SN approach can be combined with the top-down approach by placing climate change projections at a later stage to inform future risk. This approach has been applied to climate change assessment for natural flow sensitivity analysis (e.g., Guo et al., 2017), drought management (e.g., Prudhomme et al., 2015; Sauquet et al., 2019), and flood risk (e.g., Prudhomme et al., 2013a,b; Broderick et al., 2019).

The main objective of this paper is to present the vulnerability of water management in the Pyrenees under climate change and to propose several adaptation strategies, taking the example of the Aure Valley where water resources are mainly used for hydropower generation, downstream water use (irrigation, drinking water, and industrial use), and low-flow support. This study makes several contributions to the current literature. First, methodologically, we have used the management metrics that are based on the stakeholders' experience for water uses and on the mandatory legislation for the environment. Identifying management metrics together with stakeholders is beneficial in developing adaptation strategies that have practical significance. Second, in terms of local climate change impact studies, this paper constitutes the first bottom-up analysis of water management under climate change in the Pyrenees. The analysis provides complementary insights into water management vulnerability in the Pyrenean region. The paper is organized as follows: Section 2 introduces the study area. Section 3 explores the data and methods involved in analysing water management vulnerability. Results and discussions are given in Sections 4 and 5, respectively. Conclusions are finally drawn in Section 6.

2. Study area

Water resources in the Pyrenees plays an important role in addressing the issue of water shortage during summer in the South of France, known as the Gascogne region (see the left-top map in Fig. 1(a)). This intensive agriculture region in the Lannemezan plateau does not benefit from mountainous snowmelt because it is separated from the Pyrenees (Leenhardt et al., 2004a,b). An artificial channel (the Neste Canal, not shown in the map) connects the Gascogne region with a Pyrenean valley, the Aure Valley, at Sarrancolin to provide stable water supply. Therefore, the Aure Valley upstream of Sarrancolin is selected as a representative example of complexity with competing water uses.

The Aure Valley is located in the centre of the French Pyrenees. Fig. 1(a) shows the topographic characteristics of the Aure Valley, including the four corresponding sub-basins: the sub-basins (SB1-3) upstream the reservoirs (Oule, Orédon, Caillaouas, and Pouchergues) and the intermediate catchment (SB4) between the outlets of the reservoirs and Sarrancolin. The influence of westerly winds, which carry moist air from the Atlantic Ocean, is less effective in the Aure Valley than further west due to the blocking of the massifs (Ingrand, 1961). In addition, southern heat penetrates through the border ridge, particularly affecting the upper valley, and snowmelt dominates spring flows. Table 1 summarizes the physiographic and hydro-climatic characteristics for the study area.

The major water use in the valley is hydropower generation (Décamps, 1967). Two main hydroelectricity producers in the valley are the SHEM company[1] that manages the several reservoirs (in orange in Fig. 1(b)) of the valley and EDF[2] that manages the westernmost part of the valley (including the Cap de Long, Aubert, and Aumar reservoirs in Fig. 1(b)). Natural water flow to the Aure Valley is partly diverted: the westernmost part is transferred outside the valley and is thus not considered in this study. Water in the Oule and Orédon reservoirs generates hydropower in the Eget plant while water in Caillaouas and Pouchergues reservoirs generates hydropower through a cascade of plants, the Louron system, shown in Fig. 1(b). Note that the drainage area upstream the Pouchergues reservoir includes two parts and water in the left part (water intake from the Aygne-Tortes Lake) is transferred into the Pouchergues reservoir in the right part. Besides, water resource in SB4 also contributes to plants downstream Lassoula (e.g., Tramezaygues as shown in Fig. 1(b)). The management of the four reservoirs is made on an annual basis: the annual operation process starts from the beginning of April till the end of March of the next year. In addition to hydropower generation, the water system in the valley is oriented to provide at most 48 Mm^3 of water for uses (irrigation, drinking water, industrial use, and ecological flows) in the Gascogne region. The mandatory environmental legislation furthermore requires that the river flow at Sarrancolin where water extraction takes place should be larger than 4 m^3/s. If not maintained, either more water out of the reservoirs in the Aure Valley or less water abstraction at Sarrancolin for downstream use will be conducted.

To simplify the study case, the two hypotheses are: (1) SB4 is seen as near-natural due to the comparatively small regulation storage of the reservoirs in this sub-basin; (2) the Caillaouas and the Pouchergues reservoirs can be considered as a single one because they are jointly managed.

3. Data and methods

The vulnerability assessment of water resource and management in the Pyrenean Aure Valley under climate change is conducted by applying the SN framework (Prudhomme et al., 2010). A schematic flowchart of the overall analytic framework is given in Fig. 2. The SN framework evaluates vulnerability by comparing plausible climate projections to the predefined thresholds of water management metrics based on the knowledge of system sensitivity to the changes of climatic drivers (Prudhomme et al., 2013a,b). To implement the sensitivity analysis of water management, the responses of the water system's performance indicators are assessed through a spectrum of perturbed climate scenarios generated from the baseline climate. Given this, the water resource system in the Aure Valley is simulated by a rainfall-runoff model. The management metrics with their associated thresholds are designed through participatory meetings among stakeholders (including SHEM) to investigate water management vulnerability. Details of the key steps that involves data, models and the SN framework are provided in the following subsections.

3.1. Climatic drivers

3.1.1. Baseline climate: Safran reanalyses

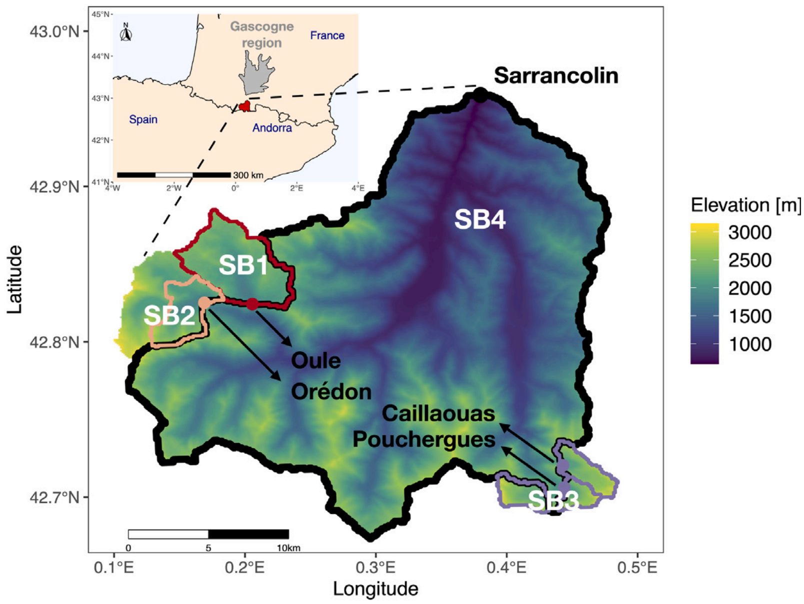
The near-surface meteorological reanalysis Safran-PIRAGUA that focuses on the Pyrenees is used in this study for driving the hydrological modelling. This dataset is a high resolution ($2.5\ \text{km} \times 2.5\ \text{km}$) surface reanalysis based on the Safran algorithm obtained by merging the Safran-France reanalysis product (Vidal et al., 2010) and the Safran-Spain reanalysis product (Quintana-Seguí et al., 2016, 2017). It provides daily climate information of air temperature and precipitation. The potential evapotranspiration information is calculated from the Penman–Monteith equation (Allen et al., 1998). Catchment-scale climatic data of the study area is computed with a weighted mean of all cells intersected by the catchment surface. The Safran-PIRAGUA dataset is available from 09/1979 to 08/2014. The Safran-France dataset is also used when the calibration period of hydrological modelling is not overlapped with the SAFRAN-PIRAGUA dataset (see e.g., Table 3). The Safran-France dataset is available from 08/1958 to 07/2018.

[1] Société Hydro-Electrique du Midi (www.shem.fr) is a French electricity producing company, a subsidiary of ENGIE group.

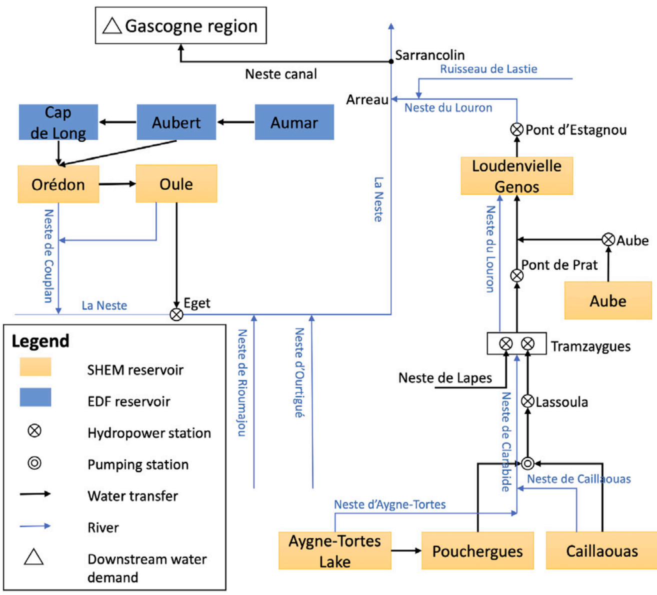
[2] Electricité de France (www.edf.fr) is a French electric utility company.

