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Climate services for water utilities: Lessons learnt from the case of the urban water supply to Valencia, Spain

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ABSTRACT

Climate change projections in many regions of the world show a critical reduction in precipitation and a significant rise in temperatures in the next decades. This change may affect the operation of water utilities in arid and semi-arid parts of the globe. The Mediterranean region is particularly vulnerable to the impacts of climate change on water resources. In this paper, we reflect on the challenges that the water utility sector may experience during the upcoming decades to continue providing its essential service under the new climate scenario. Our reasoning is based on the lessons learned during the co-creation of a climate service with the water utility company of Valencia (Spain) within the framework of the EU ERA4CS project INNOVA. The joint vision of climate, water management researchers and water utility operators resulted in a multi-scale framework for evaluating the vulnerability of the water utility to climate change. The modelling framework couples water quantity and quality and their interaction in a chain of models. The proposed framework forced all parties to consider the issue of the temporal and spatial scales, and the importance of choosing and defining the boundaries of the problem. The analytical framework has three distinct elements: (1) a combination of climate projections; (2) hydrological and water resource management model of the river basin system; (3) reservoir management and water quality model. Two Representative Concentration Pathways (RCP) 4.5 and 8.5 were considered in two timeframes for the analysis: the short term (2020–2040) and the medium term (2041–2069). The results show a significant reduction in water availability combined with an increased frequency and intensity of phytoplankton blooms and anoxia episodes. These changes result in the deterioration of the reservoir trophic state, shifting from ultraoligotrophic-oligotrophic (control period) to oligotrophic-mesotrophic (RCP 8.5). The example shows how the combination of models on different scales and the involvement of experts in the co-creation process can result in a customized climate service that provides valuable information to water utility operators that can be used to reduce the system's vulnerability to climate change.

Practical implications

- The water utility sector provides an essential service to the society and plays a vital role in economic development. The resilient adaptation of water utilities to the new climate and global scenario is a critical task that requires the cooperation of utility operators, water managers and climate scientists. This article explores the challenge of co-creating a climate service to assess the water utility's vulnerability to climate change in Valencia, Spain. The study takes into account multiple spatial scales (regional, river basin, and reservoir) and a combination of climate scenarios. The presented results are based on the ERA4CS project INNOVA, where several climate services were created by connecting the private, public and knowledge communities.
- The co-creation of the climate service for Valencia's water utility required close collaboration between the research team from the Universitat Politècnica de València and the managers from the water utility company Global Omnium. A chain of models was designed, validated and developed, consisting of 1)

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Global and regional climate models carefully selected and downscaled to obtain future projections of temperature and precipitation in the region; 2) Hydrological models of the system's sub-basins to obtain water inflows; 3) Water management model that simulates the operation of the water resource system to obtain the water inflows to the reservoir and its storage under climate change; 4) Reservoir model to simulate the water quality dynamics in the new climate scenarios.

- The results obtained by the climate service offer valuable insights into the challenges lurking for urban water suppliers in the region. Results show that the water supply to Valencia and its metropolitan area will not be at risk of systemic shortages due to climate change, since agriculture has lower priority than urban supply, being the one curtailed during water scarcity events, and the reduction in water resources foreseen by climate change scenarios is below the threshold that would drive ingrained urban supply restrictions. However, the reduction of water availability will require improved management and monitoring of the main reservoirs of the system to avoid extreme risks during prolonged drought periods. The results show an expected decrease in water quality in the Tous reservoir linked to the declining water inflows and storage in the reservoir, and to the increasing temperatures. According to the projections, anoxia events in the reservoir could last longer, starting early in late summer and ending in the middle of winter. A steep increase in phytoplankton blooms is also predicted, multiplying by almost ten compared to the peak values estimated by the models for the control period. Phytoplankton blooms could worsen the trophic state of the reservoir, which shows a low biological production (oligotrophic state) during the control period and a moderate (mesotrophic) to high (eutrophic) productivity in the climate change scenarios. These issues may affect the raw water quality, forcing the water treatment plants to adapt or change some of their processes to guarantee a safe urban water supply. The initial adaptation options identified in this contribution include changes in the operating rules of the system and different water treatment processes.
- The chain of models described in this contribution may be applicable to other cases with similar data availability and water management facilities. The climate service portrayed in this contribution aims to guide water utilities and scientists undertaking similar challenges. However, not a single product is fitted to evaluate the vulnerability of any water utility system to climate change (U.S. Environmental Protection Agency, 2010), and climate services must be customized to the needs of the specific end-users (Rubio-Martin et al., 2021). For this reason, we emphasize the importance of actively involving the end-users in the co-creation of the climate service for it to be helpful and valuable.

1. Introduction

Access to safe water for drinking, sanitation and hygiene is a basic human need. Its universalization is the sixth Sustainable Development Goal that the United Nations has pledged to fulfil by 2030 (United Nations, 2015). The tragedy of unsafe drinking water is particularly damaging for developing nations, where it is estimated to cause over 1.2 million deaths per year (GBD, 2019). In middle and high-income countries, the development of systems for the treatment and distribution of safe water has reduced the spread of diseases and premature deaths. However, water utility systems are still vulnerable to internal and external shocks, such as the ones caused by climate and global change.

Recent reports from the Intergovernmental Panel on Climate Change (IPCC) conclude that Carbon dioxide (CO2) and other greenhouse gases emissions will continue increasing in the near future and will raise the Earth's average temperature between 1 °C and 2 °C by 2065, depending on the RCP (Representative Concentration Pathways) considered (IPCC, 2014). Furthermore, the impact of climate change on rainfall patterns may be critical in arid and semiarid areas such as the Mediterranean region, which is characterized by irregular hydrological regimes, long and severe drought episodes and extreme precipitation events (Giorgi, 2006). Climate change is expected to increase the frequency and intensity of both extreme floods and drought (Fink et al., 2016; Páscoa et al., 2017). The combination of the current hydrological features, increasing temperatures and rainfall reduction may put water availability at risk in the Mediterranean area (Marcos-Garcia and Pulido-Velazquez 2017; Páscoa et al., 2017).

This new scenario derived from climate change is expected to challenge water utilities all over the world. Water shortages, water quality issues, salinization, sea level rise and lack of preparedness are the main challenges that water utilities will have to overcome related to climate change (United States Environmental Protection Agency, 2021). One of the most common issues worsened by climate change is the eutrophication of water bodies (Delpla et al., 2009). Eutrophication has multiple origins, including the increased leaching of nutrients from agriculture during heavy rainfalls and the concentration of organic matter in lakes and reservoirs during droughts. The increase in water temperature also stimulates algae growth and eutrophication problems (Nazari-Sharabian et al., 2018). Cyanobacterial blooms are promoted under these conditions worsening the trophic state of water bodies (Delpla et al., 2009; Serpa et al., 2017). Many cyanobacteria species produce flavor and toxic metabolites, and removing them is the main water quality challenge for many water utilities (Lins et al., 2016; Clercin and Druschel 2019). Eutrophic source water forces water utility operators to implement different treatment processes such as oxidation, flocculation and coagulation, clarification, filtration, or active carbon adsorption (Sharma and Bhattacharya 2017; Wang and Zhang 2018). Many water treatment plants should be prepared to face incoming water quality deterioration under climate change conditions.

The study of the impacts of climate change on the water utility sector often lacks an integrated vision. Previous assessments of the water utility vulnerability to climate change have some limitations: (i) they are focused on the basin scale and land-use changes (Serpa et al., 2017); (ii) they address exclusively the ecological status (Couture et al., 2018); or (iii) they focus on a specific parameter, such as nutrients (Baron et al., 2013; Lipczynska-Kochany 2018), phytoplankton (Winder and Sommer 2012), water temperature (Woolway et al., 2019) or dissolved oxygen (Schwefel et al., 2016), and do not study the interaction between the main parameters and processes. The integration of more essential components for water quality simulation is necessary to better replicate the actual behavior of water supply systems, and the models applied to estimate climate change impacts cannot be an exception (Gelda et al., 2019; Tzanakakis et al., 2020). Furthermore, water quality models applied to assess urban water supply tend to focus on the local scale because water quality processes are often simulated within a single water body. However, many basin-scale variables such as future precipitation and air temperature, the system's operating rules, land use, and water demands may modify water availability and water sharing mechanisms, causing an impact in the processes and dynamics of water bodies. Local-scale processes influenced by basin-scale changes include water inflows, water storage in the reservoir, and nutrient concentration in the source water.

