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Water use scenarios versus climate change: Investigating future water management of the French part of the Moselle

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ABSTRACT

Study region: French part of the Moselle catchment

Study focus: By relying on hydrological simulations forced by climate change scenarios, stakeholders can assess the magnitude of future changes in the rainfall–runoff relationship. The inclusion of human influences in water resources modelling in a non-stationary context is a way to improve the accuracy and usefulness of climate change impact studies. Here, we propose a modelling approach that explicitly considers water uses to evaluate adaptation measures for water management at the French Moselle catchment scale.

New hydrological insights for the region: The results highlight the decrease in future low flows but also the change in the balance between demand and supply. Over the Moselle catchment, whatever the water use scenario considered, climate change induces lower water availability both for environmental flows and for human uses. This leads to a potential increase in the duration of water restriction of up to 8 weeks for RCP 8.5 in the long term (2070–2099) compared to 1976–2005. This study could provide water managers with more appropriate climate impact results and potentially help them to design adequate adaptation measures.

1. Introduction

With climate change, severe low-flow levels and droughts are expected to multiply and intensify in Europe (Marx et al., 2018). In recent years, France, and more generally Europe, has experienced several severe droughts (e.g. 2018, 2019, 2020, and 2022). These events have highlighted the difficulty of managing human water demand during events of water deficit even over mid-latitude. With ongoing climate change, this imbalance between water demand and water availability is likely to increase, making it more difficult for authorities and decision-makers to manage water resources sustainably. In this context, it is necessary to design adaptation measures, e.g. modification of water uses, so as to anticipate and moderate the impact of water scarcity. Unfortunately, as scientists and water managers have to deal with uncertain projections, it remains a challenge to quantify the effects of such measures.

Observed streamflows are commonly used for hydrological modelling both for calibrating or assessing simulations (Gupta et al., 1998). However, in most cases, observed streamflows do not reflect the natural water cycle, but rather a human-influenced cycle. Therefore, the "classic" modelling approach, which rarely represents influences such as water withdrawals and releases, reaches its limitations when applied in the context of climate change. In other words, when water is withdrawn at one location, a fraction of it may

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be consumed, e.g. vaporized, transferred to another location, reinfiltrated by network leakage, or transformed to something else than liquid water. In addition, water management, especially during low-flow periods, aims at restricting water uses and therefore modifies the water cycle.

The representation of human impacts on hydrology is already at the core of scientific reflections. For example, the Panta Rhei initiative (2013–2022) focused on hydrological systems as a changing interface between the environment and society (Montanari et al., 2013). Understanding and modelling water cycle processes, with a focus on their changing dynamics with rapidly changing human systems, remains a major challenge. This scope was also highlighted by the 23 unsolved problems in hydrology (Blöschl et al., 2019), specifically the 22nd question on, "What are the synergies and trade-offs between societal goals related to water management (e.g. water–environment–energy–food–health)?" Various hydrological climate impact studies based on hydrological models have been performed without taking into account the human effects on water resources and the water supply system (e.g. Demirel et al., 2013, Hagemann et al., 2013, Donnelly et al., 2017). However, various studies have pointed out the importance of representing human influence in the hydrological model especially for climate impact studies, either in terms of water supply or water policies (Kirby et al., 2013; Collet et al., 2015; 2020). At the global scale, Nazemi and Wheater (2015) stressed the need to upgrade Earth system models by including water resources management, due to the importance of water resources management in determining the future of the global water and climate cycles. At the catchment scale, it is now considered that the improvement of hydrological modelling also involves a correct representation of the human water system (e.g. Bellin et al., 2016).

Above all, in climate impact studies, water managers are interested in the evolution of droughts or low-flow events. Various studies already demonstrated with historical data that the inclusion of human influences in the hydrological modelling framework is relevant for low-flow simulation performances. For instance, He et al. (2017) showed the importance of representing water use and management to analyse drought events. Wendt et al. (2021) proved the importance of accounting for drought policies in the modelling framework, especially since maintaining environmental flows can reduce the magnitude of droughts. In addition, Veldkamp et al. (2018) demonstrated that representing water use and management in hydrological modelling improves the representation of hydrological extremes including droughts. Some land surface models include these human-based processes, e.g. WaterGAP (e.g. Flörke et al., 2013) or PCR-GLOBWB (Wada et al., 2014), which are used as climate change impact models. At a finer scale, i.e. for regional studies, the WEAP model (Yates et al., 2005) or the J2000-Rhône model (Branger et al., 2016) are also able to represent water use and hydrological processes.

The present study aims to develop a hydrological modelling approach to evaluate the consequences of climate change and water use scenarios for water resources, both in terms of supply and satisfaction of the societal water demand. This requires coupling a classic hydrological model and a water use model and applying the coupled model to several climate and societal scenarios. To support these experiments, we worked with the Rhin-Meuse Water Agency, i.e. the water managers of the study catchment, namely the French part of the Moselle River catchment. This territory has been the subject of different studies over the past years, through the assessment of the impact of climate change on natural water resources (Thirel et al., 2019), the reconstruction of low flows since 1871 (François et al., 2020), and the assessment of the skill of ensemble seasonal low-flow forecasts (Demirel et al., 2015). However, to our knowledge, this territory has not been the subject of studies relating to the balance between water resources and water uses.

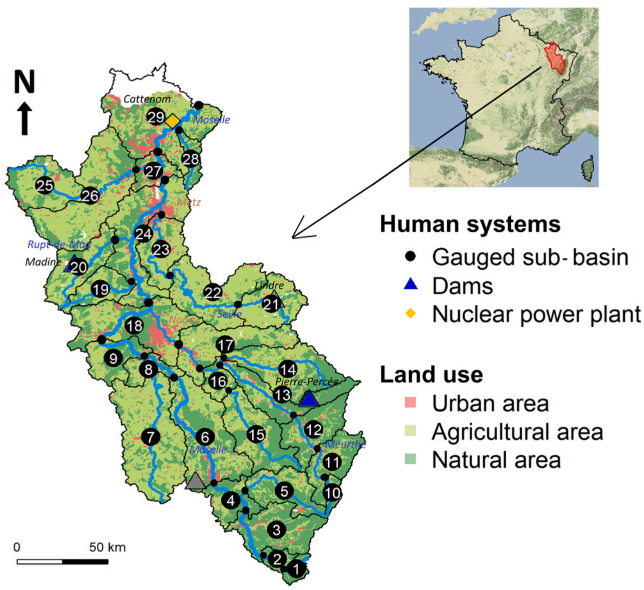


Fig. 1. Map of the study area: Moselle River catchment in France and main characteristics of geographical and human systems. A total of 29 gauging stations are used in the catchment. For correspondence between station numbers and station names, see Table 1.

2. Materials and methods

2.1. Study area: the French part of the Moselle River catchment

2.1.1. Current hydrological conditions

The Moselle River is a tributary of the Rhine River, and a transboundary river that crosses France, Germany, and Luxembourg (Fig. 1). The source of the river is located in the Vosges massif, and the catchment size of the French part of the Moselle River at Perl, which is the study area for this work, is approximately 11,000 km^2. The study area faces a temperate climate with continental influences. Based on climate data of Météo-France from the SAFRAN reanalysis (Vidal et al., 2010) from 1991 to 2020, the average monthly temperatures range from 2 to 19 °C. The average monthly precipitation is relatively regular, with a slightly wetter winter than the rest of the year. Due to the topographic gradient, the upstream part of the catchment is characterized by more abundant yearly precipitation (> 2200 mm.yr^{-1}) and colder yearly temperatures (8 °C) compared to the downstream part of the catchment (1000 mm. yr^{-1} for precipitation and 10 °C for temperature). Daily precipitation (P) and Penman–Monteith potential evapotranspiration (PET) from the SAFRAN reanalysis will be used in the hydrological model.

Daily streamflows for the Moselle River basin are available in the national HYDRO archive (Brigode et al., 2020; Leleu et al., 2014) and are used to calibrate a semi-distributed hydrological model (Fig. 1). A selection of 29 hydrometric stations was made according to the quality and the length of the available data (Table 1).

In terms of land use, natural and agricultural areas predominate while urban areas are concentrated around Metz and Nancy, the two main cities in the catchment. There are several existing hydraulic structures to satisfy the water demand of several human activities, such as reservoirs of varying sizes, waterways, and a nuclear power plant. The main infrastructures are (i) waterways crossing the Moselle catchments from west to east, (ii) the Cattenom nuclear power plant, located downstream of the Moselle, (iii) drinking water withdrawal from surface water to supply Metz and Nancy, (iv) the Pierre-Percée lake, located upstream of the Meurthe River, whose role is to compensate for the Cattenom nuclear power plant evaporation and to sustain low flows, (v) the Lac de Madine that sustains low flows of the Rupt de Mad River, to ensure drinking water supply in the Rupt de Mad sub-basin at Onville, and (vi) the Lindre lake, located upstream of the Seille River, which is emptied every 2 out of 3 years and is used for fishing.

2.1.2. Current water system

Users who withdraw more than 10,000 m^3 per year need authorization from the Water Agency and are registered. These data include information on the annual amounts of water withdrawn and the location of the withdrawal. These data can be used to assess the current influence of human activities on the Moselle River catchment. Water withdrawal data that are available for the period 2008–2018 include different water use sectors: drinking water, industrial activities, energy production, and waterway supply. The amount of water withdrawn by each sector is presented in Fig. 2. The map (Fig. 2a) shows the spatial heterogeneity of water

Table 1
Hydrometric stations in the Moselle catchment used in the study (see Figure1).