Table 1
Physiographic and hydro-climatic (precipitation P, temperature T, and naturalized inflow Q) information of the reservoirs and the sub-basins in the Aure Valley.

Reservoir	Dam type	Upstream basin	Hydropower system	Elevation range [m]	Reservoir storage [Mm^3]	Drainage surface [km^2]	Mean annual P [mm]	Mean annual T [°C]	Mean daily Q [m^3/s]
Oule	Gravity	SB1	Eget	1771–2693	16.6	28.4	1581	3.46	1.13
Orédon	Embankment	SB2	Eget	1820–2929	7.27	11.3	1585	3.39	1.18
Caillaouas	Gravity	SB3	Louron	2161–3064	25.4	6.7	1803	1.59	0.47
Poucherges	Gravity	SB3	Louron	2100–3146	0.83	9.9	1590	2.33	0.57
–	–	SB4	–	635–3147	0.002	541.0	1393	5.92	16.31



(a)



(b)

Fig. 1. (a) The topographic map of the Aure Valley with the five sub-basins. (b) The water management system of the Valley.

3.1.2. *Snow product: the gap-filled MODIS*

MODIS (Moderate Resolution Imaging Spectroradiometer, https://modis.gsfc.nasa.gov/) is an important instrument embedded in the Terra and Aqua satellites to measure the dynamics in Earth's processes, such as snow cover, vegetation index, and land-surface temperature. Daily snow cover products are adopted in this study to calibrate the hydrological model. However, the missing snow cover observations from satellites due to the coverage of clouds make it difficult to acquire a full temporal description on the study area. Gascoin et al. (2015) developed a cloud-free snow cover product in the Pyrenees based on the MODIS products and a gap-filling algorithm. The accuracy of the gap-filled MODIS products was validated against in situ snow observations and Landsat data in the Pyrenees range. The resolution of this gap-filled snow product is consistent with the original MODIS snow product ($0.5\ \text{km} \times 0.5\ \text{km}$). The dynamics of catchment-scale snow cover can thus be computed with a weighted mean of all contributive cells to the catchment surface. Time series of snow cover area (SCA) were derived from the MODIS data over the period from 09/2000 to 04/2018.

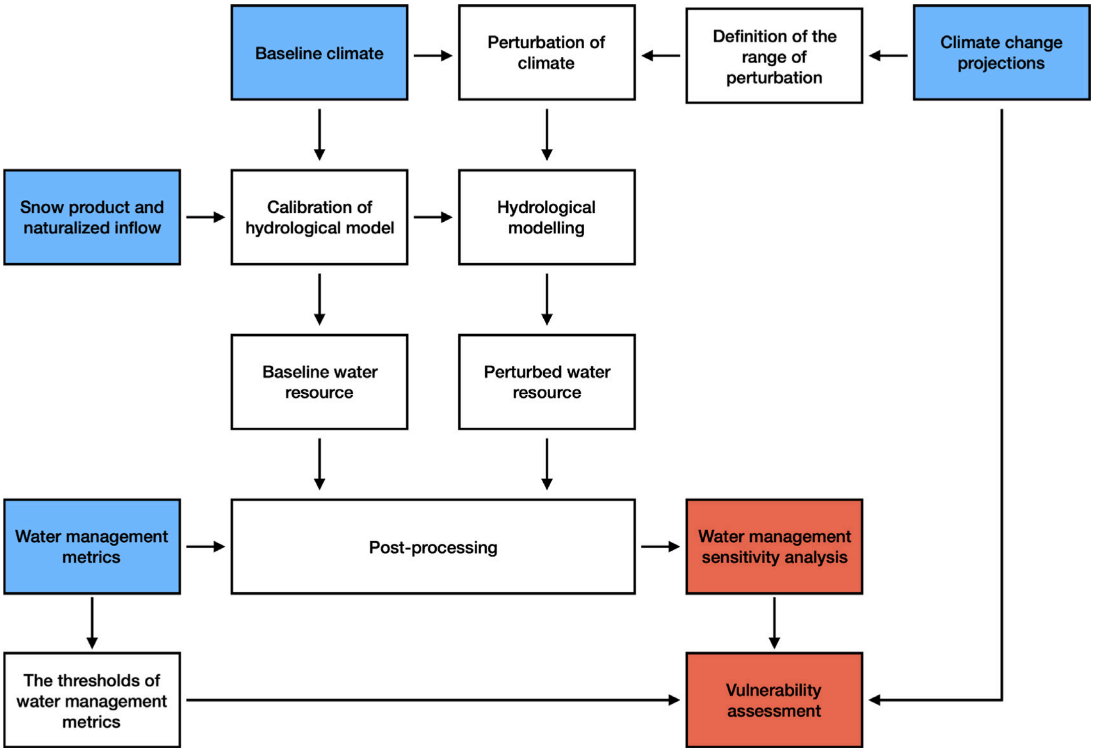


Fig. 2. The Scenario Neutral framework is applied to assessing the vulnerability of water management in the study area. The inputs and outputs are labelled in blue and red, respectively.

Table 2
List of selected CMIP5 GCMs.

Acronym	Institute	Reference
CNRM-CM5	CNRM, France	Voldoire et al. (2013)
MRI-CGM3	MRI, Japan	Yukimoto et al. (2012)
MPI-ESM-MR	MPI, Germany	Giorgetta et al. (2013)
MIROC-ESM	AORI NIES JAMSTEC, Japan	Watanabe et al. (2011)
inmcm4	INM, Russia	Volodin et al. (2010)
Bcc-csm1.1	BCC, China	Wu et al. (2013)

3.1.3. Climate change projections

Climate projections considered here originate from a subset of 6 CMIP5 GCMs as shown in Table 2 and previously selected for assessing future water resource in Spain run under RCP 4.5 and RCP 8.5 (CEDEX/MAPAMA, 2017). These projections have been previously downscaled with an analogue downscaling method to generate daily total precipitation, maximum temperature, and minimum temperature over a 5 km × 5 km grid for Spain and the Pyrenees within the CLIMPY project (Amblar Francés et al., 2017; Amblar-Francés et al., 2020). The CLIMPY projections have been here further refined in order to match both the higher spatial resolution and the multiple variables of the Safran-PIRAGUA surface reanalysis. To this aim a multi-site and multi-variable analogue resampling method has been set up following the approach proposed by Clemins et al. (2019). Results are therefore daily gridded projections over the Safran-PIRAGUA grid, with all corresponding variables – including precipitation and temperature required for the hydrological models – for 6 GCMs run under both RCP 4.5 and RCP 8.5 emissions scenarios, for the whole 1961–2100 period. Here, these projections are used to calculate the climate change trajectories under both RCPs for time slices from 1980s to 2090s (total 12 time slices and each time slice referring a period of 20 years, e.g., 1980s the period of 1971–1990). The benchmark period is from 1979 to 2014 so as to be in line with Safran-PIRAGUA.

3.2. Naturalized inflow

River flow in the Aure Valley is highly influenced due to the intensive development of hydropower (Ingrand, 1961; Décamps, 1967). A study was conducted by Falgon (2014) to reconstruct natural inflows upstream the reservoirs (SB1-3) in the Aure Valley applying a water balance approach. The principle of this approach is to sum up all exports for water use and to subtract all imports from other basins. Thus, the naturalized inflow in SB4 is the observed river discharge at Sarrancolin minus the observed outflows upstream the reservoirs. The naturalized inflows is at daily time step and the data length is from 01/2001 to 12/2018 for SB1, SB3, and SB4. However, the data length for SB2 is from 07/2014 to 12/2018.

3.3. Hydrological modelling

The conceptual lumped rainfall-runoff model GR6J, developed to improve low-flow simulation based on the extensively used GR4J model (Perrin et al., 2003) for French basins, was adopted to simulate the daily inflow into the reservoirs of the water system (Pushpalatha et al., 2011). The GR6J model was largely applied in studies including reconstruction of low-flow events (e.g., Caillouet et al., 2017), climate change projections (e.g., Givati et al., 2019), and streamflow forecasts (e.g., Crochemore et al., 2016). The GR6J model can thus be coupled with a semi-distributed snow-accounting routine CEMANEIGE that exploits snow information for five attitudinal layers of equal area (Valéry et al., 2014a,b). Recent developments have improved the performance of snow cover simulation by using MODIS observations (Riboust et al., 2018). The CEMANEIGE module takes account of the snow accumulation and melting hysteresis between SCA (Snow Cover Area) and SWE (Snow Water Equivalent), which is the dynamic lag between the two states of snow.