Climate services are the transformation of climate data, together with other relevant information, into new products such as projections, predictions, outlooks, trends, economic analysis, assessments, counselling on best practices, development and evaluation of solutions and any other related services, capable of satisfying the needs of stakeholders (European Commission, 2015). Often climate services are developed by experts in climate data without considering the specific needs of end-users. Relevant information is lost if the end-user perspective is neglected during the creation process (Swart et al., 2021). This information is crucial in the case of water utilities because the operators of the system possess the most precise and up to date knowledge about the system. At the same time, end-users are the ones who must validate the results provided by the climate service (Rubio-Martin et al., 2021).

For this reason, it is essential that climate services, especially those aimed at improving decision-making in water management, are developed using a bottom-up approach through methodologies for the co-creation and participation of the key stakeholders. The intertwining of climate science, hydrology, water resource management, water quality and water utility knowledge requires an effort of coordination and understanding of the many methodologies involved, their limitations and capabilities. However, this combination can provide detailed and valuable information for water utilities all over the world to assess their vulnerability to climate change. Knowing how climate change will impact water supply sources, in both quantity and quality, is necessary for water utilities to identify the vulnerable elements of the water supply system, assess future challenges, and reconsider purification processes.

This paper describes the development and results of a climate service co-created with a water utility company by linking several models at different spatial scales: the river basin scale to consider the management and the effect of climate change on water availability, and the reservoir scale to simulate water quality processes under climate change conditions. The modelling framework applied considers both water quantity and quality dynamics in an innovative chain of models that guarantees the preservation of the dependencies between mutually related processes. After providing some context about the water utility sector's approach to evaluating climate change vulnerability, we describe the case study and introduce the modelling framework. The results provided by the chain of models are presented and discussed, and the main potential challenges identified along the water utility operators are listed. Finally, we provide the main conclusions reached through the development of this project.

2. Vulnerability of water utilities to climate change

The water utility sector is responsible for collecting raw water and treating it for domestic and commercial applications. It thereby answers the demand for clean and safe water by the population. The treatment of wastewater is often included under the water utility umbrella. However, in this contribution, we will focus on the first stage of the water utility cycle: collecting untreated (raw) water from the different natural and human-made water sources and treating it in water treatment plants. Natural sources where water may be obtained include springs, rivers, lakes, and aquifers. Human-made infrastructures such as canals and reservoirs also play an essential role in many water resource systems. They allow the strategically storing and distributing of water considering the demands. Threats to the availability and quality of water resources include water scarcity, water pollution, water conflicts, droughts, overpumping, and climate change. Climate vulnerability assessments are crucial to develop utility specific climate action plans in order to streamline adaptive responses (Danilenko et al., 2010).

The increase in temperatures is one of the most widely known impacts of climate change. Its influence on water resource systems includes increased evaporation of surface water, alterations in the nitrification process, changes in microorganism dynamics, and the reduction of CO2 and oxygen (O2) solubility (Delpla et al., 2009; Lipczynska-Kochany, 2018). The decrease in precipitations is another of the best-known impacts of climate change, particularly in Mediterranean river basins. It increases the concentrations of biological and chemical pollutants in reservoirs when water storage decreases (Delpla et al., 2009), triggering the need for expensive disinfection treatments and filtration processes (Sharma and Bhattacharya, 2017). Furthermore, climate change could worsen water quality by modifying the environmental conditions, ecological processes, and the interaction between biological, physical, and chemical parameters (Delpla et al., 2009).

Eutrophication due to rising temperatures is one of the most agreed water quality problems that will be rising due to climate change (Moss et al., 2011). Phosphorus concentration, primary driver of eutrophication risk in rivers and lakes, may also increase through reduced dilution particularly if river flows are lower in summer (Charlton et al., 2018). Rising nutrient inputs and increasing temperature tend to intensify eutrophication. Also associated with increasing temperatures is the loss of plant cover, which increases soil erosion and the delivery of nutrients and pollutants into surface water bodies and streams. The assessment of raw water quality can be very complex, or it can be restricted to the evaluation of a limited set of key components, variables, and parameters such as temperature, rainfall, streamflow, dissolved oxygen, organic matter, nutrients, and algae (WHO, 2008).

The creation of climate services for assessing the vulnerability of water utilities to climate change has some precedents in the scientific literature. Four approaches can be defined for assessing the climate change vulnerability of the sector (U.S. EPA, 2010):

- Scenario analysis: a top-down assessment that begins by defining a set of plausible Representative Concentration Pathways (RCP) that deserve consideration by water managers. Global and Regional Climate Models outputs are downscaled to obtain sets of meteorological variables such as precipitation and temperature for the region of study.
- Sensitivity analyses: a top-down approach that is based on the use of incremental changes in relevant meteorological variables such as temperature and precipitation. Combining these changes results in a range of plausible climate altered future hydrology that can be evaluated using traditional hydrological and water resource management models.
- Paleoclimate or historical analyses: a top-down approach that uses historic climate observation to define temperature and precipitation patterns that may challenge the response of the water utility system.
- The bottom-up approach: use a qualitative system assessment to determine the elements of the system that are more vulnerable to climate change. Based on the knowledge of local water utility providers, this approach is helpful to identify critical vulnerabilities and identify portfolios of infrastructures and management changes that could address those vulnerabilities.

Nowadays, improvements in the provision of easily accessible climate projections and the increasing availability of tools and algorithms for quickly assessing the projections' skill and performing statistical adjustments have resulted in the dominance of the scenario-based analyses approach over the others for most climate service developments.

Additionally, the integration of local and expert knowledge using the bottom-up approach is a growing trend in climate service development. Currently, most climate services are shifting towards a development approach based on the co-creation between the end-users of the service and the scientists (Vogel et al., 2016; Bremer et al., 2019; Rubio-Martin et al., 2021; Suhari et al., 2022).

The climate service described in this contribution for evaluating the water utility vulnerability to climate change in Valencia (Spain) combines scenario analyses, which deliver climate projections, with a bottom-up approach. The end-user of the service (the water utility company Global Omnium) was involved in the process since the beginning and its role was essential to establish the spatial and temporal scale of the service, the water quality parameters of interest and the critical facilities where the evaluation must take place. The end-user also helped validate the results, provided an initial assessment of the vulnerability of the system based on them, and shared an initial set of potential solutions for the identified challenges.

3. Material and methods

3.1. Case study features

Climate services must be customized to the needs of the end-users and include all the unique features that characterize each specific case in order to get valuable tools for climate adaptation and decision-making (Rubio-Martin et al., 2021). In practice, this means that not a single product or service can be used to assess the vulnerability of any water utility system to climate change (U.S. Environmental Protection Agency, 2010). However, lessons can be learned from the choices and compromises taken for the co-creation of any specific climate service if enough details and context are provided.

The Jucar River basin is located in the eastern Iberian Peninsula (Fig. 1). With a typical Mediterranean climate, the basin faces periods of heavy rains, low stream flows, and multi-annual droughts. Its average temperature is driven by seasonality and ranges from 11 °C in winter to 26.6 °C in the summer (CHJ, 2022). The total annual precipitation ranges from 300 to 780 mm, with an average of around 500 mm. Its distribution is typically Mediterranean, combining intense rains in autumn and spring with dry summer periods. October is the rainiest month, with an average precipitation of 58.9 mm, while July is the driest with 12.7 mm on average (CHJ, 2022). The Jucar River system has a mean annual inflow of 1798 Mm^3, but it varies widely year-to-year between 643 and 3,416 Mm^3. The Jucar River is subject to significant pressures due to its annual water demand of 1,529.1 Mm^3, distributed between agriculture (80%), urban (16%), and industrial (4%) activities (CHJ, 2022). Furthermore, the main water demands are located in the lower basin, with many irrigated crops such as citrus and rice fields located downstream of Tous (Fig. 1). The Jucar River basin is highly regulated, carefully managed by three main reservoirs: Alarcon (1,118 Mm^3) and Contreras (361 Mm^3) in the upper basin, and the Tous reservoir (379 Mm^3) in the lower basin (CHJ, 2022).