No.	River	Gauging station	Surface (km^2)	Mean annual streamflow (m^3.s^{-1})
1	La Moselle	Fresse-sur-Moselle	71	3.2
2	La Moselle	Rupt-sur-Moselle	152	6.6
3	La Moselle	Saint-Nabord	626	24.0
4	La Moselle	Épinal	1217	37.6
5	La Vologne	Cheniménil	355	9.2
6	La Moselle	Tonnoy	1976	46.7
7	Le Madon	Pulligny	943	10.3
8	La Moselle	Pont-Saint-Vincent	3070	54.1
9	La Moselle	Toul	3338	62.7
10	La Meurthe	Fraize	67	2.0
11	La Meurthe	Saint-Dié	374	7.6
12	La Meurthe	Raon-l'Étape	727	14.4
13	La Meurthe	Lunéville	1105	18.2
14	La Vezouze	Lunéville	559	6.6
15	La Mortagne	Gerbéviller	493	5.5
16	La Meurthe	Damelevières	2280	33.2
17	La Meurthe	Laneuveville-dvt-Nancy	2780	35.8
18	La Moselle	Custines	6830	112.0
19	L'Esch	Jezainville	231	1.4
20	Le Rupt de Mad	Onville	358	3.2
21	La Seille	Moyenvic	352	2.9
22	La Seille	Nomeny	925	7.5
23	La Seille	Metz	1280	9.7
24	La Moselle	Hauconcourt	9387	129.0
25	L'Orne	Boncourt	412	3.6
26	L'Orne	Rosselange	1226	12.1
27	La Moselle	Uckange	10,770	140.0
28	La Canner	Koenigsmacker	110	0.9
29	La Moselle	Perl	11,832	163.1

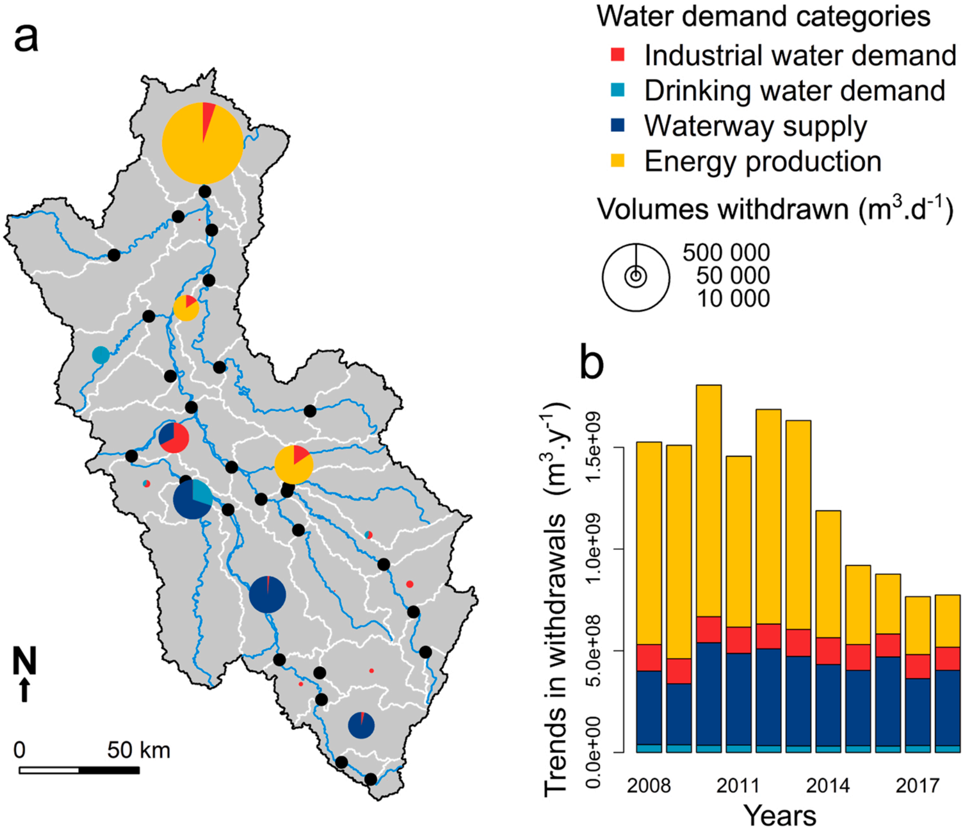


Fig. 2. Water withdrawal analysis over the French Moselle catchment during the period 2008–2018. a. Map of water withdrawal for each sub-catchment of the River Moselle catchment. b. Evolution of water withdrawals in the Moselle River catchment.

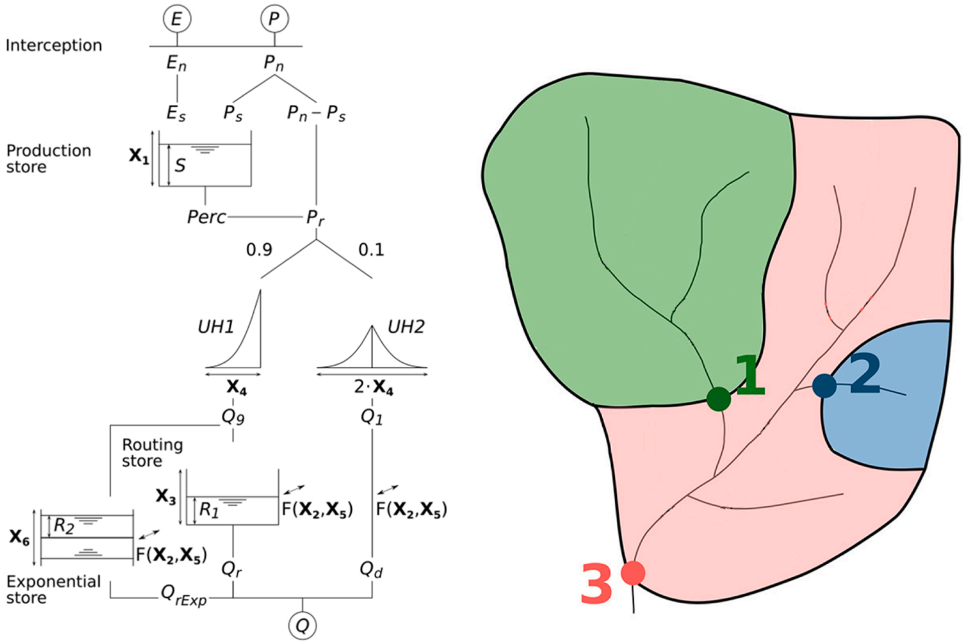


Fig. 3. Scheme of the GR6J model (left, after Coron et al., 2020); Example of the subdivision of a catchment (right, after de Lavenne et al., 2017), one GR6J model being applied on each subbasin, and the simulated upstream streamflow are routed downstream using a lag function.

withdrawal in the Moselle basin both in terms of use and amount. Fig. 2b shows a reduction in the total amount of water withdrawn, due to the recent closure of two power plants (only the nuclear plant is still operating in the downstream part of the catchment). Another influence is the presence of dams to secure withdrawals during low-flow periods. Water use sectors directly concerned by the presence of these reservoirs are energy production and drinking water supply.

During severe drought situations, water demand may not be fully satisfied for all types of water use. In these situations, water policy stakeholders apply water restriction rules to limit water withdrawals. Low-flow periods are ranked in order of importance according to their intensity: vigilance, alert, reinforced alert, crisis. Depending on the severity, a range of regulation rules are applied for each water use, from limiting water withdrawal for minor water uses to limiting withdrawal for essential uses. These rules also aim at maintaining a minimum ecological flow in the rivers. In the Moselle catchment, low-flow water management thresholds are defined for different gauging stations based on the observed VCN3 indicator (lowest 3-day flow recorded) associated with different return periods. The values of the management thresholds are presented in Appendix A (Table A.1).

2.2. *Hydrological modelling including integrated water resources management*

2.2.1. *Hydrological model*

River streamflows are simulated with the GR6J hydrological model (Pushpalatha et al., 2011), in a semi-distributed way (Fig. 3). GR6J is a daily lumped process-based hydrological model well designed for low-flow simulation (Tilmant et al., 2020), modified from the GR4J model (Perrin et al., 2003). GR6J is a bucket-type model with six parameters to calibrate. X1 and X3 are, respectively, the production and the routing store capacity parameters (mm). X4 is the unit hydrograph time base (d). X2 and X5 are, respectively, the inter-catchment exchange coefficient (mm.d^{-1}) and the exchange threshold (unitless). X6 is the exponential store capacity parameter (mm).

The catchment is discretized into 29 sub-catchments (Fig. 1), i.e. for each available gauging station. The GR6J model is applied for each sub-catchment with its climatic inputs (precipitation and potential evapotranspiration) to simulate the corresponding streamflow. Then, upstream streamflows are routed to the downstream sub-catchment with a lag function (Lobligeois et al., 2013).

2.2.2. *Coupling water use to hydrological modelling*

The "airGRiwrm" R package (Dorchies et al., 2021) relies on the airGR R package (Coron et al., 2017, 2020), which makes it possible to set up hydrological modelling with lumped and semi-distributed GR models. The airGRiwrm package enables both the automation of semi-distribution of the GR models and the integration of human water uses (e.g. withdrawals and releases, but also dams). It is noteworthy that coupling the hydrological model with a water use model or taking into account measured influence time series modifies hydrological model parameters (Fig. 4).

In the model, water use flows may be leakage, consumption, and release, providing the following equation:

Eq. 1.

$$Q_{use} = Q_{leak} + Q_{release} + Q_{withdrawal}$$

with Q_{use} the amount of water use in the modelling framework. If Q_{use} is negative, it means that more water is withdrawn than released. Q_{leak} corresponds to leak outflow leaving the system (negative value), $Q_{release}$ is the return outflow to the river due to the recycling water use (positive value), $Q_{withdrawal}$ is the outflow consumed and leaving the system for dams or definitive consumption (negative value).

One of the main assumptions we made in the proposed modelling framework, for the sake of simplicity, is that withdrawal, leakage, and release typically occur within the same sub-catchment, except for a few water uses that face important inter-catchment transfers. In case withdrawal and release are considered occurring in the same sub-catchment, the model subtracts the difference between the

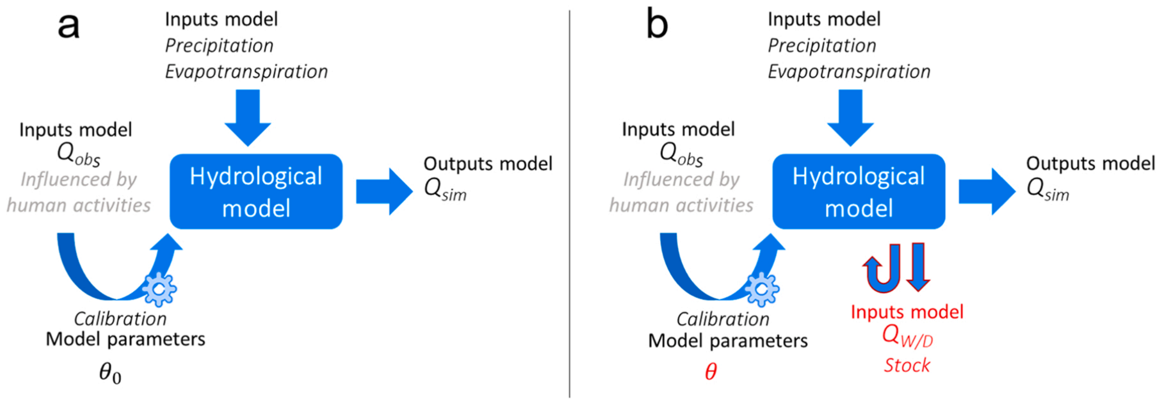


Fig. 4. Conceptual hydrological modelling frameworks. a. Classic hydrological modelling. b. Hydrological modelling integrating water uses. $Q_{W/D}$ represents the amount of water withdrawn/released to the natural system and *Stock* represents the volume of water in the reservoirs.

volume withdrawn and the volume released to affect the river flow balance. We also assume that the collection and discharge are performed on the same day and at the same location. This simplification for modelling at the sub-catchment level seems reasonable for industrial and energy uses, given the small daily variations and the short retention times in the networks. We also considered this assumption as reasonable for drinking water in rural areas. However, concerning the uses for drinking water of Metz and Nancy, and the supply of the waterways, we considered this assumption as not always reasonable, because important volumes can be withdrawn in a sub-catchment different than the one for release and consumption. Fig. 2 shows each withdrawal point in the model according to the use. In Appendix B, we show a table summarizing the water transfers as well as a schematic of water withdrawal and releases for each sub-catchment. In addition, observed water use data are disaggregated, e.g. water withdrawal or release is constant throughout the year, given the small daily variations.