The GR6J hydrological model has six parameters to calibrate while the CEMANEIGE module has four parameters to calibrate. The coupled GR6J-CEMANEIGE model should be calibrated to the two benchmark observations: naturalized inflow and SCA from the gap-filled MODIS product. The calibration process is illustrated as follows. First, a root-square transformation on runoff is chosen to reduce the bias towards high or low flows (Garcia et al., 2017). Second, the KGE criterion was used to assess the model performance (Kling et al., 2012) and its formulation is presented below:

$$KGE = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{1}$$

where r is the Pearson correlation coefficient, β the percentage bias, and γ the ratio of the coefficient of variation between simulation and observation. Third, an objective function f that involves the two observations should be optimized and its formulation is presented below:

$$\begin{cases} f = a \times KGE(\sqrt{Q}) + \sum_{i=1}^{5} b_i \times KGE(SCA_i) & (2) \\ a + \sum_{i=1}^{5} b_i = 1 & (3) \end{cases}$$

where a is the weighting coefficient for runoff Q calibration, b_i the weighting coefficient for SCA_i calibration of elevation zone i. We follow here (Riboust et al., 2018) who concluded that 75% weighting on runoff with 5% on each elevation zone gives a satisfactory compromise for the overall model performance. The calibrated hydrological model will be run under baseline and perturbed climate over the period from 09/1979 to 08/2014 to simulate water resource conditions in the SN framework as shown in Fig. 2.

3.4. The SN framework for water management

3.4.1. The SN concept

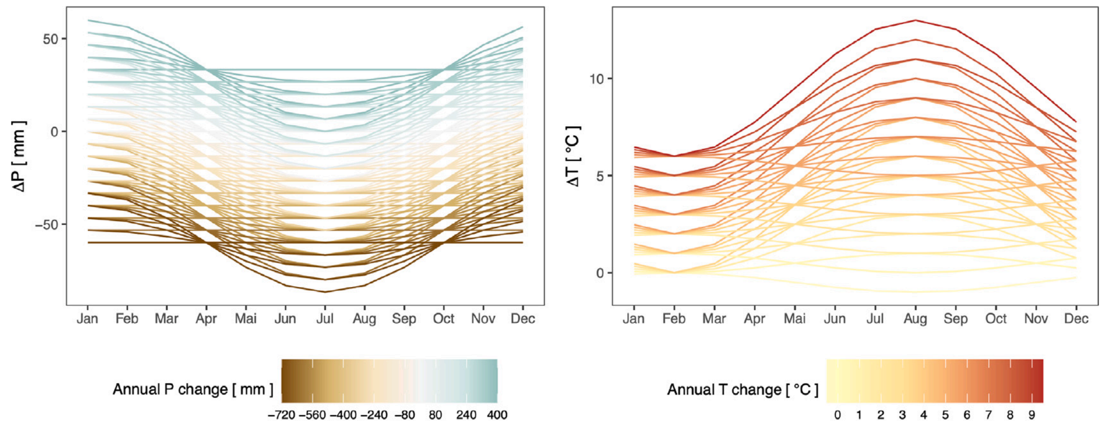
Contrary to the traditional top-down approach, the SN framework investigates water management issues under climate change by underlining the sensitivity of water systems to changes. The vulnerability analysis in the SN framework depends on three concepts: the sensitivity, the exposure, and the performance metric of the water system (Prudhomme et al., 2010, 2013a,b; Brown and Wilby, 2012; Sauquet et al., 2019). Sensitivity is the response of the water system to changes and Section 3.4.2 presents how the sensitivity domain is calculated. Exposure is the climatic changes to which the water system could be exposed and Section 3.1.3 details the regional climate projections used in this study. The performance metric is the relevant management indicator to characterize the system and its adaptive capacity threshold beyond which the system performs unsatisfactorily or cannot withstand the impact of climate change. Section 3.4.3 presents the performance metrics associated with water management for this study. As such, by understanding the sensitivity and the plausible exposure of the water system, a vulnerability assessment that compares changes to the predefined management metrics can be provided.

3.4.2. Sensitivity domain

Three steps are involved to produce the sensitivity domain: the generation of perturbed climate scenarios, the response simulation, and the response plotting.

Perturbed climate scenarios can be generated either by parametric methods (e.g., Culley et al., 2016; Sauquet et al., 2019) or stochastic methods (e.g., Guo et al., 2017). Here, the historical climatic data from the Safran-PIRAGUA over the period from 09/1979 to 08/2014 is perturbed by the "delta-change" method based on the single-harmonic function (Prudhomme et al., 2010). The sensitivity domain of the water system to climate change is quantified from the key climatic variables, which are precipitation and temperature. The detailed calculation steps are provided in the Supplementary Material.

Finally, a set of 75 precipitation and 35 temperature scenarios has been generated and combined (see Fig. 3), resulting in a total of 2625 precipitation and temperature perturbation combinations used to define the climate sensitivity domain. The colour



(a) (b)

Fig. 3. The perturbation of precipitation (P) in (a) and temperature (T) in (b) at monthly time step.

spectrum in Fig. 3(a) indicates that annual change of precipitation ranges from −720 to + 400 mm and the annual change of temperature ranges from −0.5 to + 9.5 °C in Fig. 3(b). The subsequent step is the response simulation that involves forcing the 2625 scenarios into the calibrated hydrological model to simulate the response of the water system to changes following Fig. 2. The final step is the response plotting that employs the 2D response surface to illustrate the sensitivity of the water system to changes in precipitation and temperature. Additional analysis is necessary to identify the climate variables (i.e., seasonal/annual precipitation changes and seasonal/annual precipitation changes) by which the water system is mostly influenced. The climate variables with the largest influence on the water system are chosen as the axes for the response surfaces (precipitation changes as x axis and temperature changes as y axis). Following Sauquet et al. (2019), regression analysis between the response simulation results and the climate variables is applied to determine the most appropriate axes for the response plotting. The climate variables with the highest correlation to the response simulation results are the most relevant axes.

3.4.3. Water management metrics

This section presents the management-relevant metrics that can be characterized by hydrological modelling. In this study, three water management metrics are chosen based on workshops with local stakeholders in terms of hydropower production, ecological flow management, and reservoir refill management:

(1) annual inflow volume (QA) for hydropower system production;
(2) seasonal failure days to meet the need of mandatory ecological flow (DOE) at Sarrancolin, as well as the timing of failure (tDOE) (the first day of the year when the failure appears);
(3) seasonal duration of no snow cover area (NSA) for system Eget and Louron, as well as the timing of no snow cover area (tNSA) (the first day of the year when there is no snow cover).

Water resource in the system Eget and Louron is managed by SHEM for hydropower production. The energy market in France is mostly nuclear-hydropower-mixed: nuclear plants provide base load and hydropower is generated to meet peak demands. The electricity price in the market fluctuates depending on the weather and other external factors such as gas price. Based on the experience of the water managers from SHEM, the Eget system is cost-effective when the annual water inflow into the reservoirs ranges from 28.2 to 41.6 Mm^3 for Eget (21.9 to 28.2 Mm^3 for Lassoula). Besides, there is a water contract for downstream water supply (irrigation, drinking water, and industrial water use) extracted from the four reservoirs with at most 48 Mm^3 each year. According to SHEM, the necessary water volume for SHEM to be cost-effective shows an increasing tendency towards the maximum values. Therefore, we consider the “worst” market scenario, which is 41.6 Mm^3 for the Eget plant and 28.2 Mm^3 for the Lassoula plant, and the highest scenario of downstream water demand, which is 48 Mm^3, as the thresholds for hydropower production in the vulnerability assessment. The “worst” market scenario needs the highest annual water inflow, which implies that water value is low in the energy market and that SHEM has to produce more energy (release more water) to achieve the cost-effectiveness.

The DOE requirement indicates that water flow at Sarrancolin should be larger than 4 m^3/s while this rule can be violated for 90 days over the low-flow period (summer and early autumn months). Thus, the threshold value for DOE is the value of 90 days and those for tDOE are the beginning of low-flow period (July to October). We concentrate the environmental management over the July to October period because it is a critical period with potentially environmental management issues and the downstream water demand extracted at Sarrancolin is intensive in this period.

The use of snow information is meant to test if the current refill strategy is still reliable under climate change as the storage management of reservoirs is based on how snow changes. The metrics of the duration and timing when there is no snow cover in

Table 3
GR6J-CEMANEIGE performance (KGE values).

	Calibration						Validation					
	$\sqrt{Q}$	SCA_1	SCA_2	SCA_3	SCA_4	SCA_5	$\sqrt{Q}$	SCA_1	SCA_2	SCA_3	SCA_4	SCA_5
SB1	0.79	0.79	0.91	0.91	0.93	0.93	0.70	0.76	0.89	0.92	0.95	0.94
SB2	0.72	0.80	0.92	0.96	0.95	0.88	–	–	–	–	–	–
SB3	0.83	0.83	0.90	0.92	0.92	0.87	0.84	0.84	0.93	0.93	0.92	0.83
SB4	0.87	0.74	0.74	0.72	0.87	0.92	0.86	0.75	0.75	0.73	0.87	0.92

Notes: The calibration and validation periods for SB1, SB3, and SB4 are 01/2001–08/2007 and 09/2007–08/2014, respectively. Given the length of naturalized inflow of SB2, only the calibration is conducted from 07/2014 to 07/2018 forced by the Safran-France reanalysis product (Vidal et al., 2010).

the two systems are used to inform the risk of reservoir storage management under climate change. However, there is no specifically predefined metric for the duration of no snow cover. We used here the concept of time of emergence. Climate conditions under which significant changes in the distribution of mean NSA time series emerge from that of current climate state can be used as the threshold of NSA to imply the necessity of changing reservoir refill strategy. In this study, the Kolmogorov–Smirnov (KS) test is conducted to quantitatively compare the probability distribution functions of the time series of mean NSA under one perturbed climate scenario and these under the baseline climate scenario. The KS test gives a decision value (true or false) for the null hypothesis that the time series of mean NSA from the perturbed climate scenario are sampled from the same distribution of these under the baseline climate scenario. In this study, the null hypothesis is rejected at 95% confidence level (p-value smaller than 0.05). As such, time series of mean NSA under total 2625 perturbed climate scenarios are compared with the baseline climate scenario to determine under which climate conditions the significant changes in the distribution of mean NSA occur for both Eget and Lassoula systems. Thus, the occurrences of the significant changes are used as the thresholds for the management metric NSA of the Eget and Lassoula systems. Similar application of the KS test to investigate the impact of climate change on water resource can be found in the literature (e.g., Gaetani et al., 2020; Muelchi et al., 2021). In terms of the thresholds of tNSA, the beginning dates of reservoir refill months are based on the current management experience from SHEM (April to June for the Eget system and April to July for the Lassoula system).