The operation of the Jucar River system is complex due to the combination of urban, agriculture, hydropower, environmental, and flood protection uses. This complexity is reflected in the operation of the Tous reservoir, which reconciles three often conflicting uses: a) Supply water to the downstream agricultural demands, b) flood protection during the rainy season, and c) source of water for most urban settlements located in the Valencia metropolitan area.

With more than 1.8 million inhabitants in its metropolitan area, Valencia is the third largest city in Spain. Its urban water supply is shared between the Turia and the Jucar rivers. In particular, 75% of the total supply comes from the Jucar River, more precisely from the Tous reservoir through the Jucar-Turia Canal, which connects both watercourses. It provides water to a water treatment plant located in the kilometer 36 of the canal and a second plant located where the canal meets the Turia River. With about 283.5 Mm^3/year, Tous is the primary water source for both plants.

3.2. *The co-creation process*

The collaboration between the Valencia water utility company, Global Omnium, and the team of researchers working on the INNOVA project began by establishing the research goals and objectives of the company with regards to the potential impact of climate change on the water service they provide. The overall interest of the water utility company was to research how climate change will affect the overall reliability of the water supply system (combining resources of the Jucar and Turia rivers), and the water quality at the Tous reservoir. They were also interested in the relationship between the quantitative and the qualitative aspects of the water resources, based on their previous experience during prolonged drought periods. The process followed for the co-creation was based on a business model concept to ensure that the user's perspective was considered during the whole project. Further details about the process can be found in Rubio-Martin et al. (2021).

As noted by Vogel et al. (2016), water utilities are often more interested in management issues that develop over time, rather than in particular technical issues with a definite end-point. Fulfilling this interest would require the ongoing collaboration between both parties. In the Valencia case, the interaction of the teams during the project raised additional interests of the water utility company regarding operational issues that have motivated continuing the partnership and the co-production relationship towards new goals after the conclusion of the INNOVA project.

3.3. *The climate service modeling framework*

In the climate service development context, a chain of models is a sequence of models used to transform and combine climate and other relevant information into apprehensible results useful for decision making. The chain of models developed for the climate service can be

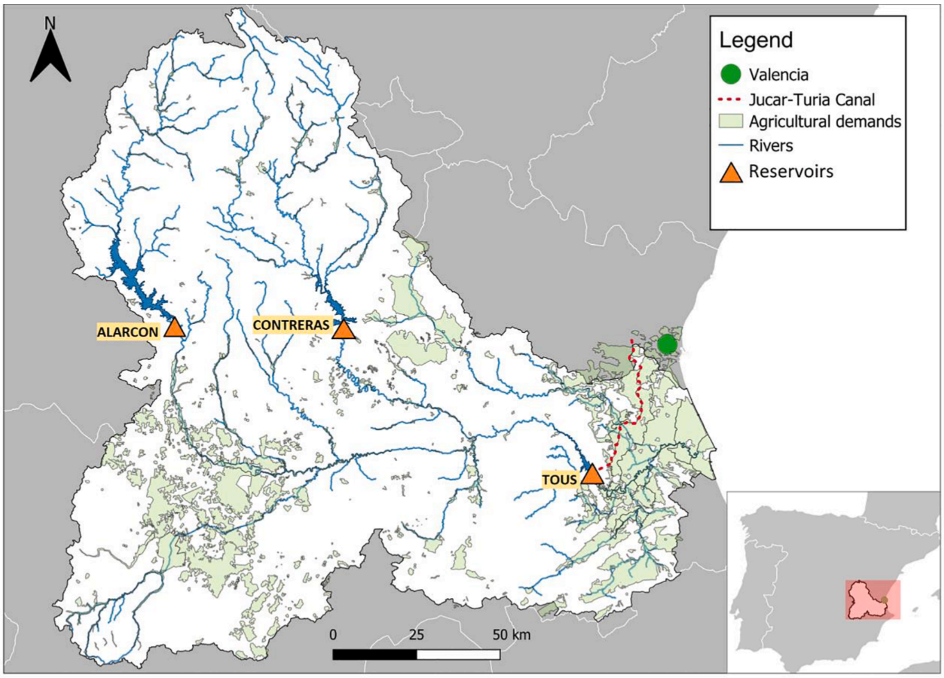

Fig. 1. Jucar River basin and location of the main components of the water resource system.

divided into three spatial scales: 1) the climate scale, formed by Global and Regional climate models; 2) the river basin scale, containing a hydrological and a water resource management model for the basin; 3) the reservoir scale, including three models that interact to simulate the chemical and biological processes taking place into the Tous reservoir. The interconnections between the models are shown in Fig. 2.

From top to bottom and left to right, the modelling framework of the co-created climate service starts with the climate projections for precipitation and temperature that are introduced in several lumped hydrological models to obtain the water inflows to the basin. A water resource management (operations) model of the basin is then used to study the climate change impact on water availability in the whole basin, and to obtain future inflows to the Tous reservoir. A management and a water quality model of the Tous reservoir were then calibrated and validated to assess the water balance at Tous in the climate change scenarios, and to analyze changes in the water quality at the reservoir. As water temperature is critical for simulating chemical and biological processes, a simple model was used to transform air temperature from the climate scenarios into water temperature at different depths in the reservoir.

3.3.1. *Climate scale: climate projections*

The first and necessary step of the modelling framework was obtaining the climate projections for precipitation and temperature. 11 combinations of Global Climate Models (GCMs) and Regional Climate Models (RCMs) from the EUROCORDEX project were selected. These combinations were used in a previous climate change study of the Jucar River basin by Marcos-Garcia and Pulido-Velazquez (2017). For each GCM-RCM combination, two RCPs were selected among those proposed by IPCC (2014): RCP 4.5 and RCP 8.5. Climate projections were divided into two periods: 2020-2040 (short term) and 2041-2069 (mid term). Furthermore, a control period (1971-2000) was used to compare the model performance with the historical observations for the selection of the best GCM-RCM combinations, and to train the bias-adjustment quantile mapping algorithm. Both precipitation and temperature historical data sets were extracted from the SPAIN 02 project (Herrera et al., 2012) with a spatial resolution of 0.11°C. Further details about the model procedure for the climate projections can be found in Marcos-Garcia and Pulido-Velazquez (2017).

3.3.2. *River basin scale: hydrological and water resource management model of the basin*

A water resource management model of the Jucar River basin was used to evaluate the impact of climate change at the river basin scale. The eleven combinations of RCM and GCM were run for the control period and for the short and mid-term projections. Seven hydrological models (Témez, 1977), lumped at the sub-basin scale and with a monthly time step, were applied first to transform the data from precipitation and temperature obtained from the climate projections into water inflows for each of the 7 sub-basins (Marcos-Garcia and Pulido-Velazquez, 2017). The water inflows will then be introduced as inputs for the water resource management model.