For drinking water use only, leakage outflow was considered based on the actual efficiency of the drinking water network (the efficiency coefficient of the drinking water network is around 73 % for rural areas and 81 % for urban areas). The net consumption was considered negligible since the wastewater is returned to the river after treatment in a wastewater treatment plant. For industrial water use, leaking outflow was unknown. We used a recycling ratio of 90 % (i.e. water consumption represents 10 % of the water withdrawn) based on the literature (Hejazi et al., 2014). For energy production, leaking outflow is negligible, and the relative consumption was provided by the power plant manager. The nuclear power station consumes by evaporation around 29 % of the water withdrawn, due to the process of cooling. Lastly, the consumption of waterways (through evaporation) is considered negligible compared to the leakage outflow of canals. This information is summarized in Appendix B.

Furthermore, dams and the associated water management rules are included in the model. First, the main dam (Pierre-Percée) in the catchment stores more than 61 Mm^3. Its main objective is to increase streamflow during low-flow events to maintain both energy production use and environmentally required streamflow. The second dam is located in the Rupt de Mad sub-catchment and has a capacity of 35 Mm^3, 10 Mm^3 of which is aimed at securing the supply of drinking water for the main city of the Moselle River catchment, namely Metz. The operating rules of this dam are based on the flow of the downstream river to secure water withdrawals. Water management rules are implemented in the hydrological model, to mimic the management of the dams and their influences (equations are described in Appendix C).

In addition to the flows and stocks described in the model, specific resource management rules need to be implemented during periods of droughts. Indeed, when the water resources are not sufficient to satisfy all the uses simultaneously, an order of priority of the uses is prescribed to the model. The first objective is to maintain a minimum environmental flow in the river (fixed at 1/10 of the mean annual observed streamflow by French legislation), then to satisfy the water demand from the nuclear power plant, followed by drinking water production, industrial production, and lastly, the water supply of waterways. For each sub-catchment, the uses are satisfied in this order. This order reflects the actual management of the Moselle basin, although this theoretical functioning can in reality be altered by specific cases and although the final decision is always made by local authorities.

2.2.3. Hydrological modelling set-up

Before using the model for prospective objectives, we assessed its robustness through a split-sample test procedure (Klemeš, 1986). The record period was limited due to the relatively short period of availability of withdrawal data (2008–2018). Thus, a split-sample test procedure was performed consisting in calibrating the model on the period 2009–2013 (the year 2008 being used as the warm-up period) and controlling on the period 2014–2018 (the year 2013 being used as the warm-up period), and vice versa.

To better represent low-flow events, a mathematical transformation was applied on streamflow before calculating the objective function used for calibration (Garcia et al., 2017). Based on the work of Santos et al. (2018) and Thirel et al. (2023), we used the KGE criterion (Gupta et al., 2009) with a Box–Cox transformation of streamflows. Moreover, the regularization method developed by de Lavenne et al. (2019) was applied to the calibration procedure, to maintain the spatial consistency of parameter values across sub-catchments.

2.2.4. Hydrological model evaluation

To evaluate the quality of simulations, and take a closer look at low-flow events, we used efficiency criteria specific to low-flow events (e.g. Nicolle et al., 2014). Low-flow events are therefore evaluated in terms of severity, through the volume of deficit (VD) (Eq. C.1), and in terms of duration (D). The volume of deficit and duration of low flows are calculated for the simulations and observations and then compared with a ratio, RVD (Eq. C.2) and RD (Eq. C.3), respectively, to qualify the deviation of simulations from observations. The estimation of VD and D requires that a threshold streamflow value be defined under which we consider that the river experiences a low-flow event. We set this threshold value at Q90, i.e. the flow which was equalled or exceeded for 90 % of the historical observed flow record period. Consequently, D represents the number of low-flow days per year, i.e. the number of days for which the streamflow is under Q90, and VD represents the cumulated difference between streamflow and Q90 for low-flow events (see full details in Appendix D).

Water managers also use more integrative indicators such as the VCN3 in the low-flow alert system and its value is compared with thresholds every week to decide whether water restrictions should be imposed or not (Eq. C.5). The ratio (RVCN3) between VCN3 calculated from observations and simulations is then calculated to analyse performance (Eq. C.6).

The calculated weekly VCN3 values are compared with thresholds determined using historical VCN3 values for different return periods. If the weekly VCN3 is below a threshold, the entire week is considered a drought event. This event is then classified into vigilance, alert, reinforced alert, or crisis event, depending on the threshold reached. To evaluate the representativeness of the low-flow event alert system by the model, a contingency table (Table C.1) is used (Sauquet et al., 2019). An event was defined when at least the vigilance threshold was crossed, and a non-event was defined as a period during which no low-flow threshold was crossed.

The capacity of the hydrological model is analysed using the probability of detection (POD, Eq. C.7), to estimate the right detection rate of the model, and conversely the false-alarm rate (FAR, Eq. C.8), for the false-detection rate.

2.3. Projections and scenarios to evaluate climate change impact

2.3.1. Climate projections

Climate projections used for this study come from CMIP5, specifically from the EURO-CORDEX initiative (Jacob et al., 2014), and were bias-corrected by Météo-France with the ADAMONT method (Verfaillie et al., 2017). Data are available on the DRIAS2020 dataset (Soubeyroux et al., 2020; http://www.drias-climat.fr/). The available climate projections are summarized in Table 2. For this study, the use of bias-corrected data is essential to provide projections of water resources with a better spatial representation at the catchment scale, thus representing water volumes following the practices of managers and decision-makers. The analysis will be carried out in terms of anomaly, with respect to the reference period (1976–2005). Among these climate model couples, which will all be used for most analyses, three are chosen to analyse the results in more detail. Indeed, the threshold effects of the management algorithms complicate the ensemblist analysis of the projections. First, ICHEC-EC-EARTH_KNMI-RACMO22E is chosen because its changing signal is very close to the median of the ensemble. ICHEC-EC-EARTH_SMHI-RCA4 is chosen as the warmest and driest future because its changing signal is very close to the 90th percentile of the ensemble. Inversely, CNRM-CM5_KNMI-RACMO22E is chosen for its low warming and low drying, since its changing signal is very close to the 10th percentile of the ensemble.

2.3.2. Exploratory scenarios for projections of water demands

Since the modelling framework explicitly includes water demand and its satisfaction through water management rules, it allows us to take into account the evolution of water demand over the catchment scale, in conjunction with the effect of climate change on the availability of water resources. To cover a large spectrum of possible water demand evolutions, three different scenarios were proposed, and each one was available for each water use sector. Basically, the scenarios were designed following different hypotheses: a scenario for which water demand is constant, a scenario that consists of a reduced water demand due to an active policy of environmental preservation (thereafter named decrease scenario), and a scenario that consists of an increased water demand due to reindustrialization and increased population (thereafter named increase scenario, see Table 3). These scenarios were designed on the basis of hypothesized trajectories until 2050. After 2050, a constant water demand (i.e. no change with respect to the year 2050) was applied, due to the difficulty of anticipating the evolution of water demand at such a long-term perspective. Given the large spread of these hypothetic scenarios of water demand, they could be considered as contrasting societal evolutions to mimic policies of potential adaptation measures. These three scenarios were presented to the Rhin-Meuse Water Agency and were considered as plausible evolutions of water uses in the catchment.

3. Results

3.1. Evaluation of the hydrological model coupled to the water use model

A split-sample test is used to evaluate the performance of the hydrological model under the integrated water resources management framework (Fig. 5). KGE scores, which aim at comparing simulated time series of discharge with observed series and whose maximum value is 1, present a good performance over all sub-catchments, except for some sub-catchments in the upstream part of the Moselle River. Because of the satisfactory performance over the two periods and the limited length of the records for the long-term hydrological simulation, the entire set of records is ultimately used to provide the most robust set of parameters. From hereon, the parameter set obtained after calibration over the whole period will be used.

The evaluation was also targeted at the ability of the model to reproduce low-flow events and the water management decision based on low-flow thresholds in the river. Firstly, Fig. 6 presents the ratio between observed and simulated VCN3 (RVCN), the volume of

Table 2
The available climate projection data from DRIAS2020. In bold, the three pairs whose results are more specifically detailed in this study.

Representative Concentration Pathway (RCP)			General Circulation Model (GCM)	Regional Climate Model (RCM)
RCP 2.6	RCP4.5	RCP 8.5		
✓	✓	✓	CNRM-CM5	CNRM-ALADIN63
✓	✓	✓	**CNRM-CM5**	**KNMI-RACMO22E**
	✓	✓	IPSL-CM5A-MR	IPSL-WRF381P
	✓	✓	IPSL-CM5A-MR	SMHI-RCA4
✓		✓	MOHC-HadGEM2-ES	ICTP-RegCM4–6
✓	✓	✓	MOHC-HadGEM2-ES	CLMcom-CCLM4–8–17
	✓	✓	**ICHEC-EC-EARTH**	**KNMI-RACMO22E**
✓	✓	✓	**ICHEC-EC-EARTH**	**SMHI-RCA4**
✓	✓	✓	MPI-ESM-LR	CLMcom-CCLM4–8–17-
✓	✓	✓	MPI-ESM-LR	MPI-CSC-REMO2009
	✓	✓	NCC-NorESM1-M	DMI-HIRHAM5
✓		✓	NCC-NorESM1-M	GERICS-REMO2015

Table 3
Summary of water demand scenarios for the different water use sectors. Population trends are the INSEE (National Institute of Statistics) trends for the region (www.insee.fr/fr/statistiques/2859843, Calzada et al., 2007), trends for industrial water demand for the decrease scenario consider a decrease by 1.1 % per year (Fujimori et al., 2017) while the increase scenario considers a linear increase up to the value of the year 2010, before the economic crisis. The efficiency coefficient for drinking water supply is 0.79 for the Moselle catchment, maintained at this value for the increase scenario and planned to increase up to 0.85 for the decrease scenario since it is the objective at the national level (https://www.legifrance.gouv.fr/loda/id/JORFTEXT000025208197/). The closure dates of the nuclear plant are hypothesized from the scenarios proposed by RTE (*Réseau de transport d'électricité*), which is the French organization responsible for the public high-voltage electricity transmission network in mainland France (https://assets.rte-france.com/prod/public/2021–10/Futurs-Energetiques-2050-principaux-resultats_0.pdf).