4. Results

4.1. Hydrological model performance

The hydrological model GR6J-CEMANEIGE was applied to simulate water resource in the water system of the Aure Valley. The outputs, including daily Q and SCA changes, are evaluated with the KGE criterion (Kling et al., 2012) by comparing to naturalized inflow and observed SCA derived from the MODIS images, respectively. Table 3 shows the KGE values for the four studied basins and the results indicate that the model performs satisfactorily with all KGE values of Q and SCA above 0.7.

The performance of the GR6J-CEMANEIGE model in reproducing seasonal dynamics is illustrated in Fig. 4 with simulated discharges compared to naturalized discharges and simulated median SCA patterns compared to observed median SCA patterns. The simulated Q follows the variability of the naturalized inflow and can capture the high peaks and low flow spells. Especially, the recession limbs during summer period are well fitted. However, the hydrological model tends to underestimate spring flow and to overestimate winter flow for SB1-4. Note that the hydrological model has a lower performance for SB2 partly due to the short record of naturalized inflow. The module CEMANEIGE can well reproduce the seasonality of snow cover changes in the five elevation bands (Fig. 4), as well as the accumulation phase of snow and relatively tardy melting processes. Besides, higher attitudinal elevation band shows longer snow cover duration as expected. However, the snow melting process simulation is less efficient than the snow accumulation process given the simple characteristics of the empirical degree-day model in representing snow thermal state changes (Riboust et al., 2018). SCA variations for SB1-4 are well simulated with a high performance in high elevation bands and a moderate performance in median elevation bands. This can be attributed to the high variability of snow cover in moderate elevation bands which is difficult to represent in the model.

Finally, the water management metrics are calculated based on both simulated Q and SCA, and then compared to the observed ones as shown in Table 4. The management metrics QA, NSA, and tNSA are calculated for SB1-3 to investigate the accuracy of the model in reproducing hydropower indices and snow changes for reservoir refill. The management metrics DOE and tDOE are computed for the Sarrancolin catchment to show the accuracy of the model in reproducing environmental indices. The simulated natural discharge of the Sarrancolin catchment is the sum of the simulated discharges of SB1-4. The simulations of management metrics are generally satisfactory. However, the simulations of DOE and tDOE can be questioned since there is no naturalized discharge available at Sarrancolin. Note that few days with flow under the mandatory ecological requirement are simulated by the model. Here, an incomplete estimate is given by the sum of naturalized discharges for the drainage area of SB1, SB3, and SB4 which stands for 98% of the Sarrancolin catchment for the period from 01/2001 to 08/2014. The calculated observed DOE and tDOE metrics for this incomplete estimate are 0.1 days and 03/Oct, respectively. These results are consistent with simulations for the period from 01/2001 to 08/2014. The simulated tDOE under both 2001–2014 and 1979–2014 periods (02/Oct and 20/Sep, respectively) have a difference of less than two weeks but locate in the early autumn, which is rather acceptable if we consider climate variability under current climate condition. Based on these considerations, and because low flows are globally well reproduced, we can trust

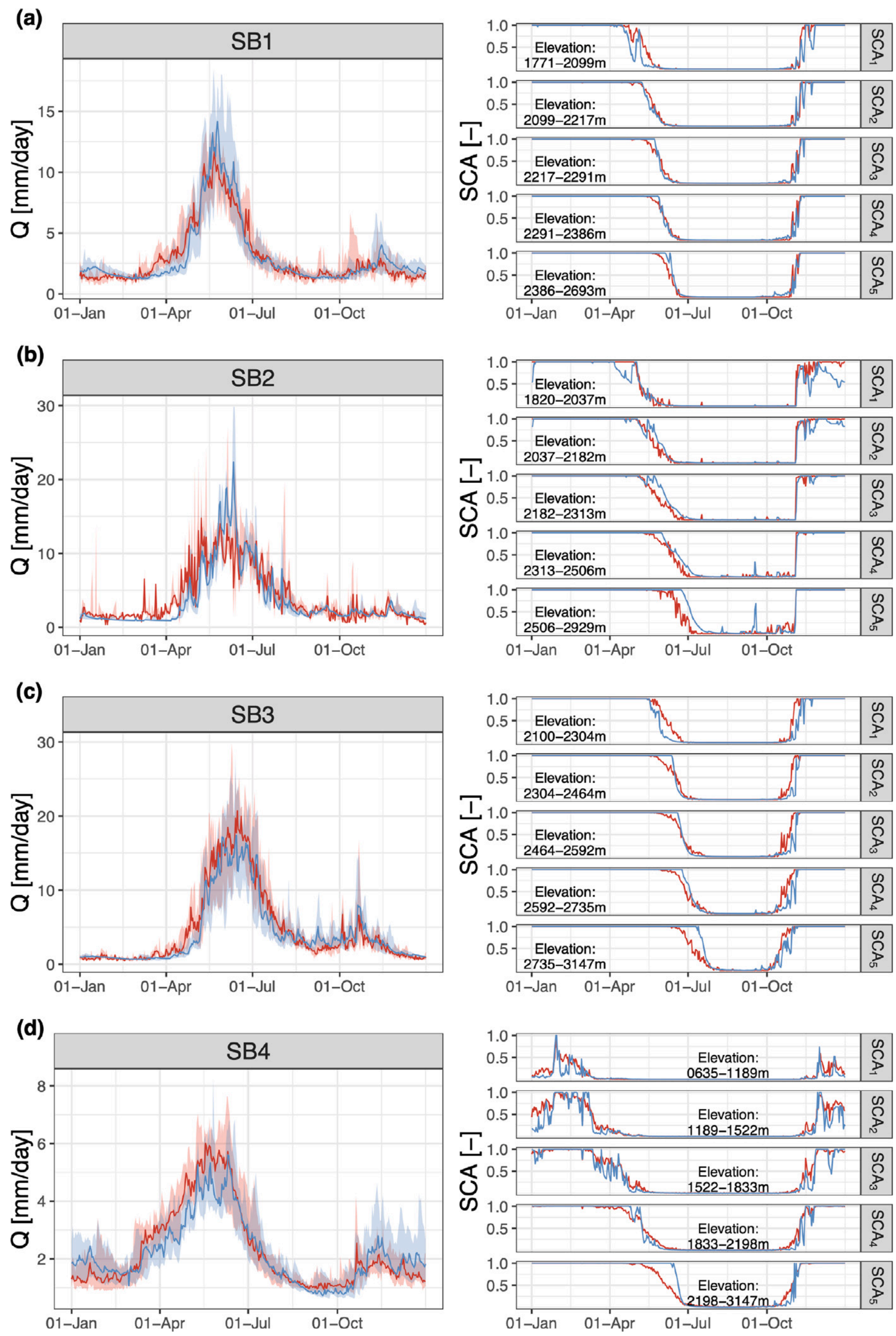


Fig. 4. Observed (red) and simulated (blue) median Q (left) and SCA (right) regimes for SB1(a), SB2(b), SB3(c), and SB4(d). The ribbon area in Q regime represents the percentile range of 25% and 75%. The SCA regimes are displayed for the five elevation bands. The observed/simulated period for SB1, SB3, and SB4 is from 01/2001 to 08/2014 while the observed/simulated period for SB2 is from 07/2014 to 07/2018.

the simulation results of DOE and tDOE. Moreover, management metric simulation of SB2 returns lower performance due to its lower quality of naturalized inflow. Table 5 summarizes the reference values of these management metrics for the water systems in the Aure Valley under baseline climate. These values are calculated with the Safran-PIRAGUA dataset over the period from 09/1979 to 08/2014 to represent the current management performance.

Table 4
The simulation results (sim and sim*) of water management metrics by the GR6J-CEMANEIGE model compared with observations (obs) in terms of QA for SB1-3, DOE and tDOE for the Sarrancolin catchment, and NSA and tNSA for SB1-3.

