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PROGRAMA DE DOCTORADO EN INGENIERÍA DEL AGUA Y MEDIOAMBIENTAL

Development of climate services for the management of Mediterranean water resource systems: case study of the Júcar system and Valencia water supply

TESIS DOCTORAL

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A mis padres y a mi hermano.

Porque, aunque no siempre lo sepan, están siempre presentes.

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Resumen

Los servicios climáticos son productos que resultan de la combinación de datos climáticos y otra información pertinente y que resultan útiles para la toma decisiones para la adaptación o mitigación del cambio climático. Idealmente, este tipo de servicios funcionan como puente entre los puros datos climáticos y los usuarios finales, de modo que la ciencia queda traducida en productos o servicios útiles y comprensibles. Los servicios climáticos para la adaptación pueden desarrollarse a escala individual, local y regional, y pueden ayudar a las comunidades y a personas a prepararse y hacer frente a los efectos del cambio climático. Con frecuencia, los servicios climáticos han sido desarrollados por expertos en datos climáticos sin tener en cuenta las necesidades específicas de los usuarios finales. Este enfoque «top-down» con frecuencia significa que no se utiliza la información más relevante para su creación y que se descuida la perspectiva del usuario final durante el proceso de diseño. La desconexión existente entre los potenciales usuarios de servicios climáticos y los propios productos ha conducido a una falta de aceptación y utilización de los servicios climáticos, incluso entre aquellos usuarios más vulnerables a los efectos del cambio climático. La co-creación de servicios climáticos junto a los usuarios que van a utilizarlos puede ayudar a solucionar muchos de los retos descritos anteriormente. Al implicar a los usuarios en el diseño y desarrollo de los servicios, es más sencillo que éstos sean pertinentes, se adapten a sus necesidades y sean fáciles de usar. Esto puede ayudar a aumentar la concienciación y la comprensión de las posibles repercusiones del cambio climático, así como a generar confianza en los servicios que se prestan. Además, la co-creación de estos servicios puede ayudar a desarrollar modelos de negocio más sostenibles para los servicios climáticos: al implicar a los usuarios en el desarrollo y la financiación de los servicios, es posible crear modelos de negocio basados en el beneficio mutuo y la propiedad compartida. Esto puede contribuir a que los servicios sean sostenibles y puedan seguir prestándose a largo plazo. La co-creación puede, en definitiva, ayudar a que los servicios se consideren relevantes y valiosos para los usuarios, y que éstos estén dispuestos a invertir el tiempo y los recursos necesarios para utilizarlos de forma sostenida a lo largo del tiempo. El objetivo de esta tesis es contribuir al desarrollo de servicios climáticos eficaces y orientados al usuario para la adaptación al cambio climático, centrándose en el sector del agua. Al promover la creación conjunta de servicios climáticos, se pretende garantizar que las estrategias

de adaptación se adapten a las necesidades específicas de los distintos usuarios de los servicios climáticos, y crear resiliencia y capacidad en las organizaciones y comunidades. El caso de estudio consiste en la co-creación de un servicio climático para la evaluación de los impactos del cambio climático en el sistema de abastecimiento de agua a Valencia y su área metropolitana. El servicio climático se creó juntamente con la empresa local de suministro de agua de Valencia (EMIVASA), en el contexto del proyecto INNOVA. Para realizar este análisis, se desarrolló un modelo de dinámica de sistemas de la cuenca del Júcar, capaz de representar las complejas interrelaciones del sistema a lo largo del tiempo, y se combinó con un modelo de calidad de aguas del embalse de Tous para realizar el análisis sobre la calidad del recurso futuro disponible. Este trabajo demuestra el valor de involucrar a los usuarios finales en la co-creación de servicios climáticos para garantizar su relevancia, utilidad y aceptación. Lo hace mediante la aplicación de esta metodología a la cuenca del Júcar y al problema del abastecimiento a la ciudad de Valencia en escenarios futuro de cambio climático. Esta aplicación permite extraer conclusiones sobre las formas de co-crear este tipo de productos y las mejores formas de abordar la co-creación de servicios climáticos en sectores clave, como el abastecimiento de agua potable.

Resum

Els serveis climàtics són productes que resulten de la combinació de dades climàtiques i altra informació pertinent i que resulten útils per a la presa decisions per a l'adaptació o mitigació del canvi climàtic. Idealment, aquest tipus de serveis funcionen com a pont entre les pures dades climàtiques i els usuaris finals, de manera que la ciència queda traduïda en productes o serveis útils i comprensibles. Els serveis climàtics per a l'adaptació poden desenvolupar-se a escala individual, local i regional, i poden ajudar les comunitats i a persones a preparar-se i fer front a l'efecte del canvi climàtic. Amb freqüència, els serveis climàtics han sigut desenvolupats per experts en dades climàtiques sense tindre en compte les necessitats específiques dels usuaris finals. Aquest enfocament «top-*down» amb freqüència significa que no s'utilitza la informació més rellevant per a la seua creació i que es descura la perspectiva de l'usuari final durant el procés de disseny. La desconnexió existent entre els potencials usuaris de serveis climàtics i els propis productes ha desembocat a una falta d'acceptació i utilització dels serveis climàtics, fins i tot entre aquells usuaris més vulnerables a l'efecte del canvi climàtic. La co-creació de serveis climàtics amb els usuaris finals pot ajudar a solucionar molts dels reptes descrits anteriorment. En implicar els usuaris en el disseny i desenvolupament dels serveis, és més senzill que aquests siguen pertinents, s'adapten a les seues necessitats i siguen fàcils d'usar. Això pot ajudar a augmentar la conscienciació i la comprensió de les possibles repercussions del canvi climàtic, així com a generar confiança en els serveis que es presten. A més, la co-creació d'aquests serveis pot ajudar a desenvolupar models de negoci més sostenibles per als serveis climàtics: en implicar els usuaris en el desenvolupament i el finançament dels serveis, és possible crear models de negoci basats en el benefici mutu i la propietat compartida. Això pot contribuir al fet que els serveis siguen sostenibles i puguen continuar prestant-se a llarg termini. La co-creació pot, en definitiva, ajudar al fet que els serveis es consideren rellevants i valuosos per als usuaris, i que aquests estiguen disposats a invertir el temps i els recursos necessaris per a utilitzar-los de forma sostinguda al llarg del temps. L'objectiu d'aquesta tesi és contribuir al desenvolupament de serveis climàtics eficaços i orientats a l'usuari per a l'adaptació al canvi climàtic, centrant-se en el sector de l'aigua. En promoure la creació conjunta de serveis climàtics, es pretén garantir que les estratègies d'adaptació s'adapten a les necessitats específiques dels diferents usuaris dels serveis climàtics, i crear

resiliència i capacitat en les organitzacions i comunitats. El cas d'estudi consisteix en la co-creació d'un servei climàtic per a l'avaluació dels impactes del canvi climàtic en el sistema de proveïment d'aigua a València i la seua àrea metropolitana. El servei climàtic es va crear juntament amb l'empresa local de subministrament d'aigua de València (EMIVASA), en el context del projecte INNOVA. Per a realitzar aquesta anàlisi, es va desenvolupar un model de dinàmica de sistemes de la conca del Xúquer, adequat per representar les complexes interrelacions del sistema al llarg del temps, i es va combinar amb un model de qualitat d'aigües de l'embassament de Tous per a realitzar l'anàlisi sobre la qualitat del recurs futur disponible. Aquest treball demostra el valor d'involucrar als usuaris finals en la co-creació de serveis climàtics per a garantir la seua rellevància, utilitat i acceptació. Ho fa mitjançant l'aplicació d'aquesta metodologia a la conca del Xúquer i al problema del proveïment a la ciutat de València en escenaris futurs de canvi climàtic. Aquesta aplicació permet extraure conclusions sobre les formes de co-crear aquest tipus de productes i les millors formes d'abordar la co-creació de serveis climàtics en sectors clau, com el proveïment d'aigua potable.

Abstract

Climate services result from combining climate data and other relevant information and are valuable for climate change adaptation or mitigation decision-making. Ideally, such services function as a bridge between pure climate data and end-users so that the science is translated into useful and understandable products or services. Climate services for adaptation can be developed at individual, local and regional scales and help communities and individuals prepare for and cope with the effects of climate change. Climate services have often been developed by climate data experts without considering the specific needs of end-users. This top-down approach often means that the most relevant information is not used in their creation and the end-user perspective is neglected during the design process. The disconnect between potential users of climate services and the products themselves has led to a lack of uptake and use of climate services, even among those users most vulnerable to the effects of climate change. Co-creation of climate services with the users who will use them can help to address many of the challenges described above. By involving users in the design and development of services, it is easier to make them relevant, tailored to their needs and easy to use. This can help raise awareness and understanding of the potential impacts of climate change and build trust in the services provided. In addition, co-creating these services can help develop more sustainable business models for climate services: by involving users in developing and financing services, business models based on mutual benefit and shared ownership can be created. This can contribute to making services sustainable and able to continue to be provided in the long term. Co-creation can ultimately help to ensure that services are seen as relevant and valuable to users, and that users are willing to invest the time and resources to use them on a sustained basis over time. This thesis aims to contribute to developing effective, user-driven climate services for climate change adaptation, with a focus on the water sector. Promoting the co-creation of climate services aims to ensure that adaptation strategies are tailored to the specific needs of different users of climate services, and to build resilience and capacity in organisations and communities. The case study consists of co-creating a climate service to assess climate change impacts on the water supply system of Valencia and its metropolitan area. The climate service was created jointly with the local water supply company of Valencia (EMIVASA), in the context of the INNOVA project. To carry out this analysis, a system dynamics model of the

Júcar basin, capable of representing the complex interrelationships of the system over time, was developed and combined with a water quality model of the Tous reservoir to perform the analysis on the quality of the future resource available. This work demonstrates the value of involving end-users in co-creating climate services to ensure their relevance, utility and acceptability. It does so by applying this methodology to the Júcar river basin and to the problem of supplying the city of Valencia in future climate change scenarios. This application allows conclusions to be drawn on ways to co-create this type of product and the best ways to address the co-creation of climate services in critical sectors, such as the drinking water supply.

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1. INTRODUCTION

Anthropogenic climate change has proven to be one of the most significant challenges facing humanity in the 21st century. There are several reasons why climate change is such a complicated issue to tackle. One of the main reasons is that it is a global problem that requires collective action from countries and organizations around the world. This can be difficult to achieve because each country has its own set of domestic priorities and may be hesitant to take action that could potentially hurt its economy. Additionally, many of the actions that need to be taken to address climate change, such as reducing greenhouse gas emissions, require major changes to how societies operate and how people live their lives. Furthermore, coordination between countries would be required in order to avoid freeloading and to ensure a level playing field. Finally, the effects of climate change are often slow to emerge, which can make it difficult for people to see the urgency of the problem and motivate them to take action (Moser, 2010). In this context, individual initiatives for the mitigation of climate change are commendable and important but rather ineffective if they are not actually supported by most actors in the global scene. Instead, it is necessary for governments, organizations, and relevant stakeholders to work together to develop and implement effective strategies for mitigating and reducing the emission of global greenhouse gases. The adaptation to the future scenario, on the other hand, leaves room for more individualistic approaches. Actions at the individual, local and regional scale, such as improving energy efficiency in buildings, developing stronger and more resilient cities, growing drought-resistant crops, and conserving water, can help communities and individuals to prepare for and cope with the effects of climate change. However, the temptation to not act is still persistent for a large group of stakeholders that need to understand the value of early action.

Climate change is having a profound impact on water resources, both in terms of quantity and quality. The rise in global temperatures is causing significant changes in precipitation patterns, leading to more frequent droughts and intense floods in some regions (Trenberth, 2011; AghaKouchak et al., 2020). This is causing a decline in the overall availability of water, particularly damaging in areas already affected by frequent droughts such as the Mediterranean region (Cramer et al., 2018). However, while the projected quantity of available water is an important consideration, the quality of the water is often neglected in discussions about future water resources under climate change. This is a significant oversight, as climate change is also affecting the quality of water in many ways. Warmer temperatures can lead to increased evaporation and the concentration of pollutants. The growth of phytoplankton, harmful microorganisms and some species of cyanobacteria intensifies under higher temperature conditions (Moss et al., 2011). Such organisms can pose serious health risks to humans, particularly in contexts where surface water is used as drinking water supply. Additionally, the rising levels of carbon dioxide in the atmosphere are causing the acidification of oceans which can have serious consequences for the survival of aquatic plants and animals (Gobler and Baumann, 2016). Finally, increased runoff caused during heavy rains can quickly alter the chemical composition of rivers and lakes (Lipczynska-Kochany, 2018).

Scientists and policy makers must therefore take into account both the quantity and quality of water when considering the future of water resources under climate change. This requires a more comprehensive understanding of the many interrelated factors that determine water availability and quality, as well as a more integrated approach to managing these resources. Often, discussions about the future of water resources under climate change focus exclusively on the quantity issue. However, the quality of the available water is equally important. By neglecting this aspect, we risk overlooking serious consequences for the health and well-being of both people and the environment. Adaptation is a critical component of the response to the changing water resources scenario brought on by climate change. The water sector must adapt to the new realities of both water quantity and quality in order to ensure that communities have access to sufficient and safe water (Delpla et al., 2009; Vogel et al., 2016). In that regard, science plays a crucial role in improving the understanding of stakeholders by translating climate data into information that can be used for taking action.

Climate services were envisioned as one of the main tools to bridge the gap between science and decision makers. Climate services are tailored products that result from combining 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, useful for stakeholders to take decisions (European Commission, 2015). Often climate services are developed by experts in climate data without considering the specific needs of end-users. This top-down approach often means that relevant information is not used for the creation of climate services and the end-user perspective is neglected during the design process (Swart et al., 2021). This is one of the reasons behind the perceived the weakness of the climate service market in Europe, even after years of research and support at the European and global scale. Many researchers have discussed the reasons for the perceived weaknesses and challenges faced by the climate service market (Bessembinder et al., 2019; Brasseur & Gallardo, 2016; Tart et al., 2019; Damm et al., 2020). In the following paragraphs we will summarize the main ones.

One major challenge to the adoption and effective use of climate services is a lack of awareness among societal actors of their vulnerability to climate change. This can lead to a lack of understanding of the potential impacts of climate change on various sectors, as well as a lack of appreciation for the need to adapt to and mitigate these impacts. Furthermore, climate change often competes with other issues for attention and resources. In many cases, other issues such as economic growth, public safety, and social welfare may be perceived as having a higher priority, leading to a lack of focus and investment in climate change adaptation and mitigation efforts.

A different challenge is the lack of relevant services provided by the scientific community. Many climate services providers may not have the necessary expertise or experience to develop and deliver services that are tailored to the specific needs of different sectors and stakeholders. In some cases, the format in which climate services are provided may be inappropriate for the intended users. For example, the information may be too technical or complex, or it may not be presented in a way that is accessible or easy to understand. As a result of this, users of climate services may not perceive the value of these services, either because they do not understand their potential benefits or because they see them as too costly, too alien to their needs or complex to use. This can lead to a lack of uptake and utilization of climate services, even among those who are most vulnerable to the impacts of climate change.

Another factor that can hinder the use of climate services is a lack of trust from the users. This can be due to a variety of reasons, such as a lack of transparency or accountability on the part of the climate services provider, or a lack of credibility in the information being provided. Finally, inadequate business models adopted by climate services providers can also be a barrier to the effective use of these services (Brasseur & Gallardo, 2016). In many cases, climate services may be provided on a voluntary or non-profit basis, which can limit the scope and sustainability of the services. Alternatively, climate services may be provided on a fee-for-service basis, which can make them too costly for some users to afford.

Co-creating climate services with the actors or stakeholders who are going to use them can help to address many of the challenges described above. By involving users in the design and development of the services, it is possible to ensure that the services are relevant, tailored to their needs, and easy to use (Lemos et al., 2018). This can help to increase awareness and understanding of the potential impacts of climate change, as well as to build trust and confidence in the services being provided. Co-creation can also help to overcome the challenges of competing priorities and perceived value, by involving users in the decision-making process and demonstrating the benefits of using the services (Bremer et al., 2019). This can help to ensure that the services are seen as relevant and valuable to the users, and that they are willing to invest the time and resources needed to make use of them.

Additionally, co-creation can help to improve the format and accessibility of the services, by involving users in the development of user-friendly interfaces and delivery mechanisms. This can help to ensure that the services are easy to understand and use, and that they are presented in a way that is appropriate for the intended users. Finally, co-creation can also help to develop more sustainable business models for climate services. By involving users in the development and financing of the services, it is possible to create models that are based on mutual benefit and shared ownership. This can help to ensure that the services are sustainable and can continue to be provided over the long term.

At the local level, individuals and organizations are often the best positioned to understand the specific impacts of climate change on their activities because they have first-hand knowledge of the local conditions and challenges. They are also likely to have a better understanding of their own needs and priorities, as well as the potential benefits and limitations of different climate services. Their first-hand knowledge of the challenges and opportunities they are facing puts the final user in a unique position to develop effective strategies for adaptation. In contrast, the up-down creation of climate services, where services are developed by outside experts and imposed onto users, may not take into account their specific needs and context. As a result, the services may not be relevant or effective, and may not be used or supported.

Co-creation, on the other hand, requires involving local users in the design and development of the services. This can help to ensure that the services are tailored to the specific needs of each user, organization or community, and that they are relevant, user-friendly, and effective. This is the case for climate services co-created with water utilities, where the data provided by the final user is essential to ensure the usefulness of the final service (Vogel et al., 2016). Involving the final users in the co-creation process can help increase transparency and trust on the service, increasing the resilience and capacity within communities. It can also help to create a sense of ownership and shared responsibility for their success. This can help to increase the uptake and utilization of the services, and to make them more sustainable over the long term. Finally, empowering individuals and organizations to take part on the co-creation process may increase their capacity to adapt to the challenges of climate change, and to ensure that they are better prepared to deal with future challenges.

1.1 Objectives

Overall, the objective of this thesis is to contribute to the development of effective, user-driven strategies for climate change adaptation, with a focus on the water sector. By promoting the co-creation of climate services, it aims to ensure that adaptation strategies are tailored to the specific needs of different climate services users, and to build resilience and capacity within organizations and communities. In order to reach the overall objective, we aimed at the following goals:

- To explore the concept of co-creation and its potential role in climate change adaptation.
- To conduct a case study of successful co-creation for climate change adaptation, and analyse the factors that contributed to its success.
- To develop a framework for co-creation of climate services for adaptation, based on the findings of the case studies and the existing literature.
- To identify potential barriers to the co-creation of climate services for adaptation and propose strategies for overcoming these barriers.
- To make recommendations for policymakers, practitioners, and other stakeholders on how to promote and support the co-creation of climate services for adaptation.

The case study used for the co-creation of a climate service is the assessment of the impacts of climate change in the urban water supply system of Valencia (Spain). The climate service was co-created with the local water utility company of Valencia (EMIVASA), in the context of the INNOVA project. The projected co-creation had the following goals:

- To engage the main stakeholder from the water utility company as well as the local government in the co-creation of a climate service, and ensure that the service meets the needs and interests of all parties involved.
- To gather and analyse data on the impacts of climate change on the water utility company's operations, both in terms of water availability and water quality, and
- To use this information to inform the design and implementation of tailored strategies for the water utility company's adaptation to climate change, and identify potential areas for improvement.
- To document the process of co-creating a climate service with a water utility company, and propose lessons learned that can be applied to similar initiatives in the future.
- To contribute to the broader body of knowledge on climate change adaptation, and provide practical guidance for other organizations looking to co-create climate services.

In order to analyse the effects of climate change on the Jucar River system, both in terms of water quantity and quality, a system dynamics model was developed.. The goals of the system dynamics model for the Jucar River system were the following:

- To integrate into a single modelling framework the main network of the system, main demands, reservoirs and stream aquifer interaction.
- To define operating rules for the reservoir based on the historical data and interviews with the reservoir and basin managers.
- To allow and represent the complex interrelationships of the system over time, which facilitates the analysis of the long-term effects of climate change on the Jucar River basin, taking into account the potential feedback loops and other dynamic interactions within the system.

- To build the model in a modular and scalable way so that new components or data can be easily integrated into the existing model.
- To connect the model to a water quality model for a more integrated analysis of the impact of climate change in the future available resources.

The three sets of defined objectives match with the three papers that structure the main body of the thesis and, combined, they contribute to the development of effective, user-driven climate services for climate change adaptation by providing insights into the challenges and barriers to the development and use of climate services, and by developing and testing a framework for co-creating these services with users. This could help to improve the relevance, usability, and sustainability of climate services, and to support more effective adaptation to climate change.

1.2 Structure of the Thesis

The structure of this Thesis follows the rules defined by the Universitat Politècnica de València. The introduction has served to provide a brief overview of the overall context and background of the research. The objective section has defined the overall objective of the thesis as well as the more specific goals required to reach it.

Following, we will present the three papers that structure this body of research. They will be ordered in a thematic order, starting with the *Water* article on the system dynamics model for the Jucar River basin, which describes the development and application of a system dynamics model to understand the dynamics and feedbacks of the Jucar River basin water resource system. This paper provides a detailed analysis of the model and presents the results of simulating different scenarios and interventions for drought management.

The second paper, published in the journal *Climate Services*, describes the development and results of the climate service co-created with the water utility company of Valencia. The climate service is based on the system dynamics model developed in the first paper, used in combination with a water quality model at the reservoir scale to simulate different climate scenarios, and to evaluate the potential impacts on water availability and quality. It also proposes a series of measures for the adaptation to these impacts. Finally, the paper provides valuable insights and suggestions for other water utilities in similar contexts.

Finally, the third paper, published in the journal *Earth's Future,* summarizes the co-creation process and proposes a business model-based framework for the co-creation of climate services. This paper provides a synthesis of the findings and insights from the first two papers and presents a business model-based framework for co-creating climate services.

Overall, these three papers provide a comprehensive overview of the research on co-creating climate services for the adaptation to climate change of a water resource system, focusing on the specific use for water utilities, and present a framework for co-creation that can be applied to other contexts and sectors.

Listed below the reference of each publication:

- Rubio-Martin, Adria; Pulido-Velazquez, M.; Macian-Sorribes, Hector; Garcia-Prats, Alberto. (2020) System Dynamics Modeling for Supporting Drought-Oriented Management of the Jucar River System, Spain. Water, 5 (12), 1 - 19. 10.3390/w12051407
- Rubio-Martín, Adrià; Máñez-Costa, María; Pulido-Velazquez, M.; Garcia-Prats, Alberto; Celliers, Louis; Llario, Ferran; Macián Cervera, Vicente Javier. (2021) Structuring Climate Service Co-Creation Using a Business Model Approach. Earth's Future, 1 (9), 1 - 18. 10.1029/2021EF002181
- Rubio-Martín, Adrià; Llario, Ferran; Macian-Sorribes, Hector; Pulido-Velazquez, M.; Garcia-Prats, Alberto; Macián Cervera, Vicente Javier. (2023) Climate services for water utilities: Lessons learnt from the case of the urban water supply to Valencia, Spain. Climate Services (29)1 - 13. 10.1016/j.cliser.2022.100338

The three main publications are reproduced on sections 2.1, 2.2 and 2.3 of the book. Section 2.4 lists the other two publications where the candidate has collaborated as co-author. Both published in the journal Climate Services, they delve on the in-depth analysis of the role that climate services play in municipal and regional planning, as well as the role that culture plays in contextualising the phenomenon of co-creation of these services at local and regional scales. Section 2.5 details the list of conference presentations made by the PhD student. These cover topics ranging from the co-creation of climate services to the development of system dynamics models, to the analysis of the impact of climate change on the qualitative status of future water resources in the Valencian region.