Water use sector	General equation of withdrawal demand (Q_{WD})	Variables and water demand changes for the **constant scenario**	Variables and water demand changes for the **decrease scenario**	Variables and water demand changes for the **increase scenario**
Drinking water	$Q_{WD}(y) = r_{c_E}(y) \bullet r_{Pop}(y) \bullet r_{UWD}(y) \bullet Q_{WD}(2018)$ y is the year r_{UWD} is the ratio of unit water demand ($m^3.s^{-1}$ per capita) to the unit water demand in 2018 r_{Pop} is the ratio of population count to the population count in 2018 r_{c_E} is the ratio of the efficiency coefficients c_E of the drinking water network ($c_E = 0.79$ for year 2018)	$r_{Pop}(y) = 1$ $r_{UWD}(y) = 1$ $r_{c_E}(y) = 1$ Relative change of Q_{WD} from 2018 to 2050 = 0 %	$\begin{cases} r_{Pop}(y) = 1 - 0.00272 \bullet (y - 2018) \text{ if } y \leq 2050 \\ r_{Pop}(y) = 0.913 \text{ if } y > 2050 \end{cases}$ $\begin{cases} r_{UWD}(y) = 1 - 0.00625 \bullet (y - 2018) \text{if } y \leq 2050 \\ r_{UWD}(y) = 0.800 \text{ if } y > 2050 \end{cases}$ $r_{c_E}(y) = \frac{0.79}{0.79 + 0.001875 \bullet (y - 2018)} \text{ if } y \leq 2050$ $r_{c_E}(y) = \frac{0.79}{0.85} = 0.93 \text{ if } y > 2050$ Relative change of Q_{WD} from 2018 to 2050 = −32.0 %	$\begin{cases} r_{Pop}(y) = 1 + 0.00406 \bullet (y - 2018) \text{ if } y \leq 2050 \\ r_{Pop}(y) = 1.131 \text{ if } y > 2050 \end{cases}$ $r_{UWD}(y) = 1$ $r_{c_E}(y) = 1$ Relative change of Q_{WD} from 2018 to 2050 = +13.1 %
Industry	$Q_{WD}(y) = r_{eff}(y) \bullet Q_{WD}(2018)$ r_{eff} is the correction factor due to either technological improvements of industrial processes (in the case of decrease) or reindustrialization policies (in the case of increase).	$r_{eff}(y) = 1$ Relative change of Q_{WD} from 2018 to 2050 = 0 %	$\begin{cases} r_{eff}(y) = 1 - 0.00844 \bullet (y - 2018) \text{if } y \leq 2050 \\ r_{eff}(y) = 0.730 \text{if } y > 2050 \end{cases}$ Relative change of Q_{WD} from 2018 to 2050 = −27.0 %	$\begin{cases} r_{eff}(y) = 1 + 0.00475 \bullet (y - 2018) \text{ if } y \leq 2050 \\ r_{eff}(y) = 1.152 \text{ if } y > 2050 \end{cases}$ Relative change of Q_{WD} from 2018 to 2050 = +15.2 %
Energy	$Q_{WD}(y) = io(y) \bullet Q_{WD}(2018)$ io(y) is a coefficient taking a value of 0 or 1 depending on the closure of the nuclear plant projected before 2050.	$io(y) = 1$ Relative change of Q_{WD} from 2018 to 2050 = 0 %	$\begin{cases} io(y) = 1 \text{if } y \leq 2035 \\ io(y) = 0 \text{if } y > 2035 \end{cases}$ Relative change of Q_{WD} from 2018 to 2050 =-100 %	$\begin{cases} io(y) = 1 \text{ if } y \leq 2045 \\ io(y) = 0 \text{ if } y > 2045 \end{cases}$ Relative change of Q_{WD} from 2018 to 2050 = −100 %
Waterways	$Q_{WD}(y) = Q_{WD}(2018)$	Relative change of Q_{WD} from 2018 to 2050 = 0 %	Relative change of Q_{WD} from 2018 to 2050 = 0 %	Relative change of Q_{WD} from 2018 to 2050 = 0 %

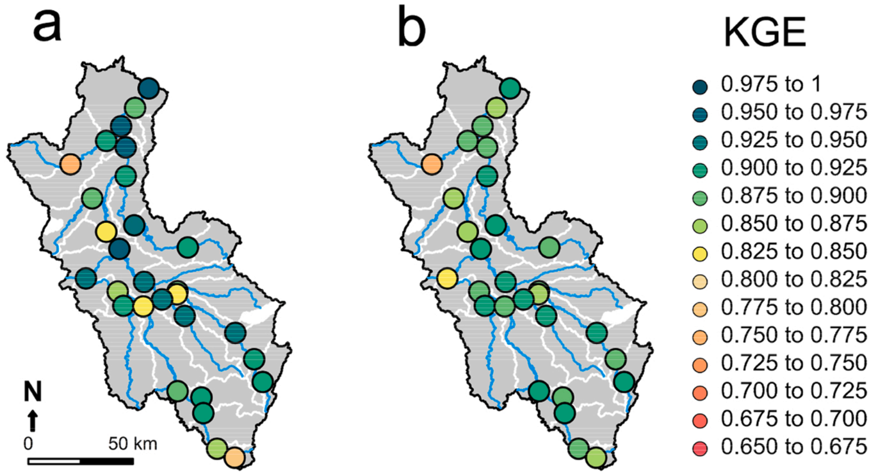


Fig. 5. KGE values with Box–Cox streamflow transformation for hydrological simulation nodes from the split-sample test procedure. Scores are shown for the evaluation period only: a: calibration on 2008–2013 and evaluation on 2013–2018; b: calibration on 2013–2018 and evaluation on 2008–2013.

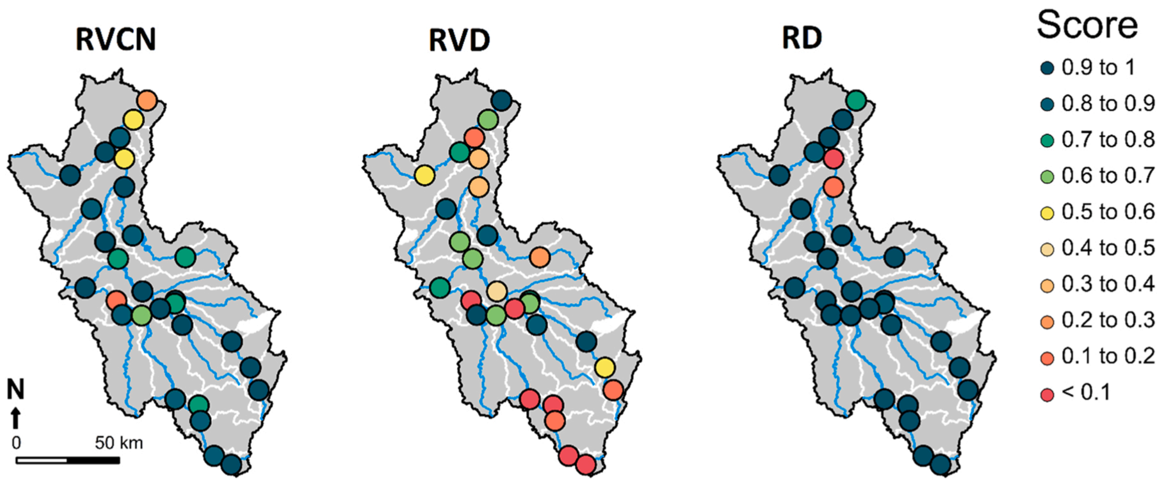


Fig. 6. Low-flow criteria scores for hydrological simulations over the complete period 2008–2018: a. Score RVCN (1-|1-RVCN3|); b. Score RVD (1-|1-RVD|); c. RD (1-|1-RD|).

deficit (RVD), and the duration of low flows (RD). RVCN and RD criteria show good performance over all sub-catchments. However, the RVD criterion presents a poor performance for some sub-catchments. This could be due to a water balance problem (see RVD), e.g. possibly caused by poor precipitation estimates at higher altitudes, or caused by the fact that this indicator is calculated, for such small catchments, on very low volumes and is therefore very sensitive to small differences. In addition, the upstream part of the Seille River catchment (catchment 21) suffers from a volume issue; which could be due to the presence of the Lindre pond, which is emptied for fishing at the end of the summer/beginning of autumn around every 2 out of 3 years, and refilled during winter, two operations that are not represented in the model. This pond therefore affects the water balance, but not necessarily the duration of droughts. Finally, in the downstream part of the Seille River catchment and at the confluence with the Moselle River, the VD and the D criteria suffer from biases. A possible explanation could be the presence of a large city in the area, Metz, whose urbanization and water uses may impact the performance of the model, despite the efforts made for collecting data and representing these uses in the model.

The occurrence of drought alerts of various levels was calculated at the hydrometric stations included in the low-water monitoring network for both observed and simulated flows and is presented in Fig. 7a. Overall, drought alerts are correctly represented based on simulated flows, but the drought severity level seems more difficult to reproduce correctly. Note that while the implementation of restrictions is automatic in the model, it is not so in the real world, since restrictions are decided by a human authority, who may adjust the restrictions in terms of volume or make exceptions for certain users.

To go further, a contingency table for water restrictions was computed. The number of water restrictions in the contingency table was defined as any legally binding water restriction of at least a “vigilance” level. The model shows satisfactory performance for the

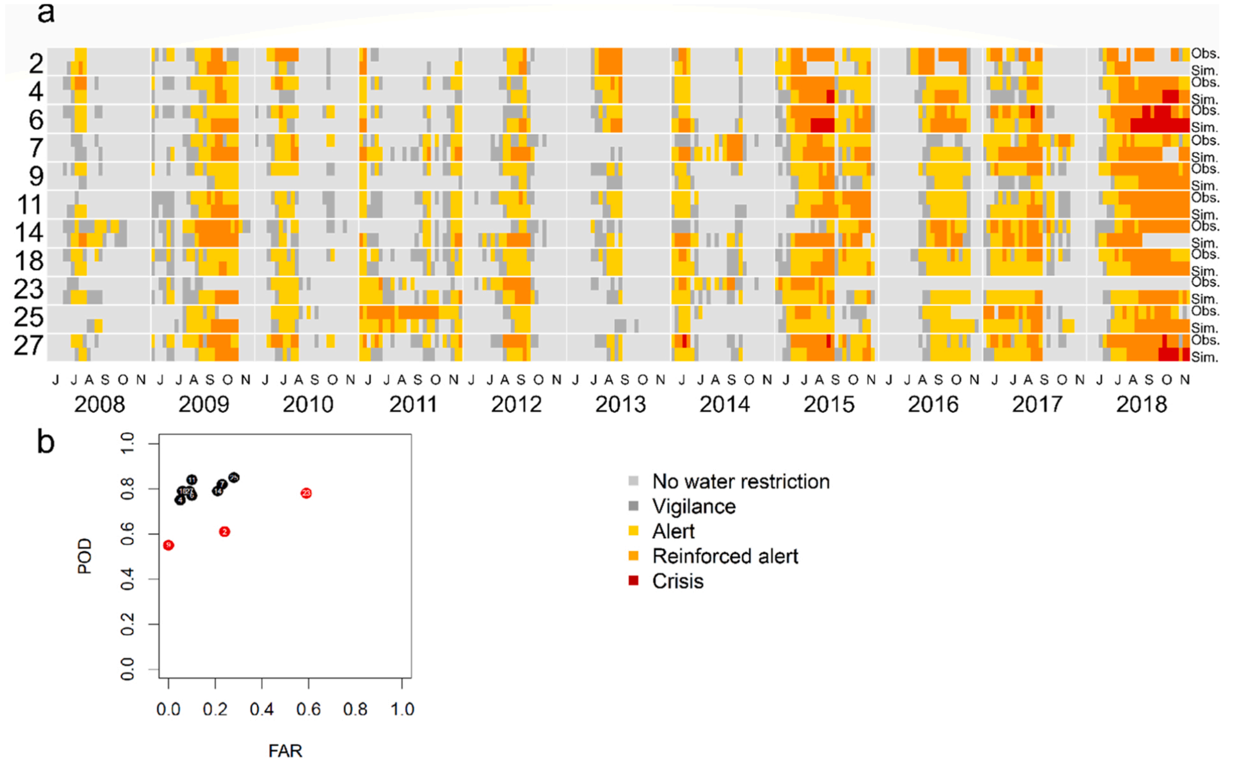


Fig. 7. Theoretical water restrictions determined from observed and simulated streamflows for low-flow reference-gauging stations used by water managers. a. Comparison of water restriction levels between observations and simulations, from June to November during the period 2008–2018. Numbers correspond to the station numbers (see Table 1). b. POD and FAR scores for water restrictions estimated from simulated streamflows. Note that for station 23, there is no record after 2015. Stations 2, 9 and 23, mentioned in the text, are figured in red.