	SB1			SB2			SB3			Sarrancolin		
	obs	sim	sim*	obs	sim	sim*	obs	sim	sim*	obs	sim	sim*
Calculation period	01/2001 to 08/2014	01/2001 to 08/2014	09/1979 to 08/2014	07/2014 to 07/2018	07/2014 to 07/2018	09/1979 to 08/2014	01/2001 to 08/2014	01/2001 to 08/2014	09/1979 to 08/2014	01/2001 to 08/2014	01/2001 to 08/2014	09/1979 to 08/2014
QA [Mm^3]	37.5	37.7	37.1	16.7	15.1	16.2	33.9	30.5	29.7	–	–	–
DOE [days]	–	–	–	–	–	–	–	–	–	–	2.8	2.8
tDOE [date]	–	–	–	–	–	–	–	–	–	–	02/Oct	20/Sep
NSA [days]	64.6	60.2	57.4	47.6	35.7	38.8	28.5	29.4	25.1	–	–	–
tNSA [date]	12/Jun	29/Jun	02/Jul	04/Jul	24/Jul	22/Jul	15/Jul	30/Jul	05/Aug	–	–	–

Notes: The sim results for SB1, SB3, and Sarrancolin catchment are calculated with the Safran-PIRAGUA dataset over the period from 01/2001 to 08/2014 while those for SB2 are calculated with the Safran-France dataset over the period from 07/2014 to 07/2018. The sim* results for SB1-3 and Sarrancolin catchment are calculated with the Safran-PIRAGUA dataset over the period from 09/1979 to 08/2014. In terms of the observed management metrics DOE and tDOE for the Sarrancolin catchment, there are no references under current climate (the short record of naturalized inflow of SB2 over 07/2014–07/2018 makes the calculation of naturalized inflow of Sarrancolin over 01/2001–08/2014 impossible).

Table 5
The current management reference values for the water systems in the Aure Valley.

	Eget	Lassoula	Eget+Lassoula	Sarrancolin
QA [Mm^3]	53.3	29.7	82.9	–
DOE [days]	–	–	–	2.8
tDOE [date]	–	–	–	20/Sep
SCA [days]	46.0	25.1	–	–
tSCA [date]	15/Jul	05/Aug	–	–

4.2. Water management sensitivity analysis

Water management metrics (QA, NSA, and tNSA for the Eget and Lassoula systems; DOE and tDOE for the Sarrancolin catchment) are generated through the calibrated GR6J-CEMANEIGE model forced with the total 2625 perturbed climate scenarios as described in Section 3.4.2. The calculated 2625 values of each management metric are classified into groups and each group incorporates several perturbed climate scenarios (at least 5) that gather the close precipitation and temperature values. As such, the classified groups can be localized in the response surface space with average precipitation and temperature changes of the scenarios in the groups. The classified groups are symbolized as circles with colour gradient indicating the average management metric values and with size indicating the standard deviation (SD) of the scenarios in the groups.

Fig. 5 displays the 2D response surfaces developed for water management metrics and associated study area. Concerning the mean value changes of the response surfaces, the management metrics degrade when climate conditions are warmer and drier. The values of SD display a patchier pattern for both NSA and tNSA than other metrics. Large values of SD may reveal transition zones of the hydrological regime and high sensitivity to the way changes (see Section 3.4.2) are distributed within the year.

The response surfaces of QA for the Eget and Lassoula systems are generated over the whole year period to investigate the annual water volume that is potential for hydropower production. The response surfaces of DOE and tDOE for the Sarrancolin catchment are generated over July to October period when environmental flow management is usually menaced by low water availability and high irrigation water demand downstream. The response surfaces of NSA and tNSA for the Eget and Lassoula systems are generated for December to August period that incorporates the actual reservoir refill management timing from the beginning of April to the end of July. Besides, based on the regression analysis, the most appropriate axes of the response surfaces of NSA and tNSA are winter–spring (December to May) precipitation changes as x axis and spring (March to May) temperature changes as y axis. This also suggests that winter–spring precipitation and spring temperature dominate the snowmelt process.

From Fig. 5, QA for both Eget and Lassoula systems are more sensitive to precipitation changes, and QA decreases with the decrease of precipitation. It is also notable that QA of the Eget system is slightly responsive to temperature because the increase in PET associated with temperature increase can compensate the increase in precipitation and thus QA of the Eget system is decreased. In contrast, the Lassoula system does not clearly show this character. This can be explained by the different land cover types of the two hydropower systems: the Eget system that includes SB1 and SB2 is covered with forest and meadow (active evapotranspiration processes) while the Lassoula system that only includes SB3 is covered with bare rocks (no water demand from vegetation). As such, the evapotranspiration is more intensive in the Eget system where vegetation cover is developed, which results in a higher temperature sensitivity of QA in the Eget system than the Lassoula system.

Fig. 5 shows that DOE and its associated tDOE for the Sarrancolin catchment are sensitive to both precipitation and temperature changes in July to October period. DOE becomes longer while tDOE becomes earlier with the increase of temperature and the decrease of precipitation. As the Sarrancolin catchment is covered by vegetation (mainly forest) in the most part, an increase in temperature leads to higher evapotranspiration and thus less water availability during July to October period. The effect of reducing precipitation by around 100 mm for both DOE and tDOE is close to the effect of increasing temperature by around 10 to 12 °C.

In regard to NSA and tNSA for the two hydropower systems, the contrasting sensitivity to temperature changes is highlighted in Fig. 5. The values of NSA becomes longer and tNSA becomes earlier with the increase of temperature. When the increase of temperature is relatively limited (less than 3 °C), the precipitation changes in the winter–spring period also have an impact on these metrics. However, when the temperature increase exceeds 3 to 4 °C, the impact of precipitation on both NSA and tNSA metrics is no more obvious and changes in these two metrics are predominantly controlled by temperature change. For example, the effect of increasing temperature by 1 to 2 °C for the Eget system is close to the effect of reducing precipitation by 300 mm. The high sensitivity of Pyrenean snow to temperature changes is also reported in other studies (e.g., López-Moreno et al., 2008b, 2012, 2017). López-Moreno et al. (2017) explained that the snow state in the Pyrenees is warm and thick, and thus a slight increase in temperature could trigger snowmelt.

4.3. Water management vulnerability assessment

Figs. 6, 7, and 8 display the vulnerability of water management of the study area under climate change in regard to hydropower production, environmental management, and reservoir refill, respectively. Based on the knowledge of the water management sensitivity to climate change, threshold lines for each management metric that indicate the limit of the water system's satisfactory performance, and climate change pathways that indicate future climate trajectories are overlaid on the sensitivity domain to assess the vulnerability. Climate change trajectories are presented as line-linked squares for the time slices from 1980s to 2090s. The