Section 3 follows with an overview of the results obtained and shown in the three main articles. Section 4 details the main conclusions reached through the development of this work. And, finally, Section 5 briefly describes the future lines of work that can be explored.

2. PUBLICATIONS

2.1 System dynamics modeling for supporting drought-oriented management of the Jucar River system, Spain

System dynamics modeling for supporting drought-oriented management of the Jucar River system, Spain

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Abstract: The management of water in systems where the balance between resources and demands is already precarious can pose a challenge, and it can be easily disrupted by drought episodes. Anticipated drought management has proved to be one of the main strategies to reduce their impact. Drought economic, environmental, and social impacts affect different sectors and activities often interconnected. There is a need for water management models able to acknowledge the complex interactions between multiple sectors, activities, and variables to study the response of water resource systems to drought management strategies. System dynamics (SD) is a modeling methodology that facilitates the analysis of interactions and feedbacks within and between sectors. Although SD has been applied for water resource management, there is a lack of SD models able to regulate complex water resource systems at a monthly time-scale and considering multiple reservoir operating rules, demands and policies. In this paper, we present an SD model for the strategic planning of drought management in the Jucar River system, incorporating dynamic reservoir operating rules, policies, and drought management strategies triggered by a system state index. The DSS combines features from early warning and information systems, allowing the simulation of drought strategies, evaluating their economic impact, and exploring new management options in the same environment. The results for the historical period show that drought early management can be beneficial for the performance of the system, monitoring the current state of the system, and activating drought management measures results in a substantial reduction of the economic impact of droughts.

Keywords: water management; resources; system dynamics; drought management; drought impacts

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1. Introduction

Drought is a natural hazard and, as such, has to be understood as a natural feature of climate. Whether or not a drought becomes a disaster depends on its social, economic, and environmental impacts [1]. Therefore, the key to understanding drought is to acknowledge its different dimensions. Drought affects both surface and groundwater resources and can lead to reduced water supply for in-home consumption and agricultural and industrial activities. Furthermore, it can deteriorate water quality by rising nitrate, ammonium and phosphate concentrations, and disturb riparian habitats [2,3]. Agriculture is the most affected sector by droughts, but many other sectors may suffer relevant losses, including energy production, tourism and recreation, transportation, urban water supply, and the environment. Sustained drought can cause social, economic and energy crises, even leading to migration from affected zones (often rural and agricultural-focused) to other regions or nearby countries [4]. Drought is not the only issue that water resource systems have to face regarding water availability. Water scarcity refers to continued unsustainable use of water resources and it can be influenced by water management [5]. Increasing water demand due to population growth and the development of the agricultural, energy, and industrial sectors has increased the frequency of water scarcity events that occur when there is a lack of freshwater to meet the demands [6]. Climate change is expected to further aggravate water scarcity because of the increase in drought frequency, severity, and duration [7,8].

There is an increasing concern worldwide about the ineffectiveness of most common drought management practices, largely based on crisis management and on treating symptoms (impacts) rather than the underlying causes associated with them [7]. The European Union has promoted the move from crisis management to drought risk management since 2007 [9]. However, there are gaps in the current water scarcity and droughts policy of the EU, including [10]: conceptual gaps on the understanding of causal relationships between drivers, pressures, status, and impacts; limited data on current and future water demand and availability; policy, governance and implementation gaps regarding measures to increase water supply and to target pressures and impacts caused by droughts.

Drought management plans are tools that aim to reduce the impact of droughts in water resource systems providing a framework for proactive, risk-based management [9]. A coordinated drought plan includes monitoring, early warning and information systems, impact assessment procedures, risk management measures, preparedness plans, and emergency response programs. Without these plans, nations will continue responding drought in a reactive, crisis management mode [7]. A key feature of drought management plans is the use of indices to establish a link between the state of the river basin and the measures to be taken [11]. Drought indices have been developed for assessing drought parameters including intensity, duration, severity, and spatial extent, and are effective tools in the monitoring and management of droughts [2,12]. However, traditional drought indexes often fail at detecting critical events in highly regulated systems, where natural water availability is conditioned by the operation of water infrastructures such as dams, diversions, and pumping wells. Here, ad hoc index formulations are usually adopted based on empirical combinations of several significant hydro-meteorological variables through customized formulations [13]. A system of drought indicators based on levels or thresholds depending upon the degree of water scarcity, and several management actions aiming to mitigate critical situations have been developed in the Jucar River system [11,14]. The creation and institutionalization of multi-sector partnerships have reinforced the development of efficient drought management [15]. To support drought management, scientific approaches including drought characterization, development of risk indicators, and the analysis of economic instruments for risk mitigation are involved in conjunction with the identification, selection, and prioritization of measures to lessen the effects of drought [16]. Decision support systems (DSS) have been developed to study effective drought management strategies, as they are considered one of the most effective tools for integrated water resource management [6]. The use of DSS tools for drought risk management has been increasing during the last decades [17–20]. Studying resource allocation requires the development of DSS able to apply drought management strategies and to dynamically evaluate the status of water resource systems [12]. Multi-criteria decision analysis tools (MCDA) are also oriented to assist the decision-making process in the operation of water resource systems. Nevertheless, a major problem in developing MCDA processes is to understand the risk associated with persistent drought conditions, as risk management involves subjective considerations [6]. The water sector's importance for other sectors requires policies and management strategies that are aware of the potential widespread impacts [21]. Very often, undesired effects can be derived from the execution of drought management strategies. For example, increased groundwater extraction to compensate for the reduction of surface water availability can lower base flows of rivers and streams, and reduce the piezometric level of aquifers [22]. These unexpected consequences can affect river biota, agriculture income, and urban supply in ways that are more damaging or long-lasting in time than the aforementioned drought. Consequently, there is a need for management models able to simulate the complex interactions between different sectors and activities to study the response of water resource systems to drought management strategies.

System dynamics is a theory of system structure and a set of tools for representing complex systems and analyzing their dynamic behavior [23]. This methodology is particularly useful for studying complex water resource systems with interacting elements and policies, whose behavior cannot be easily predicted [24]. The development of system dynamics models to analyze and improve water resource management has a tradition that dates back to the late 1960s. Since then, and thanks to the development of computer technology and user-friendly system dynamics software, all types of qualitative models have been developed for improving system understanding in water resource systems. However, system dynamics has not been yet applied to highly regulated and complex water resource systems for testing drought management strategies with a quantitative approach and integrating a drought early warning system.

The objective of this paper is to develop a decision support system (DSS) based on system dynamics for the efficient drought management of the Jucar River system. The DSS simulates the management of the Jucar multi-reservoir system integrating monthly-defined reservoir operating rules, stream-aquifer interaction and conjunctive use of surface and groundwater, drought management measures (linked to a system state index), and all this taking into account current water demands and allocation criteria. The tool allows studying the effect of policy and management measures in the system, and it serves as a stepping stone towards the understanding of water resource systems as a holistic system. The DSS provides quantitative results comparable to the historical records for the calibration and validation period. The calibrated model facilitates the design, testing and selection of new drought management strategies. Section 2 introduces the system dynamics modeling method, details some applications of the methodology for the management of water resource systems and describes the Jucar River system case study. Section 3 introduces and describes the main features of the system dynamics model developed for the case of study. Section 4 shows and discusses the results, first validating the behavior of the model and later discussing the hydrological and economic results for the simulated scenarios. Finally, Section 5 exposes the conclusions.

2. Materials and Methods

2.1. System dynamics for water resource systems modeling

System dynamics modeling is a methodology of model development that facilities a holistic understanding of water resource systems, as it allows analyzing how different elements of a system relate to one another and permits studying the changing relations within the system when different decisions are included [25,26]. The usual purpose of the analysis of system dynamics is to understand how and why the dynamics of concern are generated and to look for managerial policies that can improve the system performance [27]. In system dynamics, the system structure is determined by the positive and negative relationships between variables, feedback loops, system archetypes, and delays [28,29]. The totality of the relationships between the system components constitutes the system structure, and the system's structure defines its behavior [30]. This methodology focuses on understanding how the physical processes, information flows, and managerial policies interact to create the dynamics of the different variables of interest [31]. To achieve this knowledge, qualitative/conceptual and qualitative/numerical modeling methods are applied.

Qualitative modeling (e.g. causal loops diagrams and definition of the positive and negative relationships between variables) improves our conceptual system understanding [29]. This type of modeling is often seen as a propaedeutic step to quantitative modeling, where the behavior of the system and the effects of different intervention policies can be visualized through simulation. Qualitative models can be further developed into quantitative models (Figure 1). This change requires a deep knowledge of the existing physical, analytical, and statistical relationships between the variables of the system. In system dynamics, the relationships between variables can be expressed by linear, non-linear mathematical equations and logical expressions such as IF-THEN statements, to introduce management policies and rules. To assess the truthfulness of the quantitative models they are validated by comparing their results to the available historical records.

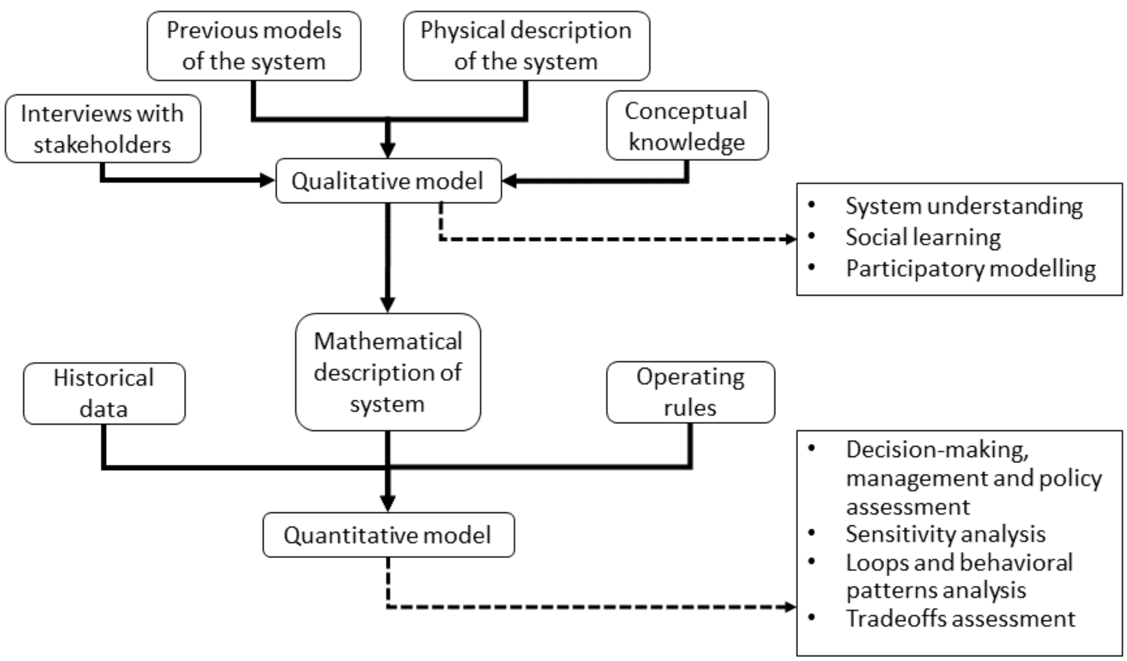


Figure 1. System dynamics modeling framework.

Traditionally, water resources management models were designed with a one-dimensional optimal engineering approach, performed with little regard for social, environmental, or cultural aspects [32]. However, the increased recognition of complexity and uncertainty has promoted the use of more flexible simulation-based tools such as the ones provided by system dynamics [28]. System dynamics provides tools for the graphical representation of systems, facilitates flexible and transparent modeling, eases the holistic understanding of the problem, captures long-run behavioral patterns and trends, facilitates clear communication of model structure and results, promotes sharing modeling, facilitates sensitivity analysis, and it is suitable for policy assessment and selection [25]. System dynamics modeling environments include Powersim (Powersim Corp., 1993), Simile (Simulistics, 2002), Stella (High Performance Systems, 1992), and Vensim (Ventana Systems, 1996). Nowadays, these environments are able to assist modelers and can handle many variables, delays, and interdependent subsystems, allowing the creation of modular object-oriented models, therefore increasing interchangeability and reusability.

The application of system dynamics in water resource management has grown since the 90s. Nowadays, we find applications of system dynamics modeling to study a large variety of water resource issues [29]. They range from region-scale models with multiple demands and frequent water scarcity events [33,34], to models coupling surface and groundwater dynamics for a basin [35], flood management or predicting models [36,37], reservoir operation and water supply for multiple water users [38], and the design of water pricing policies [39]. However, system dynamics application to simulate the management of highly regulated water resource systems integrating multiple reservoirs, operating rules, dynamic drought management, groundwater use, and conflicting water demands remains very limited. Yet all these features are required to analyze the issue of drought early warning and management in complex water resource systems.

Drought management is a multidimensional concept that includes meteorological, ecological, hydrological, environmental, and socioeconomic perspectives. The development of DSS for improving drought management requires the combination of several models [6]. Coupling and analyzing the interactions between these models is often a difficult issue. System dynamics is a methodology that provides a common playground for the interaction of different subsystems and submodels, facilitating the analysis of the existing relationships and providing a holistic view of the issue.

2.2. Case study: drought management in the Jucar River system

The Jucar River system is located in Easter Spain. The system is subjected to a tight equilibrium between total water demand (1505 Mm^3/year, 2009-2015 period average) and water resource availability (1548 Mm^3/year) [40]. Agriculture is the largest water use by far (89%), followed by urban (9%) and industrial uses (2%). The Jucar is the main source of urban water supply to the city of Valencia and its metropolitan area (about 1,500,000 inhabitants, third largest municipality in Spain). Water from the Jucar is diverted to the Turia River through a 60 km canal (Canal Jucar-Turia), also used for irrigation of mainly citrus and vegetables. Furthermore, there is an intense water use for irrigation in the lower Jucar, downstream of Tous reservoir, with traditional irrigation districts holding senior water rights dating back to the Middle Ages. Non-consumptive water demands include minimum ecological instream flows and hydropower generation.

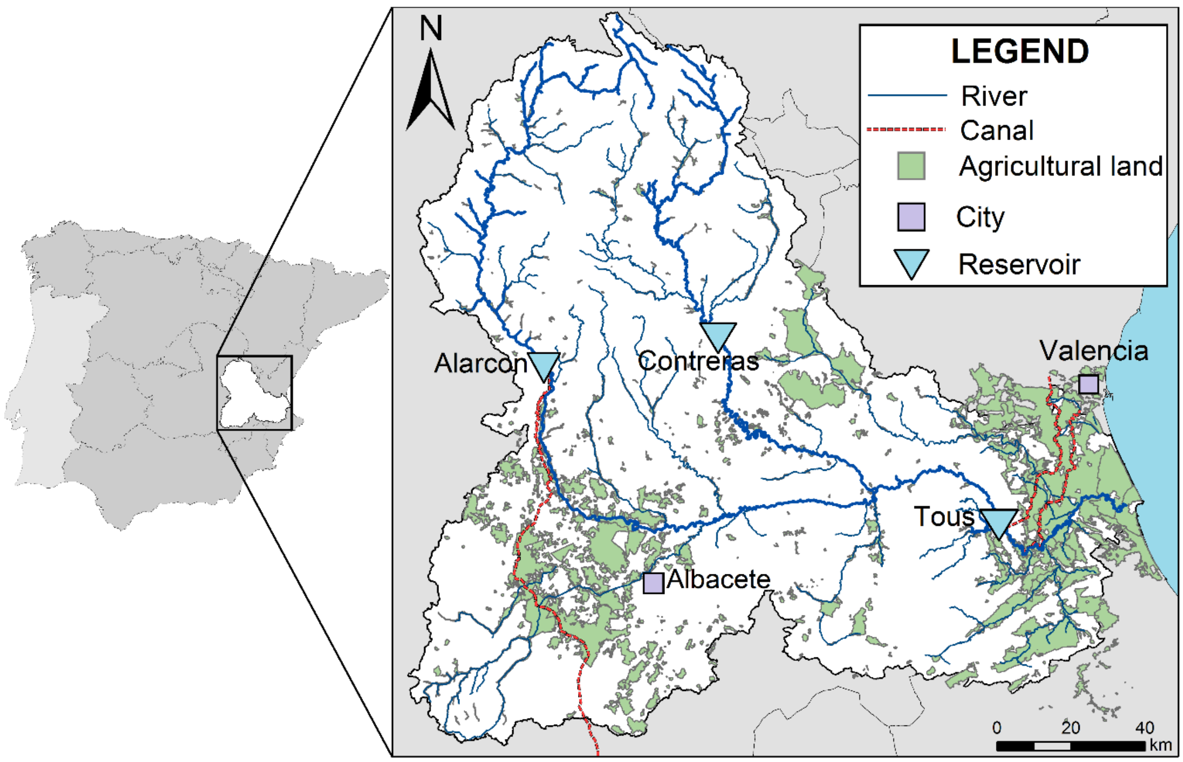


Figure 2. Main features of the Jucar River system included in the model.

The main surface reservoirs are Alarcon (1112 Mm^3 of capacity), Contreras (463 Mm^3 of useful capacity), and Tous (378 Mm^3). The regulation capacity of these reservoirs is mainly multi-annual: Alarcon and Contreras are devoted to consumptive uses, while Tous is mostly used for flood protection. The intense overexploitation of the main groundwater body, the Mancha Oriental aquifer (middle basin, near Albacete), for irrigation since the 1970s has shifted the stream-aquifer interaction between Alarcon and Tous from gaining to losing river, diminishing downstream surface water availability. The sustainable use of this aquifer is one of the challenges in the management of the system [41,42]. During droughts, the Plana de Valencia Sur aquifer, located in the lower basin (downstream of Tous), is used as an alternative water source.

Water scarcity, irregular hydrology, and groundwater overdraft result in droughts with significant economic, social, and environmental consequences. This situation is expected to be exacerbated by the impacts of climate and socioeconomic (global) changes and increasing institutional impediments from political disputes among the two main riparian regions, Castilla-La Mancha (upstream; mainly Albacete province) and Valencia (middle and downstream basin). A range of different innovative solutions are considered to face the main water management issues, such as pumping-water right acquisitions during droughts, increasing wastewater reuse, “in lieu” recharge (providing surplus surface water to groundwater users, keeping groundwater in storage for later use), water-saving in agriculture through drip irrigation, new water allocation mechanisms, water banks, water pricing, and irrigated crop drought insurances (among others), which makes this case a real lab for analyzing risk management strategies to cope with drought, extreme events, and climate change [43].

The operation of the system, managed by the Jucar River Basin Authority (Confederacion Hidrografica del Jucar, CHJ), is subject to physical, environmental, and legal constraints. The main physical constraints correspond to the reservoir, river, and canal capacities. The environmental constraints are the minimum flows prescribed in certain river reaches and the inflow requirements of the Albufera wetland. The main legal constraint in the Jucar River system is the Alarcon Agreement, signed between the Spanish Ministry of the Environment and the senior users of the Jucar River—mainly farmers— gathered together in the Unidad Sindical de Usuarios del Jucar (USUJ). The agreement divides Alarcon in two zones by a rule curve. If the water level in Alarcon is above the threshold, water can be freely allocated, but if the storage is below certain value, water in the system is reserved exclusively for the USUJ members. In this case, other water users who want to access water from the Jucar River would have to pay a financial compensation to USUJ. The operators also follow additional criteria to decide the releases during the irrigation period (May-September): not causing undesired spills from Tous (the downstream reservoir), not storing more than 450 Mm^3 in Contreras to avoid stability problems, and not storing more than 72 Mm^3

in Tous at the end of the summer to avoid flood damage during autumn due to intense rainfall events [42].

The Jucar River basin, as most Mediterranean and south-eastern basins of Spain, is very vulnerable to droughts [11]. The recurrence of these events is also an important factor when considering the management of the system, as a high-frequency appearance of droughts do not allow the system to properly recover water storage to face future water-scarcity events. The latest drought periods (1991-1995; 1997-2000 and 2004-2009) were classified as extreme droughts using the SPI index [14]. During the drought period 2005-2008 surface water available for agriculture decreased by up to 40% compared to the average. Because of this, drought emergency wells in the lower basin were activated. Despite of these efforts, the drought caused an important economic impact, especially to agriculture activities. The situation is expected to be exacerbated by the impact of climate change [8,44].

A key feature of drought management plans are the indices that define the different drought stages and trigger mitigation measures. Drought indices should capture the state of the water resource system as a whole, allowing the planner to active measures to reduce its impact. Some of the measures for drought management include conjunctive use of surface and groundwater, awareness campaigns to promote domestic water savings, economic tools, control of the supply to agricultural demands from reservoirs, and water reuse [16]. Traditionally, the management of droughts in the Jucar Basin was regulated as an emergency, and the application of Royal Decrees was necessary to mitigate their impacts [12]. From 2007, drought management in the Jucar River system is regulated by a drought management plan [14,40] that stablishes a state index to monitor the system and a set of drought management measures triggered by the different drought stages. This index is calculated using different variables distributed in the area of the river basin, including reservoir storages, groundwater levels, streamflow, precipitation, and reservoir inflows. The state index takes values between 0 and 1, with four system states: normal, pre-alert, alert, and emergency. Then, different drought management measures are applied depending on the system’s state index. These measures can be divided into 2 groups, 1) control of water supply for urban and agricultural uses and, 2) increase of water availability by drought emergency wells use and increasing water reuse.

2.3. System dynamics for the Jucar River system

The system dynamics model developed for the Jucar River system represents its current management with a monthly time step, including the state index of the system and the management measures linked to this state. The software Vensim Pro [45] has been used for the creation of the model. The Jucar model was divided into 5 subsystems:

1. General view of the system: defines the system structure, its three main reservoirs, the connections, intakes, and outflows from the river (Figure 3).

2. Mancha Oriental aquifer: simulates the aquifer using a two-cell embedded multi-reservoir model, in line with the one used by the CHJ in its water resource management models [40,42].

3. Water demands: defines the different monthly water demands, the distribution of water, and the system deliveries and deficits.

4. Reservoir operation: defines the seasonal operating rules of the system.

5. State index: calculates the state index and defines the management measures to take based on it.

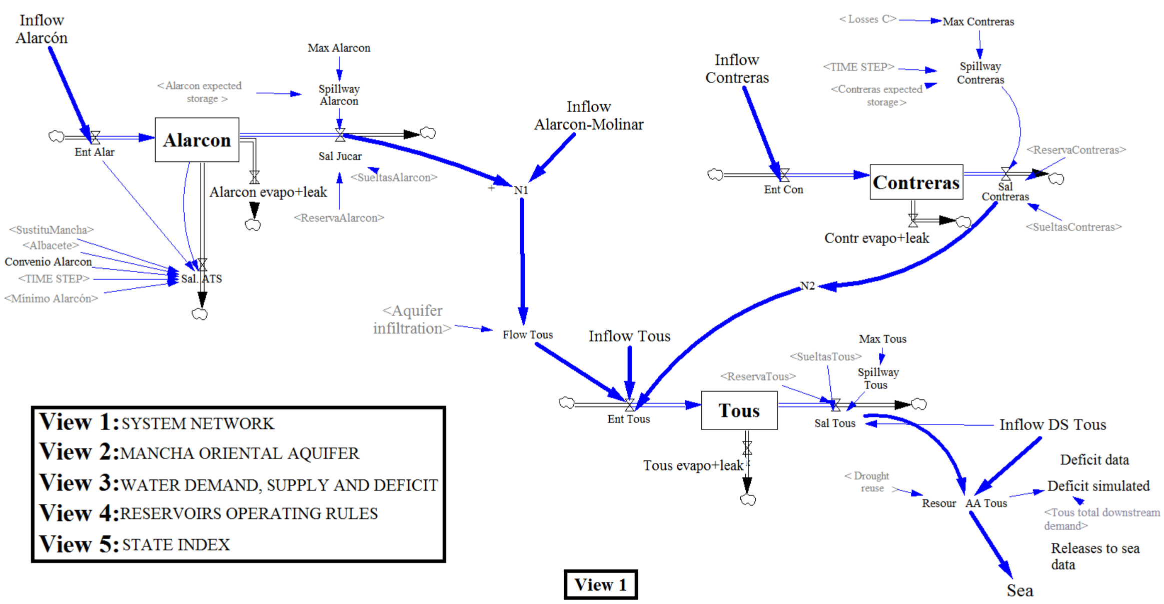


Figure 3. Subsystem for the general view of the system.