FAR and POD criteria on most of the stations analysed (Fig. 7b). The majority of stations show a minimal false-alarm rate, combined with a good alert detection performance, except for the Moselle River at Rupt-sur-Moselle (2), the Moselle River at Toul (9), and the Seille River (23) sub-catchments, which had previously shown poor performance on other low-flow criteria. The model, therefore, seems to be usable for reproducing water restrictions in the Moselle basin, but it should be noted that the correct alert level is difficult to reproduce.

Based on an assessment of the water resources available in a sub-catchment and the water requirements of each use in this same sub-catchment, we can evaluate whether all water demands can be fulfilled simultaneously, while at the same time respecting the minimum river flow required for good ecological functioning. When not all needs can be fulfilled, withdrawals are restricted (the model applies theoretical restrictions) according to their order of priority, as explained above. Fig. 7 shows over the historical period, i.e. the period with observed water use data available, the rate of satisfaction of the water demands of the sub-catchments of interest, i.e. those directly exploited by various human activities. Fig. 8 shows that not all sub-catchments are subject to the same human pressures, and therefore we focus more closely on the most highly exploited sub-catchments. Uses in the upstream catchments and at the borders of the catchment are the most exposed to restrictions. The Moselle indeed has relatively low flows upstream compared to other sections, but it is heavily used for navigation (waterways) and industry. As a consequence, during low-flow periods, these uses can be restricted or even stopped to keep a river flow sufficient for maintaining good environmental conditions. Downstream, in the Perl sub-catchment, which provides water for the nuclear power plant, water demands for power generation cannot be fully satisfied at all times during the summer.

3.2. Evolution of water resources under climate change

Hydrological projections are presented in Fig. 9 and focus on low-flow aspects, for the four selected stations. Simulations are presented here for different RCP scenarios and a single water use scenario: a constant water demand. The evolution of low-flow indices is presented in terms of an anomaly with a 30-year rolling mean, the median is represented as the change signal associated with an uncertainty range (the confidence envelopes correspond to the 10th and 90th percentiles of the different GCM/RCM pairs). Future hydrological trends show moderate divergence according to climate scenarios (RCPs) before 2050, but the time series clearly diverge by the end of the century.

By 2070–2099, the Moselle at Saint-Nabord (no. 3) shows a median change in VCN3 of approximately −22.4 % (-41.8 % to +8.6 % depending on the climate model outputs) for RCP 4.5 for the end of the century, and −39.1 % (-78.5 % to −6.6 %) for RCP 8.5, while

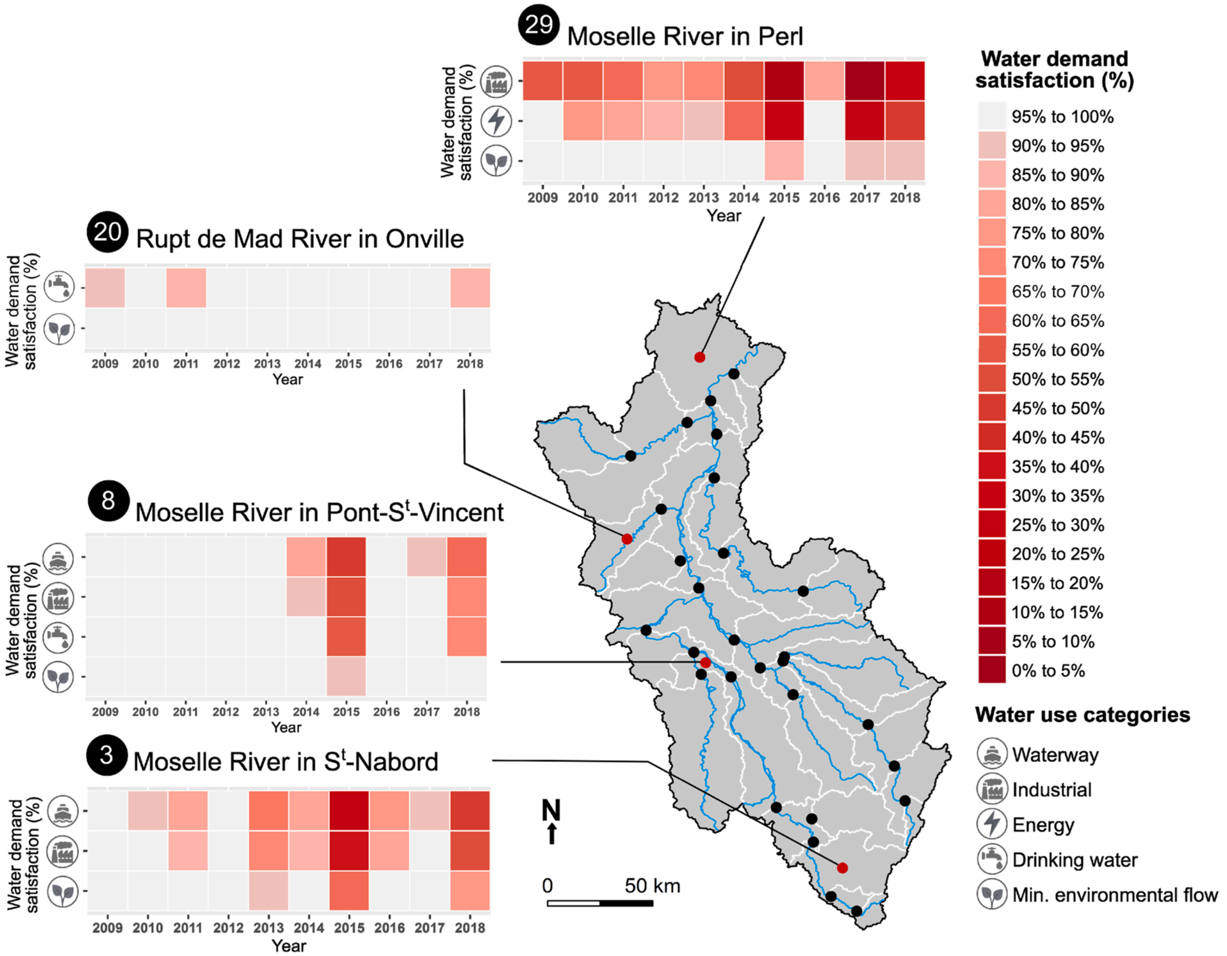


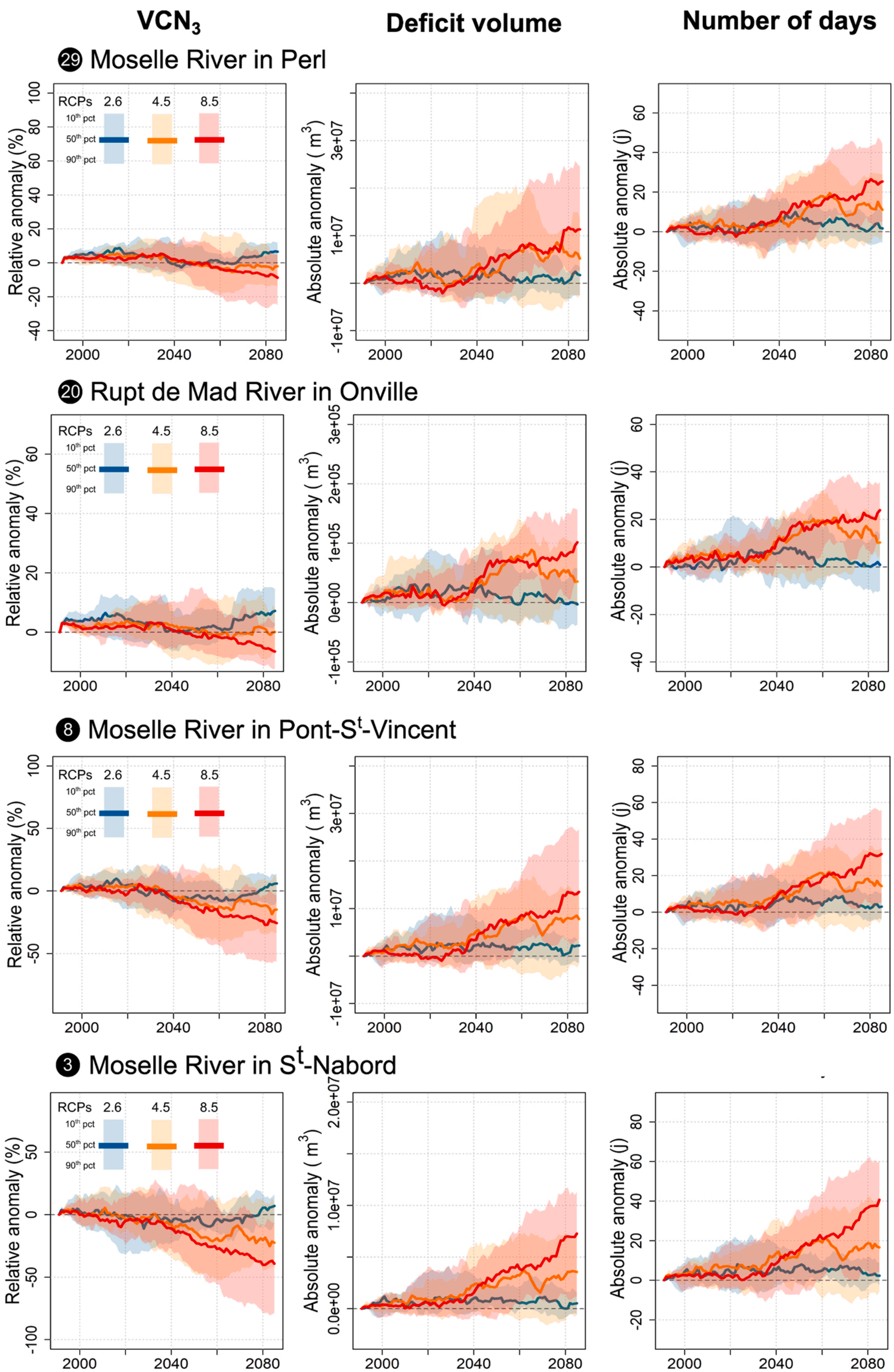
Fig. 8. Theoretical water demand satisfaction computed on the historical period (2009–2018) for summer months (June, July, August) using the SAFRAN reanalysis and the coupled model.

for the RCP 2.6 scenario, a median increase in VCN3 of +7 % (-2.7 % to +14 %) is projected. Consequently, projections suggest a higher low-flow deficit than for the reference period: for RCPs 4.5 and 8.5, respectively, but also for RCP 2.6, albeit lower. Moreover, the number of low-flow days under the reference period threshold also show an increase that is higher for RCPs 2.6, 4.5, and 8.5. The Moselle at Pont St-Vincent (no. 8), and the Moselle at Perl (no. 29), located further downstream than the Moselle at St-Nabord, show the same trends as those described above.