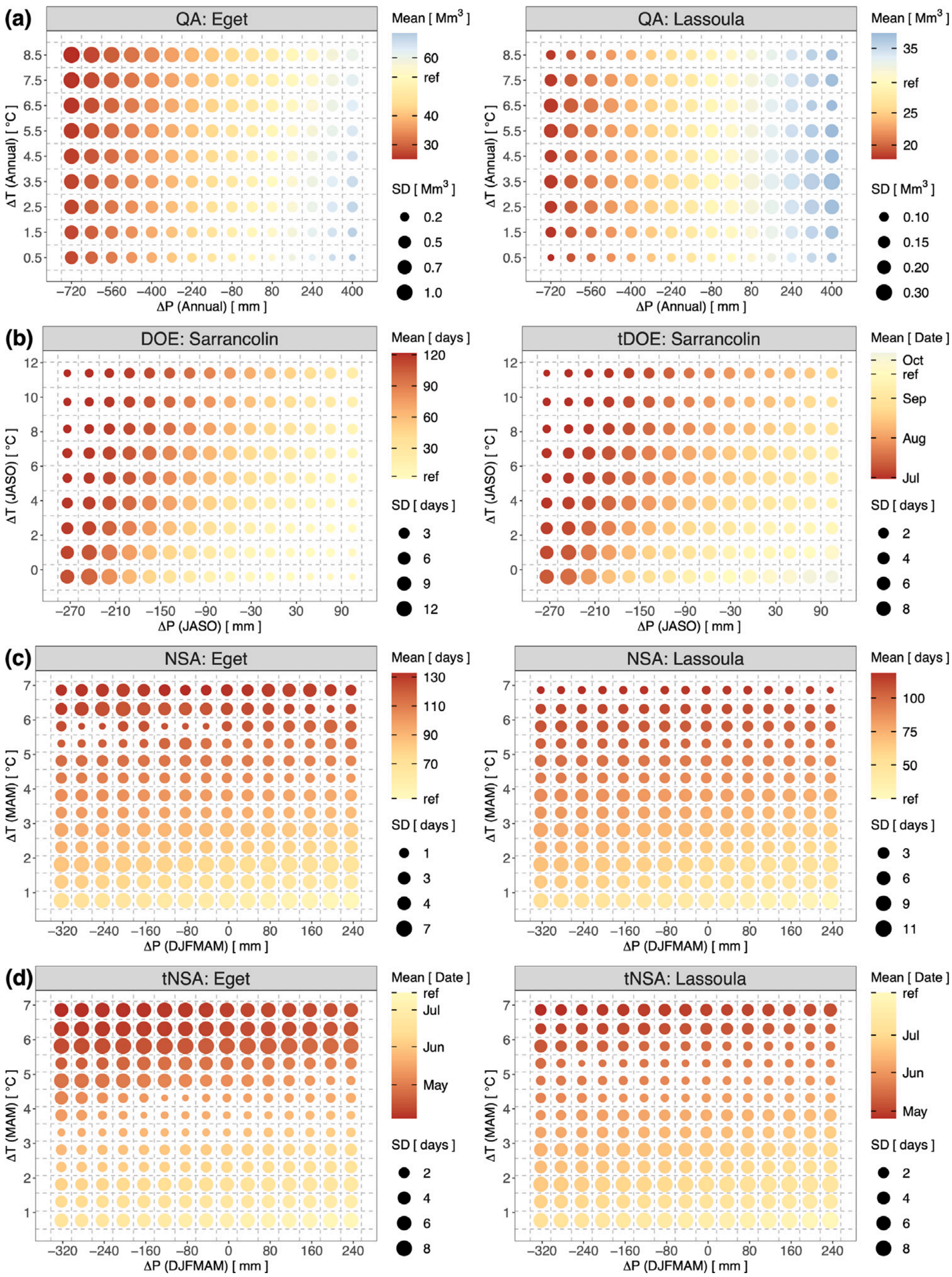


Fig. 5. Response surfaces of water management metrics to climate change for QA(a), DOE and tDOE(b), NSA(c), and tNSA(d) with their associated study area. Note the difference in *x* (precipitation changes) and *y* (temperature changes) axes with each response surface. The metrics under current climate condition (ref) are also provided (see Table 5 for corresponding values).

mean climate driver changes are the central points. Ribbon squares give an insight of uncertainty on climate (minimum changes are right-bottom points while maximum changes are left-top points of the ribbon squares.)

Hydropower management in Fig. 6 is generally more difficult given the future warmer and drier conditions. In the Eget system, the current performance of value 53.3 Mm^3 is not warranted anymore in most cases when annual precipitation decreases by 100 mm. The threshold of 41.6 Mm^3 that is the necessary water volume for hydropower production in the scenario of the lowest energy price in the market could be guaranteed under RCP 4.5. However, the Eget system would not be cost-effective after the middle of the century under RCP 8.5. Compared with the Eget system, the Lassoula system is more vulnerable due to its threshold (28.2 Mm^3) that is relatively close to the reference value (29.7 Mm^3). The Lassoula system would not be cost-effective in most climate change scenarios of two RCPs. As for the total hydropower production of the two systems, the current performance of value 82.9 Mm^3

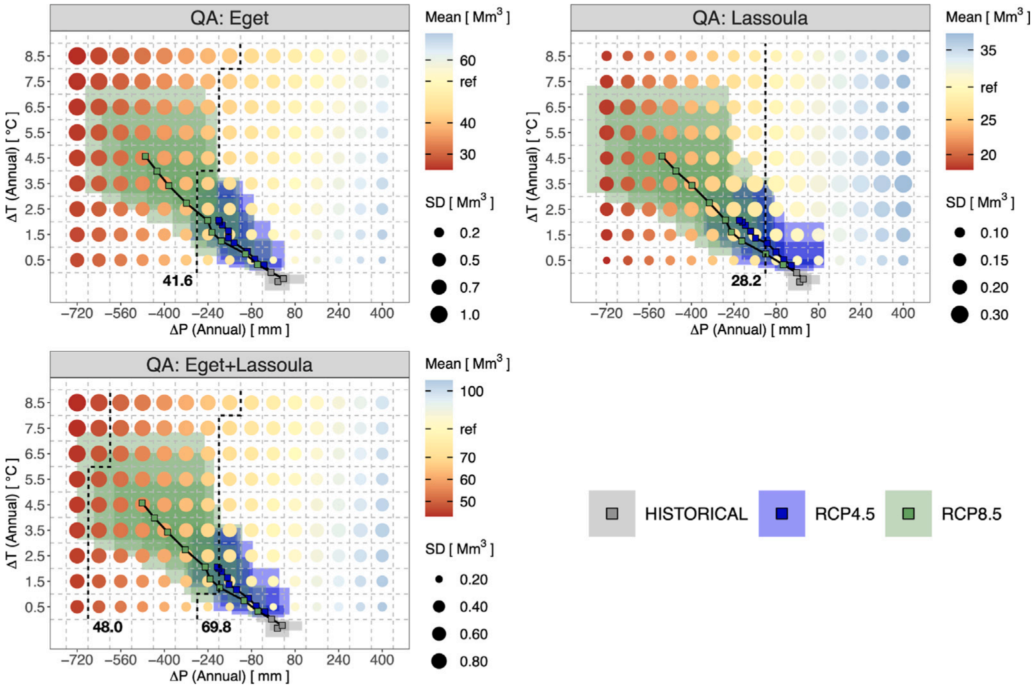


Fig. 6. The vulnerability of annual hydropower production under climate change for the Eget and Lassoula systems. The vulnerability is assessed by combining the sensitivity domain of QA, the current hydropower cost-effectiveness thresholds, and the climate change trajectories under RCP 4.5 and 8.5, respectively. The black dashed lines are the isolines that represent the cost-effectiveness thresholds for the management metric QA.

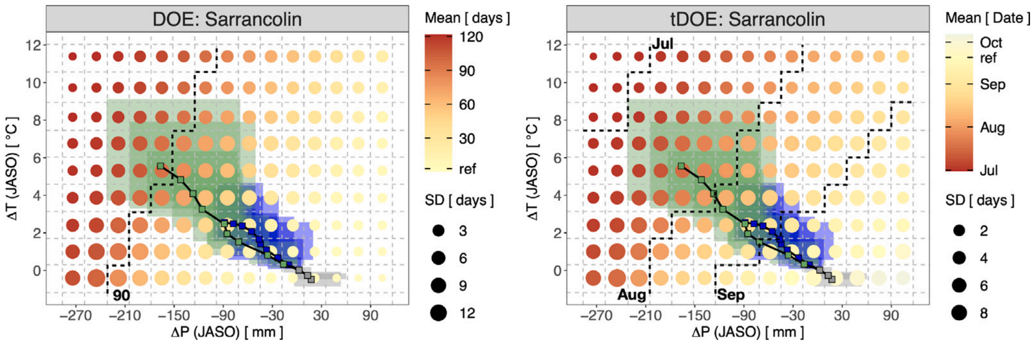


Fig. 7. As in Fig. 6 but for the environmental management metrics DOE and tDOE of the Sarrancolin catchment.

would not be warranted anymore under two RCPs and the cost-effectiveness of value 69.8 Mm^3 would not be achieved under RCP 8.5. Besides, water demand of the downstream Gascogne region, which is 48 Mm^3 at most, could be guaranteed for most of the climate change scenarios under two RCPs. The demand of 48 Mm^3 could not be meet if considering the conservative attitude of water managers for hydropower, especially in the climate change scenarios under RCP 8.5.

The vulnerability of environmental management metrics DOE and tDOE during July to October period is shown in Fig. 7. The climate change pathways under RCPs 4.5 and 8.5 are heading towards warmer and drier July to October period. The current performance for both metrics would not be warranted when July to October precipitation decreases by 50 mm or July to October temperature increases by 3 °C. The number of DOE failure days should stay below the 90-day threshold for RCP 4.5 while the threshold could be violated at the end of the century under RCP 8.5. Besides, the timing of DOE failure is earlier under both RCPs with more extreme condition for RCP 8.5. Particularly, at the end of the century under RCP 8.5, the timing of DOE failure date could occur in July when the downstream Gascogne region might demand water for summer irrigation. This causes water competition as either less water abstraction for irrigation or more reservoir release should be conducted to keep river flow at Sarrancolin larger than 4 m^3/s.

NSA and tNSA are shown in Fig. 8 to assess the vulnerability of the current refill strategy. In the response surface of NSA for the Eget system, the empirical distribution of NSA deviates from the current one when temperature increases by 1 °C in spring

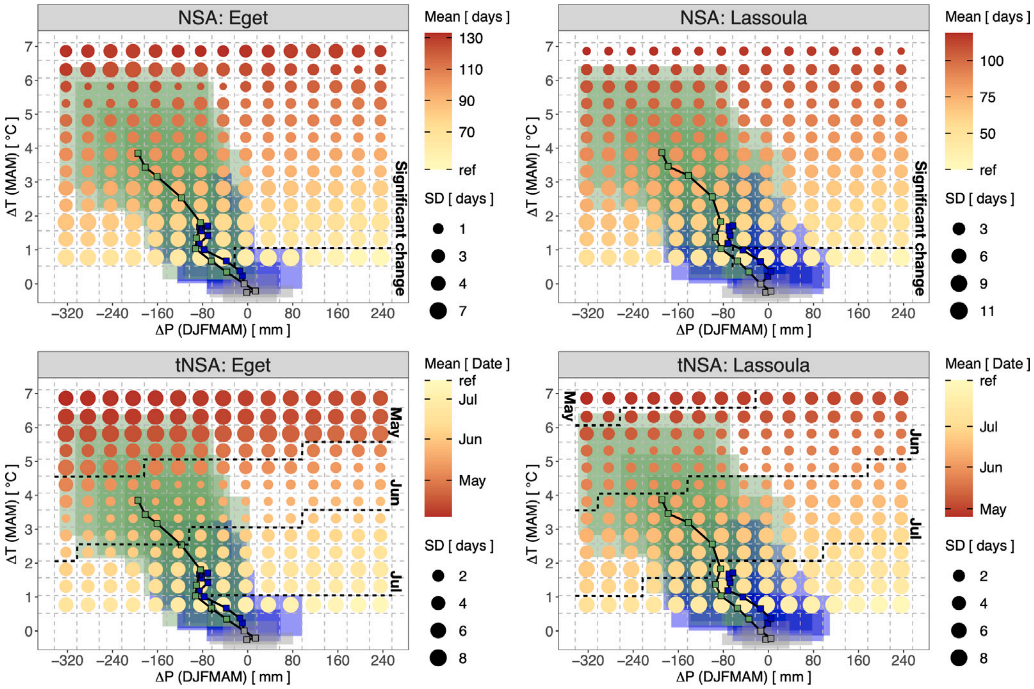


Fig. 8. As in Fig. 6 but for the reservoir refill management metrics NSA and tNSA of the Eget and Lassoula systems.