The model incorporates monthly water inflows in 5 sub-basins where data from CEDEX [46], the Spanish institution responsible for collecting and supplying data on civil engineering and water, has been obtained and processed. The main view of the model (Figure 3) captures the water flows through the Jucar system, including water infrastructures and stream-aquifer interaction with the Mancha Oriental aquifer. This structure is based on previous models for the area [42], and provides a general framework to visualize the system's network and to allow the integration of other sub-models. The model incorporates a submodel that simulates the current operation of the system (Figure 4), based on historical records and trends of the main variables.

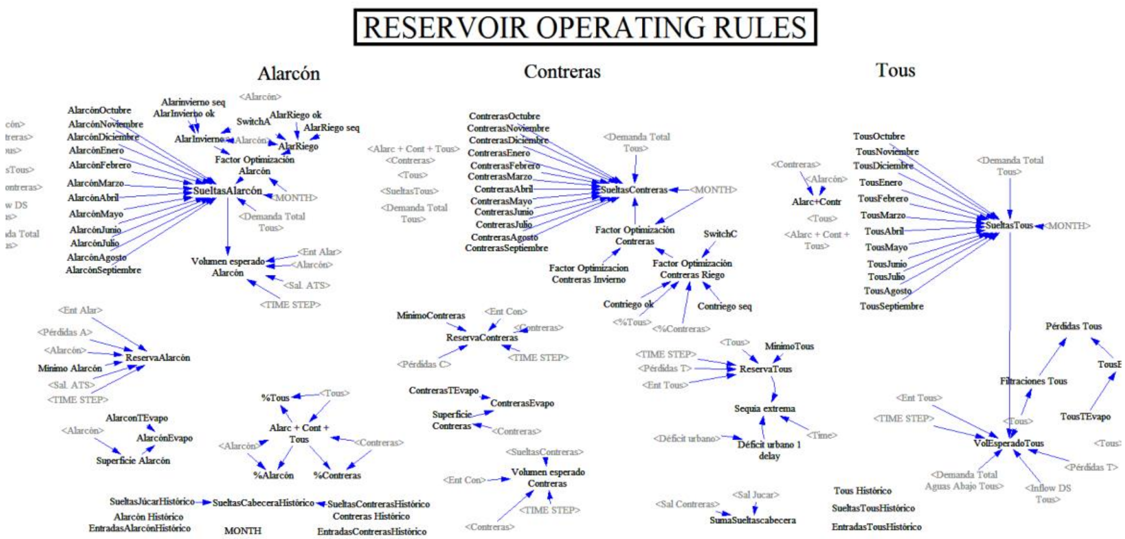


Figure 4. Reservoir operating rules subsystem that incorporates the monthly operating rules for each reservoir, variables, and seasonal parameters that determine final releases.

The operating rules of the three reservoirs are defined at the monthly scale, mimicking the operation of the system for the 2003-2013 period, and introducing the constrains that bind the seasonal operation of the Jucar River system. The rules were obtained using fuzzy rule-based systems (FRB), co-developed with the experts from the Operation Office of the Jucar River Basin Authority [42]. A series of workshops and surveys were used to extract the decision-making processes followed in the seasonal operation of the Jucar River system. The implicit operation of the system was encoded into two FRB systems that were validated against historical records on reservoir storages and releases, streamflows and deliveries to consumptive demands for the 2003-2013 period. The developed FRB were introduced into the SD model through piecewise linear regressions equations (Figure 5). Some flexibility is lost in the process of transforming the FRB rules into linear regressions, as it can be observed in the figure.

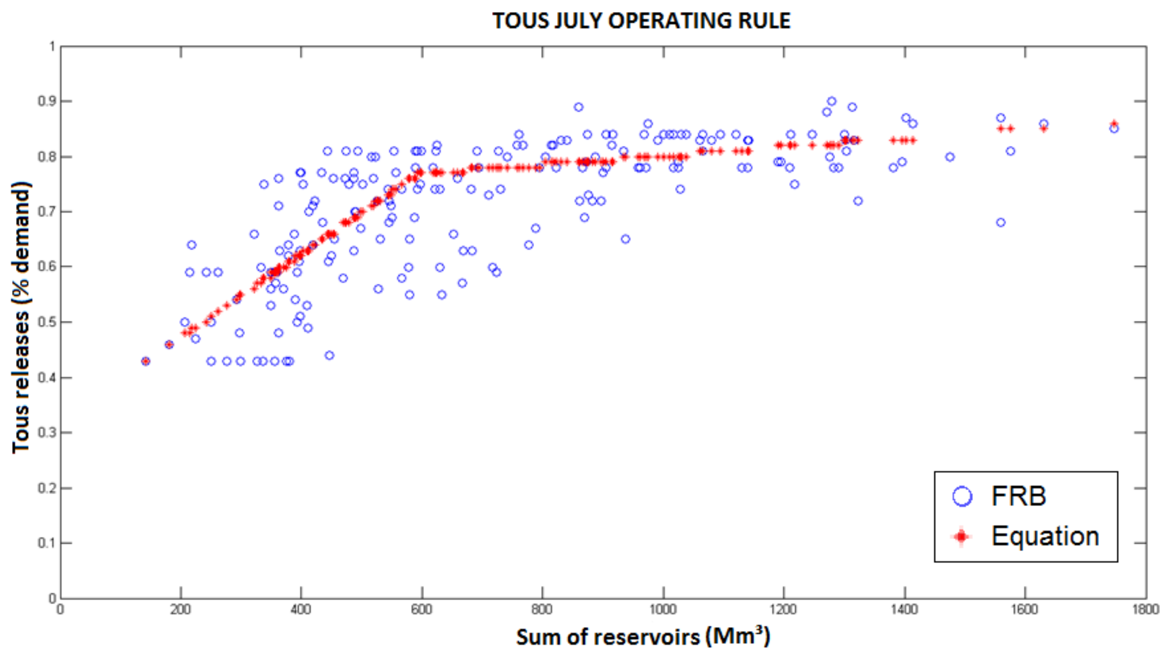


Figure 5. Graphical representation of the simulated operating rule of Tous reservoir in July. Blue dots represent the values of releases using fuzzy logic. Red crosses show values for the piecewise linear regression introduced into the SD model.

To compensate this loss of flexibility, the obtained rules for Alarcon and Contreras reservoirs were adjusted using seasonal factors (depending on whether it was or not irrigation season) and a scarcity factor different for both winter and summer seasons, to account for differences observed in the management of the system that were not correctly captured by the calculated piece-wise linear equations. Releases from Tous were computed as the minimum value between the downstream demand and the releases calculated by the piecewise linear equations. This implies that the system will not release more water from Tous than needed, minimizing unwanted releases to the sea while still capturing the seasonal behavior provided by the operating rules. The Alarcon Agreement was explicitly introduced into the model's formulation.

The water demands considered by the model are divided into urban and agricultural demands and were located and compiled from the public information provided by the CHJ [47]. Most of them are located downstream Tous, although the model also accounts for the demands located in the middle basin, one of them being a groundwater demand that affects the stream-aquifer interaction. The current operating rules of the system prioritizes water allocation to urban uses. Environmental requirements have been considered as a restriction and are captured by the operating rules of the reservoirs.

The model simulates stream-aquifer interaction between the Mancha Oriental aquifer and the Jucar River using a two-cell Embedded Multi-reservoir Model (Figure 6) [48]. Its formulation is based on the analytical solution of the stream-aquifer flow equation applied to linear systems, as well as it analogy with the state equation. Groundwater discharge can be expressed as the theoretical sum of an infinite number of linear reservoirs whose discharge is linearly proportional to the stored volume. In normal conditions, a limited number of linear reservoirs is enough to adequately reproduce groundwater discharge. Although the EMM does not calculate spatially-distributed heads and internal groundwater flows, it can provide an accurate representation of stream-aquifer interactions, even in karstic aquifers [50] and it is used in some general DSS services for water resource management [42,51]. Groundwater flow is calculated as the integration of the outflow of 2 linear reservoirs in which the discharge is linearly proportional to the volume stored. The EMM built for the Mancha Oriental aquifer represents exclusively the impacts of the anthropic stresses on stream-aquifer interaction, since the natural discharge was already included in the natural inflow time series of the model [42]. The anthropic-induced net recharge corresponds to the agricultural percolation minus groundwater abstractions. As shown by Macian-Sorribes et al., 2017, the calibrated EMM was able to capture well both the over-year trend and the seasonal variation of the historical values.

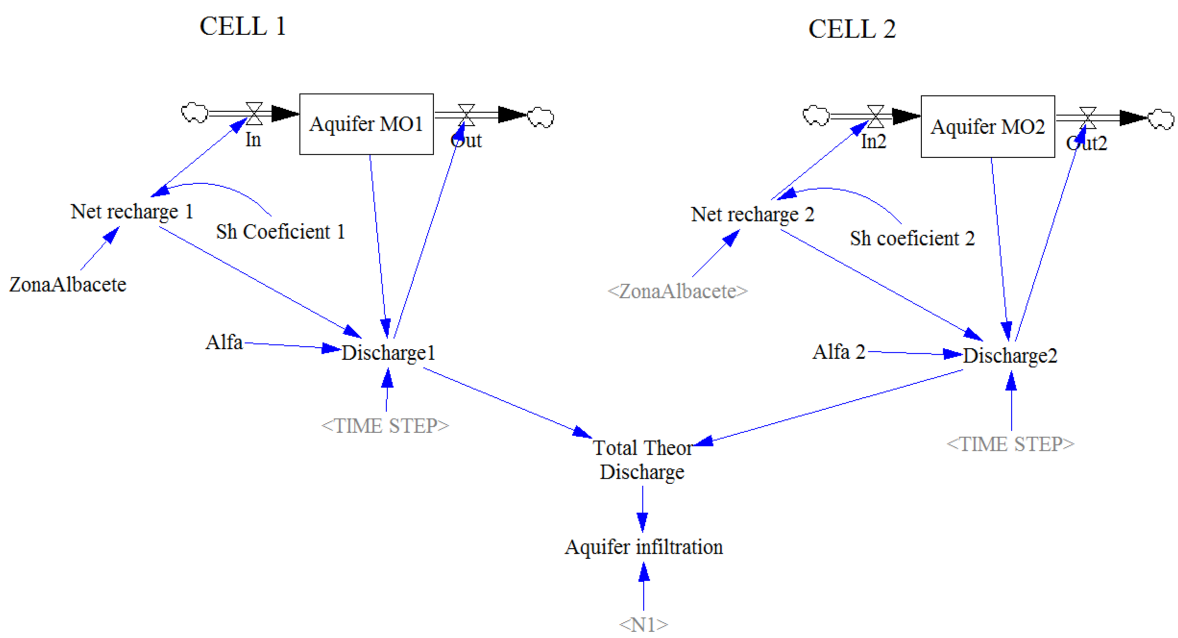


Figure 6. Subsystem for the stream aquifer interaction between the Jucar River and the Mancha Oriental aquifer.

The model also implements a state index subsystem. This subsystem checks the state of the system each time-step during the simulation, as does the state index used by the CHJ on a monthly basis. The equations defining the relationship between past and present system states are taken from the Jucar drought management plan [14,52].

The monthly system state index ($\boldsymbol{S_i}$) has the following expression:

$$S_i = \frac{1}{2}\left[1 + \frac{V_i - V_{av}}{V_{max} - V_{av}}\right] \quad if\ V_i \geq V_{av}$$

$$S_i = \frac{V_i - V_{min}}{2(V_{av} - V_{min})} \quad if\ V_i < V_{av}$$

Where $\boldsymbol{V_i}$ is the value of the variable at the beginning of the month i and $\boldsymbol{V_{av}}$, $\boldsymbol{V_{max}}$ y $\boldsymbol{V_{min}}$ are the recorded average, maximum and minimum monthly values of the variable since 1982. In the case of the SD model, the subsystem uses historical data of the average, maximum, and minimum value of water storage for each one of the three reservoirs and compares the recorded values to the current state of the system. Although the evaluation of the system state index executed by the water authority for the Jucar River basin takes into account 9 additional variables other than the water storage (including piezometric levels and water inflows), in regulated systems the volume stored in the reservoirs is regarded as a good approximation of the actual status of the whole system [53],

The state index subsystem is able to trigger drought management measures depending on the current state of the system (Figure 7).

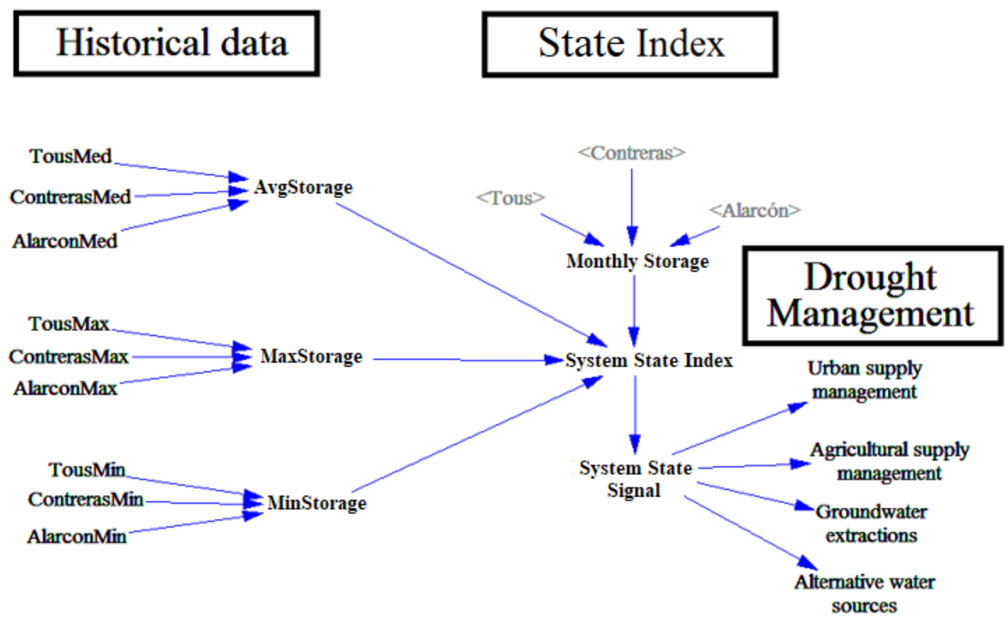


Figure 7. State index subsystem to calculate the system's state comparing with historical data and incorporating drought management strategies.

The system state index takes values that range from 0 to 1. Each month, the model transforms the system state index (a floating-point number) to the corresponding integer state (normal, pre-alert, alert, and emergency) applying the thresholds defined by the water authority. Drought management strategies defined in this subsystem are introduced as actions into their respective subsystems using shadow variables. The measures implemented consider both supply and demand side solutions. For instance, when triggered, the variable "Agricultural supply management" is linked to the agricultural supply on the "Water demand, supply and deficit" subsystem applying a restriction of 20% or 40% on the deliveries to the agricultural demands, depending on the state index. “Urban supply management” restricts the water delivered to the urban demand in alert or worse situations by 5%, reproducing the estimated effect of the water saving awareness campaigns proposed by the water authority [14,52]. “Groundwater extractions” and “Alternative water sources” variables simulate the use of wells and the reuse of wastewater respectively for agricultural supply; the intensity of both actions depends on the monthly state of the system. All the values and management measures represented in the state index subsystem are based on the current drought management plan for the system.

3. Results and discussion

3.1. Model evaluation

The system dynamics model of the Jucar River system was evaluated using the 2003-2013 period. The comparison between the model’s results and historical records showed that the model is able to capture the observed operation (Figure 8). Residual plots for the same variables can be found in Appendix A. Total storage was closely reproduced by the model, as can be observed in the plot and in the R-squared index. The Alarcon and Contreras releases were adequately reproduced on a broader view, due to the resemblance of the intra-annual patterns. However, the model results depart from the historical observations in some years. This is due to the fact that the middle basin is modeled in less detail than the lower one. For instance, hydroelectric production has not been included in the middle basin. In any case, storages in Alarcon and Contreras are adequately reproduced (Figure A2) and the overall in-year dynamics of the system was matched, so these deviations do not have a significant impact on the performance of the model. Tous releases results correctly fit the available data. These releases have a major importance for the model since the majority of the surface water demands are located downstream. As for water supply deficits, the simulated values matched the observed data adequately, including the main peaks associated with the 2005-2008 drought, especially during the years when the drought was more severe. Differences between observed and simulation results can also be explained by the fact that the model assumes a constant annual demand for the whole simulation period while, actually, demands changed due to population change, variation in irrigated areas and shift from gravity to drip irrigation [47].

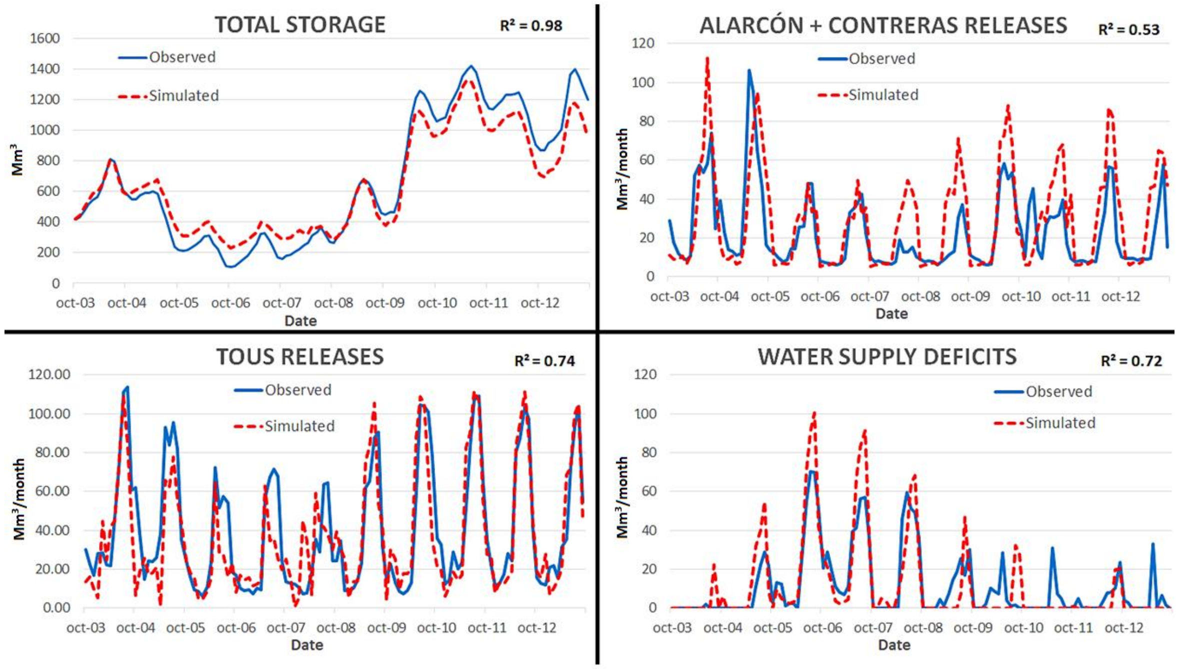


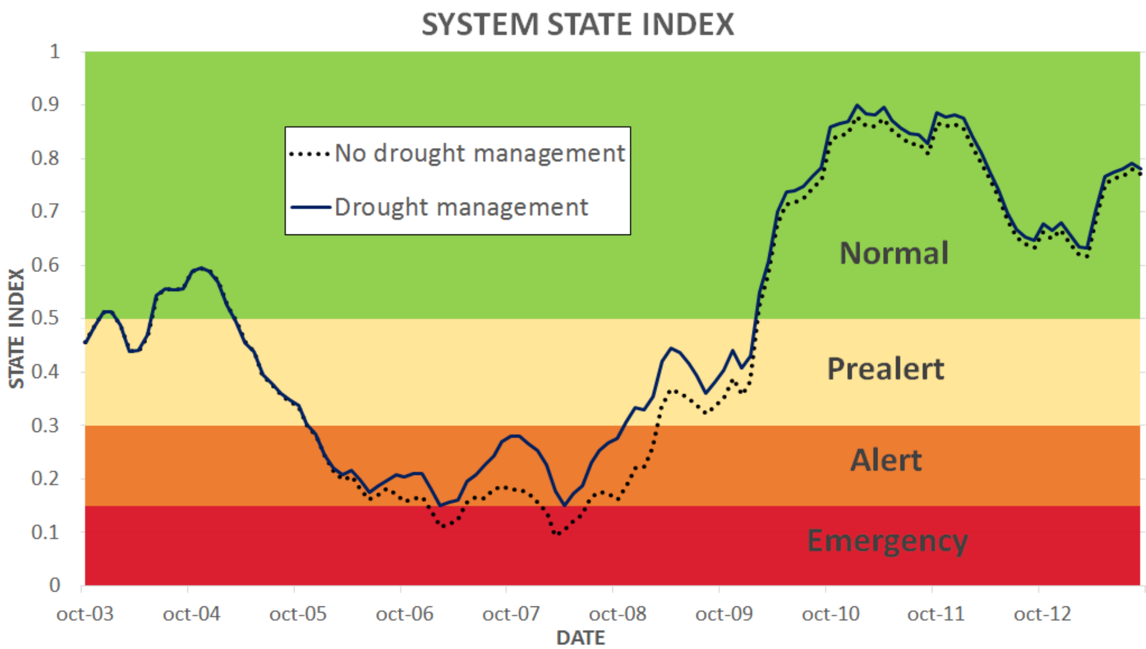
Figure 8. Comparison between observed and simulated values for key variables of the system.

Releases from Alarcon and Contreras are cumbersome to model because of the uncertainties of the middle basin, changes in downstream demands, and varied criteria of releases and management over the simulated period. Although it would be possible to introduce variable demands into the model, there is no available data to represent the variation of all the demands during the simulation period. Furthermore, although the model incorporates monthly operating rules for the reservoirs based on a fuzzy logic representation of the system operation reported by the managers [42], those rules cannot reproduce discretionary changes in the operation of the system during the simulation period.

Once verified that the developed model matches adequately the historical behavior of the Jucar River system, further simulation were launched to test different management assumptions and scenarios.

3.2. System state index and drought management strategies

The SD model has been applied to study the interaction between the previously indicated drought management strategies and other variables of the system. A comparison between simulations with and without the drought management strategies introduced into the management in 2007 was performed. Results obtained when applying the drought management measures show improvements for the state index of the system and for the system's total water storage (Figure 9).