The water resource management model was developed following a system dynamics approach. System dynamics (SD) is a method for automating systems thinking, seeking to understand how the interactions among different subsystems drive the system's overall behavior. In this way, it facilitates a holistic understanding of water resource systems and strategic decision making (Mirchi et al., 2012). The SD model of the Jucar River basin simulates the monthly operation of the system considering the main infrastructure, inflow time series, stream-aquifer iteration, and water demands. The operation of the system is driven by priorities in the supply to water demands, the reservoir operating rules, stream-aquifer interaction in the middle basin, the water demands, the evaporation and infiltration in reservoirs and the

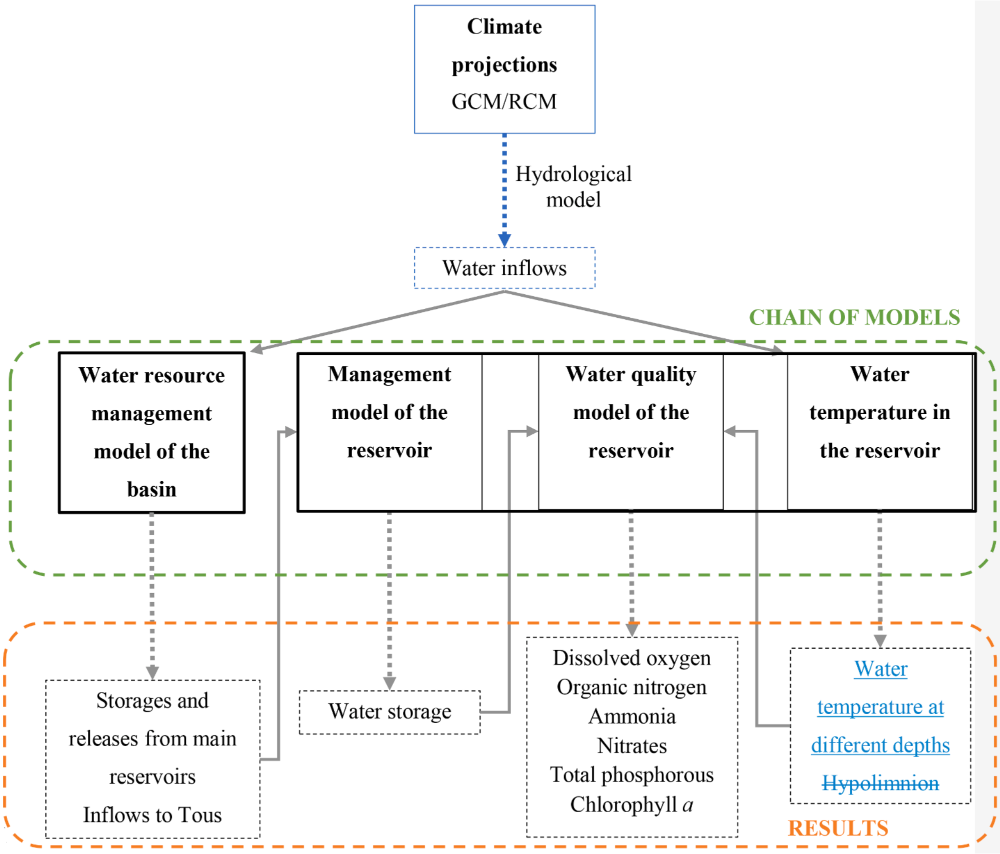

Fig. 2. Modeling framework of the co-created climate service.

drought management plan triggering water supply restrictions depending on the state of the system (Rubio-Martin et al., 2020). The operating rules of the three reservoirs of the model were adapted from the fuzzy logic rules obtained through a previous co-development process with the Jucar River Basin managers (Macian-Sorribes and Pulido-Velazquez, 2017).

Results from the climate projections were introduced into the model as time series of monthly inflows in the upper, middle, and lower sub-basins. Other variables from the water resource management model, such as the monthly defined operating rules, the agricultural and urban water demands and environmental flows, were considered constant across all climate change scenarios. Consequently, researchers can isolate the effects of climate change on the water resource system and compare the performance of the system under the climate change scenarios to the performance of the system during the control period (1970–2000). Some of the key results obtained by the model for the climate service were the monthly water inflow to Tous reservoir, monthly water storage in Tous, and total monthly storage of the system.

3.3.3. *Reservoir scale: water quality model*

Water temperature plays an essential role in water quality issues (Caissie, 2006). The relationship between air and water temperatures was modeled using a non-linear regression approach after Mohseni et al. (1999). Future water temperatures derived from the climate projections were estimated in the epilimnion (top-most layer) and hypolimnion (bottom layer), considering the interannual stratification process in the Tous reservoir.

An intermediary model between the water resource management model and the water quality model was developed to simulate in detail the variation of water storage in the Tous reservoir. Developed using SIMGES, the simulation module of the AQUATOOL software (Andreu et al., 1996), the model estimates reservoir storage through balance, considering inflows from the river basin model, evaporation, seepage losses and reservoir operation rules.

The last step of the modelling framework was the estimation of water quality in Tous. This step requires shifting from the river basin scale to the reservoir scale. The Tous reservoir model was developed using GESCAL, the water quality module of AQUATOOL (Paredes-Arquiola et al., 2013), which will take the outputs of SIMGES and the water temperature projections previously referred. GESCAL considers the stratification processes in reservoirs and the interaction between water and sediments, modeling the epilimnion and hypolimnion layers separately. GESCAL models dissolved oxygen, phytoplankton, nitrogen and phosphorus cycles, including their mutual interactions as first order kinetic processes (Fig. 3) (Paredes-Arquiola et al., 2013). Following the water utility operators' requests, the water quality parameters analyzed were dissolved oxygen, ammonia, nitrate, organic nitrogen, and total phosphorus in the epilimnion and the hypolimnion.

3.4. *Model calibration and validation*

The hydrological models developed for the seven sub-basins used monthly discharge data from the gauging stations at the outlet of each sub-basin for the period 1971–2000 as data for the calibration and validation. Results showed that the models were able to properly represent the hydrology of the system (Marcos-Garcia et al., 2017). The system dynamics model developed to simulate the water resource management system was also able to reproduce the behavior of the overall system (Rubio-Martin et al., 2020). Fig. 4 shows the outcomes of the model for the Tous reservoir water storage.

The balance at Tous was particularly challenging to calibrate for several reasons. Located downstream from the two main reservoirs of the systems, Alarcon and Contreras (see Fig. 1), its inflow depends on the correct calibration of the releases of the upstream reservoirs. The reservoir operating rules are subjected to restrictions during the rainy season for flood protection, which limits the amount of water that can be kept during that period. It has a minimum water storage of around 35 Mm^3 all year, which must be maintained. With two managed outlets, one mainly for agriculture and the other for urban water supply, the second takes priority over the first one. Monthly operating rules were derived and recalibrated from the fuzzy rules of the reservoir (Macian-Sorribes and Pulido-Velazquez, 2017) to properly represent the complex management of the system of reservoirs.

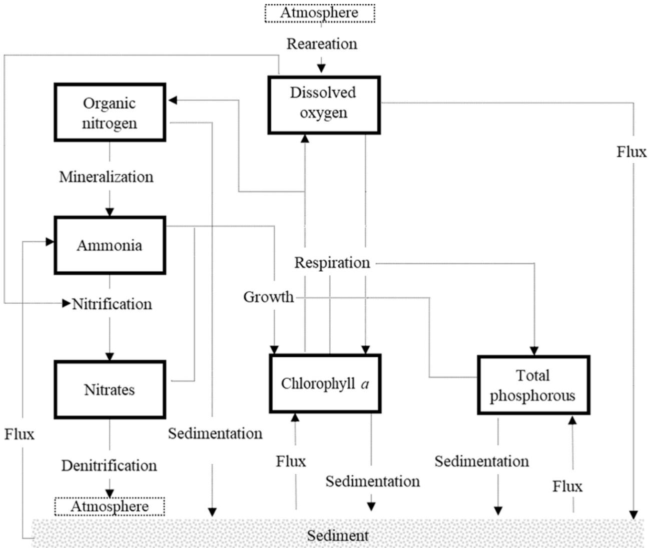

Fig. 3. Water quality parameters relations reproduced by the GESCAL module, AQUATOOL. Flowchart modified from Paredes-Arquiola et al. (2013).

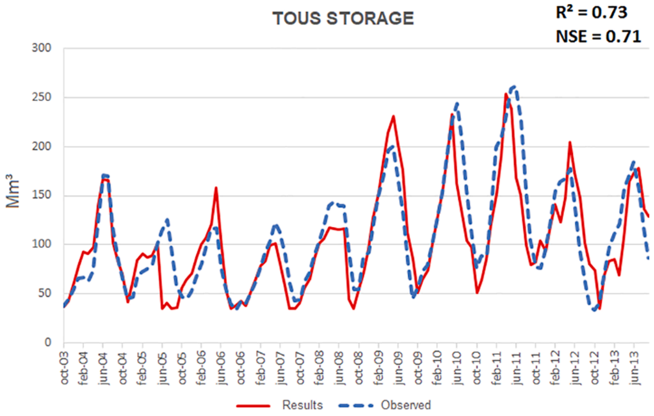

Fig. 4. Comparison between model results and historical records for Tous monthly water storage in the 2003-2013 period.