and precipitation decreases of around 30 mm in the winter–spring period. In the Lassoula system, significant changes appear when temperature increases by 1 °C in spring and precipitation decreases of around 60 mm in the winter–spring period. The duration of NSA for both systems for December to August period becomes longer under climate change trajectories of RCP 4.5 and RCP 8.5. The thresholds considered here for both systems cannot withstand most climate change projections, which indicates the high vulnerability of current refill strategy to climate change and thus suggests urgent adaptation actions. From the two response surfaces of tNSA, tNSA for December to August period will be earlier for both systems. In the worst conditions (RCP 8.5), no more contribution from snow melting could be expected after May and June for Eget and Lassoula, respectively, making the target of a maximum of storage around the current dates uncertain. More precisely, in the current reservoir management, there is a specific period dedicated to reservoir storage that is based on snow melting duration and timing (April to June for the Eget system and April to July for the Lassoula system). Once the reservoirs are refilled, future water uses for downstream in summer and hydropower in winter can be satisfied. However, the duration of NSA is longer and the timing of tNSA is earlier for both systems under climate change, which implies that the contribution from snow melt to reservoir refill is shorter and the end of snow melt is earlier. As such, the current reservoir storage management should be adapted with the snow changes.

5. Discussion

5.1. Contribution to bottom-up studies

Assessing the performance of water management remains a critical challenge in the bottom-up approach. In another word, the central question can be expressed as "what is the threshold (or the boundary) of water management that shifts from acceptable to unacceptable?" The answer to this question is barely known in the hydrological community. An acceptable water management activity can be related to the satisfaction of profitable, safe, and ecological requirements. The thresholds mostly used in the literature are system performance indices, such as, the RRV (Reliability, Resilience, and Vulnerability) metrics and the robustness index (see applications of water supply reliability and robustness Whateley et al., 2014; Brown et al., 2012). Giuliani and Castelletti (2016) argued that different definitions of the system performance indices could lead to different decision-making consequences. Some studies used the benchmarks under current climate as the thresholds to inform future management risks (e.g., Prudhomme et al., 2015; Broderick et al., 2019). The application on the management metrics that are used by stakeholders for water management remains rare in the literature. In this study, we used the management metrics (hydropower cost-effectiveness metric QA, environmental regulation metrics DOE and tDOE, and reservoir refill metrics NSA and tNSA) centred on the stakeholders' interest to investigate their vulnerability under climate change. These management metrics can be simulated by hydrological modelling under current and perturbed climate conditions. The thresholds of these management metrics were identified during the workshops with stakeholders. The direct use of the management metric and the associated thresholds interests stakeholders in the participation of adaptation designing (i.e., stakeholders are more familiar with these metrics than hydrologists and alternative adaptation actions that potentially change the thresholds can be tested within the vulnerability assessment, see Section 5.3).

5.2. Contribution to Pyrenean studies

This paper implements the first trial of the bottom-up approach, alternative to the traditional top-down approach, for the climate change impact assessment in the Pyrenean region by taking the central Aure Valley as an example. Water management vulnerability in the Valley in terms of hydropower (QA), environmental regulations (DOE and tDOE), and reservoir refill (NSA and tNSA) are investigated by integrating the sensitivity of water management metrics to perturbed climate scenarios, to the predefined thresholds of current management capacity, and to the plausible exposure of future climate change projections. Previous studies applied the top-down approach and demonstrated that climate change could severely impact water resource and management in the Pyrenees by generating discrete "snap-shots" of future time slices for comparison with the current state (e.g., Haro-Monteagudo et al., 2020). However, how the Pyrenean water systems respond to climate change, and at what degree of climate change the performance of water systems shifts from acceptable to unacceptable cannot be fully addressed by the top-down approach. Understanding the response of Pyrenean water systems to changes is critical for water managers to design mitigation and adaptation strategies.

The sensitivity of these three management components is studied for different temporal scales as seasonal meteorological attributes show different importance for management issues. The sensitivity of QA for the selected Eget and Lassoula systems is studied for the whole annual scale. Annual precipitation was found to be a key meteorological driver for QA and consequently for hydropower production. The higher sensitivity to temperature for the Eget system reveals that land cover types in this catchment induces more intensive PET when temperature increases, which then reduces the water availability for hydropower production. Still, annual precipitation changes dominate the hydropower management in the two systems with moderate impact from annual temperature changes. By combining the predefined threshold and plausible climate change pathways, the vulnerability of hydropower can be perceived that the Lassoula system is more vulnerable, highlighting the need for short term actions to reduce vulnerability. Both DOE and tDOE metrics of the Sarrancolin catchment are studied for the July to October period when river flow is low and downstream irrigation demand is intensive. The two metrics are sensitive to both precipitation and temperature changes as the Sarrancolin catchment has a large soil moisture content. Given the warmer and drier tendency of climate change, the current DOE threshold of 90 days is sufficient for most climate change scenarios before the end of the century. It is notable that water competition in this period should be dealt with caution. As for the metrics NSA and tNSA of the two hydropower systems, the study is focused on the December to August period that includes recharge and spring melting processes. A higher sensitivity of both NSA and tNSA to temperature changes is observed, compared to the other metrics. A warmer climate will induce an earlier snowmelt, whatever precipitation changes. More liquid precipitation as a result of temperature increase, instead of solid precipitation, would flash into the reservoirs, which may endanger the reservoir safety and cause water spills and losses for future use. Current reservoir refill strategy should be adapted to climate change.

The sensitivity and vulnerability analyses in the Aure Valley are a powerful visual aid for identifying water management problems. In general, hydropower production and reservoir refill are the most vulnerable management indices among the study area, particularly for the Lassoula system that incorporates the Caillaouas and Pouchergues reservoirs. However, the large storage volume of the Caillaouas reservoir could mitigate the effect of earlier and more flashy inflow. As such, dedicated actions should be implemented to adapt to climate change.

5.3. Potential mitigation and adaptation actions

On the premise of the vulnerability assessment of water management in the Aure Valley, mitigation and adaptation actions can be adopted from two sides to reduce climate change risk: water supply and demand sides, jointly and independently. Considering the drier projections in the Aure Valley, increasing reservoir storage is not the best move, let alone the intensive investment and the concern of environment (Maran et al., 2014; Zarfl et al., 2015; Poff et al., 2015). On the contrary, on the water demand side, modernization of irrigation method (e.g., sprinkler or drip irrigation system), crop promotion for less water requirement, and changes in crop calendars are efficient in adapting to climate change, especially for the Mediterranean area (e.g., Malek and Verburg, 2017; Galindo et al., 2018; Harmanny and Malek, 2019).

Given the high vulnerability of hydropower production under climate change, we test the adaptation strategy of increasing the current water-energy transfer coefficients for the Eget and Lassoula systems that can be realized by increasing the turbine efficiency. The current turbine efficiency values for both systems (around 85%) are tested to increase by 10%. Less water is thus needed to achieve the cost-effectiveness for both systems. Correspondingly, the thresholds of QA for both systems are reduced by a factor of 1+10% (37.8 Mm^3 for the Eget system and 25.6 Mm^3 for the Lassoula system) as illustrated in Fig. 9. The Eget system can achieve the cost-effectiveness in the "worst" market scenario till the 2060s under RCP 8.5 by this strategy (compared with the original timing of the 2050s under RCP 8.5). However, this strategy is more effective for the Lassoula system because it enables to achieve the cost-effectiveness in the "worst" market scenario for most climate change scenarios under RCP 4.5 and till the 2050s under the RCP 8.5 (compared with the original high vulnerability to most climate change scenarios under both RCPs). This example illustrates how the SN framework can be used to test adaptation strategies and other actions that eventually decrease the thresholds of QA for both systems should be considered. Besides, shifting the hydropower production from winter (for heating) to summer (for cooling) to align several water uses (hydropower, irrigation, and environmental regulations) is possible to reduce water competition in the Aure Valley (Pereira-Cardenal et al., 2014).

