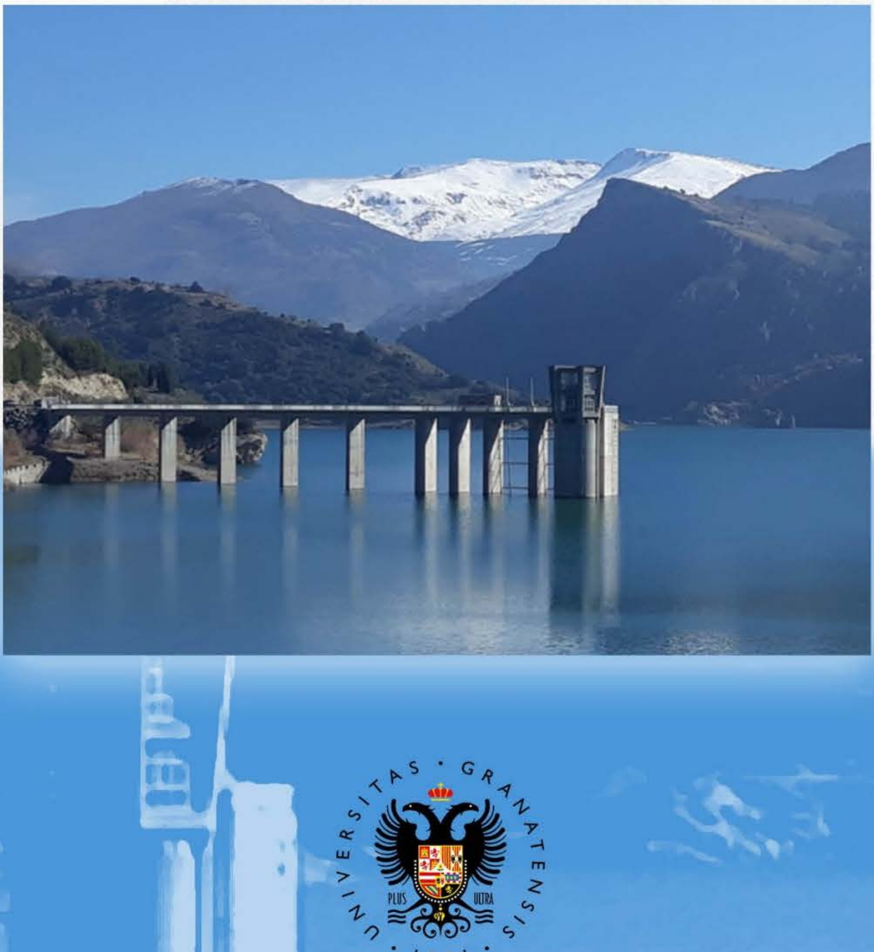
DOCTORAL THESIS

TOOLS FOR DROUGHT MANAGEMENT AND WATER COST RECOVERY THAT ENCOURAGE AN EFFICIENT AND SUSTAINABLE WATER USE

Carmen Hervás Gámez



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TOOLS FOR DROUGHT MANAGEMENT AND WATER COST RECOVERY THAT ENCOURAGE AN EFFICIENT AND SUSTAINABLE WATER USE

Memoria presentada por Dña. Carmen Hervás Gámez para
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Caminante, son tus huellas
el camino y nada más;
Caminante, no hay camino,
se hace camino al andar.
Al andar se hace el camino,
y al volver la vista atrás
se ve la senda que nunca
se ha de volver a pisar.
Caminante no hay camino
sino estelas en la mar.

Antonio Machado (*Proverbios y cantares -XXIX*)

A la memoria de mis queridos abuelos Andrés, Juan y Carmen,

A mi querida abuela Catalina y adorable tía Inma,

A mis amados padres Diego y Dolores,

A mis amados hermanos, Juan Diego y Andrés,

Por estar siempre, acompañarme en mi camino y guiarme
para ser mejor caminante.

La doctoranda **Dª. Carmen Hervás Gámez** y el director de la tesis **Dr. D. Fernando Delgado Ramos**:

Garantizamos, al firmar esta tesis doctoral, que el trabajo ha sido realizado por la doctoranda bajo la dirección del director de la tesis y hasta donde nuestro conocimiento alcanza, en la realización del trabajo, se han respetado los derechos de otros autores a ser citados, cuando se han utilizado sus resultados o publicaciones.

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Last but not least, I would particularly like to thank my family because without them this would not have been possible. I feel extremely fortunate to have been raised in my family. They have taught me vital ethical values (such as respect, responsibility, empathy, loyalty, honesty and fairness) that have greatly helped me throughout my life. I am extremely grateful for their unconditional love, care and support throughout my life, but especially during my PhD period (during which I returned home after almost eight years living in another country and had to start building a new life). I am profoundly grateful to my dad for his immense help and unceasing encouragement on any occasion, but especially when I needed him most during the difficult times. Because I know that I can always rely on them and that is an enormous privilege.

AUTHOR'S BIOGRAPHICAL SKETCH

I graduated from the "*Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos*" (University of Granada, Spain) with a MEng in Civil Engineering in 2009. Later on, I achieved my MSc in Water Resources Technology and Management at the University of Birmingham in England (awarded with Distinction, 2011). These academic achievements provided me with a good understanding and deep insight into Water Engineering, including river flow fundamentals, hydrology, flooding, water resources management, water quality, drainage and design of water infrastructures.