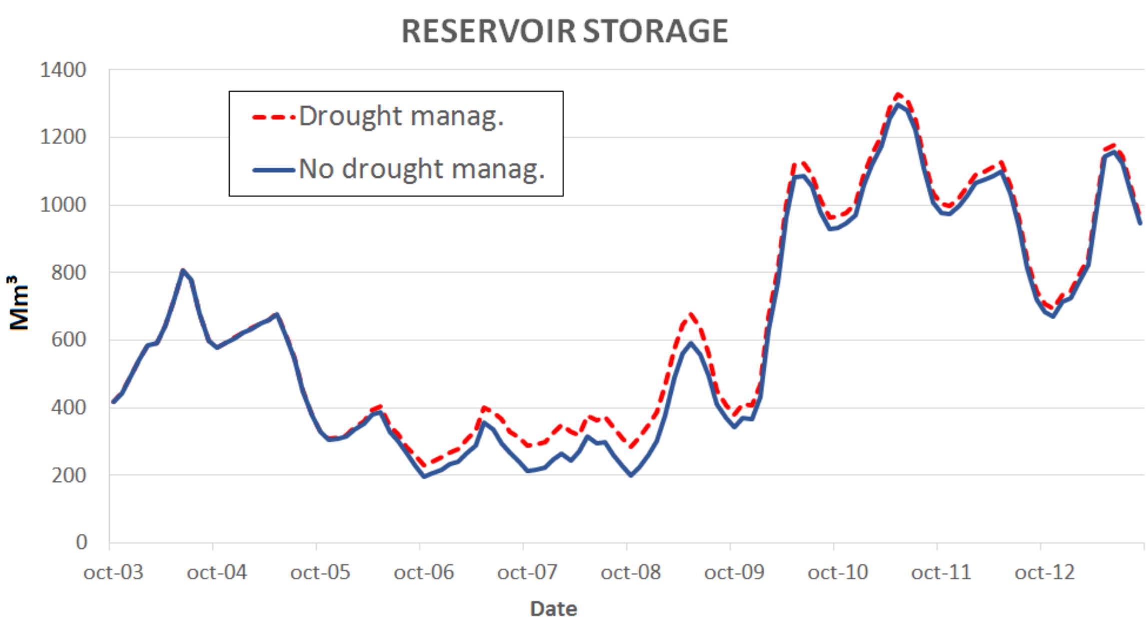


Figure 9. State index and total storage with and without drought management strategies.

The system state index benefits from applying the drought management strategies defined in the state index subsystem. Thanks to them, the system state does not drop into an emergency state during the 2005-2008 drought. It also recovers earlier from the alert state during that drought, and it enters the prealert stage months before than the scenario with no drought management measures. After the system enters a normal state, it is worth pointing out that the state index is higher for the drought managed model, even when the drought is over (from 2010 onwards). According to the model, water storage in reservoirs is increased significantly when drought management measures are applied. The difference is up to almost 100 Mm^3 during October 2008. This is the result of the management strategies taken in anticipation thanks to the state index and the four threshold levels defined. The anticipated management also allows to reduce the system vulnerability by 62% in comparison with the scenario without drought management and considering vulnerability as the ratio between total water supply deficit and the number of failures to meet the demands during the whole period. A reduction in vulnerability means that the average water shortage is lower, although the frequency of these shortages may increase. These drought management measures entail the use of drought emergency wells for water abstraction within a maximum of 98 Mm^3/year (Figure 10) following the plan defined by the water authority [14,52].

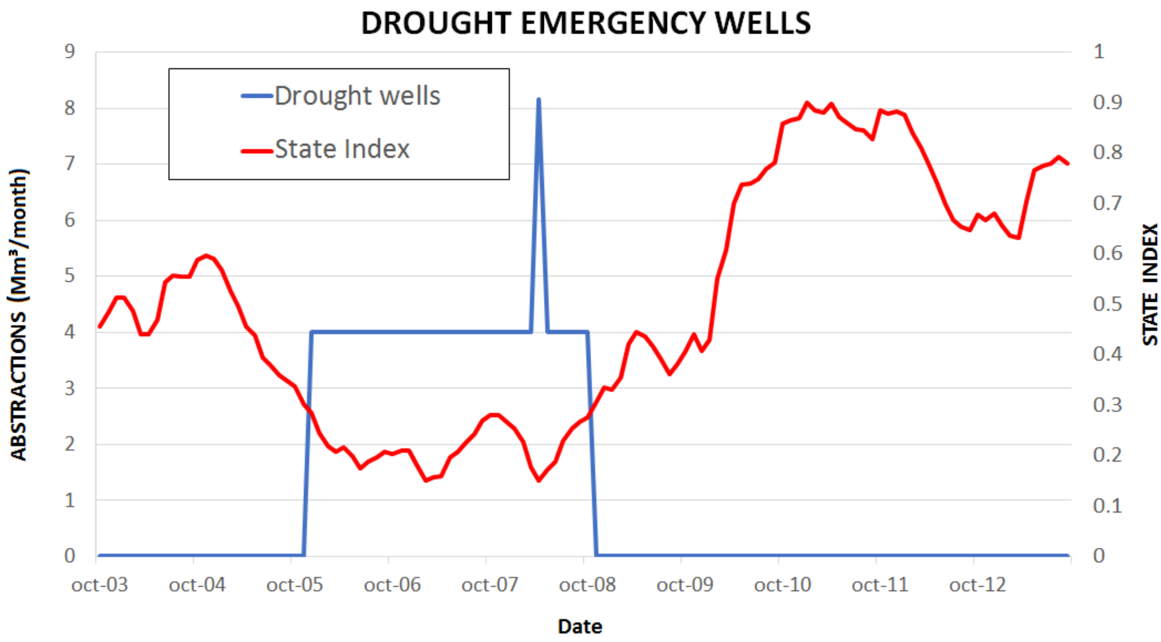


Figure 10. Water abstraction from emergency wells during drought compared to the system state index.

Water pumping from drought emergency wells located in the lower basin compensates the reduced surface water supply and alleviate the drought impact on agriculture. These groundwater abstractions are activated when the system falls into the alert state, and water abstraction scale up above 8Mm^3/month if the emergency state is reached (Figure 10).

3.3. Economic impact of droughts

Results show that the total reservoir storage of the basin improves when drought management measures are applied. It is to expect that the gained storage will benefit the early recovery of the system allowing for more regular deliveries to agricultural demands. Indeed, it is possible to calculate the economic losses associated with the mismanagement of droughts for the 2003-2009 period (Figure 11).

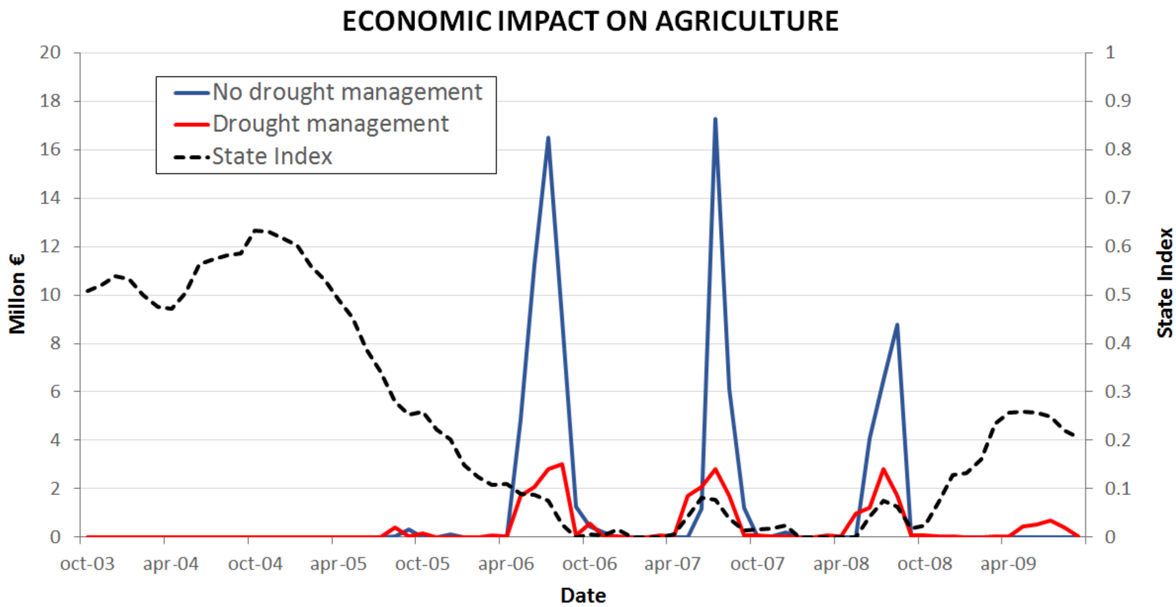


Figure 11. Estimation of economic losses for agriculture compared to the system state index during the 2000's drought.

Economic losses were calculated by economically characterizing the monthly demands of the system defined as targets [47] using demand curves or functions obtained by Positive Mathematical Programming (PMP) [54] for the different agricultural demands [55]. Benefits were obtained as the integration of the demand function between zero and the level of supply. It can be observed (Figure 11) that economic losses concentrate on the drought period (2005-2008), particularly when the system state index stays in alert for several months (2006-2008). During the irrigation season in drought periods is when economic losses rise due to water scarcity. The fact that, as defined by the drought management strategies subsystem, in alert and emergency states the water supply for agriculture is reduced by up to 40% its original demand could be thought of as detrimental for agricultural interests. However, according to the simulations, the water saved helps a faster recovery of the system, guarantees urban water supply, and reduces the long-term impact of droughts. In the model, the economic impact of the 2005-2008 drought was reduced from 89M€ to 29M€ thanks to the drought management strategies implemented. Due to conjunctive use of superficial and groundwater, agricultural activities suffer lower impact even considering the significant restrictions they suffer during the alert and emergency states. When the amount of available water is scarce, using groundwater to supply crops under deficit irrigation guarantees the survival of the plantations and minimizes economic losses.

4. Conclusions

This paper presents a system dynamics DSS for drought management of the Jucar River system, taking into account the combination of a state index and several drought management strategies. The resulting DSS showed the potential of system dynamics for simulating the management of multi-reservoir systems, integrating monthly-defined operating rules for the reservoirs, stream-aquifer interaction, conflicting water demands, and drought management strategies. The model adequately reproduces the operation of the system and is able to produce accurate quantitative results, as shown by the comparison with the historical records.

The DSS takes advantage of the holistic concept that drives the methodology and incorporates components from different disciplines (hydrology, economics, social sciences, laws, etc.) into its modular structure. The state index subsystem is an example of how it is possible to integrate policies and management strategies into a water resource model using a system dynamics approach. Likewise, water policy or legislation has been incorporated into the model —e.g. the Alarcon agreement.

The DSS opens up the possibility of analyzing different drought management strategies and assessing the interactions, feedbacks, and impacts within and between multiple sectors and variables.

Results showed that drought management strategies have a net positive effect in the Jucar River system from both the economic (agriculture) and the water management perspective. The defined measures lowered agricultural losses for the 2005-2008 drought period and increased the amount of stored water during drought allowing the faster recovery of the system. Although the model provides quantitative results similar to the historical data available, the main goal of a system dynamics model is neither to forecast nor to optimize, but studying patterns, trends, and interactions between different variables of the model [24]. Modeling and dynamically simulating the change in water resources over time provides a scientifically defensible basis for proactive management strategies, enhancing our prospects to maximize the adaptive capacity of the system as a whole [29].

Moreover, the same methodology used to study drought management strategies can be applied to study the impact of different realities and inputs into the system. The DSS model developed for the Jucar River system uses a quantitative approach for its simulation. Consequently, it requires numeric data and well-tuned equations to capture the behavior of the system in detail. Qualitative variables and inputs can also be implemented in this kind of model. Qualitative modeling often introduce “soft” variables to study the general patterns of behavior of the model, rather than precise numbers [56]. In this case, qualitative modeling can be restricted to new subsystems for the testing of different non-easily-quantifiable hypothesis.

The model herein presented was successfully developed for the Jucar case study and it could be replicated in any basin or system where enough information and data are available. The development of quantitative system dynamics models requires the use of a large volume of data coming from different fields (from hydrological to economic and reservoir data) as well as a deep understanding of the system structure and behavior. Very often, the most complex issue of this type of model is the development of the monthly operating rules for the reservoirs. In this case, the final rules were inferred using fuzzy logic, but additional tests showed that it is possible to simulate the operation of the system using other approaches and calibrating the rules with the historical records for the releases and water storage of the reservoirs. Although the model is able to reproduce the stream aquifer interaction between the Jucar River and the Mancha Oriental aquifer, it simulates neither groundwater heads nor aquifer storage. Groundwater head specifically is a determinant factor for the Mancha Oriental aquifer, as it has suffered continuous drops in groundwater levels due to intense pumping since the early 1970s. To assess the effect of drought policies on groundwater levels, it would be necessary to apply a detailed groundwater model, such as finite-difference model, coupling it with the system dynamics model either through scripting, wrapping, or spreadsheet coupling [57].

The model developed using system dynamics for the Jucar River system has the potential to grow and increase its scope by integrating new dynamics that can modify the behavior of the whole system. Future lines of work include linking the agricultural demand subsystem and a land-use subsystem, which would allow introducing changes in agricultural land use based on economic benefit from previous years and on changes in land-use policies. System dynamics provides an excellent framework to study trade-offs that land use changes can introduce in specific sectors and communities [58]. Furthermore, it is already possible to activate population growths or losses over time to study how changes in urban demand can affect the system. These functionalities are required to test the effect of different climate change narratives within the next decades, which is also a future line of research to explore.

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Appendix A

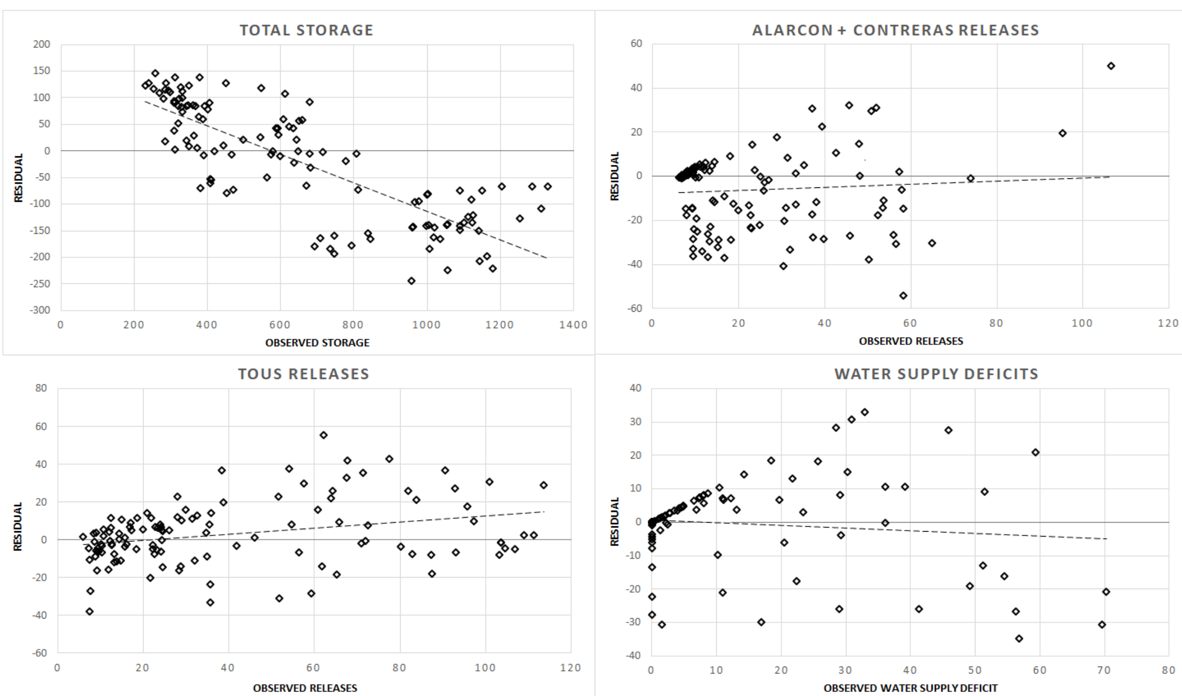

Figure A1. Residual plots of the variables presented in Figure **8.**

The residuals for the variables of Alarcon & Contreras releases, Tous releases, and water supply deficit show a lack of general pattern and are distributed pretty symmetrically around the 0 line. Total storage, however, shows a pattern that was already observed in Figure 8: the model tends to store more water at the beginning of the decade and during the drought period, and it storages less water towards the late period. Several reasons have been given to explain this pattern. As most water resource management models, stationary conditions have been assumed for water demand and reservoir operation during the whole period. However, in reality, water demand and the operation of the reservoirs was changing during the 10-year period. There is not available data to correctly represent the variation of all the water demands, but we know that the demand at the beginning of the decade was greater than during the last years, due to changes in regulation and the improvement of control. We have assumed an average water demand based on the available data. This may explain in part why the model has more water than the observed at the beginning (in reality, the water demand was greater than the introduced) and less at the end (the water demand introduced is greater in the model). The same trend can be observed in Figure A2. Regarding the impact of the operating rules in the results, the rules are based on interviews and analysis performed in collaboration with the decision-makers [42] and are, in some regard, influenced by the knowledge gained during the decade simulated in our model. In reality the logic behind the operation of the reservoirs was evolving and changing during the whole period.

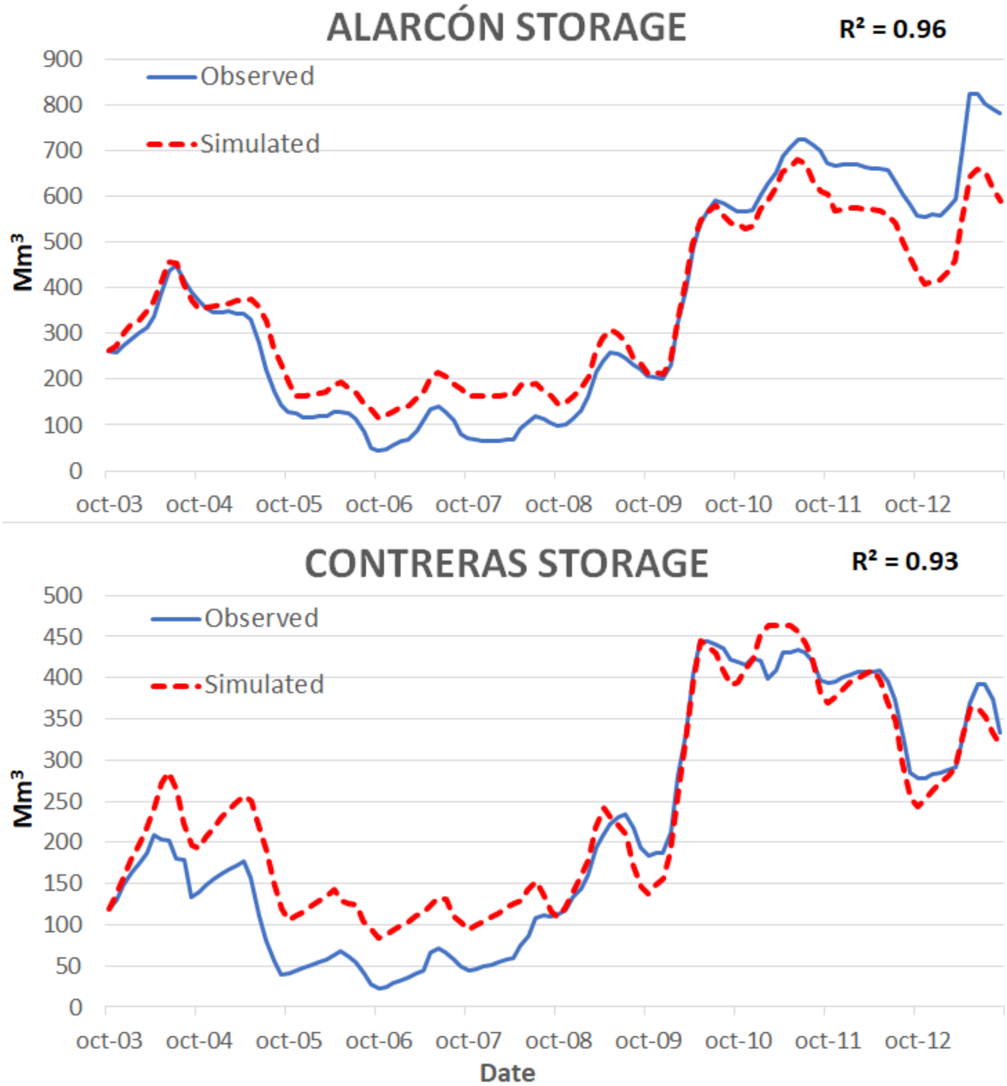

Figure Observed vs simulated storage in Alarcon and Contreras reservoirs.

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

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) 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.

Keywords: Climate Services, Vulnerability assessment, Climate adaptation, Water utility, Climate projections, Water supply, Mediterranean Water Resources, Resilient cities.

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 1ºC and 2ºC 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 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-Martín 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 & 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; and 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 11ºC in winter to 26.6ºC 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 1,798 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).

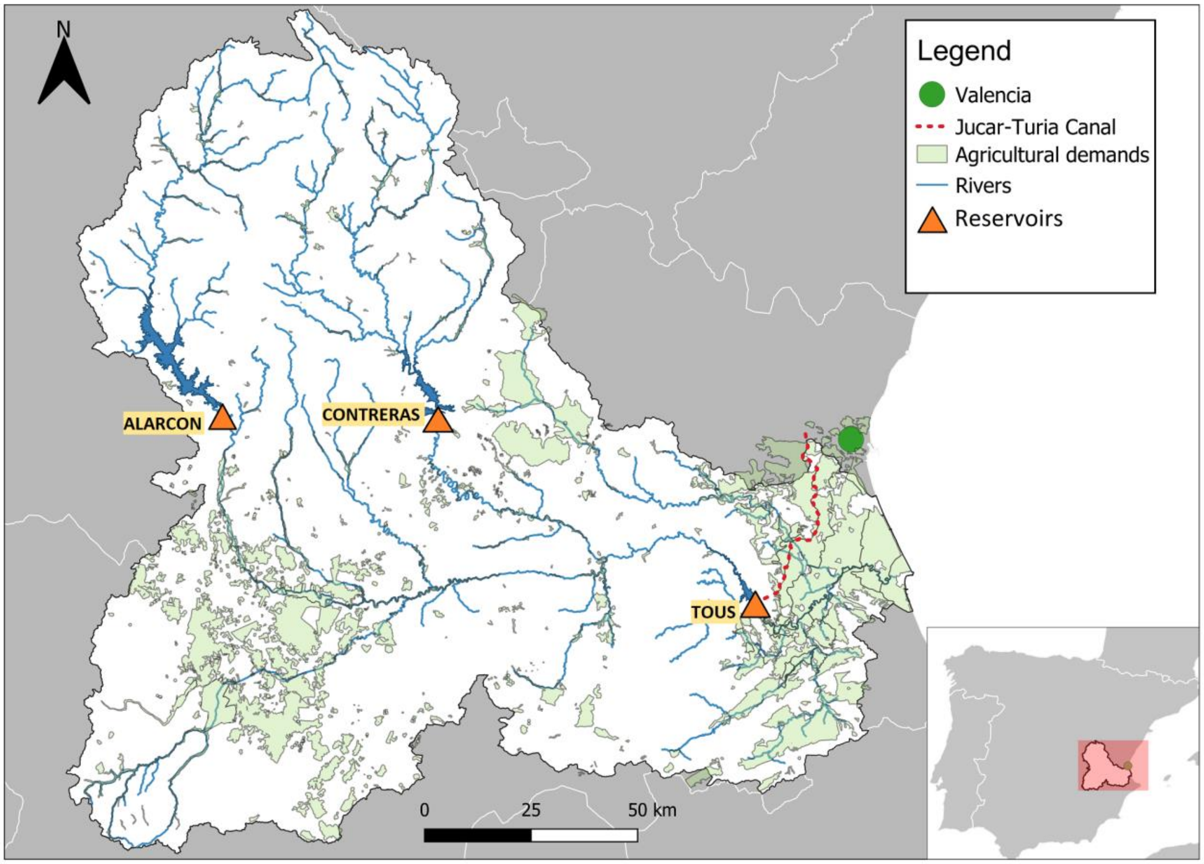

Fig. 1 Jucar River basin and location of the main components of the water resource system.