The original refill management that starts from April and ends in July for the two hydropower systems seems too late and too long in the face of warmer climate. As such, reservoir refill strategies might be changed with an earlier start and a more flexible duration. Increasing the reservoir spillway capacity should also be considered so as to avoid the extreme high inflow events into

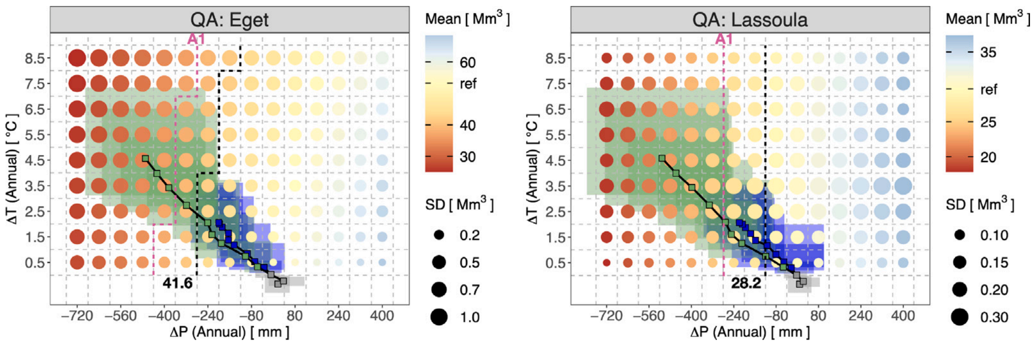


Fig. 9. The adaptation strategy of increasing the current turbine efficiency by 10% (A1) for the Eget and Lassoula systems.

the reservoirs that endanger reservoir safety. In particular, given the small storage volume of the Pouchergues reservoir and large storage volume of the Caillaouas reservoir, increasing the capacity of water transfer from the Pouchergues to the Caillaouas reservoir could mitigate water loss from spillway release. However, these changes should be scrutinized with caution as managers might be conservative in changes.

5.4. Limitations and future works

This study simplifies the water management processes and thus it is important to acknowledge the limitations that are likely to induce biases in the analysis. Future works focusing on these limitations will help to improve the understanding of water management vulnerability in the study area.

Firstly, uncertainty is partially examined here. The study focuses on climate-related uncertainty, exploring a broad range of climate conditions. The uncertainty of water management metrics to climate change is displayed by the SD values in the response surfaces with larger SD values indicating high dispersion in values for the specified changes. Parts of the uncertainty are due to natural processes that are not perfectly taken into account by the models. For example, the snow melting process simulation is less efficient than the snow accumulation process (see the SCA regimes of Fig. 4). This results from the choice of the empirical degree-day model CEMANEIGE and the difficulties in representing snow thermal state changes (Riboust et al., 2018). Although the GR6J-CEMANEIGE model has shown satisfying performance, different hydrological models show significant variations in water resource estimation (e.g., Vidal et al., 2016). Besides, a hydrological model calibrated under current climate may not perform robustly for perturbed climate scenarios due to parameter non-stationarity (e.g., Westra et al., 2014; Guo et al., 2017). These variations would propagate to the sensitivity domain, which may induce biases in the vulnerability assessment (Broderick et al., 2019). A physically-based hydrological model that explicitly simulates complex hydrological processes could be beneficial to deepen the understanding of the sensitivity to climate change. Therefore, a multi-model method that involves structurally or conceptually different hydrological models can provide valuable insights in the uncertainty quantification.

Secondly, the term “vulnerability” for water management in this study is not presented as a specially defined index but in a manner of description. Traditionally, vulnerability is used to characterize the performance of water systems in terms of the severity of their failure and the mathematical definition is given in Hashimoto et al. (1982). Some studies have examined the vulnerability of water management by calculating the water deficit to meet the total demand (e.g., Sandoval-Solis et al., 2011; Loucks and van Beek, 2017; Haro-Monteagudo et al., 2020). Furthermore, vulnerability in the bottom-up framework is derived as "the proportion of exposure simulations that fail below the critical threshold" in Sauquet et al. (2019) (not computed here), or the combination of the three components that includes sensitivity, exposure, and threshold (e.g., Mastrandrea et al., 2010; Prudhomme et al., 2013a,b). In the water management context, the evaluation of management performance is sometimes qualitative (e.g., reservoir refill) and problematic to be simplified as an index. Therefore, vulnerability in this study is given by subjective description with the participation of regional water stakeholders.

Thirdly, downstream water demand is assumed to be the maximum water allocation portion, which is 48 Mm^3 for irrigation, drinking water and industrial use, and to remain constant under all the scenarios investigated. In the historical experience of downstream water demand, the maximal value is actually reached for years 2005 (47 Mm^3), 2006 (48 Mm^3), 2007 (48 Mm^3), and 2011 (48 Mm^3). As such, a possible adaptation strategy may suggest to increase maximum water allocation portion by making new water contracts between SHEM and downstream water users. Besides, scenarios of land use and water use changes are worth being included in the sensitivity analysis. Previous studies highlighted land use and land cover changes, mostly the forest regeneration due to warming effect in the Pyrenees, could yield less water availability by more intensive PET of vegetation (e.g., López-Moreno et al., 2011; Morán-Tejeda et al., 2014; Buendia et al., 2015; Vicente-Serrano et al., 2019).

Finally, the generation of perturbed climate scenarios is based on the “delta-change” method that parametrically perturbs daily historical climate data with monthly change factors. This method, applied here for reasons of simplicity (straightforward to apply), has well-known limitations (e.g., not suitable for extreme events). However, the delta-change approach was considered relevant to address the vulnerability of a system sensitive to changes in water resources. Alternatives to the parametric method are stochastic methods, such as weather generators (e.g., Culley et al., 2019; Steinschneider et al., 2019). In addition, the climate perturbation is limited to precipitation and temperature in this study. Although precipitation and temperature mean changes are the main drivers in water management, the investigation of other variables, such as PET (Guo et al., 2017), precipitation variability (Poff et al., 2015) and water demand Foti et al. (2014), could also impact the performance of water systems.

6. Conclusion

Water resource and management in the Pyrenees under climate change remains a continuous regional issue. In this study, we illustrated a bottom-up approach to analyse the vulnerability of Pyrenean water management under climate change with an example of the central Aure Valley. To achieve this, we firstly developed a hydrological model GR6J-CEMANEIGE calibrated to the naturalized inflow and observed snow cover derived from satellite images, and the simulation results point to satisfactory water resource and management estimation. The next step is to apply the delta-change method, a parametric method, to perturb historical climate conditions. The current and perturbed climate series are finally forced into the calibrated hydrological model to simulate potential changes of water management metrics for sensitivity analysis. Changes in water management metrics (hydropower production, environmental regulations, and reservoir refill management) are demonstrated by the 2D response surface in answer to precipitation and temperature changes, which is visually practical in identifying the sensitivity of water management to climatic variables. Response surfaces overlaid with performance threshold isolines and plausible climate change pathways are essential for the exploration of key vulnerability.

Our findings confirm the high sensitivity of water management in the Aure Valley to seasonal/annual changes in precipitation and temperature. By integrating the exposure and the performance metrics of water systems in the Aure Valley, the vulnerability of water management under climate change can be assessed. The results in the study can be summarized as follows.

- Annual hydropower production is mostly dominated by changes in annual precipitation, and secondary by changes in annual temperature. Particularly, the Lassoula hydropower system is vulnerable to future drier climate conditions as the production threshold cannot be maintained under most future climate change projections.
- The environmental regulations for the Sarrancolin catchment are sensitive to both precipitation and temperature changes in summer and early autumn. Environmental management is less vulnerable to climate change while the timing of environmental water requirement would induce an intensive water competition among irrigation and hydropower.
- Reservoir refill management is extremely sensitive to changes in temperature for the winter–spring–summer period. The earlier snowmelt induces water loss and reservoir safety issues if the refill strategy remains unchanged.

On the basis of these vulnerability analyses, corresponding adaptation and mitigation actions can be designed to manage climate change risks. Non-structural measures can be suggested, which target the efficient use of water, especially in the irrigation domain. Other actions, such as increasing hydropower plant efficiency and increasing water transfer capacity for more flexible reservoir management could be also appreciated in mitigating hydropower losses. Given the earlier snowmelt, reservoir refill strategy should be correspondingly adjusted accompanied with the increase of spillway capacity for the reservoir safety.

Although there are some limitations, this study demonstrated valuable insights on the impact of climate change on water resource and management by firstly applying a bottom-up framework in the Pyrenean region. Future works, such as testing other hydrological models with different structure for uncertainty quantification, generating perturbed climate scenarios with more extreme events, testing water management stress to other climate variables or socio-economic changes, could advance the understanding in water management vulnerability. This framework is applicable to other Pyrenean regions for vulnerability assessment and adaptation design under climate change.

CRediT authorship contribution statement

Peng Huang: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Eric Sauquet:** Conceptualization, Methodology, Software, Writing – review & editing, Supervision. **Jean-Philippe Vidal:** Conceptualization, Methodology, Software, Writing – review & editing, Supervision. **Natacha Da Riba:** Investigation, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the project EFA210/16 PIRAGUA, cofounded by the European Regional Development Fund (ERDF) through the Interreg V Spain-France-Andorre Programme (POCTEFA 2014-2020) of the European Union.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ejrh.2022.101241.

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