Water temperature was calibrated for the 2005–2012 period and validated for 2013–2018 using historical air temperature data from a weather station located by the Tous reservoir (Fig. 5).

Linear regressions to infer water temperature in the epilimnion and hypolimnion from air temperature were fitted minimizing the root mean square error (RMSE). Regarding the stratification process, it was assumed that the Tous reservoir remains homogeneous during winter, as shown by the historical data (CHJ, 2019). The Willmott index (Willmott et al., 2012) indicates a good agreement between the observed and simulated values for the temperature in the epilimnion, and an acceptable agreement for the hypolimnion (Table 1).

The calibration of the parameters controlling the water quality model built using GESCAL was performed using a 4-year period with sufficient data, except for organic nitrogen and nitrates in the hypolimnion, which were only available for a 3-year period due to data availability constraints. A period with five years of data was used to

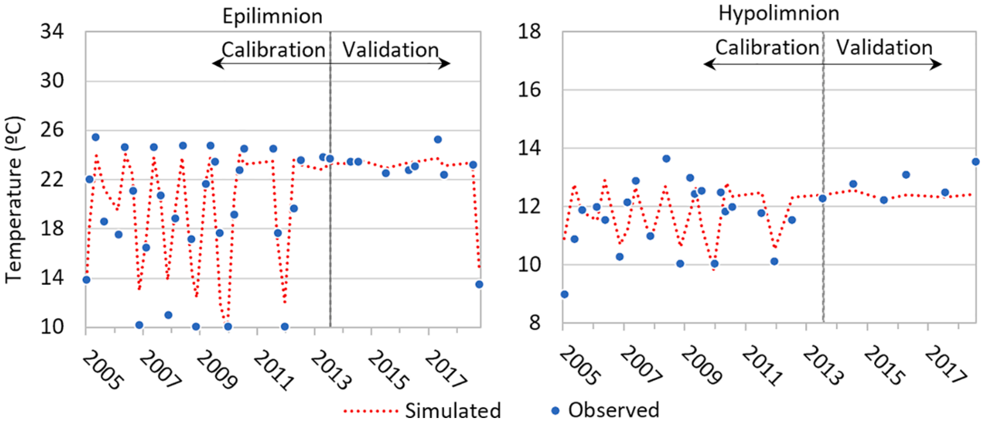

Fig. 5. Water temperature calibration and validation for the epilimnion and hypolimnion.

validate the model. All data records were obtained from the Jucar River Basin Agency (CHJ, 2019). The calibration was performed by adjusting the parameters of the model to match observations, within a predefined range of most common values. An adequate adjustment of chlorophyll *a* was prioritized due to the role of phytoplankton in water treatment processes and the interest in knowing how climate change can affect phytoplankton growth, as expressed by the end-user of the climate service. Additionally, the adjustment of the epilimnion was prioritized over the hypolimnion because the intake used by the Jucar-Turia Canal in the Tous reservoir is located within the former layer. The calibration and validation graphs for dissolved oxygen, ammonia, total phosphorous and chlorophyll *a* are shown in Fig. 6.

Although GESCAL estimates chlorophyll *a* in the epilimnion, it is not capable of estimating it in the hypolimnion. However, samples collected by the Jucar River Basin Agency and the water utility company show a significant chlorophyll concentration in the hypolimnion (CHJ, 2019). Comparing data samples of Chlorophyll *a* in the epilimnion and hypolimnion for the same period, it was found that they show similar values particularly during late autumn and early winter, when the thermocline of Tous breaks down, which allows the water to mix and homogenizes the chlorophyll *a* concentrations. The correlation between the concentrations of chlorophyll *a* found at both layers was fitted through a linear regression equation with a coefficient of determination (R^2) = 0.7102.

$$\mathrm{Chla}_{\mathrm{Hypolimnion}}\ (\mu\mathrm{g/l}) = 0.8785\,\mathrm{Chla}_{\mathrm{Epilimnion}}\ (\mu\mathrm{g/l}) + 0.0115$$

The water quality model developed for Tous adequately reproduces the water quality dynamics during the calibration and validation period for dissolved oxygen and, partially, for ammonia and Chlorophyll *a;* while the reproduction of phosphorus concentrations could be improved. The results in the hypolimnion are less accurate than the ones for the epilimnion, in agreement with other models developed previously for the same basin (Paredes et al., 2010, Momblanch et al., 2015). However, as previously explained, the results in the epilimnion are of the most important for the water utility company because the intake of the Jucar-Turia Canal in the reservoir is located within the epilimnion layer. The correct adjustment of Chlorophyll *a* was emphasized following the end-users demands due its importance in the water treatment processes.

Table 1
Willmott index for the temperature fitting.

	Calibration period	Validation period
Epilimnion temperature model	0.989	0.943
Hypolimnion temperature model	0.822	0.786

4. Results and discussion

4.1. Quantitative results for water utility

Climate projections show that climate change will reduce annual precipitation and increase the air temperature in the Jucar River basin. The reduction of water resources in the Jucar River basin is consistent with the trends observed in other Mediterranean basins in Spain (Amblar et al., 2017; Zittis et al., 2019). In the Jucar River basin, the reduction is expected to be more intense in the upper basin, with an average reduction of inflows to Alarcon and Contreras greater than 40% in the 2040-2070 scenarios (Marcos-Garcia and Pulido-Velazquez, 2017) mainly driven by a decrease in precipitation. Considering that the upper basin is the source and storage of most available water resources in the Jucar River system, the impact of climate change on the whole basin is expected to be severe, particularly for water-intensive uses such as irrigated agriculture. As shown in Table 2 for variations in total storage in the system, the results for different climate scenarios are varied, but a downwards trend is predominant.

The variations showed in Table 2 are a direct consequence of climate change, as the water management infrastructures, operating rules of the reservoirs, agricultural and urban demands and drought management strategies simulated in the model are the same as in the reference period. The average system's total water storage decreased 21% in the short term (2020-2040) compared to the control period, evenly distributed within the year and per RCP. For the medium-term scenario (2040-2070), the average variation of total water storage is −41%. However, the reduction is a couple of percentage points more prominent during the winter and autumn months (−43%) when compared to spring (−39%) and summer (−41%). This is a concerning trend because winter and autumn are the seasons that historically provide more water resources for the basin.

Results in the Tous reservoir show a higher degree of seasonality. In the short term, a severe reduction in water storage is experienced in winter with -19% for the RCP4.5 scenario and −12% in the 8.5. In the medium term, Tous average seasonal variation is −16% in autumn, −31% in winter, −23% in spring, and −24% in summer months, with minor differences between both RCP's scenarios. Fig. 7 shows the seasonal variation of water storage in Tous compared to the control period.

Boxplots represent the median, 25th percentile and the 75th percentile. The whiskers indicate the 10th and 90th percentiles, and single points are outliers.