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 Mm3/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 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 Figure 2.

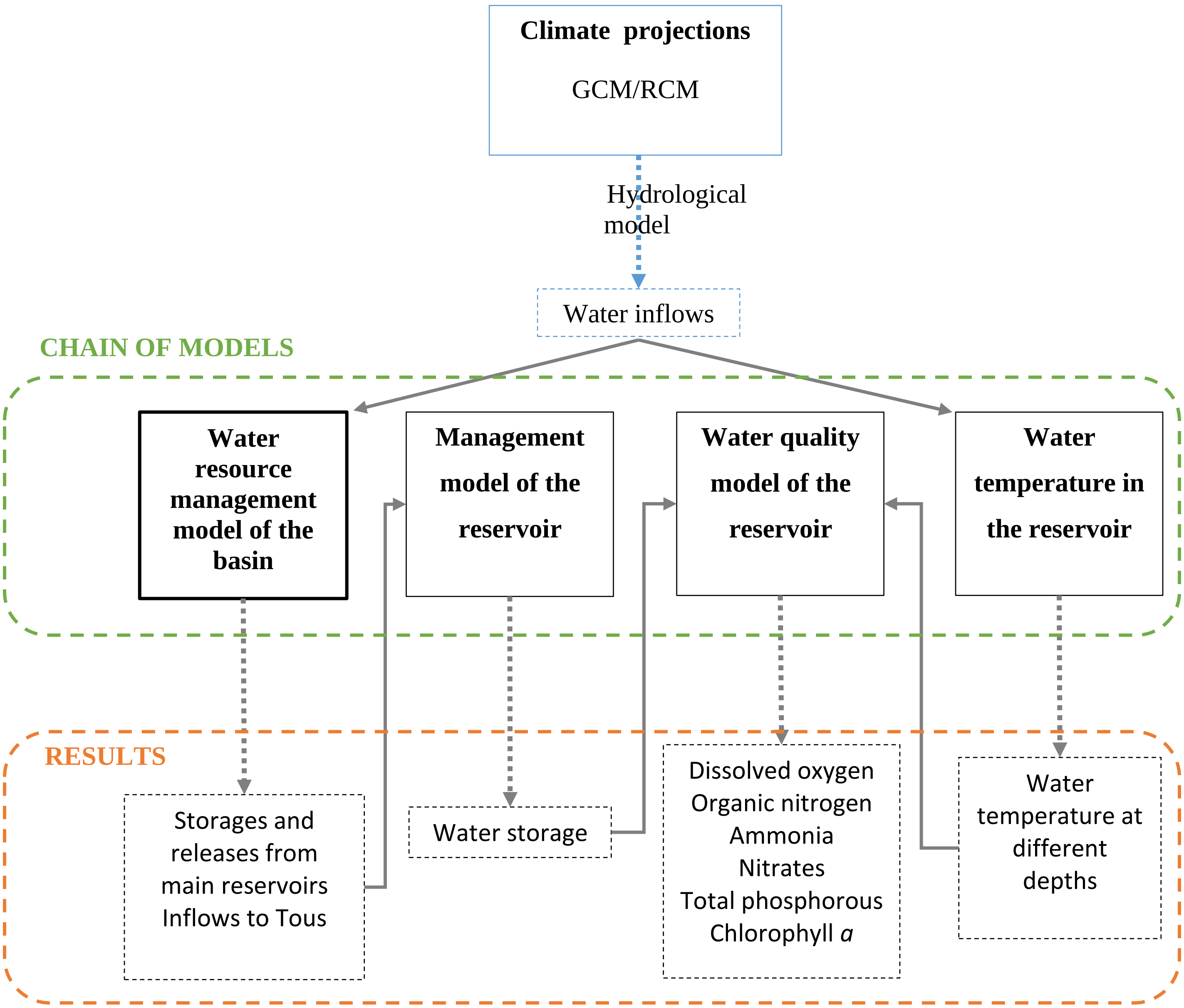

Fig. 2 Modeling framework of the co-created climate service.

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., 2010) with a spatial resolution of 0.11ºC. 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 (Temez, 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 & 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 drought management plan triggering water supply restrictions depending on the state of the system (Rubio-Martín 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 & 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.

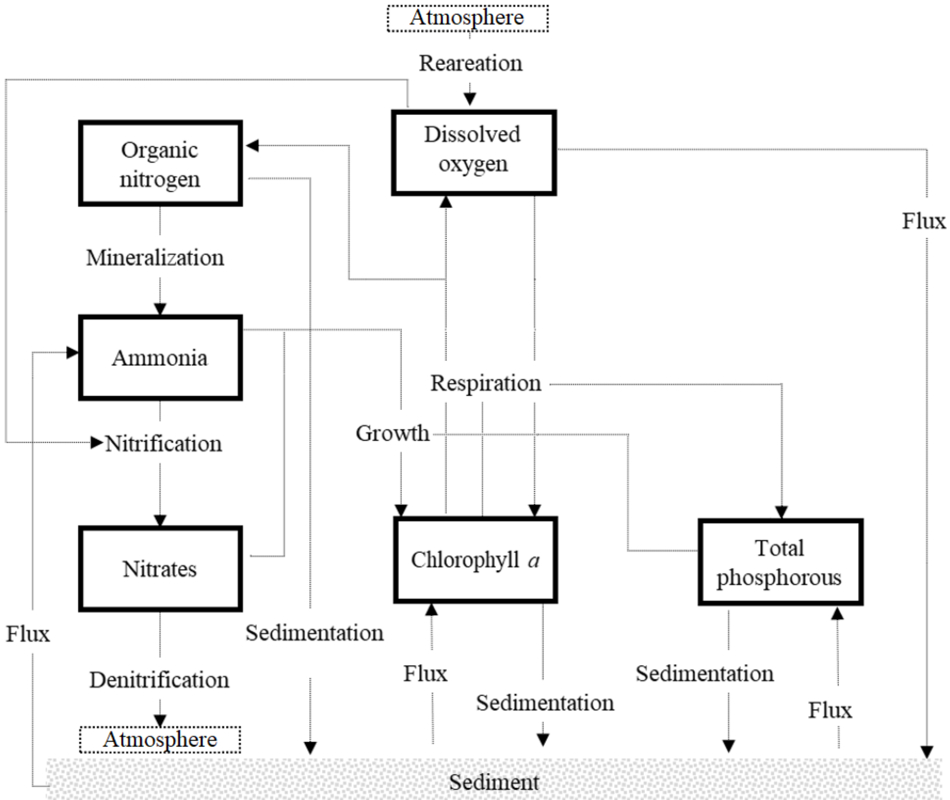

Fig. 3 Water quality parameters relations reproduced by the GESCAL module, AQUATOOL. Flowchart modified from Paredes-Arquiola et al. (2013).

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 (Marco-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). Figure 4 shows the outcomes of the model for the Tous reservoir water storage.

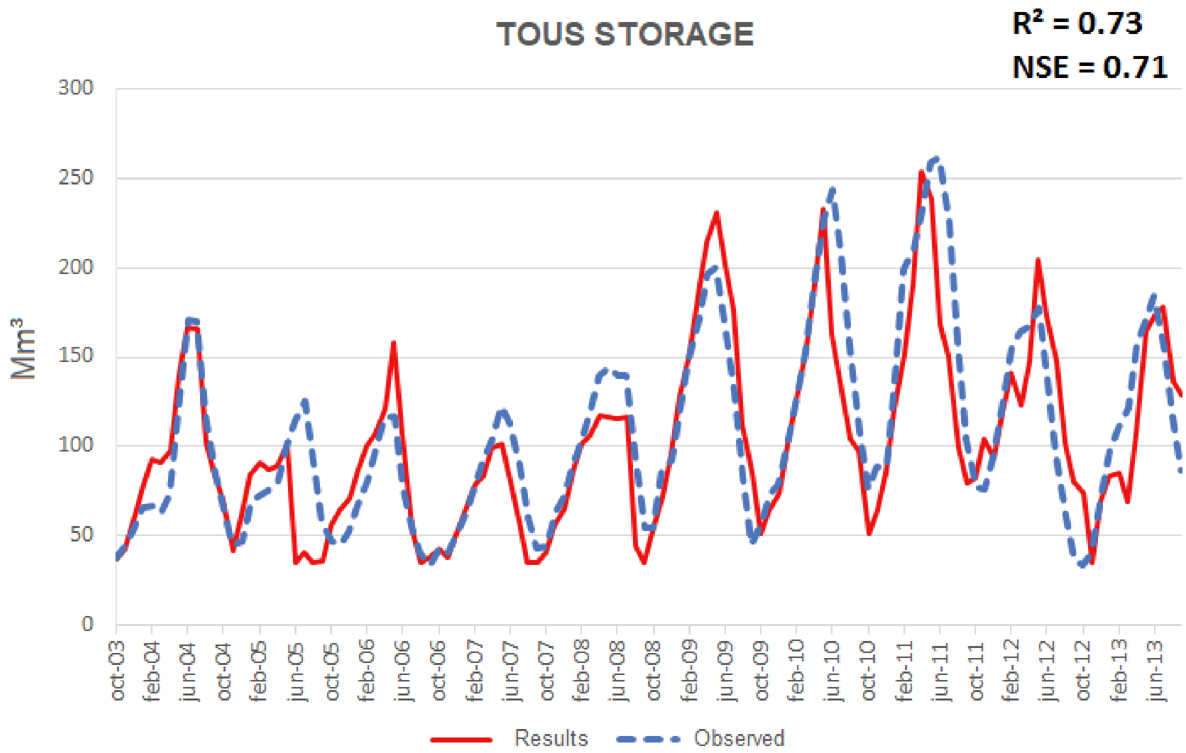

Fig. 4. Comparison between model results and historical records for Tous monthly water storage in the 2003-2013 period.

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 et al., 2017) to properly represent the complex management of the system of reservoirs.

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).

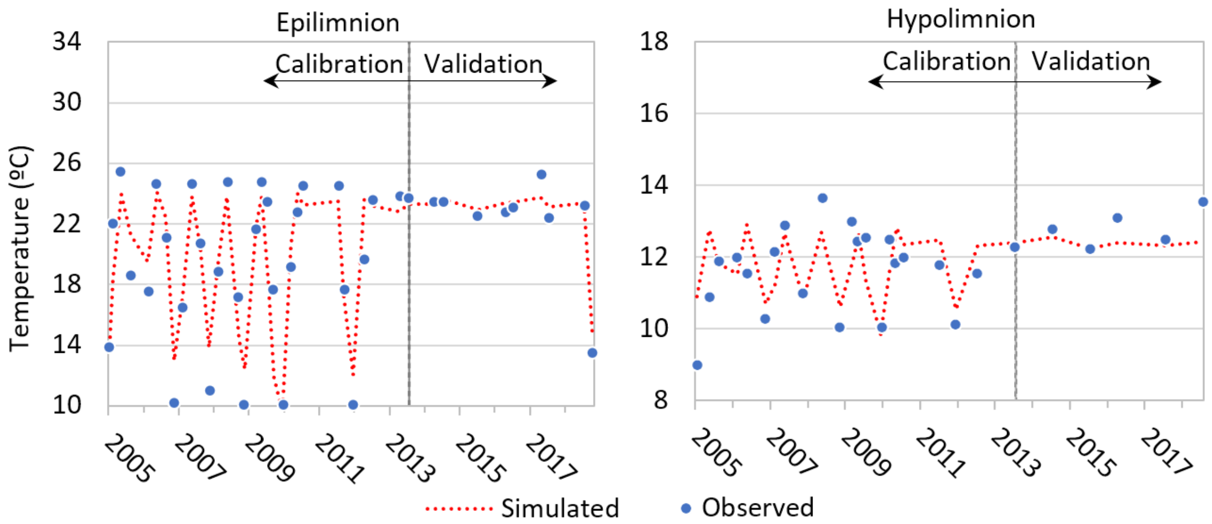

Fig. 5 Water temperature calibration and validation for the epilimnion and hypolimnion.

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., 2011) 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).

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

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 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.

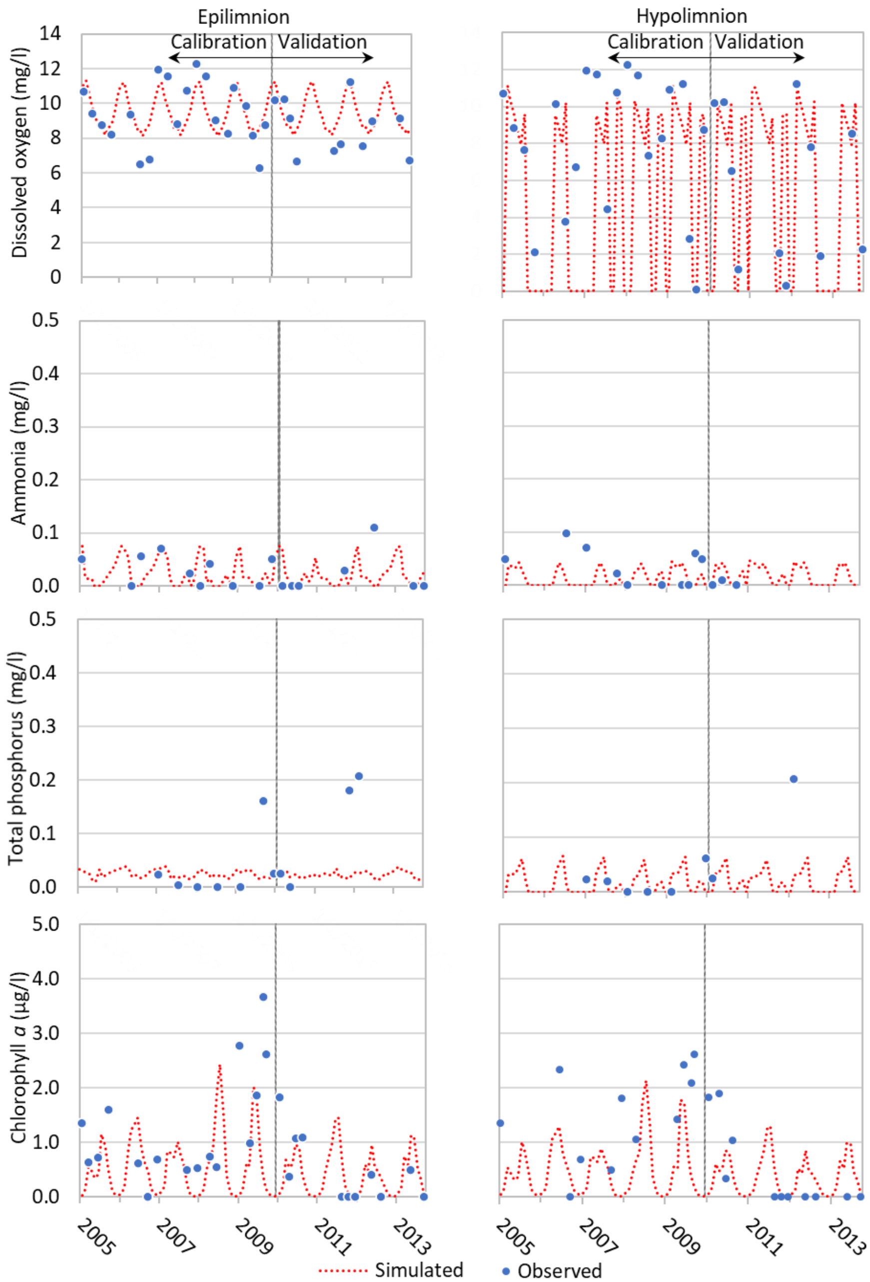

Fig. 6 Dissolved oxygen, ammonia, total phosphorous, and chlorophyll a calibration and validation in the epilimnion and hypolimnion.

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.

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

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.

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.

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%

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. Figure 7 shows the seasonal variation of water storage in Tous compared to the control period.

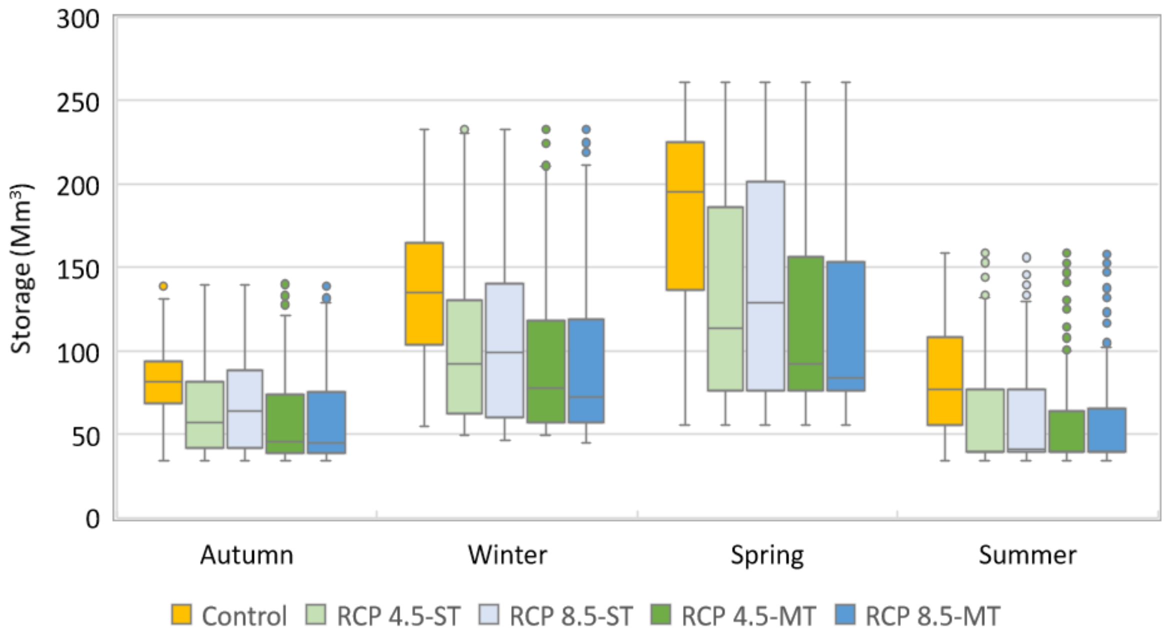

Fig. 7 *Tous reservoir storage in the control period (1971–2000) and in scenarios RCP 4.5 and 8.5 in the short (ST) and medium term (MT) scenarios.*

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 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 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 2.5ºC and 3.4ºC 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 1.05ºC on average in the RCP 4.5 scenarios and 1.47ºC in the RCP 8.5 scenarios. Hypolimnion temperatures raise 0.25 and 0.56 ºC 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 (Figure 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).

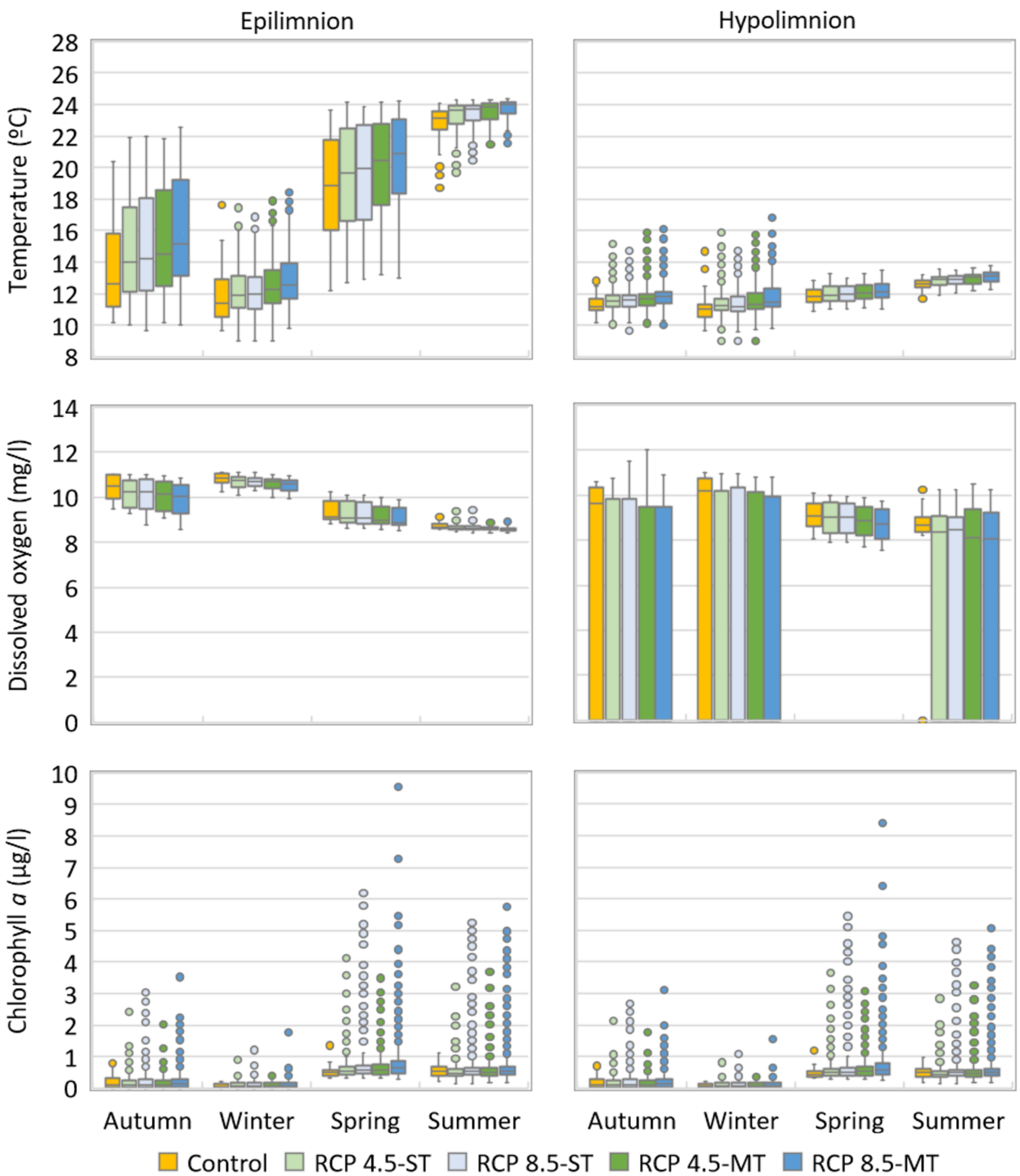

Fig. 8. Comparison of model results for water temperature, dissolved oxygen, and chlorophyll a

Blooms of chlorophyll *a* were observed during several drought episodes in 2008, rising by around 3.5 µg/l, as shown in Figure 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.

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 Medium 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%

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 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; Breutel 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.

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2.3 Structuring climate service co-creation using a business model approach

Structuring climate service co-creation using a business model approach

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Key Points:

- Climate services are the result of the combination of scientific and practice-based knowledge.
- This paper describes a method for the co-creation of climate services using a business focus approach.
- The approach is applied to co-design and co-develop a climate service that aims to support the adaptation of the Valencia (Spain) urban water supply system to climate change.