However, results differ slightly for the Rupt de Mad sub-catchment at Onville (no. 20), which is a basin heavily influenced by a reservoir, used to support low-water levels and to secure the supply of drinking water to the Metz urban area. Here we see highly contrasting changes in low-water flows, depending on the climate scenario and time horizon considered, with RCP 2.6 showing a moderate decrease of VCN3 by the end of the 21st century, RCP 4.5 showing an uncertain evolution, and RCP 8.5 showing a slight increase for the median. Median low-flow deficit volumes also show an increase for RCPs 4.5 and 8.5, but slight changes only for RCP 2.6. The median number of days of low flows compared with the reference period also increased for RCPs 4.5 and 8.5, but barely change for RCP 2.6.

To sum up, whatever the station: (i) the trend is similar, i.e. a decrease in low-flow rates, an increase in flow deficits and low-flow days; (ii) the different RCPs lead to similar flow trends up to 2050 while diverging afterward, with 2.6 being very different from the two others (lower anomalies); (iii) the relative anomalies can be very different from one station to another for VCN3, whereas the increase in the number of low-flow days is quite similar from one station to another. The deficit volume is very closely linked to the size of the basin and, as a result, inter-comparison between stations is not possible.

Taking into account the low-flow trends presented above, the water demand satisfaction rate will be at stake only for RCPs 4.5 and 8.5. Indeed, RCP 2.6 does not show any clear trend of worsening low-flow conditions in the long term, for most of the GCMs/RCMs pairs. The analysis of the evolution of the balance between water resources availability and water demand focuses on the most critical season: summer. Fig. 10 shows the evolution of water demand satisfaction for different sub-catchments over the years in the future under climate change. To illustrate the uncertainties that exist, the evolution of water demand satisfaction is presented for three



(caption on next page)

Fig. 9. Evolution of relative anomaly, compared to 1976–2005, for low-flow indicators under climate change on the Moselle River sub-catchments.

contrasting climate scenarios: EC-EARTH_RCA4 (a), a pessimistic scenario (with significant future drying and warming); EC-EARTH_RACMO22E (b), a median scenario; and CNRM-CM5-LR_ALADIN63 (c), an optimistic scenario (i.e. with lower warming and lower drying). In the case of the Moselle at St-Nabord (station 3), the river capacity to fully satisfy industrial and navigation demands while maintaining a minimum environmental flow is declining over the years (Fig. 10). For the Moselle at Pont-St-Vincent (no. 8), hydrological projections also indicate a decrease in the rate at which water demand will be satisfied. The impact of climate change on industrial and waterway uses is relatively high compared with the impact on drinking water abstraction, due to the highest priority set to drinking water use. In addition, the minimum environmental flow required to maintain the good environmental condition of the river is slightly and occasionally affected. The Rupt de Mad catchment (no. 20), used for the drinking water supply of the city of Metz, shows a relatively modest decline in the satisfaction of demand, and difficulties are not recurrent. However, the existing infrastructure is no longer sufficient to fully secure the drinking water supply in this sub-catchment. Partial satisfaction of water demand for drinking water supply preserved the Rupt de Mad environmental flow. The Moselle at the Perl sub-catchment provides cooling for the Cattenom nuclear power plant and has very low satisfaction rates for industrial and energy uses. In addition, despite its high priority compared to human water uses, the minimum environmental flow is impacted. This situation, compared to other sub-catchments, is partly explained by the fact that the human pressure over this sub-catchment is already high under the current climate.

However, the uncertainties arising from hydrological projections regarding the evolution of water demand satisfaction are becoming harder to understand. Here, the impact of management thresholds on the full or partial satisfaction of water demand makes it difficult to analyse the whole set of projections, especially for uncertainty. As expected, satisfying water demand is less successful and recurrent for projections based on the EC-EARTH_RCA4 climate model, and the opposite can be noted for projections based on the CNRM-CM5-LR_RACMO22E climate model.

In addition to the water demand satisfaction, the analysis of the occurrence of dropping below flow thresholds enables quantification of the impact of climate change on water management. As an overview, results for two stations of the low-flow monitoring network are presented: the Moselle station at Epinal represents low-water management in the upstream section of the Moselle basin, while the Moselle station at Uckange represents the downstream section. Fig. 11 shows the anomaly in the number of weeks affected by vigilance, alert, reinforced alert, and crisis. Results for the Moselle at Epinal with RCP 8.5 show a mean anomaly in the number of weeks under different low-flow alert thresholds ranging from +2 weeks to +8 weeks, depending on the model. For RCP 4.5, the mean change in the number of weeks under vigilance, alert, reinforced alert, or crisis is more modest (ranging from +0.3 to + 2.2 weeks). Similar results are obtained for the Moselle at Uckange. The increased number of weeks under vigilance, alert, reinforced alert, or crisis depends greatly on the climate projections: This number nearly doubles for RCP8.5 projections compared to RCP4.5 projections, and the two extreme climate models lead to very different numbers of weeks. To summarize, the projections show concerning trends, in particular with an increase in the number of weeks under vigilance, alert, reinforced alert, or crisis. However, these results are highly dependent on the climate projections and highlights uncertainty issues concerning the choice of the RCP and the climate model.

4. Discussion

4.1. Consequences for water resources management

The results show a decrease in surface water resources and an intensification of low-flow periods along the 21st century. Using hydrological modelling coupled with integrated water resources management, we also show a decline in the balance between available water resources and water demand, when considering a constant-demand scenario. Water demand satisfaction rates are declining, and situations of vigilance, alert, reinforced alert, or crisis are increasing under climate change. With these results on the impact of climate change on hydrological indicators, but also on indices used for water resources management, the study provides valuable information for water managers.

In the context of global change, one may wonder what the implications of changing water uses are on the balance between available resources and demand. Fig. 12 shows the long-term evolution of water demand satisfaction according to changing water demand scenarios for RCP 8.5. The evolution of water demand satisfaction according to water demand scenarios under RCP 4.5 is shown in the Supplementary Material (Figure S4). To analyse the effect of water demand scenarios compared with previous results, satisfaction rate projections are presented in terms of comparison with projections assuming a constant water demand over time (i.e. the scenario that was presented in previous sections).

Overall, Fig. 12 shows that changing water demand scenarios only marginally affects the water demand satisfaction rate, whatever the climate model used. This means that the balance between water supply and water demand is primarily driven by climatic conditions. The water demand satisfaction rate is slightly improved (respectively, worsened) under the decrease (respectively, increase) scenario, particularly for the Moselle at Pont-St-Vincent and for the Rupt de Mad River at Onville sub-catchments. Interestingly, for the latter, the drinking water demand becomes entirely satisfied, which is critical for providing drinking water to Metz. The increased satisfaction rate for industry in the Moselle at Perl sub-catchment is due to the decreased water demand for the energy sector, because of the shutdown of the nuclear power plant forecasted by 2035 and 2045 under the "decrease" and "increase" water demand scenarios, respectively.

Adaptation solutions are more likely to compensate for a slight imbalance between water supply and water demand, rather than to compensate for drastic changes. However, other types of adaptation solutions have not been tested but exist, such as supply

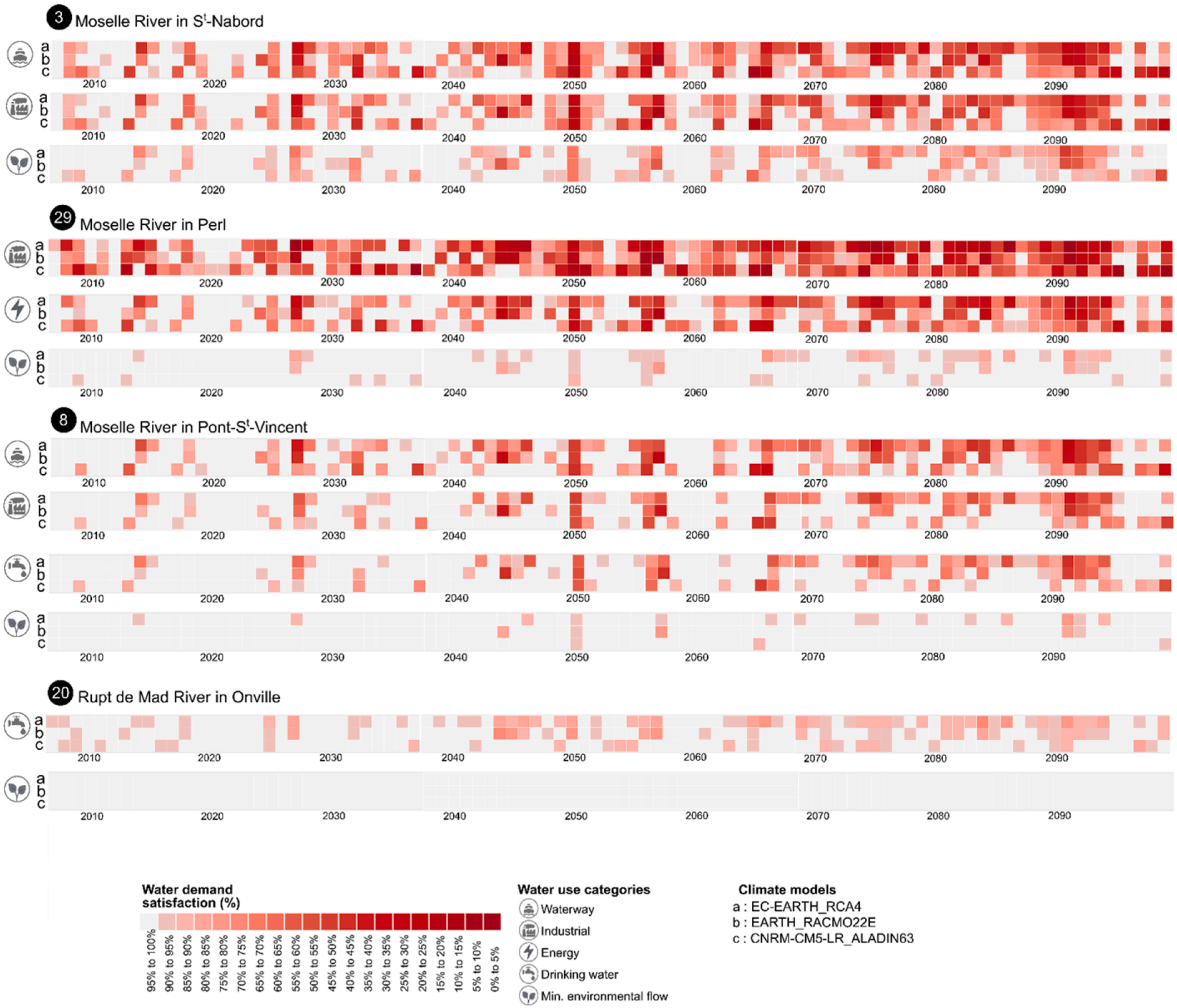


Fig. 10. Evolution of water demand satisfaction with climate change in summer (June-July-August) with RCP 8.5 for 2006–2099, considering constant human-based water demand.

enhancement measures which are sometimes planned by water managers. In all cases, the approach developed in this work, based on hydrological modelling coupled with water use and management, shows good potential for supporting water resources managers by providing hydrological projections that take human influence into account, while allowing them to test adaptation approaches through water use scenarios. This could help water resources managers to better develop their adaptation plans and to determine the efficiency and limits of the measures envisaged.