A question remains to be answered: Does the reduction of water availability in the system and Tous reservoir jeopardizes the water supply to the city of Valencia and its metropolitan area? A statistical analysis of the results shows that events of theoretical failure of water supply occur 1.9% of the months for the RCP8.5 short term scenario and 0.9% of the months for the medium-term scenario. Events of water

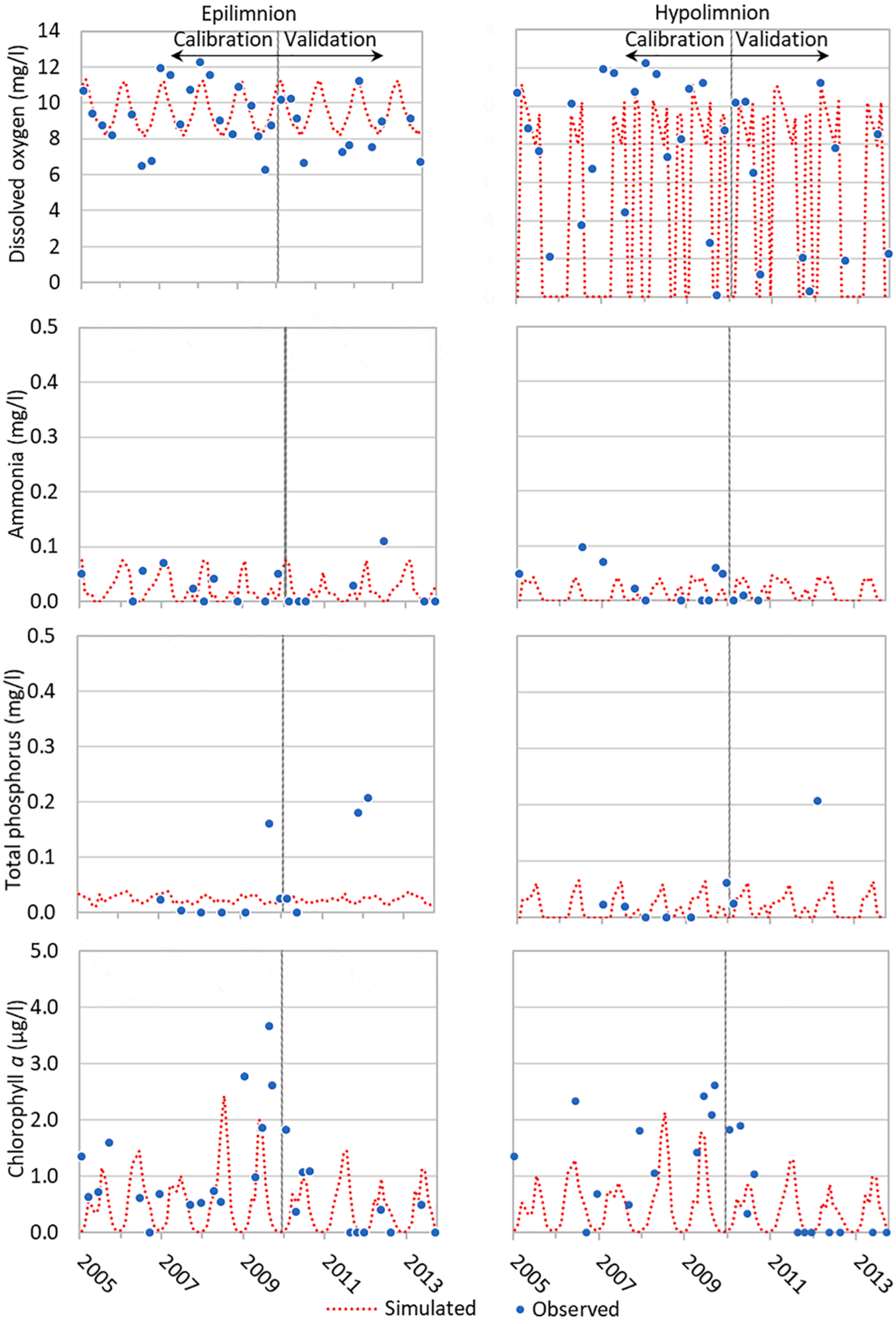

Fig. 6. Dissolved oxygen, ammonia, total phosphorous, and chlorophyll *a* calibration and validation in the epilimnion and hypolimnion.

supply failure were not observed when running the simulations for the reference period. These results must be understood in the context of the climate service and should not be interpreted as an exact prediction of what it is to come. The water utility activity is performed on a daily basis, and single events of accidental water supply failure should not be discarded based on the outcomes of a modelling framework running climate change scenarios in a monthly time step. However, ingrained risk of failure to provide urban water seems unlikely based on the obtained results. The buffer resource available in the Tous reservoir is able to cope with changes in urban demands and reduced inflows. Regulation ponds and emergency wells located in the region can also provide additional water resource in case of extreme emergency. Consequently, the probabilities of the city of Valencia suffering failures at the daily scale caused by insufficient water supply from Tous that are not acknowledged at the monthly scale are negligible. These results, however, also indicate some concerning trends: 1) water management in the Jucar River basin is going to increase in complexity as water availability decreases; 2) conflicts between water users from the upper and the lower basin are likely to increase; 3) the operating rules of the system of reservoirs may have to change to address the challenges introduced by climate change.

Urban uses take priority over other water demands in the basin according to the plans developed by the Jucar River Basin Agency (CHJ, 2019). Hence, the likelihood of systemic water shortages is low for the sector, even in the medium term. However, the effect that such as significant reduction on water availability may have in the quality of the

Table 2
Average monthly variation in % of total water storage of the system for the RCP8.5 short term scenarios compared to the reference period.

	CNRM_RCA4	CSIRO_RCA4	ICHEC_RCA4	MIROC_RCA4	MOHC_RCA4	MPI_RCA4	MPI_CCLM4	MPI_REMO_1	MPI_REMO_2	NCC_RCA4	CCCma_RCA4
October	-17%	18%	-28%	-25%	-15%	-50%	-14%	-30%	-7%	-29%	-28%
November	-16%	19%	-27%	-25%	-14%	-49%	-15%	-30%	-7%	-29%	-29%
December	-15%	19%	-27%	-25%	-14%	-48%	-16%	-30%	-8%	-30%	-30%
January	-15%	19%	-28%	-26%	-15%	-49%	-17%	-32%	-9%	-31%	-30%
February	-14%	16%	-29%	-26%	-17%	-48%	-15%	-32%	-10%	-32%	-28%
March	-14%	16%	-29%	-26%	-18%	-47%	-14%	-32%	-10%	-33%	-27%
April	-12%	16%	-27%	-24%	-18%	-47%	-13%	-32%	-10%	-31%	-26%
May	-12%	14%	-26%	-23%	-16%	-47%	-14%	-33%	-10%	-31%	-25%
June	-14%	13%	-27%	-24%	-16%	-49%	-14%	-34%	-11%	-32%	-26%
July	-15%	10%	-28%	-25%	-16%	-50%	-16%	-34%	-11%	-29%	-27%
August	-17%	12%	-29%	-26%	-16%	-52%	-16%	-34%	-10%	-29%	-28%
Septemb.	-18%	13%	-30%	-25%	-16%	-52%	-17%	-34%	-8%	-29%	-29%

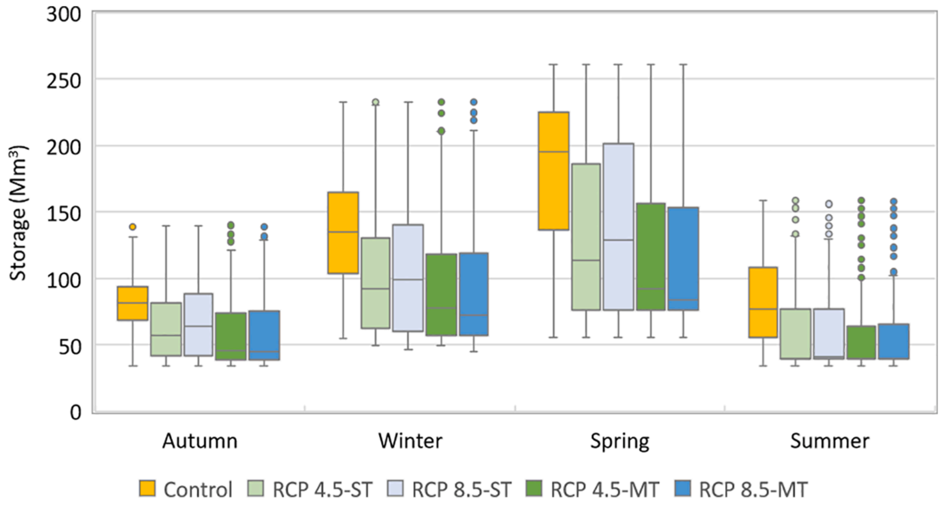

Fig. 7. Tous reservoir storage in the control period (1971–2000) and in scenarios RCP 4.5 and 8.5 in the short (ST) and medium term (MT) scenarios.

raw water resources is a significant concern for the operators.