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Abstract

Climate services are tools or products that aim to support climate-informed decision making for the adaptation to climate change. The market for climate services is dominated by public institutions, despite the efforts made by the European Commission to increase private enterprise in the market. The business model perspective has been proposed as a framework for enabling market growth through the development of appropriate business models for the provision of climate services. However, there is a lack of structured knowledge on how to approach climate service design and development from a business model standpoint. In this contribution, we first analyze the role of stakeholders in the design and development of climate services and identify opportunities for engaging users in the creation process. Afterwards, we explain our approach to climate service design and development using a business model perspective. To illustrate the proposed approach, we describe the co-creation of a climate service to support the adaptation to climate change of the urban water supply system in Valencia, Spain, and discuss the main findings and lessons learned from applying this approach.

Plain Language Summary

This is optional but will help expand the reach of your paper. Information on writing a good plain language summary is available here.

1 Introduction

Climate change impacts are global, multi-sectoral and diverse depending on the region and the scale of interest. In the global landscape, climate services have assumed the role of supporting tools and services for climate-informed decision making, taking into account not only climate information. Climate services are customised products such as projections, forecasts, information, trends, economic analysis, assessments, counselling, evaluation of solutions and any other service that may be of use for the society at large (EC, 2015). Climate services were described as crucial products for sustainable development already in the 2009 World Climate Conference. Years later, the European Commission expressed in their Roadmap for Climate Services the objective of building Europe's resilience to climate change by developing a strong global market for climate services (EC, 2015). After years of research and support at European and global scale, doubts regarding the strength of the climate service market have already arisen, and many researchers have discussed the perceived weaknesses and challenges faced by the market (Bessembinder et al., 2019; Brasseur & Gallardo, 2016; Tart et al., 2019). The public sector has been the driving force of the development and the main user of climate services, while the impact on the private sector has remained minor (Tart et al., 2019). A further analysis of the current state of climate services providers in the European Union shows that the sector is still dominated by public institutions such as universities, research institutions and public climate service centres (Cortekar et al., 2019) and that, despite the support of public funding at the European and national scales, private actors are still mainly concerned about the financial structure of climate adaptation and climate services (Larosa and Mysiak, 2020).

Given the limited uptake by the private sector, a “business model design” approach has been proposed as a method for enabling market growth through the development of appropriate business models for the provision of climate services (EC, 2015). The term business model is broadly used to represent core aspects of a business, including purpose, activities, customers, organizational structures, and operational processes, as well as to describe how an organization creates, delivers, and captures value (Shafer et al., 2005). The commercial success of a business model depends on its ability to sustain itself in time while delivering a useful service to a set of customers or users. A business model approach could be useful to take a more user centered and marketable approach to the design of climate services. Previous research indicate that the market for climate services remains on its infancy and many authors have proposed potential reasons for why this is the case (Brasseur & Gallardo, 2016; Hoa et al., 2018; Damm et al., 2020):

1. Insufficient awareness by societal actor of their vulnerability to climate change.
2. Other issues rather than climate change receive higher priority.
3. Lack of relevant services provided from the scientific community.
4. Lack of perceived value by users.
5. Lack of trust from the users.
6. Inappropriate format in which the service is provided.
7. Inadequate business models adopted by climate services providers.

In his famous speech from 2015, Mark Carney, governor of the Bank of England, referred to climate change as the “tragedy of the horizon”, as its impact will be felt beyond the traditional horizons of most decision-makers, including those of business and policy. “Once climate change becomes a defining issue for financial stability, it may already be too late” (Carney, 2015). To avoid this, we need to ensure that the users can perceive the value of the provided climate services. In order to do this, we must improve our knowledge of the current needs of the potential climate service users and to identify the resources and actions required to provide valuable services to these users. A business focus approach to climate service development puts users in the centre of the development process and understands that making users part of the process increases the acceptability and usefulness of the resulting service (Larosa and Mysiak, 2020).

Webber and Donner (2016) indicated that climate services should be driven by users (adaptation and disaster managers) instead of scientists or science-funding agencies that make assumptions regarding useful data and the climate impacts that are of most concern to managers. Co-design is increasingly recognised as a method to match adaptation needs, user's skills and climate-services-providers capabilities. Business models have been on the core of two Horizon 2020 projects about climate services: MARCO3 and EU-MACS (Hoa et al., 2018). The research presented in this paper has been developed within INNOVA, an ERA4CS project that aims to bridge the gap between climate service providers and targeted users integrating business model practices to the co-design of climate services.

This paper describes a framework for the co-creation of climate services using a business-focus approach aligned with the needs of the climate service market and users at the local scale (bottom-up approach). We test the implementation of this process in Valencia, Spain, co-creating a climate service jointly with a water treatment and supply company. The barriers for climate change adaptation in water management organizations, include the ones previously listed and issues such as cognitive barriers (e.g. on risk perception), the lack of relevant information at the appropriate scale, inadequate human-financial resources, the lack of confidence, interest or leadership, the focus in the short term, or the lack of clear and consistent policies (Azhoni et al. 2018). For these reasons, water management companies are the perfect candidate to test and validate new methods to co-develop climate services. We are proposing that the business approach for climate service development is useful in two ways: Firstly, it serves as a roadmap for the market-driven or user-based creation of climate services. A business-focus approach is inherently aligned with the emerging concepts of co-design and user-focused climate services. Secondly, the proposed approach bridges the gap between the scientific and practice-based development of climate services. The creation of climate services sustained by a business approach is essential to engage the private sector into the process.

The paper is structured as follows. Section 2 starts by reflecting on the role of end-users in the creation of climate services and categorizes the potential climate service users based on their knowledge of climate data and their position in the adaptation cycle. Section 3 describes the proposed framework for creating climate services using business model thinking. Section 4 showcases the described procedure for the Valencia case study: the co-creation of a climate service for the urban water sector. Finally, Section 5 presents the main conclusions of the research.

2 Engaging stakeholders for climate service creation

A climate service is the transformation and use of climate data and knowledge for helping decision-makers (Vaughan & Dessai, 2014). According to the EU Roadmap, the customized products known as climate services can be projections, forecasts, trends, economic analysis, assessments, counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be used for the society at large (Street et al., 2015). Climate services should be user-centric, supported by active research, based on the use of detailed data and information about the future (including predictions) and, usually, involving participation of government, business, organized civil society, and academia (Brasseur & Gallardo, 2016). Climate services must integrate climate and non-climatic information to be able to adequately answer the stakeholder's needs and demands (Vincent et al., 2018). End-user participation is essential during the production of climate services.

The creation of climate services can be divided in two distinct phases: the design and the development phases. Although "designing" and "developing" are two verbs commonly used as synonyms in the climate service literature, we would like to underline some differences that may be useful to characterize the role of end-users during the whole process. The co-design phase is when users and developers agree about the features and purpose of the service. After an understanding is reached, the development team will materialize the service or product that was envisioned, thus beginning the development phase. The participation of end-users in the development process is not always required, but they often cooperate by -for instance- providing data or feedback. Although conceptually the design and development phases are different entities, in practice it is common to loop between both. For instance, if problems arise during the development, it may be necessary to return to the design phase to come up with an agreed solution.

The success of a climate service requires that stakeholders are meaningfully engaged from the beginning in the joint design and evaluation of the product (Bremer et al., 2019). Therefore, identifying the potential users of climate services is a fundamental step in the process. There is not a single and correct way to categorize climate service users. Some studies have described and grouped users based on their needs and economic sector (Tart et al., 2019). According to these analyses, agriculture and forestry, environmental agencies, water and energy utilities, and research and development organizations are the main economic sectors using climate services. Most users, however, do not operate within a single sector, and utilities is the top sector for State-owned companies, while energy and agriculture are the main sectors for private enterprises (Tart et al., 2019).

The users of climate service can also be characterized according to how they use climate information (Skelton et al., 2019). Methods of classifications based on how users interact with climate data are better for identifying systemic barriers for the uptake of climate services. The lack of interest of users in climate services often results from lack of awareness of the existing relevant data, or for lacking knowledge about the specific threat that climate change creates for their activities (EC, 2015).

In order to identify promising users interested in the co-creation of customized climate services, we propose characterizing users based on their knowledge of climate data and their awareness about the potential impact of climate change on their respective field of interest. This method serves two purposes: first, it helps to assess the readiness of users to participate in the co-design and co-development of the climate service. Second, it will provide insights to climate service developers regarding the potential actions required for promoting the engagement of users with insufficient level of readiness or awareness. Figure 1 depicts the process in which potential users of climate services may become aware of the need for climate services. The entry points where climate service developers can provide external support to certain users are identified.

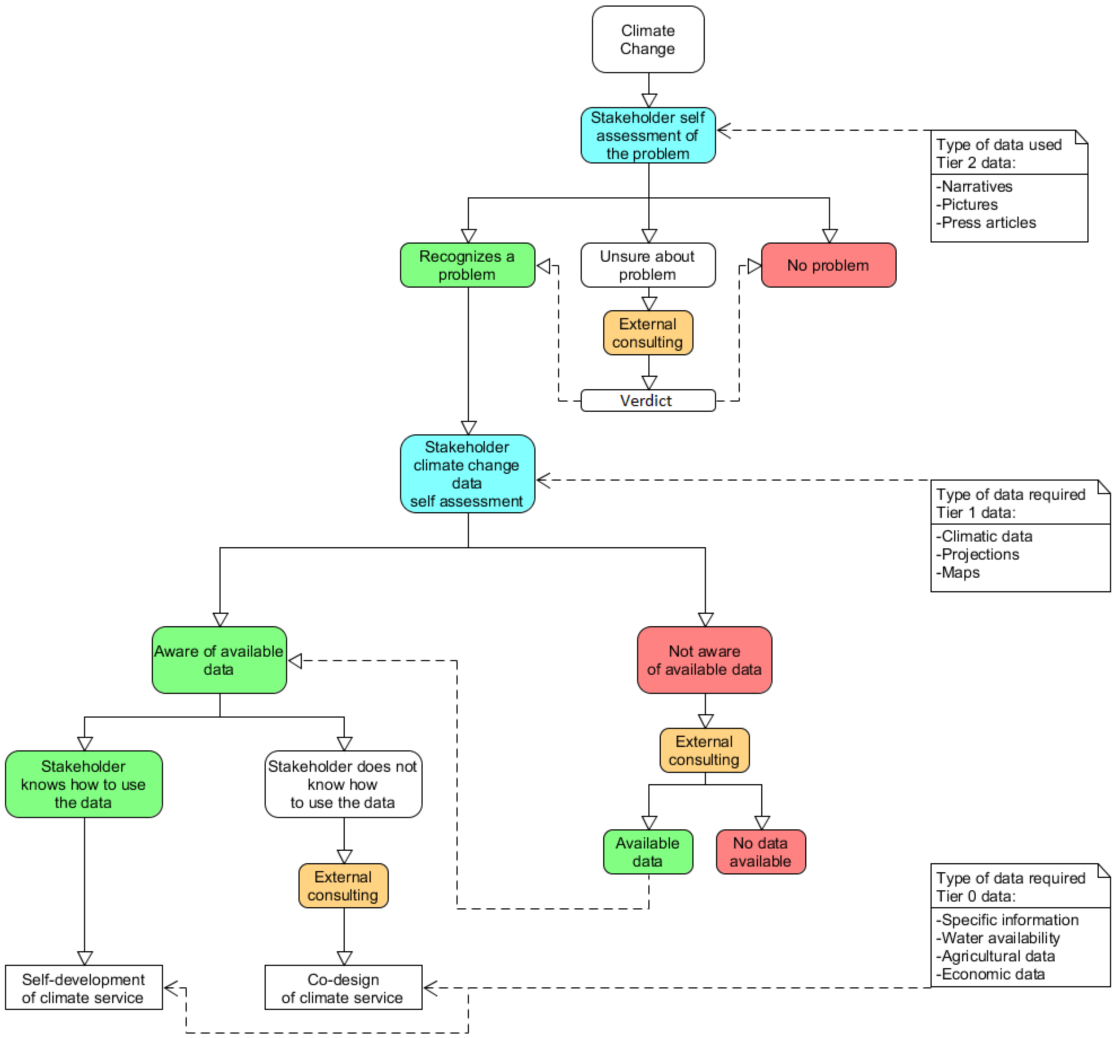

Figure 11. Stakeholder pathway from problem awareness to climate service demand.

During the process of coming to an awareness of the climate change-related problem, we have distinguished three stages that stakeholders go through. Each step has primary information that can be classified according to the spatial and temporal resolution, quality, quantity and level of detail. In all cases, the legitimacy, credibility and usability of data is essential for the user to remain interested and confident. Tier 2 information is general and easy to understand data about climate change impacts and threats. This data is usually heavily processed and it is presented in the shape of articles, pictures, and infographics. Tier 1 data is semi-processed data such as climate maps and climate projections of certain variables such as temperature and precipitation for a specific region and time scale. Tier 0 data is raw data on climate, economy, agriculture, water and detailed information about any sector interested in climate services provision. During the climate service co-development process, tier 0 information is very often partially provided by the end-user of the climate service, to ensure that the climate service is useful for their decision-making process.

Understanding this process may help climate service developers and providers to comprehend the decision context of the user facilitating the communication between all parts and promoting the interest in the co-creation of climate services. Users with preliminary knowledge are users who would like to know more about climate change in general and its potential impacts on themselves. These users would benefit more from tier 2 data such as narratives, pictures and press articles to access to easy to digest information for recognizing and identifying their potential problems and interest on the issue. Users who have a deeper knowledge and awareness of climate change are likely to be in search of tier 1 data to support their decision-making processes to progress towards climate adaptation. Having recognized the problem, they aim at tackling it. These users could start getting familiar with the climate change data and projections. As familiartity of users with data increases, they can start requesting more detailed information based on their specific requirements (tier 0 data). At this point, if all data is available, users with complete understanding, knowledge and skill would be able to design and develop the climate service that they need. Of course, this degree of proficiency and skill is not found very often, hence the need for climate service developers to assist into the co-design and co-development of the service.

The process followed by users in Figure 1 can be linked to the famous climate change adaptation cycle (Figure 2).

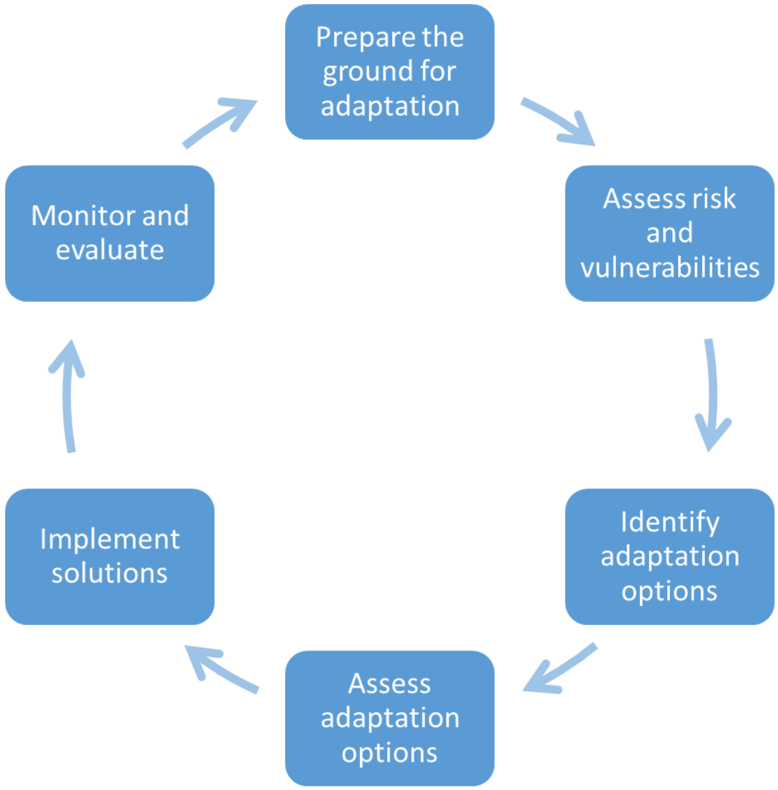

Figure 12. Climate change adaptation cycle (Redrawn from Climate-Adapt EEA).

The climate change adaptation cycle represents the different steps in which stakeholders progress in their path towards climate change adaptation. Starting from preparing the ground for adaptation and finishing at the monitoring and evaluation of the already implemented adaptation strategies. Depending on the phase of the process there are also different information needs. In Figure 1, we suggested the type of information that would be useful in each step of the process. Relating this evaluation to Figure 2, we can also see how the data required is more specific and detailed as users advance in the adaptation cycle. For example, the data used to assess the risk generated by climate change is often easier to obtain and process than the information required to evaluate the best adaptation solutions. The latter requires further information and processing, such as developing models to calculate the impact of climate change under each management alternative and scenario. In general, users will need more detailed and refined information as they increase their awareness and knowledge of the problem. For climate service developers, the required information is not limited to ordinary data collection on easily quantifiable variables, it entails analyzing the decision context of the users and detailed information provided by the users, as well as having into account their needs and expectations.

The application of this knowledge may benefit climate service developers and providers that are trying to engage users into the process. From the point of view of climate service providers, the co-creation process begins from the identification of the impacts that climate change is going to have at the area and scale of interest. Finding stakeholders affected by those impacts is the next step of the process. Identifying the affected stakeholders is essential for developing climate services, as the resulting product or service has to respond to the needs and demands of the end users. As mentioned before, the involvement of users during the co-design of the service is required. Ideally, the result of the co-design process will be a detailed description of the objective and features of the climate service. This will be called the “value proposition” of the climate service in our proposed framework. User participation during the development process is also possible but not always required. During the development users can provide fundamental data, essential feedback or even their own knowledge and resources such as models and facilities. Drafting a preliminary list of potential user helps developers to narrow down the ideas for potential climate services. It also allows climate service providers to obtain and process useful data and information for engaging users and get their attention.

The orange boxes in Figure 1 indicate the different points where a climate service provider could assist the user into the solution of their specific problems. The service offered by the providers must be different in each phase of the process. In the first phase —that takes place from the starting point to the point where the stakeholder recognizes a climate-related problem— the service may take the form of a climate change risk assessment. The risk assessment will be classified as a climate service if the user interacts with the providers in a meaningful way to specify their uncertainty realm and their specific needs. Otherwise, at this initial stage the service will more often be a preliminary consultation that a provider may offer to potential candidates for climate service co-design. In the second phase, the climate service developer may help to identify the useful information for the user, both for improving the first risk and impact assessment and to start identifying relevant information required for the development of adaptation strategies. In the third and final phase, the climate service developer and the user will work together to co-create the tailored service to solve the specific problem identified during the process. A single climate service developer might support the user during the whole process, from problem recognition to solution development. However, some users may require the assistance of a climate service developer just for the designing phase (3rd phase) or for the data availability phase (2nd phase). Again, these phases are related to the different steps described in the adaptation cycle (Figure 2). Progressing in the adaptation cycle means that more socio-economic and technical information will be required for developing climate services. The most simple climate services are usually located in the assessing risk and vulnerabilities phase, and they use mostly climate information. As we advance in the adaptation cycle, more information is required —often provided by the users involved in the co-development process— and the resulting climate service will be more customized, transdisciplinar and specific to the needs expressed by the users.

3 Development of climate services using business model thinking

3.1 Process overview and objectives

The term "business model", which originated in entrepreneurship and e-commerce, is nowadays used for all business strategy research, often including public sector discussion (Ranerup et al., 2016). The most essential definition of business model states that it is the description of how an organization creates, delivers and captures value (Shafer et al., 2005). This definition immediately raises questions such as who is creating value, for whom, how the value is created and how it is delivered and perceived. Within the project INNOVA (INNOVA D3.1, 2018), we have defined the following process for creating climate services by using business model concepts (Figure 3).

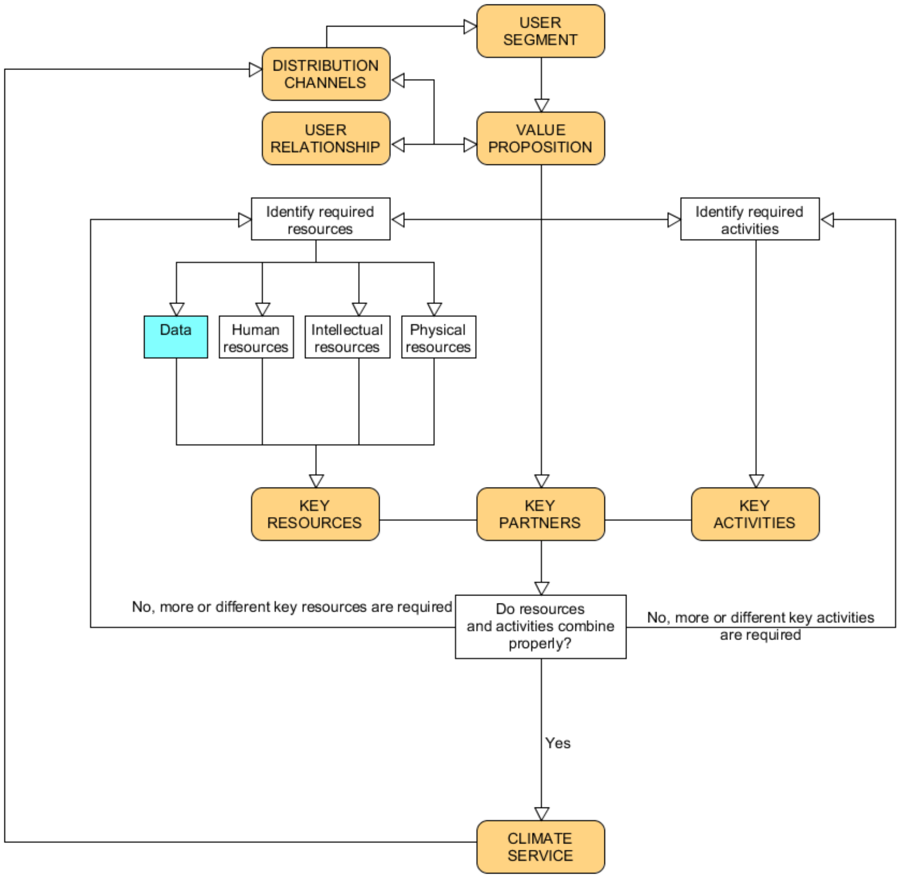

Figure 13. Process for creating a climate service using business model concepts.

The process uses concepts taken from the business model world to describe the design and development of climate services. The business model terms are contained in orange boxes. This facilitates the transition from the description of climate service development to business model description, helping climate service developers to think about how their climate service relates to end users and market needs. Each one of the processes represented in Figure 3 can be broken down into smaller steps for describing in more detail the dynamics involved. The process presented in Figure 3 describes a loop, meaning that after the climate service is delivered to the user, the user can express if there is a need for more or different services, effectively restarting the co-design process. The objective of this guideline is to narrow the conceptual gap between climate service and business model creation, facilitating business model thinking and the transition from conceptual design to climate service and business model development, as illustrated in Figure 4.