4.2. *Added value of coupling water use and hydrological modelling*

When addressing the impact of human activities on water resources at the catchment scale, it is essential that the hydrological model explicitly represents these human influences. The model proposed in this study enables the quantification of changes in water resources as well as the projected imbalance between water supply and water demand. In contrast to several previous studies where the assessment of water demand satisfaction was performed after hydrological modelling, in this study the withdrawals, releases, and management are linked directly to the hydrological modelling and taken into account time step by time step. The proposed approach is already a step ahead because it extends the hydrological model representation of the catchment rainfall–runoff relationship to include flows caused by human activities. Because the modelling in this research is more detailed and realistic, new insights may emerge that are more useful for water management.

In addition, while not being the primary focus of this paper, analyzing the impact of the inclusion of human influences in hydrological modeling on the performance of the model for low flows is itself an interesting research question. How the performance of the model on low flows was impacted by the inclusion of human influences was analysed in Lemaitre-Basset (2023) (see section 5.3.1 and figures 5.9–5.15). Lemaitre-Basset (2023) showed that in both cases, the performance of the models on low flows was rather good. Including the human influences did not significantly improve the performance of the model, and the performance deteriorated for some stations. Nonetheless, we must stress that the inclusion of human influences is necessary for studying adaptation strategies and when dealing with water restriction thresholds. In addition, the use of a hydrological model coupled explicitly with water uses strengthens its application in a climate impact study. This may limit the issue of the influence of water use on the parameter sets of the hydrological model, used in a non-stationary context for the impact study. Therefore, this step is necessary for studying hydrology under changing conditions (Thirel et al., 2015).

Despite these advances, significant uncertainties remain over simulations, whatever the indicator considered. For hydrological

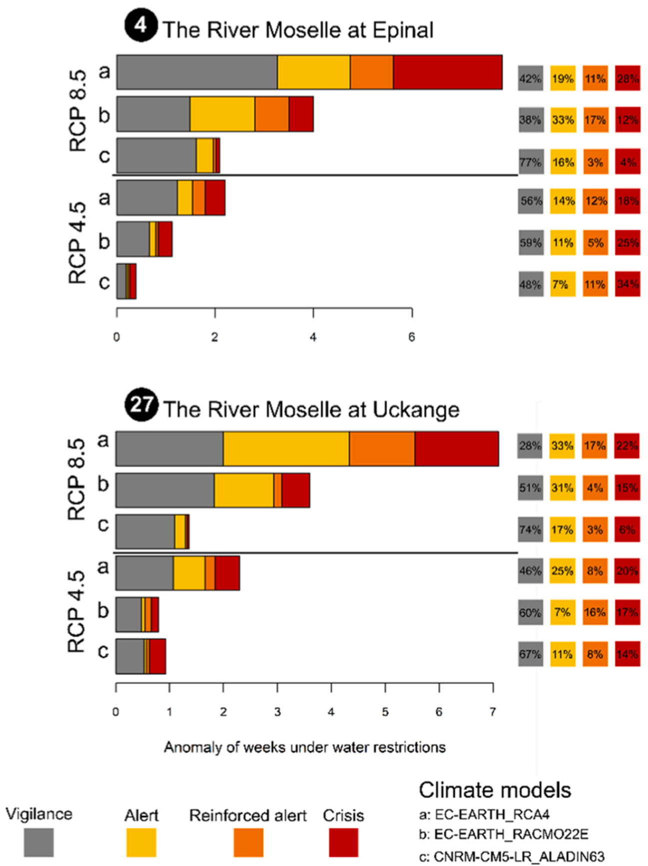


Fig. 11. Anomaly of weeks under water restriction in the long term (2070–2099) compared to 1976–2005 over the summer period.

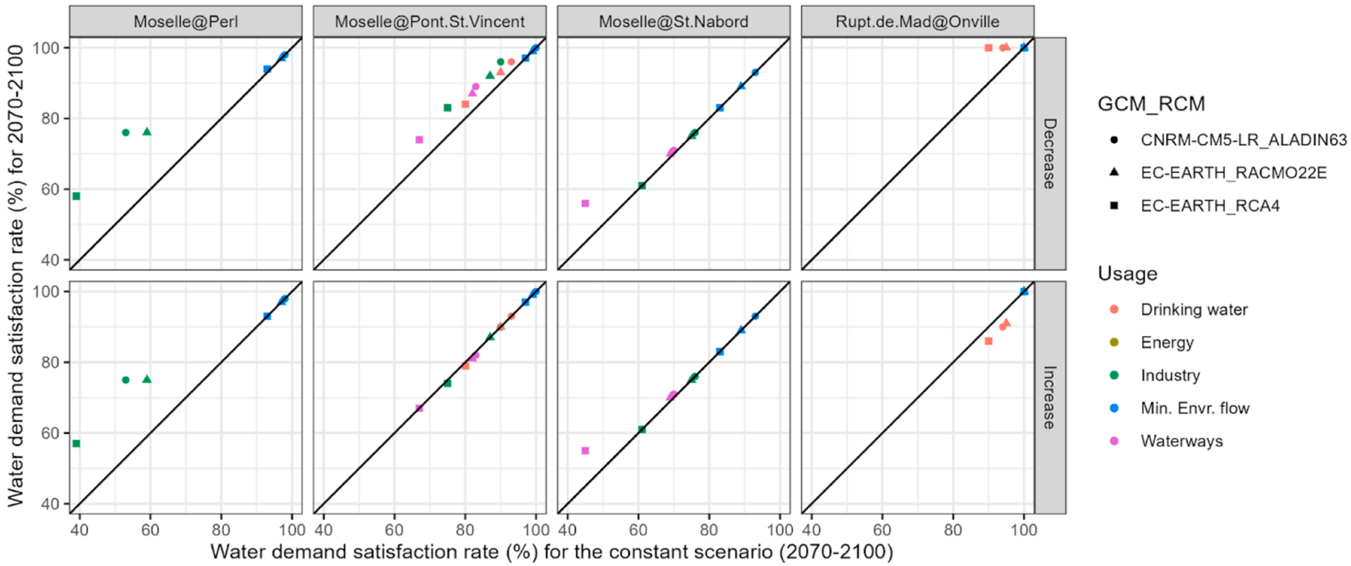


Fig. 12. Sensitivity of the summer (JJA) water demand satisfaction rate according to the water use increase (bottom row) and decrease (top row) scenarios, for 2070–2100 for RCP 8.5, compared to the constant water use scenario.

simulations, as shown by the evaluation of simulations over the historical periods, low flows for some sub-catchments remain poorly represented by the model. Indeed, beyond the uncertainties associated with the hydrological model, strong assumptions remain concerning the representation of water uses, which adds new uncertainties. For example, the choice of hierarchical order to determine theoretical restrictions on water uses in the model, or the representation of water uses at the scale of a sub-catchment, based on data limited to those provided by the Water Agency, could be questioned. Partial or poor representation at certain stations means that low flows cannot yet be represented correctly, and improvements of data quality and the modelling tool are still needed to reduce the uncertainties associated with the coupled model. Moreover, for hydrological projections, the magnitude of the changes modelled is uncertain, and these uncertainties are also related to the overall climate couples used to feed the modelling chain. The top–down approach typically leads to an increase in uncertainty at each stage of the modelling chain. Completing the projections on the evolution of water resources and the vulnerability of water uses with a study using a bottom–up approach seems to be a good way of improving the explanatory scope of projections for managers.

5. Conclusion

This work enabled the implementation of a hydrological modelling approach coupled with human uses and management, to then be integrated into a climate impact study on water resources and use for a regional catchment. In addition, sensitivity tests were carried out on future water resource projections under climate change, based on water use scenarios. The use of a coupled hydrological and water management model responds to the need of water managers for more appropriate results in terms of climate impacts, water resources vulnerability, and adaptation solutions. In addition, this approach participates to addressing the scientific issue of stationarity of the hydrological parameter sets used for climate impact study.

Hydrological projections based on a multi-scenario, multi-model approach were first analysed in the case of constant water demand, to assess the vulnerability of existing management practices under climate change. The results focused on describing the evolution of low-flow levels using indicators useful to water managers, such as the VCN3, but also the expected evolution of droughts according to the severity levels used for water resources management. Despite uncertainties, hydrological projections show a worrying situation, with longer and more severe low-flow periods and droughts.

An analysis of the vulnerability of the balance between resource availability and demand has been carried out based on three contrasting scenarios of changing water demand. As expected, the “decrease” sober scenario showed a more optimistic trend than the others but its effect remains limited to compensate for the reduction in water resources. Finally, in this study, the use of the hydrological model coupled with water uses and human influence is limited to the French Moselle River catchment, which is an area of interest that is moderately affected by human activity compared to some other catchments. Applying the approach developed here to other river basins that are more heavily influenced by human activities or have much more water-limited hydroclimatic conditions may lead to very different results for adaptation solutions.

CRediT authorship contribution statement

Ludovic Oudin: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **David Dorchies:** Writing – review & editing, Software, Methodology. **Thibault Lemaitre-Basset:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Guillaume Thirel:** Writing – review & editing, Supervision, Software, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Guillaume Thirel reports financial support was provided by Regional Water Agency Rhin-Meuse. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The authors do not have permission to share data.