4.2. Water quality projections

Assessing the impact of climate change on the water utility in Valencia requires studying the effect on the water quality at the Tous reservoir. The reduction of inflows and the rise in water temperatures will affect the chemical and biological processes in the reservoir. With temperature rising 2.5°C and 3.4°C in RCP 4.5 and 8.5 scenarios compared to the control period, summer is the season that shows more significant increases (Fig. 8). The increasing air temperature results in a rise of epilimnion temperatures up to 1.05 °C on average in the RCP 4.5 scenarios and 1.47 °C in the RCP 8.5 scenarios. Hypolimnion temperatures raise 0.25 and 0.56 °C in scenarios RCP 4.5 and 8.5, respectively (Fig. 8).

On an annual average, dissolved oxygen decreases by 0.3 mg/L in the worst-case scenario (RCP 8.5 medium term) in the epilimnion, which is not significant. The primary process behind the dissolved oxygen concentration in the epilimnion is the re-aeration produced by wind and oxygen dispersion, which is unchanged in the modelling framework. In contrast, dissolved oxygen in the hypolimnion is lower in all scenarios compared to the control period. The most important effect of climate change linked to dissolved oxygen will be the extension of anoxia events. Currently, anoxia events occur during the last days of September and can last until early winter (CHJ, 2019), representing around 23% of months. Results show that hotter summers and winters may cause anoxia events to start in early summer and last until winter due to stratification (Fig. 8). Under climate change scenarios, months with anoxia represent around 38.5% of months in the short term and 47.5% of months in the medium term in both RCPs. Similar trends have been observed in other water bodies as a consequence of climate change (Fink et al., 2016; Woolway et al., 2019).

Blooms of chlorophyll *a* were observed during several drought episodes in 2008, rising by around 3.5 µg/l, as shown in Fig. 6. Results for future scenarios show similar average values of chlorophyll *a* compared to the control period. However, a significant increase in the frequency and intensity of extreme blooms of phytoplankton is also observed. With peaks of around 4 µg/l in the short term and between 6 and 9.5 µg/l in the medium term in scenarios RCP 4.5 and 8.5, respectively, results illustrate conditions of extreme eutrophication crisis (Fig.8).

Chlorophyll *a* results are consistent with the trends identified by Ward et al., (2020) in Sunapee lake (USA), where authors observed that the peaks of chlorophyll *a* concentration in the short term could double the ones from the reference period.

The Jucar River Basin Agency considers that the Tous reservoir generally has an oligotrophic to mesotrophic state (CHJ, 2019). This measurement follows the OECD (1982) methodology, which uses the mean chlorophyll *a* and mean total phosphorous concentrations. The model results for the control period shows that Tous alternates between oligotrophic and ultraoligotrophic states. The trophic state is worse in both climate change scenarios compared to the control period (Table 3). Scenario RCP 8.5 shows the worst trophic state, being between oligotrophic and mesotrophic in both timeframes.

Under climate change scenarios, organic nitrogen, ammonia, nitrates, and phosphorus concentrations follow similar trends as in the control period. Organic nitrogen average levels do not increase significantly, although peaks of 0.13 and 0.21 mg/l were observed in the medium-term RCP 4.5 and 8.5 scenarios, respectively. Hypolimnion organic nitrogen values follow the same trend as for the epilimnion: peaks of organic nitrogen are seen during spring and summer, and they

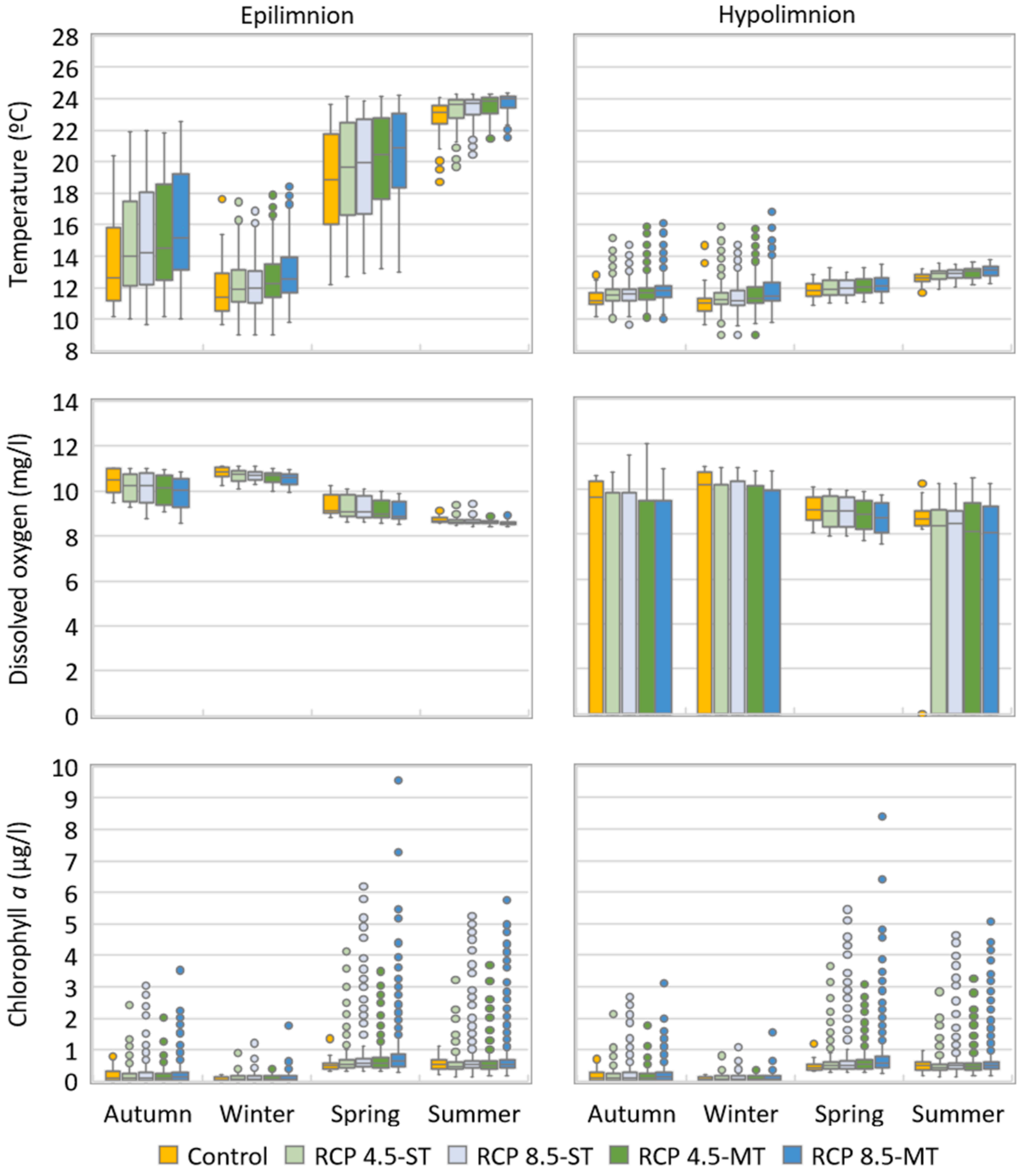

Fig. 8. Comparison of model results for water temperature, dissolved oxygen, and chlorophyll *a*

Table 3
Comparison of the trophic state of the Tous reservoir in the control period and RCP 4.5 and 8.5 scenarios.

Trophic state (% of months)	Control	RCP 4.5 Short term	RCP 8.5 Short term	RCP 4.5 edium term	RCP 8.5 Medium term
Ultraoligotrophic	39.9%	31.4%	0.0%	25.2%	0.0%
Oligotrophic	60.1%	68.4%	80.6%	74.5%	74.1%
Mesotrophic	0.0%	0.2%	19.1%	0.3%	25.8%
Eutrophic	0.0%	0.0%	0.3%	0.0%	0.1%

disappear in autumn and winter due to the renewal of water. The fact that no external source for nutrients was added to the modeling framework for the climate change scenarios may explain the little change observed. The decision not to increase external intake for nutrients was highly debated within the team and with the water utility operators. Ultimately, the decision was to keep the scenarios as climate-centered as possible, not including additional anthropogenic hypotheses.