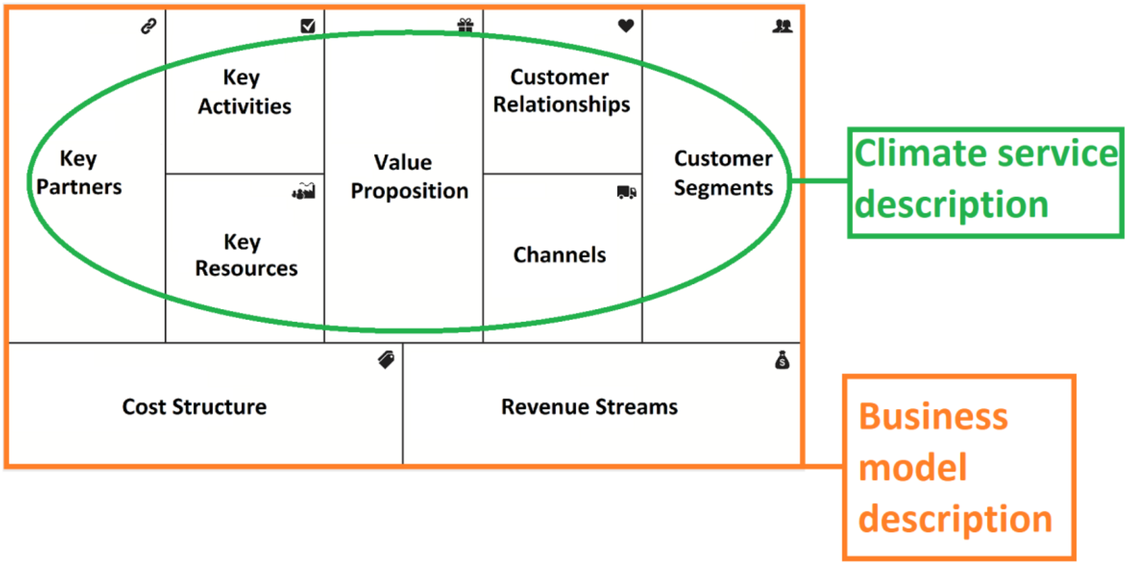

Figure 14. Relationship between climate service and business model description based on the business model canvas (Osterwalder and Pigneur 2010).

The fact that climate service development is a co-design implies that the collaboration between developers and end-users is required during the whole development process. As a result, stakeholders interested in participating in the co-design can be part of the user segment. Characterizing the users by using the classification described in the previous section will help to better identify the needs, expectations and data required for the co-development of the climate service. Climate data is essential for developing climate services, as the best available climate information is the initial resource of every service. However, limiting the use of information exclusively to climate information may result in narrow and risk-oriented climate services that may lack the customization required from the final users. The need for additional non-climate information may be revealed in the co-design phase or during the iterative co-design and co-development process. In this regard, the final user of the service often is an indispensable data provider for the developer, as it may have access to specific data (economic, agricultural, environmental…) corresponding to the specific economic or professional activity that they perform. Climate services are user-oriented services and it is more likely that additional user-specific and non-climate information is required to co-develop them as the level of customization is increased. The integration of the users' knowledge into the co-development process will result in the combination of know-hows that regularly will come from different branches of sciences, resulting in truly transdisciplinary outcomes.

The traditional notion of business models requires the definition of the cost-revenue structure, as seen in Figure 4. However, the fact that the public sector has been the driving force in the development and use of climate services (Tart et al., 2019) is an essential issue when addressing the economic side of climate services. For many stakeholders, climate change defies the traditional cost-benefit analysis (CBA) that just expresses cost and benefits in monetary units because the deep uncertainty and the scale of the expected impacts obstruct pure economic evaluation (Scovronick et al., 2019). Additional obstacles that can be added to the ones listed in the introduction for private involvement and use of climate services derive from two facts: 1) Climate change impacts are often widespread and mainly affect resources that are frequently considered common goods. 2) Climate change impacts do not occur abruptly but develop progressively in time (Swart et al., 2013). The first point drives some stakeholders to inaction and apathy, as climate change may seem too broad or abstract to tackle and acting upon it can easily per perceived as the responsibility of others. The second point is one of the main motives behind the tragedy of the horizon as described in the introduction and causes some stakeholders to delay their response to climate change until it may be too late. Despite all of these obstacles and constraints, significant opportunities have been identified in different sectors like water resources and risk, energy and agriculture (Cavelier et al., 2017). Furthermore, new CBA methods that are suitable for Climate Adaptation analyses and capable of integrating additional factors not expressed in monetary units have been developed and are gaining traction (Souvignet et al., 2016; Bresch and Aznar-Siguan, 2021).

3.2 Process description

The process of developing the climate service can be described in 3 steps that contain the concepts borrowed from the business model literature (Figure 5).

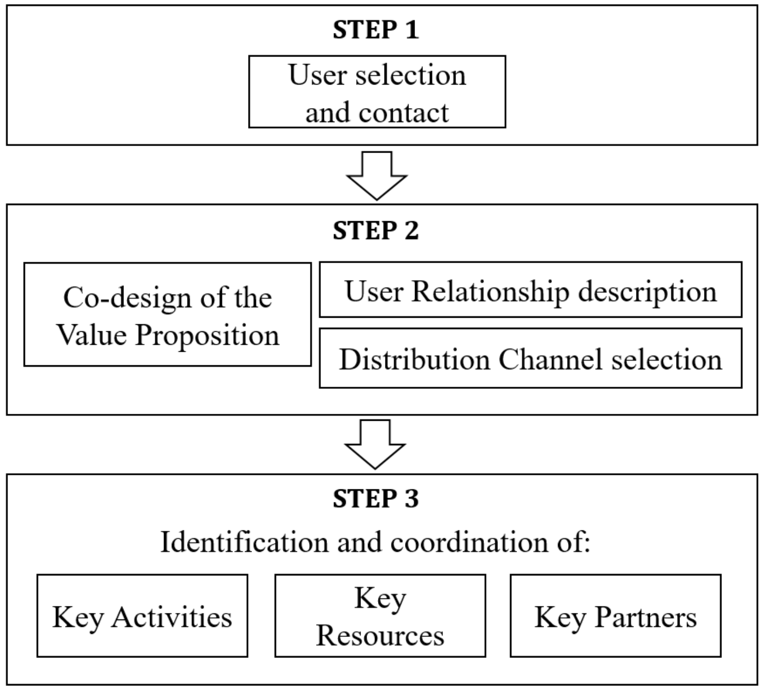

Figure 15. Steps required for the creation of climate services using business model concepts.

The Step 1 requires identifying and verifying the composition of the *user segment*. This process can happen top-down or bottom-up. Conceptualized as a top-down process, the climate service provider identifies which users are the ones in need of a service. As a bottom-up process, users, based on their experience and knowledge may contact a climate service provider to address their needs. Due to stakeholder’s general lack of awareness of climate services as a product, it is most likely that a top-down approach is required at this stage. If that is the case, the processes described in Section 2 and Figures 1 and 2 will help climate service providers to understand the context of the potential users, facilitating the identification of the most promising stakeholders and enabling better communication between all parts. The user segment may be formed by a group of different users that can be segmented based on their different needs and attributes to ensure the appropriate development of a service that meets the specific needs of each group (Hedman & Kalling, 2003). The business model literature describes a diversity of users, differentiating between mass users, niche users, multi-sided users or segmented users inside a business field (Osterwalder & Pigneur, 2010).

Step 2 is the stage in which the co-design happens. In this step, the aim is to co-design with the user the goal of the climate service, and its main features, including the format and the kind of relationship that will be established between user and provider during and after the creation of the product or service. The concepts from this step are known in business language as *value proposition, user relationship* and *distribution channel*. The value proposition is the collection of products and services a climate service developer or provider offers to meet the needs of its users (Richardson, 2008). In the climate service context it defines the objective, added value and competitive advantage that the proposed climate service will provide to the user. If the user asks for a service that already exists, the value proposition of the service should include a competitive advantage over other similar products available for the user (Zhang et al., 2019). The competitive advantage provided by the climate service may be an additional value for the price, a deeper customization of the product compared to the existing offer in the market or any other feature that signifies a special value for the user. This step includes reaching an agreement on the preferred user relationship. The user relationship is the type of relationship that developer and user are going to create (Osterwalder & Pigneur, 2010). Some examples of user relationship are personal assistance, self-service, automated services or on-demand service. User relationship can change and evolve in time according to the needs and capacities of the targeted user and providers. The distribution channel refers to the methods used to deliver the climate service to the end user. Effective channels will be agreed with the users and will be designed depending on the user's needs (Osterwalder & Pigneur, 2010). The distribution through these channels must be as efficient and cost-effective as possible for the end-users. A climate service provider can communicate with its clients through different channels. Examples of channels are climate fact sheets, counselling or a web-product. User relationships and channels are intrinsically related, as the channel of communication can limit or influence the type of relationship that the end-user is going to maintain with the service developer. In some cases, user relationships can even be outsourced to partners specialized in communication and dissemination.

The Step 3 is to identify the *key activities* required for the development and delivery of the climate service or product. These activities include ways to achieve and maintain the developer-user communication, or users' relationship, through the previously specified channels. Processing and managing climate and other relevant data is almost guaranteed to be a fundamental activity for most climate services. Climate data is one of the critical resources that should be identified and collected during the process. *Key resources* are all the assets needed to sustain and support the climate service development. These resources can be human, financial, physical, and intellectual (Osterwalder & Pigneur, 2010). Although climate projections and climate information are essential resource for developing climate services, they are often not enough to provide an useful service to the end-users. *Key partners* are the external associates required to create and deliver the climate service, or to establish and optimize operations and communication (Chesbrough & Schartz, 2007). In many cases, developers need to find key partners that will support the development or delivery of the climate service with key resources or key activities. Data supply, technical support or communication are some of the activities that are often outsourced to third parties. Public organization may be accounted as key partners of the climate service when the service depends on their funding. From our experience, users involved in the co-design of climate services end up participating in the co-development process as key partners. Their involvement is very often needed for the success of the final service, as they can provide essential data and valuable feedback required to customize the service to their own needs.

After the third step is finished, the climate service will be completed and prepared to be delivered to the user. As mentioned before when describing the design and development phases, steps have not to be taken as tasks to be finished, but as a part of a creation process. This means that at any step of the process, the climate service developer may need to engage again with the user to modify the value proposition, change or add new key partners, add additional resources not previously considered, etc. Once the climate service has been delivered, the relationship between user and developer does not necessarily end. The climate service may require several iterations to be useful for the user, or it may require the support of the developer over time. The after-delivery support to the user will be described when defining the user relationship (Step 2). Guaranteeing support to the end-user after the delivery of the climate service increases trust and promotes better cooperation between providers and users during the co-creation process.

4 Application: Climate service for the drinking water supply of the city of Valencia (Spain)

4.1 Case study and user description

Valencia is a coastal city located on the east coast of Spain, in a semi-arid region that suffers from long and frequent droughts due to its Mediterranean climate. With around 1,600,000 habitants in the city and its metropolitan area, Valencia is the third-largest city in Spain (INE, 2019). Extreme weather events typical of the Valencian region, such as droughts and floods have a very well-known negative effect on both water quantity and quality (Hrdinka et al., 2012). Water scarcity is the main issue for the agricultural sector —responsible for 80% of the water consumption in the region— while issues derived from water quality affect mainly the urban water supply sector. EMIVASA is the company responsible for purifying and providing water to the habitants living in the city of Valencia and the surrounding cities (Figure 6).

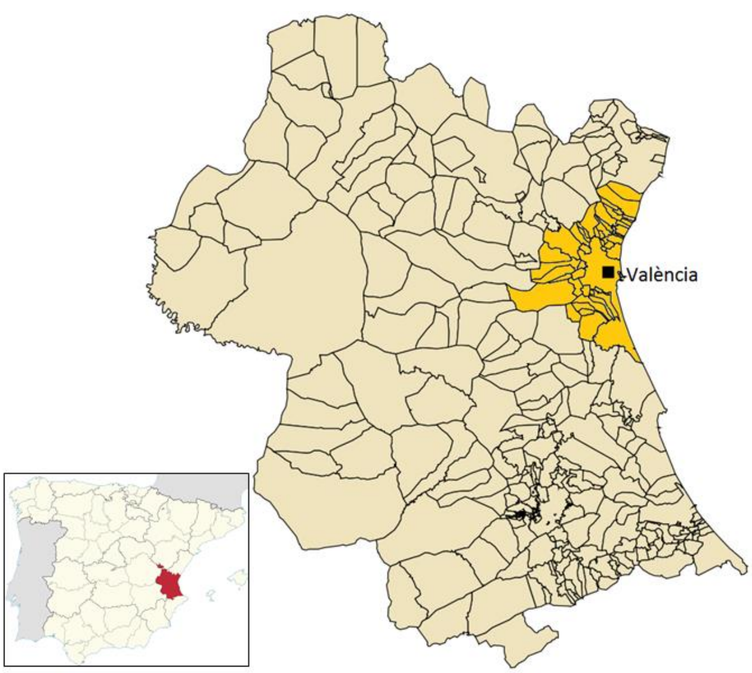

Figure 16. Area where EMIVASA is currently operating

EMIVASA is a public-private partnership. Global Omnium owns 80% of EMIVASA, and is a private company that provides services to more than 300 municipalities in Spain and has projects in Africa, Asia and Latin America. The company was founded in 1890, and operates in the water sector as a whole, purifying, supplying and treating water, while leading and promoting R&D projects to ensure the future development and synergies with other business and territories. The remaining 20% of EMIVASA is owned by the Municipality of Valencia.

The metropolitan area of Valencia receives water from the Jucar and Turia Rivers. The qualitative and quantitative status of both rivers are critical factors to consider for EMIVASA. Around 75% of the water supplied to Valencia and its metropolitan area comes from the Jucar River. The water transfer from the Jucar to the Turia River is carried out through a 60 km channel that starts at the Tous reservoir and finishes at the Manises water purification plant, where the Jucar and Turia water is mixed (Figure 7). The current Tous reservoir was built in 1996, it is the downstream reservoir of the Jucar River basin and it is used for flood control, hydroelectric production, irrigation and urban water supply.

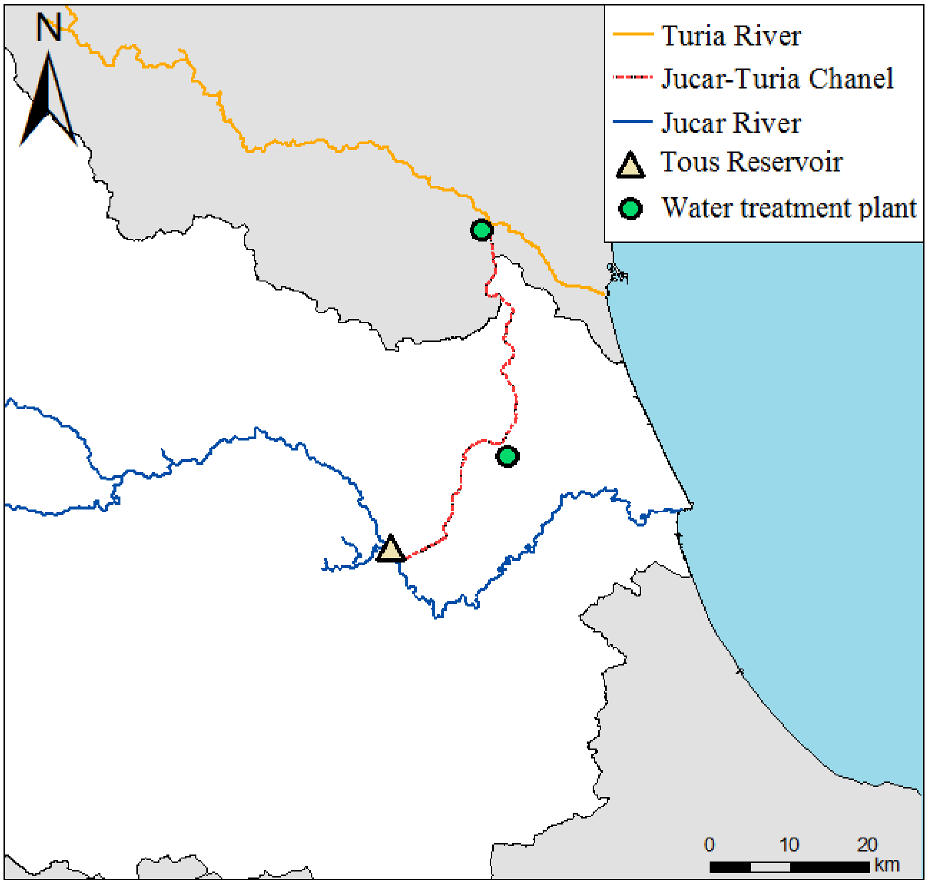

Figure 17. Water management infrastructures involved in the raw water management and treatment for Valencia City and its metropolitan area.

4.2 Climate service co-creation with the water utility company of Valencia

The climate service creation started by identifying the stakeholders in the region that are more vulnerable to climate change impacts. The partnership with the main user, EMIVASA, was built based on previous experiences between both partiers. The co-design of the objectives and features of the climate service (value proposition) was carried out with EMIVASA. During this meetings both parties identified other users potentially interested in the climate service. EMIVASA and the development team also reached agreements upon the communication and distribution channels. Following the process described in S3.2, step 1 recognized the following main and secondary users:

STEP 1
User segment: - EMIVASA (main user): Formed by Global Omnium, company responsible for purifying the water for the city of Valencia and its metropolitan area, and the Valencia Municipality. - EMSHI Metropolitan Area Authority for Water Supply: interested in the results. - Water Authority of the basin: interested in the results.

The challenge that climate change presents for the water utility system in the region is caused by the impact that the combined effect of increasing water scarcity and higher temperatures may have on the raw water quality.

The elements belonging to the Step 2 of the process are the following:

STEP 2
Value proposition: Assessing the effect that climate change will have on the future raw (untreated) water available in the Valencia region in terms of both quality and quantity. Assist EMIVASA into finding the best strategies to treat and manage this resource and calculate the cost of the adaptation strategies. **User relationship:** - Periodic meetings and email communications (early stages) - Reports and presentations submitting (mid stages) - Periodic visits to the water treatment plant (late stages) - On-demand consulting (after project completion) **Distribution channels:** - Reports with the predicted state of the system in terms of water quantity and water quality for current and future climate change scenarios - Counselling on the best treatments strategies for the future water

- Final report to EMIVASA and the water authorities including cost

The value proposition of the co-designed service was to analyze the effect that climate change will have on the future raw water available in the Valencia region, in terms of quality and quantity. The first co-design meetings were used to clarify how the climate service could be of most use for EMIVASA. This included aligning the climate service to the company's decision-making process in terms of time and spatial scales. Subsequent meetings tackled issues such as identifying the main water quality parameters of interest for the company (physical, chemical, and biological). Contact with the company remained active during the different phases of the co-development of the climate service. Some of the following meetings were held at the water treatment plant of the company, and involved the technical staff from the plant to discuss the provisional results obtained.

The Water Authority of the Júcar River Basin, "Confederación Hidrográfica del Júcar" (CHJ) was also engaged during the co-development of the climate service. This public entity is attached to the national government of Spain as an autonomous body under the Ministry for Ecological Transition and Demographic Challenge. The bilateral meetings with representatives from this institution were held during May 2019 in the main office of the entity, located in Valencia. The operating officer and several engineers involved in the management of the channel responsible for providing water to the city of Valencia and its surroundings assisted the meetings. The contact with the water treatment company afterwards has continued for data and knowledge exchange through email. Finally, due to the scope of the climate change impact on the region, agricultural associations were contacted and several meetings were held between 2018 and 2019 with representatives of the irrigation communities of the farmlands surrounding the city of Valencia. The purpose of these meetings was to show them the predicted water resources availability obtained by our models under the different climate change scenarios, in order to explore the possibility of co-creating an ad-hoc climate service. However, this line of work was not further advanced due to time constraints and the increasing complexity of the climate service already under development.

Step 3 of the process started by identifying the required resources for the development of the service. Key activities and partners were also identified.

STEP 3
Key resources: - Global and regional climate projections (selected scenarios: RCP4.5 and 8.5 for the 2020-2040 and 2040-2070 periods). Obtained from the Copernicus open repository and EURO-CORDEX (Copernicus Climate Change Service, 2017; Jacob et al., 2014) - Historical data of natural inflows on the region's different sub-basins from 1970 to 2013 (MAPAMA, 2018) - Historical data of the reservoir storage, water demands and main users of the system - Data of environmental flows for the Jucar and Cabriel Rivers. - Scientific publications and previous research on the operating rules of the system during the 2003-2013 period - Historical data on the water quality parameters (nutrients, phytoplankton and physical parameters) - Data on the water infrastructures that affect the user segment operation - Human resources: 2 professors, 2 postdocs, 1 pre-doc student and additional support of EMIVASA employees during the late stage of the project - Material resources: 4 computers, licenses for modelling software (Vensim Pro, GAMS, Aquatool/GESCAL) - Physical resources for the construction of a testing scaled-down model of the plant by Aguas de Valencia - Data on the cost of the different water treatments for EMIVASA - Information about potential innovations for the water treatment **Key activities:** - Data gathering and processing - Downscaling and bias-correction for climate projections. Comparison with the reference period for the region and selection of regional/global combination - Development of hydrological model of the Jucar River basin at the sub-basin scale - Scientific literature revision for the creation of both the water resource management

model and the water quality model

- Development of a basin-scale water resource management simulation model to assess future water availability in the region
- Periodical meetings with the final user to select the water quality parameters of interest and to obtain additional data of water quality
- Periodical meetings with the final user to report on advancements and receive validation and feedback
- Development of a water quality model of the Tous reservoir
- Internal exchange between the water management development team and the water quality modelling team to coordinate the development and ensure inputs/outputs compatibility
- Results processing. Models results were processed and statistical analysis was developed to assess the impact of every qualitative and quantitative scenario for the future water resource
- Design and construction of a scaled-down model of the water treatment plant (done by EMIVASA)
- Operation of the testing plant under the scenarios provided by the models (done by EMIVASA)

Key partners:

- EMIVASA: as the final user of the climate service, their cooperation for the co-design of the service is capital for the success of the project. They also provided data on water quality for the Tous reservoir and the Jucar-Turia Channel
- *Confederación Hidrográfica del Júcar*: as the water authority of the basin, they are the main data providers for hydrological information. Including some data of water quality for Tous.
- *Comunidad General de Usuarios del Canal Jucar-Turia*: this irrigation community provided information about the Jucar-Turia channel configuration and its operation
- Valencian municipality: they provided data of water quality for the Tous reservoir and the Jucar-Turia Channel

- Coordinated Regional Climate Downscaling Experiment EURO-CORDEX (Jacob et al., 2014) and Copernicus Climate Change Service (2017) : to obtain the regional and global raw climate projections data
- AEMET (Spanish National Meteorological and Climate Agency, 2019) for the data on precipitation and temperature in the region

Historical data of natural inflows in the region's different sub-basins was obtained from the online repository of the Spanish Ministry of Agriculture, Fisheries, Food and Environment (MAPAMA, 2018). It was used to calibrate the water management model, in combination with past data on the reservoir storage, water demands, environmental flows and main users of the Jucar system (Confederación Hidrográfica del Júcar, 2019). Historical data about the water quality parameters of the Tous reservoir (Confederación Hidrográfica del Júcar, 2019) was collected and processed to create the water quality models. Key partners were contacted to access not freely available data of infrastructures such as the Tous reservoir and the Jucar-Turia channel. The output of the water management model running the selected climate change scenarios was introduced to the water quality model to estimate the effect of climate change both in terms of water quality and quantity. The initial results of the models were processed and presented to the end-user to validate them and to receive feedback on different variables and scenarios of interest.

4.3 Summary of results obtained by the co-designed climate service

The co-designed climate service developed for the water utility company of Valencia obtained numerous results during the 3-year process of its creation. The first valuable results were the ones that described the effect of climate change on the water availability for EMIVASA and the system as a whole. The results for the different climate scenarios were processed and presented in figures and graphics (Fig. 8).