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Appendix A. Hydrometric stations

Table A.1
Hydrometric stations for low-flow monitoring and water restriction thresholds used by stakeholders during droughts

River	Place	Threshold vigilance (m^3/s)	Threshold alert (m^3/s)	Threshold reinforced alert (m^3/s)	Threshold crisis (m^3/s)
Moselle	Rupt-sur-Moselle	1.13	0.90	0.58	0.25
Moselle	Epinal	9.33	7.46	4.98	2.50
Moselle	Tonnoy	10.83	8.66	5.83	3.00
Madon	Pulligny	1.83	1.46	1.06	0.65
Moselle	Toul	13.13	10.50	6.75	3.00
Meurthe	St-Dié	2.38	1.90	1.35	0.79
Vezouze	Lunéville	1.59	1.27	0.97	0.66
Moselle	Custines	31.68	25.34	17.57	9.80
Seille	Metz	1.88	1.50	1.09	0.67
Orne	Boncourt	0.20	0.16	0.09	0.02
Moselle	Uckange	34.63	27.07	21.85	16.00

Data are from the Regional Environment Directorate website in charge of implementing a policy to manage and protect water resources: https://www.grand-est.developpement-durable.gouv.fr/bulletin-de-suivi-d-etiage-grand-est-a16960.html

Appendix B

Table B.1
Location of releases, and percentages of leakage, release and net consumption for each water use in the Moselle catchment.

Human water use	Location of releases	Leakage percentage	Release percentage	Net consumption percentage (evaporation)
Drinking water	Releases occur at the locations of waste water treatment plants locations, i.e. in the Metz and Nancy areas for the drinking water of these cities, while withdrawals are made in upstream catchments. Releases occur in the same modeling unit as withdrawal for rural areas	21 %	79 %	0 %
Energy (nuclear plant)	Releases occur in the same modeling unit as withdrawal	0 %	71 %	29 %
Industry	Releases occur in the same modeling unit as withdrawal	0 %	90 %	10 %
Waterways	Releases occur at the junctions of the river and waterways downstream	20 % (mean of the 7 waterways within the catchment, from 5 % to 40 % depending on the waterway)*	80 % (mean of the 7 waterways within the catchment) 30 % for the Vosges waterway	0 % except for one waterway that releases 0.4 $m^3\ s^{-1}$ to the Saone River in the Vosges area (out of 7.1 $m^3\ s^{-1}$ withdrawn in total)

* after Voies Navigables de France, the organism in charge of the waterways

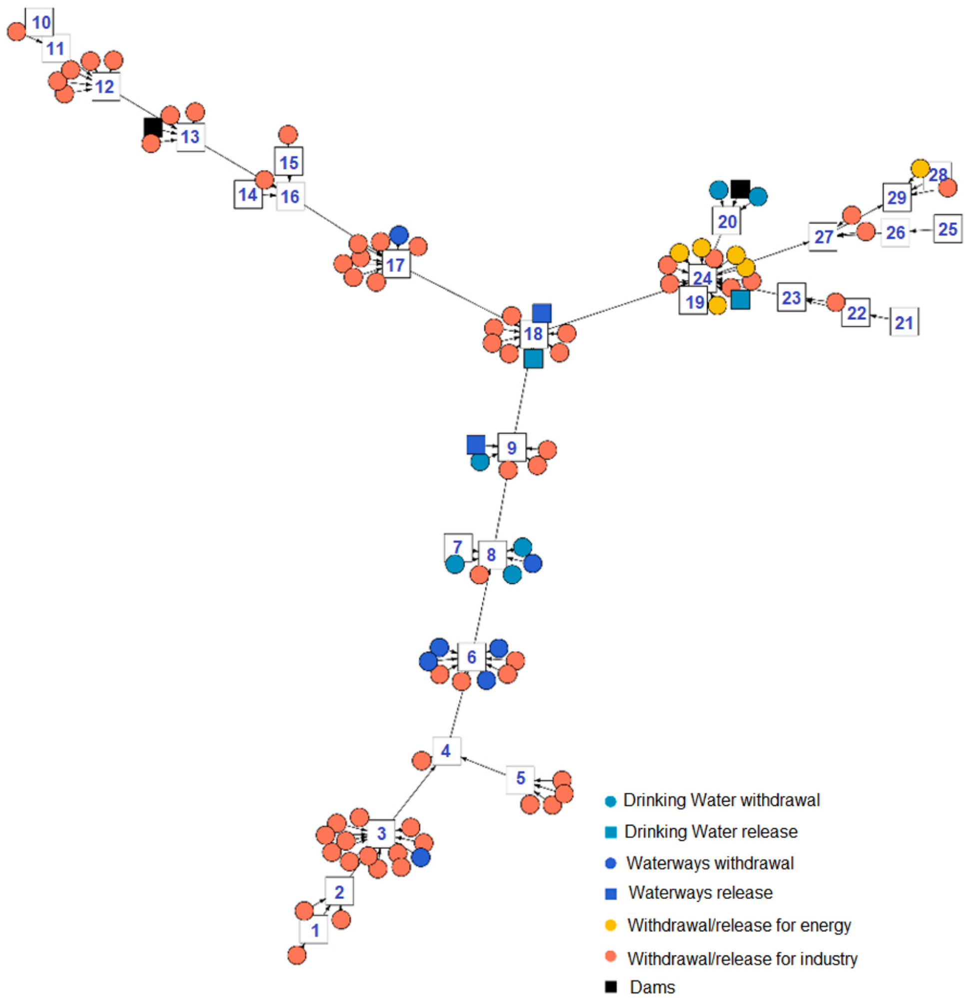

Figure B.1. Location of the water withdrawals and releases for each sub-catchment. See Table 1 for the stations numbering (station 29 is the outlet).

Appendix C. Equations describing rules for managing dams

Equations describing the functioning of the Pierre-Percée dam in the model to support the Meurthe River and Moselle River low flows, and to maintain energy production and minimal environmental flows at Perl, are as follows:

Decision to store:

- ***If*** $Q_{Meurthe} > 14.5\ m^3.s^{-1}$ *and*, $V_{res} < V_{max}$ *and*, $Q_{Moselle} > 29\ m^3.s^{-1}$ ***then***:
- ***If else***: $S = 0$

Compute stored water with respect to min flow requirement:

- ***If*** $Q_{Plaine} > 0.4\ m^3.s^{-1}$ *and*, $Q_{VieuxPre} > 0.055\ m^3.s^{-1}$ ***then***:
- $S = max(Q_{Plaine} - 0.4\ m^3.s^{-1}, 11.7\ m^3.s^{-1}) + Q_{VieuxPre} - 0.11\ m^3.s^{-1}$
- ***If else***: $S = 0$

Updating the volume of water in dam:

- $V_{res} = V_{res} + S$

Water release decision to support Moselle River low flows:

- ***If*** $Q_{Moselle} < 29\ m^3.s^{-1}$ and $Q_{Meurthe} > 7\ m^3.s^{-1}$ ***then***:

Compute released water:

- $q_r = \min(29\ m^3.s^{-1}$ - Q_{Moselle}, $6\ m^3.s^{-1})$

Updating the volume of water in dam:

- $V_{res} = V_{res}$ - q_r

Water release decision to support Meurthe River low flows:

- ***If*** $Q_{Meurthe} < 7\ m^3.s^{-1}$ *and* $Q_{Moselle} > 29\ m^3.s^{-1}$ *and* ***then***:

Compute released water:

- $q_r = \min(7\ m^3.s^{-1}$ - Q_{Meurthe}, $4\ m^3.s^{-1})$

Update the volume of water in dam:

- $V_{res} = V_{res}$ - q_r

Water release decision to support Moselle River and Meurthe River low flows:

- ***If*** $Q_{Moselle} < 29\ m^3.s^{-1}$ *and* $Q_{Meurthe} < 7\ m^3.s^{-1}$ ***then***:

Compute released water:

- ***If*** $(29\ m^3.s^{-1}$ - $Q_{\text{Moselle}}) + (6\ m^3.s^{-1}$ -$Q_{\text{Meurthe}}) < 6\ m^3.s^{-1}$ ***then***:
- $q_r = (29\ m^3.s^{-1}$ - $Q_{\text{Moselle}}) + (6\ m^3.s^{-1}$ -$Q_{\text{Meurthe}})$
- ***If else***: $q_r = 6\ m^3.s^{-1}$

Updating the volume of water in dam:

- $V_{res} = V_{res}$ - q_r

With: *QMeurthe* the streamflow of the Meurthe River at the gauging station Damelevieres (station no. 16); $Q_{Moselle}$ the streamflow of the Moselle River at Perl (station no. 29); q_r the streamflow released from the dam; V_{res} the volume of water in the dam; S the streamflow stored in the dam.

Equations describing the functioning of the Lac de Madine in the model to support the low flows of the Rupt de Mad River, to ensure drinking water supply in the Rupt de Mad sub-basin at Onville are as follows:

Decision to store:

- ***If*** $Q_{Onvil} > 0.1\ m^3.s^{-1}$ ***so*** :

Quantity to store:

- $S \leftarrow Q_{Madin} - 0.06\ m^3.s^{-1}$

Available space in the dam:

- ***If*** $V_{res} = 35.0 Mm^3$ ***so*** :
- $S \leftarrow 0$

Updating the volume of water in dam:

- $V_{res} = V_{res} + S + P - E$

Water release decision:

- ***If*** $Q_{Onvil} < 0.1\ m^3.s^{-1}$ ***so*** :
- $q_r \leftarrow 0.1\ m^3.s^{-1} - Q_{Onvil}$
- ***If*** $V_{res} = 25.0 Mm^3$ ***so*** :

- $q_r \leftarrow 0.06 m^3.s^{-1}$

Updating the volume of water in dam:

- $V_{res} = V_{res} + q_r + P - E$

Appendix D. Low-flow criteria used in the study

VD: Volume deficit under the low-flow threshold.
Eq. C.1

$$VD = \sum_{n=1}^{i} \max(0; Q_{threshold,i} - Q_i)$$

with Q_i the streamflow for day i and $Q_{threshold}$ the threshold under which there is a deficit. The volume deficit can be calculated for both observed and simulated streamflow, the ratio between the two (RVD) enables comparison.
Eq. C.2

$$RVD = |1 - \frac{VD_{sim}}{VD_{obs}}|$$

D: Duration of low-flow events (in days) under the low-flow threshold per year.
The ratio of simulated to observed days below the low-flow threshold is known as RD.
Eq. C.3

$$RD = |1 - \frac{D_{sim}}{D_{obs}}|$$

VCN_d: Minimum annual flow rate calculated over d consecutive days.
A moving average over d days is calculated for each year and then the minimum value for each year is used.
Eq. C.4

$$MAQ_d = \frac{1}{d}\sum_{i=1}^{d} Q_i$$

Eq. C.5

$$VCN_d = \min(MAQ_d)$$

The ratio between the VCN_d calculated from observations and simulations is used to assess the quality of the low-flow simulations as a criterion used by water managers of the water catchment.
Eq. C.6

$$RVCN_d = |1 - \frac{VCN_{d,sim}}{VCN_{d,obs}}|$$

Table C.1
Contingency table for low-flow events, considering the "vigilance" threshold

Contingency table		Observed streamflow	
		Yes	No
Simulated streamflow	Yes	Hit	False alert
	No	Miss	Correct negative

Efficiency criteria associated with the contingency table to evaluate the capacity of the model:
POD: Probability of detection.
Eq. C.7

$$POD = \frac{\sum Hit}{\sum Hit + \sum Miss}$$

FAR: False-alarm ratio
Eq. C.8

$$FAR = \frac{\sum False\ alert}{\sum False\ alert + \sum Hit}$$

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