The striking effects of climate for the phosphorous and nitrogen concentrations observed by other authors (Cha et al., 2017; Gibbs and Howard-Williams 2018; Beutel et al., 2020) are not observed in the Tous reservoir under climate change. Reasons include the mentioned lack of additional inflows of nutrients, the position of the photic zone close to the hypolimnion (Cantin et al., 2011), and the speed at which nutrients are consumed by phytoplankton producing phytoplankton blooms, which then come to an end as new water inflows and releases renew the water (Watanabe et al., 2016; Cha et al., 2017; Leite and Becker 2019).

4.3. Vulnerability assessment and pathways towards adaptation

The results obtained using the co-created climate service were thoroughly discussed with the water utility team during the project. A vulnerability analysis was performed based on the results, and initial adaptation options were identified.

The increase in the frequency and intensity of phytoplankton blooms was the primary concern for both operators and researchers. The predicted deterioration of the reservoir trophic state may force the operators to adapt their primary treatment process or install equipment to reduce the quantity of phytoplankton reaching the water treatment plants during bloom events. The current flocculation and coagulation processes would not be able to deal with the projected phytoplankton blooms. Although the climate service did not directly predict the phytoplankton composition, the average for the ratio of inorganic nitrogen and inorganic phosphorus (N–P) is similar in the control period (393), and in the climate projections (379 and 380 for the RCP 4.5 and 8.5 respectively, in the medium term). The most recent phytoplankton analyses in the Tous reservoir (2016–2020) show diatom domination, with around 50% of the total phytoplankton, followed by chlorophytes and cyanobacteria. Diatom dominance is characteristic in the eastern Iberian Peninsula due to high levels of silicate in its basins, such as the Jucar River basin (Sebastiá et al., 2013). However, future hydrological droughts accompanied by organic nitrogen peaks occasionally increase N:P ratios and increase the presence of cyanobacteria in reservoirs (Brasil et al., 2016; Lins et al., 2016). Additionally, higher temperatures and longer stratification periods reduce CO_2 solubility, thereby promoting cyanobacteria and reducing the presence of other phytoplankton groups (Rolland et al., 2013; Brasil et al., 2016). Such changes were observed in lakes and reservoirs by Fonseca and Bicudo (2008), and Hayakawa et al. (2015). The presence of cyanobacteria in the Tous reservoir is already a source of concern for the water utility operators, and future conditions favorable to an increasing number of cyanobacteria events would suppose an additional challenge for the water treatment plants.

The projected rise in organic nitrogen —although not as intense as the Chlorophyll *a* increase— may have a significant impact on the water treatment plants of Valencia. This component can react with some disinfectants to form disinfection subproducts with carcinogenic effects, such as haloacetonitriles, halonitromethanes, or N-nitrosodimethylamine (Lee and Westerhoff 2006; Li et al., 2019). Currently, the two water treatment plants in Valencia use chlorine dioxide to perform primary disinfection. However, future peaks of organic nitrogen in raw water may increase the production of disinfectant subproducts and may put at risk the bactericidal efficiency of the current treatments. This new situation will force the water treatment plants to consider methodologies that can remove organic matter without increasing disinfectant subproducts, such as advanced oxidation. Moreover, the predicted increase in anoxia events may increase the risk of mobilizing chemical pollutants from the sediment, such as pesticides or heavy metals (Delpla et al., 2009).

Changes in the operating rules of the main reservoirs of the system could mitigate the impacts of climate change on the water quality. Many water quality problems correlate with low water storage in the reservoir. Increasing the inflows into Tous and strategically raising its water level may alleviate some issues. This measure may be particularly beneficial for controlling phytoplankton blooms by reducing hydraulic retention times and the water temperature in the reservoir. Furthermore, the intake tower located in Tous for water utility has three intake points, each located ten meters above the preceding one. Currently, water is drawn from the lowest level available (17 m above the reservoir bed). Modifying the intake during summer and autumn may help mitigate the risks of taking water closer to the hypolimnion layer.

5. Conclusions

The water utility sector is one of the most vulnerable to climate change, particularly in regions where water quality and water availability issues are already occurring. Climate services can assist water utility operators in assessing their vulnerability to climate change and may help them to start planning adaptation strategies. The sector's adaptation to the new climate conditions is critical to ensure one of the most basic human needs: safe water for drinking, sanitation, and hygiene. However, this adaptation requires the cooperation of researchers and water utility operators to ensure that the resulting climate services capture each case's specific features and address the needs of the professionals working in the field and taking decisions.

The climate service co-created with the water utility company of Valencia (Global Omnium), combines the river basin and reservoir scales, and includes the most relevant raw water quality parameters for water utility. Decisions such as the time or spatial scales to be implemented in the models resulted from healthy discussions and debates between the research team and the water utility operators. The evaluation of the main water quality parameters to be implemented into the project also resulted from the interaction between all parties, although in some cases was limited by data availability. The resultant climate service aspires to be a valuable tool for the water utility managers to make better and more informed decisions in their process toward climate change adaptation. Although the modelling framework is a climate service co-created ad hoc to evaluate the effects of climate change in the specific case study, the process followed can be adapted to other water utilities worldwide in a straightforward way subject to the model ability to reproduce their climate, hydrology and water system features, as well as the existence of enough data to support the development of the modelling chain..

The INNOVA project provided the context for the collaboration between the university and the water utility company in Valencia, resulting in the climate service described in this contribution. It also motivated the teams to keep working together in future endeavors and has provided some lessons that may be useful for both researchers and water utility managers. The initial engagement between the scientific team and the end-user is critical for the following steps if a co-creation is to be established. In the case of the Valencia water utility company, previous collaborations with the university in innovation and research projects facilitated the initial understanding between all parts. Additionally, Global Omnium has an R&D&i unit to encourage and promote initiatives for the technological development of the sector. Water utilities that lack this goal may be harder to engage in the process. The issue of scale, both temporal and spatial, was one of the main points of difference between the teams. Utilities are often focused on the day-to-day operation and management, and climate change projections at a monthly time step do not capture the daily variability of the management. They do, however, indicate trends and changes in the overall status of the water resource system that may significantly affect the management of the existing facilities. Furthermore, water utility companies often have a limited spatial scope when considering the location and origin of the raw resource they are treating. Nevertheless, climate services for water utilities that draw water from a downstream location in a highly managed system must consider the regional scale and how climate change will impact the whole system.

The results obtained by the climate service show that the reduction of water availability for the water utility in Valencia and its metropolitan area will not be at risk of systemic water shortages, which will be mainly suffered by the agricultural sector as the largest user of water with lower priority than the urban supply. However, changes in the management and monitoring of the main reservoirs may be required to avoid risks during prolonged drought periods. Furthermore, the worsening of the water quality in the Tous reservoir due to the foreseen reduction of water storage and water inflows and the increasing air and water temperatures is concerning for the water utility. According to the projections, anoxia events could last longer, starting early in late summer and ending in the middle of winter. The steep increase in phytoplankton blooms is captured by Chlorophyll a rising to 10 μg/l in the worst conditions predicted, multiplying by almost ten the peak values estimated by the model for the reference period. Phytoplankton blooms may worsen the trophic state of the reservoir, from ultraoligotrophic-oligotrophic, to oligotrophic-mesotrophic. Consequently, the raw water quality for the supply to Valencia is expected to drop, forcing the water treatment plants to adapt or change some of their processes to guarantee a safe urban water supply.

Finally, some models developed for the modelling framework (Fig. 2) could be used to test policy changes and adaptation strategies at the river basin scale, integrating expert knowledge and users' information into a single modelling environment.

CRediT authorship contribution statement

Adria Rubio-Martin: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ferran Llario:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Alberto Garcia-Prats:** . **Hector Macian-Sorribes:** Conceptualization, Methodology, Writing – original draft, Validation, Data curation, Writing – review & editing. **Javier Macian:** Conceptualization, Data curation, Validation. **Manuel Pulido-Velazquez:** Conceptualization, Resources, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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