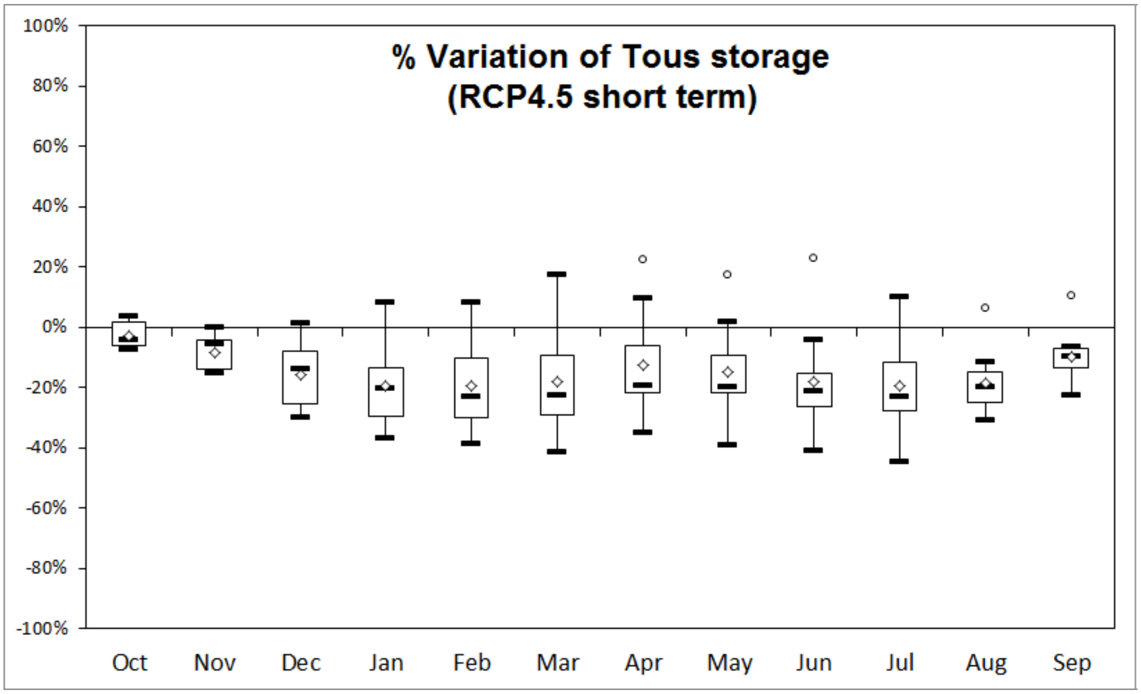

Figure 18. Average monthly variation of Tous water storage for the RCP4.5 short-term scenario compared to the reference period.

The water management model developed was able to show not only the water storage in the different reservoirs of the system, including Tous, but also the monthly inflows and outflows of the three reservoirs of the system and the water shortages that each typology of water user suffered during the different RCP scenarios. The predicted reduction in water availability does not compromise the water supply to Valencia and its metropolitan area in terms of water quantity. However, it puts in jeopardy the water supply to other stakeholders of the Jucar River system, particularly agricultural users. Furthermore, analyzing the effect that the forecasted available water resources and the new climate conditions may have on the quality of the raw water storage in Tous required a previous assessment of the water resources availability in the whole basin.

The second set of results of the climate service analyzed the impact that climate change will have in the quality of water. The analysis focused on the parameters of most interest for EMIVASA. The complete list of parameters and results that have been obtained is collected in Table 1. Results were obtained for the RCP4.5 and 8.5 scenarios in a monthly time step. For the water quality parameters, results were obtained separately for the hypolimnion and the epilimnion of the Tous reservoir. All simulations used the same reference period 1970-2000 as comparison to show the variation that each climate projection introduces. The chain of models developed to achieve these results include:

1) System dynamics model to simulate the management of the basin and fed by the climate projection data achieved for the main water inflows of the basin (Rubio et al., 2020);
2) A water quality model of Tous reservoir developed using the SIMGES module from Aquatool (Andreu et al., 1996) and able to simulate the interaction of physical, organic and chemical components present in water.
3) A fuzzy logic model of the Tous reservoir to estimate the concentration of Methylisoborneol (MIB) and geosmin, the two main organisms responsible for causing unpleasant taste and odor to the water of Tous.

PARAMETER	WATER BODY	UNITS	RESULTS	
			2020-2040	2040-2070
Water storage	Jucar basin	Mm³	-22%	-41%
Water storage	Tous	Mm³	-11%	-23%
Water temperature	Tous	ºC	+1ºC	+1.5ºC
Chlorophyll *a*	Tous	µg/l	x4 peak concentration	x10 peak concentration
Oxygen dissolved	Tous	mg/l	+15% anoxia events	+25% anoxia events
Organic nitrogen	Tous	mg/l	x10 concentration on bloom events	x12 concentration on bloom events

Ammonium	Tous	mg/l	Not significant	Not significant
Nitrates	Tous	mg/l	Not significant	Not significant
Total phosphorus	Tous	mg/l	Not significant	Not significant
Mib	Tous	µg/l	+40% events +45% concentration	+60% events +55% concentration
Geosmin	Tous	µg/l	+20%	+30%

Table 1. Main parameters and summary of results obtained by the climate service.

The short and medium-term results presented in Table 1 are average results obtained for the RCP4.5 and 8.5 climate scenarios. The detailed climate service results provided to EMIVASA, however, do differentiate between different RCP scenarios, climate projections, monthly averages and seasonal variation.

In terms of water quality, the concentrations of ammonium, nitrates and, total phosphorus do not increase significantly due to the fast assimilation of these nutrients by the more abundant phytoplankton. The phytoplankton, measured by the Chlorophyll a concentration, benefits from the increasing water temperatures and nitrogen concentration. The blooms of Chlorophyll a during the warmer months (spring and summer) will require from EMIVASA to adapt the current treatment facilities and methodologies. The trophic state of the Tous reservoir will change from the optimal oligotrophic state to mesotrophic. MIB concentration increasing by 50% in some scenarios would not be manageable by the existing water treatment facilities, and would require the adaptation of the water treatment plant. The same issue arises from the increasing geosmin concentrations. The optimization of the water treatment processes for the removal of MIB and geosmin is an on-going line of research by EMIVASA that the co-designed climate service has further justified. Currently, the results obtained by the co-created climate service are being used to assess the cost of adapting the existing water treatment processes to the new climate scenarios. To do so, the testing plant is being used to assess how the present technologies handle the predicted raw water. Additionally, operational and technological changes are being analyzed to select the most efficient and cost-effective solutions. The collaboration between EMIVASA and the climate service providers is continuing in the search of the best alternatives for the adaptation of the water treatment plant.

5 Conclusions

This article highlights the value of involving users in the co-design of climate services to fully comprehend their system understanding, previous assumptions and specific demands for climate data and information. Additionally, users' knowledge has been integrated into the process supporting a truly transdisciplinary outcome. In this article, we propose to use a business model perspective to support the co-design of climate services, and we explain how the business-focus approach has been applied to develop a climate service for the water utility company of the city of Valencia, Spain. The resulting climate service is a customized product that has answered the specific needs and requirements of the water utility company. The integration of the user knowledge during the co-design phase was essential to find the appropriate spatial and time scales. Engaging the user in the co-design process also allowed to discover the most critical water infrastructure for the modelling analysis. During the co-development, the end-user provided essential data, feedback and validation. Additionally, they built and started to operate a testing water treatment plant to assess the impact of the new raw water into their system. The successful application of the approach to the described case study facilitates replication and learning by other actors interested in climate service development. In the water utility sector, we pave the way for recreating the service in other areas with similar conditions, replicating the co-design process and learning from the insights provided.

The way we have engaged stakeholders in the co-design has provided multiple advantages. Firstly, it has supported constructive and targeted discussions relevant to the identification of needs for climate services design tailored specifically to the user. Secondly, it has allowed the integration of local knowledge in the process supporting the integration of a variety of data. Thirdly, co-designing the services this way, we avoided user rejection on the produced service. Finally, the process itself has promoted awareness and collective learning of those participating in the co-design.

The development of climate services that generate knowledge for the adaptation is essential in many sectors that need to carefully plan in advance their adaptation pathway. In the case of the water utility industry, future water quality problems may require infrastructure changes and additional investments in research to find the best solutions for treating and delivering tap water safely. In this context, climate services allow to contemplate future scenarios in advance, smoothing the decision-making process for adaptation, and the potential success of any adaptation strategies or actions (Bowyer et al., 2014).

The business model approach here introduced has not addressed in detail the economic side of business models. As mentioned in section 3.1 traditional CBA is hardly applicable to climate change and the topic of who has the economic responsibility for climate change adaptation is an issue that would deserve its own analysis. Particularly when talking about private-sector companies that supply critical services or infrastructures for public benefits, such as water supply companies. Many authors (Zürn et al., 2005; Bruijne and Van Eeten, 2007) agree that the ultimate responsibility is on the state, because the state is responsible for public security. However, private businesses that provide public services are subject to public scrutiny regarding climate change adaptation, as they hold a secondary responsibility as operators. Previous authors have considered that climate services that serve a public good are anticipated to be funded in large part by the taxpayer (Brasseur et al., 2016). These are some reasons why the financial aspect of business models is not as significant for climate service development as it is for traditional private plans. However, we must seek to explore the use of our business focus approach for the development of climate services in the private sector with a greater focus on the cost and revenue streams. To do so, new CBA methods able to capture externalities and the public value of climate adaptation may be required.

The application of the INNOVA climate service development approach to the Valencia water supply case shows how public and private collaboration can be a powerful instrument for climate change adaptation. The co-creation of customized and useful climate services require the coordination of climate service providers and users. As shown in the example, a business model approach can help to bridge the gap between scientific and practice-based knowledge, supporting climate service development and climate change adaptation.

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3. GENERAL DISCUSSION OF RESULTS

The main findings of the articles have been discussed in the results section of each of the pieces. Overall, the three papers highlight the importance of integrating multiple disciplines and involving stakeholders in the development and use of decision support systems and climate services for managing and adapting to the impacts of climate change. The DSS and climate service in the Jucar River basin demonstrate the potential of these tools for simulating and analysing the interactions, feedbacks, and impacts of different variables and strategies on the system, and for assisting decision-makers in proactively planning for and responding to changing climate and social conditions. The climate services developed for the water utility company in Valencia, Spain, combines the river basin and reservoir scales, and includes relevant raw water quality parameters for the evaluation of the climate change impact in the water utility system. The service is intended to be a valuable tool for water utility managers to make better-informed decisions in their process of adapting to climate change. Furthermore, the process followed in the development of the service can be adapted to other water utilities, subject to the availability of sufficient data and the ability of the model to reproduce the relevant climate, hydrology, and system features. The collaboration between the university and the water utility company has also led to ongoing works for improving the representation of water quality processes in the model under different climate conditions and scenarios. Finally, the business model approach taken for the co-design of the climate service was explained and generalized, trying to emphasize the value of involving users in the process of developing climate services that are tailored to their specific needs and requirements, and that integrate local knowledge and expertise. These approaches and tools can be replicated and adapted for the development of climate services in other industries and regions, subject to the availability of sufficient data and understanding of the system features.

Results showed how the creation of climate services can be improved by implicating the final users in their design. By doing so, climate services can be tailored to specific needs and requirements of the final users, resulting in services that are better suited to their specific needs and contexts. The integration of local knowledge allows local and specialized expertise to be introduced into the development of climate services, leading to a more comprehensive and relevant product. Engaging stakeholders in the co-creation process can lead to increased buy-in and acceptance of the resulting climate service, as stakeholders feel more invested in and connected to the product. Co-creation can facilitate collective learning among stakeholders, as they work together to identify challenges and opportunities and share knowledge and experiences. All the advantages from co-creation allows for the integration of feedback and validation from stakeholders during the development process, which can help to ensure that the resulting climate service is more adaptable and responsive to changing conditions.

Overall, the results show that co-creation of climate services can lead to more targeted, relevant, and effective products that are better able to meet the needs of stakeholders and assist them in adapting to the impacts of climate change.

System dynamics is a methodology that, using computer-based models to simulate and analyse the interactions and feedbacks between variables in complex systems over time, can be advantageous for the development of customized climate services that integrate the knowledge, needs, and requirements of final users. The benefits of this methodology come in several ways:

- Holistic perspective: System dynamics takes a holistic perspective on complex systems, considering the interconnections and feedbacks between different elements and disciplines. This allows for the integration of a wide range of variables and considerations into the model, including the knowledge, needs, and requirements of final users.
- Dynamic simulation: System dynamics allows for the simulation and analysis of the change in system variables over time, which can be useful for understanding the impacts of different scenarios or interventions on the system. This can help to inform the development of customized climate services that are tailored to the specific needs and requirements of final users.
- Modular structure: System dynamics models are often structured in modular form, which allows for the integration of different components or subsystems into the model as needed. This can facilitate the customization of climate services by allowing for the inclusion of specific variables or processes that are relevant to the needs and requirements of final users.
- Informed decision-making: The use of system dynamics models can provide a scientifically defensible basis for decision-making, by simulating and analysing the

potential impacts of different options on the system. This can assist final users in making more informed decisions about how to respond to the impacts.

The results of the climate service developed for the water utility company in Valencia demonstrate the advantages of co-creating climate services in several ways. Some of the key benefits of co-creation in this case include:

- Customized to specific needs: The climate service was developed through a process of co-creation with the water utility company, allowing for the integration of the company's specific needs and requirements into the service. This resulted in a customized product that was tailored to the company's specific needs and contexts, including water quality parameters of interest, an adequate time scale for the analysis and the definition of the optimal sampling points for the analysis.
- Integration of local knowledge: The co-creation process allowed for the integration of local knowledge and expertise from the water utility company into the development of the climate service. This helped to ensure that the service was more relevant and comprehensive, and better able to address the company's specific challenges and needs. This knowledge was essential for the evaluation of the impact that climate change caused on the system, both in terms of water availability and water quality. The early design and first selection of alternatives for the management of the system under the new expected conditions is also a result of the integration of the expert knowledge into the process.
- Improved buy-in and acceptance: By engaging the water utility company in the co-creation process, we were able to build buy-in and acceptance of the resulting climate service among the company's decision-makers. This increased the likelihood that the service would be used and effectively applied by the company. This is because co-creation involves collaboration and mutual decision-making, which can foster a sense of ownership and commitment to the resulting climate service.

  The development of a strong working relationship and trust between the company and the university has led to an ongoing collaboration through the SÀPIDES project

(INNEST/2021/276, “Predicción de compuestos sápidos en el agua prepotable para la mejora de su gestión y adaptación al cambio climático”). This project takes the results obtained in the described work and further inspects how an early warning system could improve the management that the water treatment plant carries out for sapid compounds.

- Enhanced collective learning: The co-creation process facilitated collective learning among the research team and the water utility company, as they worked together to identify challenges and opportunities and share knowledge and experiences. This contributed to the overall effectiveness and impact of the climate service.

  Collective learning also means learning from the partner in the co-creation process. The increased familiarity with each other's work styles, processes, and preferences has allowed a better understanding of how the other operates. The communication channels created during the project allowed identifying the most effective ways to communicate establishing protocols for decision-making and problem-solving, and establishing lines of communication between relevant individuals and departments.
- Improved adaptability: Finally, the co-creation process allowed for the integration of feedback and validation from the water utility company during the development of the climate service, which helped to ensure that the service was more adaptable and responsive to changing conditions.

Overall, the results of the climate service in Valencia demonstrate the value of co-creating climate services with stakeholders, as it allows for the development of customized, relevant, and effective products that are better able to meet the need. The process, when successful, also allows the development of trust and confidence in each other's capabilities. This can result in future collaboration in new projects, as the perceived uncertainty and risk are reduced and the perception of higher likelihood of successful collaboration is increased.

4. CONCLUSIONS

The three main sections of this work demonstrate the potential of co-creation for the development of climate services, the use of system dynamics as a methodology for developing such services and models, and the use of business models based approaches for the co-development of climate services. All three contributions contribute to the research of processes that help towards the development of effective and context-relevant climate change adaptation strategies.

Co-creation involves the active engagement of stakeholders in the development process, allowing for the integration of their knowledge, needs, and requirements into the resulting product. This can lead to more targeted, relevant, and effective climate services that are better able to meet the needs of stakeholders and assist them in adapting to the impacts of climate change. The case study of the climate service developed for the water utility company in Valencia illustrates the potential benefits of co-creation, including a customized product tailored to specific needs, the integration of local knowledge, improved buy-in and acceptance, enhanced collective learning, and improved adaptability.

System dynamics is a methodology that uses computer-based models to simulate and analyse the interactions and feedbacks between variables in complex systems over time. This approach can be advantageous for the development of climate services because it takes a holistic perspective on complex systems, allows for the simulation and analysis of change over time, has a modular structure that facilitates customization, and can provide a scientifically defensible basis for decision-making. The papers describe the use of system dynamics in the development of a system dynamics decision support system (DSS) for drought management in the Jucar River system and a climate service for the water utility company in Valencia, both of which demonstrate the potential of this methodology for the development of customized climate services that integrate the knowledge, needs, and requirements of stakeholders.

System dynamics models can be either quantitative or qualitative, depending on the type of data and information that is used to build the model. Quantitative system dynamics models are built using numerical data and mathematical equations to represent the relationships and dynamics within a system. These models can be used to make predictions about how the system will behave over time based on the data inputs. Qualitative system dynamics models, on the other hand, are built using qualitative data and descriptive language to represent the relationships and dynamics within a system. These models may not be as precise as quantitative models, but they can be useful for understanding complex systems and identifying trends and potential areas for improvement or intervention. Both quantitative and qualitative system dynamics models can be useful for understanding and analysing complex systems, depending on the goals of the analysis and the type of data and information that is available, and to integrate interdisciplinarity in a single modelling framework. Interdisciplinarity can not only help to better understand complex systems, but it can also provide a more comprehensive comprehension of the system being studied and help identify relationships and feedbacks, as well as incorporate a wider range of data and knowledge from different fields, resulting in a more accurate representation of the system being studied. In some cases, qualitative and quantitative information, may be necessary to use both types of models to fully understand the dynamics of a system.

In a climate service where the inputs are largely qualitative, qualitative models are better suited to representing complex systems using descriptive language and non-numerical data. Qualitative system dynamics models allow introducing narratives and nuanced considerations expressed by the users into the modelling framework. This can be particularly useful when the focus of the analysis is on understanding the underlying dynamics and relationships within a system, and for communicating the results of the analysis to a wider audience. There are a variety of methods and tools that can be used to build qualitative system dynamics models, including causal loop diagrams, stock and flow diagrams, and scenario planning. These tools can be used to represent the relationships between different factors and variables within the system, and to identify feedback loops and nonlinear dynamics that may be influencing the system's behaviour.

Mixing qualitative and quantitative system dynamics models can be a useful way to take advantage of the strengths of both types of models and to get a more complete understanding of a complex system. Hybrid models combine both qualitative and quantitative elements in a single model. For example, using qualitative descriptions of the relationships between variables, but incorporate numerical data to represent the magnitude of these relationships. Hybrid models can be useful for understanding systems where both qualitative and quantitative data are available, and can provide a more complete and nuanced understanding of the system's dynamics. There are several ways to mix qualitative and quantitative models. Another approach to mix qualitative and quantitative data is to build a qualitative model first, and then use it as a basis for developing a more detailed and precise quantitative model. The qualitative model might be used to identify key drivers and relationships within the system, while a quantitative model could be used to make more precise predictions about the system's behaviour.

Overall, system dynamics models can be a useful tool for co-creating climate services that rely on quantitative data (such as climate projections or water demand information) and qualitative inputs from the final user, as they can help to capture and represent the complexity and nuances of these systems in a way that is both meaningful and actionable. System dynamics models can be used to explore different scenarios and "what-if" scenarios, which can help to identify the most effective strategies for addressing climate-related challenges. This can be particularly useful in the co-creation process, as it can help to identify options and trade-offs that may not be apparent from more traditional approaches.

Overall, the results reached in this work are highly policy-relevant, as they aim to contribute to the development of effective strategies for climate change adaptation in the water sector. By promoting and involving the final users in the co-creation process of the climate services, we can help to ensure that climate services are tailored to the specific needs and priorities of the users, which can increase their relevance and effectiveness. Additionally, it can help to ensure that adaptation strategies are better aligned with the needs of different stakeholders, and that they are designed with a focus on building resilience and capacity within organizations and communities. By involving users and other stakeholders in the model-building process, it can be easier to understand their needs and priorities, and to build buy-in and acceptance of the resulting service. This can be particularly important in the climate services field, where the success of a service often depends on the extent to which it is used and applied by the intended users, and where the needs and priorities of different user groups can vary significantly.

Additionally, collaborative model-building can help to build strong working relationships and partnerships between the providers of climate services and their users. This can also help to increase transparency and accountability, as the decision-making process is more open and inclusive. This can be important in the climate services field, where there may be a need to demonstrate the value and impact of the service to different stakeholders. The co-creation process can also be beneficial in the long term, as it can facilitate ongoing collaboration and support for the climate service.

5. FURTHER RESEARCH

The overall methodologies explained in this Thesis, co-creation and system dynamics can be a powerful tool for developing models and services that diverge from the explained climate services. For instance, the Water, Energy, Food and Environment (WEFE) nexus can be analysed from a holistic point of view using a SD to aggregate the varied views of the WEFE nexus from a multi-sectorial and multi-stakeholder perspective (González-Rosell et al., 2020; Susnik et al., 2021). This can be particularly useful in identifying unexpected relationship between policies and sector, trade-offs and potential unintended consequences of different actions.

System dynamics models can also be used as a decision-support tool for the long-term planning of policies and resources allotment in sector such as water utility and water management to help stakeholders and policy makers to make informed choices about how to manage, allocate and utilize resources. This can be valuable in cases where there are competing demands for resources, or where there are complex and interconnected relationships between different resources.

Additionally, climate services can play a valuable role in the adaptation of Mediterranean water resource system to climate and global change. They can help stakeholders to identify and understand the risks and challenges they are facing, and to start designing the most appropriate adaptation strategies. In the Mediterranean context, climate services can focus on sector that are particularly vulnerable to the increasing temperatures and reduced precipitation. The water utility sector is the main sector analysed in this study. The analysis of the effect of climate change not only on the projected amount of future available water, but also on the quality of said resource and the interaction of water quality and quantity in the context of climate change is a topic that has not being sufficiently analysed in the past and that requires further research. Anticipating the effect that climate change may have on the qualitative status of surface water may help us prevent serious consequences for the health and well-being of both people and the environment.

Climate services for the adaptation of agriculture to the future scenarios are the most likely to succeed in the coming years, due to the severe impact that climate change will have on some of the most productive agricultural regions in the world and the new opportunities that it will provide to some currently under-utilised land. Climate services for ecosystems, and water utilities are likely to also attract attention. Certain climate services can help policy makers at the national to continental scales to prioritize their adaptation efforts and to allocate resources more effectively, as well as to identify the most effective and cost-effective measures for mitigating risks and vulnerabilities.

Over the past few years, there has been a growth in the exchange of knowledge regarding the co-design and co-production of climate services (Larosa & Mysiak, 2019). This is an important development, as it highlights the growing recognition of the need for user-driven climate services. However, it is important to establish mechanisms for ongoing feedback and review of climate services. This can involve regular engagement with users to assess the effectiveness of the service and identify areas for improvement. It can also involve ongoing monitoring of climate data and trends to ensure that the co-developed services remain relevant and up-to-date. Another important aspect of maintaining the relevance of climate services is to ensure that they are flexible and adaptable to changing needs and circumstances. This may require ongoing refinement and adaptation of the service over time, based on feedback from users and changes in the climate and other relevant factors and data, such as new data and projections supplied by the most recent IPCC reports.

Finally, the surge of co-creation of climate services can facilitate collaboration and knowledge-sharing among stakeholders in the Mediterranean water basin, including governments, NGOs, academics, and the private sector. This can help to build capacity and expertise in adaptation planning and implementation and can also facilitate the exchange of best practices and lessons learned among users facing similar problems.

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