Fortunately, I had the golden opportunity to develop this theoretical knowledge further and put it into practice by working for two leading engineering consultancy firms in the UK: Peter Brett Associates (from July 2011 to April 2016) and Mott McDonald (from May 2016 to October 2017). During this period, I gained considerable professional expertise across a wide range of engineering disciplines and played different roles in diverse multidisciplinary project teams in numerous development schemes all across the UK.

I delivered projects from feasibility (masterplanning) conceptual design stage to construction stage for different residential, commercial and industrial schemes, facing numerous site-specific constraints. Particular and relevant experience includes the preparation of flood risk assessments and flood compensation strategies, as well as drainage design (wastewater/stormwater) and Sustainable Drainage Systems.

Apart from the technical work, I also performed the role of Project Manager in some projects. I was the main point of contact for the Client, prepared contractual documentation, managed internal project teams (civils, structures, geo, hydro, environmental, etc.), co-ordinated external project teams (planners, architects, landscape architects, ecologists, etc.) and key Stakeholders (Local Water Authorities, Local Highway Authorities, Lead Local Flood Authorities, Environment Agency, Highways England, etc.), organised meetings, kept track of actions, issues, risks, etc.

As a result of my work, all the technical, commercial, managerial and organizational development objectives set out by the Institution of Civil Engineers in the UK (https://www.ice.org.uk/) were signed off as part of my personal Training Agreement.

In 2017, I was offered the fantastic opportunity to join the research project titled "*GRwaterDSS Decision Supporting System for the Upper Genil River Water Resources Management*". This was commissioned by Emasagra (Local Water Authority of Granada and metropolitan area) to the University of Granada in collaboration with CETAQUA ("*Fundación Centro Andaluz de Investigaciones del Agua*").

It was at the end of 2017 when my career path changed from engineering design and advice (mainly in flooding and drainage) to the research in the area of drought management, and the exciting adventure of developing my PhD started…

SUMMARY

Droughts are natural phenomena that affect countries throughout the planet, albeit unevenly. The duration, magnitude and frequency are specific to each climate region and determine the impact on water resources and ultimately, the impact on the rest of water-dependent sectors (environment, society, economy). According to climate change projections, it is expected that they will become more frequent and intense as the 21st century progresses.

This doctoral thesis assesses and develops different tools for improving drought management by providing: (1) a critical review of the strengths and weaknesses of European and Spanish water legislation and planning policies; (2) a critical analysis of the limitations and practical implications of applying the most recent 2018 Guadalquivir River Basin (GRB) Drought Management Plan (DMP), with a special focus on the methodological approach and operational framework; (3) a critical assessment of the real influence of the public participation and consultation process in shaping the 2018 GRB DMP; (4) a practical streamflow forecasting tool to support strategic water decisions; and (5) a hydro-economic methodology to provide transparency in the water cost recovery calculations and identify potential cross-subsidies among water users.

At the EU level, droughts are succinctly dealt with in the Water Framework Directive (WFD 2000/60 / EC). In fact, the elaboration of DMPs is not compulsory but only recommended (by the 2007 EC Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*") as supplementary documents of the River Basin Management Plans (RBMPs). On the other hand, even though there has been a significant improvement in developing drought data and management tools (EDR, EDII, EDO, WEI+, etc.) which are instructive and informative, there are still key challenges related to the practical integration and application of this information as well as its periodic upgrade (so that EU members could maximise their use in practice).

In Spain, the preparation of DMPs is mandatory in line with art. 27 of Law 10/2001, of July 5, of the National Hydrological Plan. The first DMPs for all inter-community river basins were approved in 2007 and ten years later, these were revised and then adopted in December 2018. Important innovative aspects have been integrated such as the objective differentiation of droughts events (natural climatic events) from water scarcity situations (anthropic interaction with water resources) by setting out a different diagnosis system (indicators, thresholds and phases) and measures to deal with each phenomenon separately. The great advantage of this common methodology is that diagnosis results are comparable across all river sub-basins, and similar measures should be applied. This highlights not only the significant strides made by all River Basin Authorities (RBAs) in Spain towards the harmonization of technical procedures but also an effective intergovernmental coordination between all the organizations and processes involved at the political, technical, and institutional levels. Nevertheless, important technical aspects (such as the methodology applied to calculate the water scarcity thresholds) remain practically unchanged and hardly differ from those used over a decade ago in the first 2007 DMPs.

At the GRB management level, significant deficiencies have been found in the 2018 DMP, including the following: (i) streamflow forecast models (or seasonal climate forecasts) are not used to improve drought management; (ii) specific technical, environmental, and economic assessments are not provided to support the proposed drought and water scarcity management measures; and (iii) a sound climate change assessment is not included. An alternative methodology to calculate the water scarcity thresholds has been proposed, and the benefits of using those in combination with streamflow forecasting tools have been demonstrated.

Additionally, it was found that the **public participation** (PP) and stakeholder involvement process had, in reality, a negligible influence in shaping the 2018 GRB DMP. Only 8% of the total number of comments received was actually accepted. From this small proportion, the majority corresponded to typo, conceptual or calculation errors, while only a minority were related to improvements in the drought management strategy. This means that there was a very limited incorporation of the local knowledge and experience of participants, which highlights the absence of a truly inclusive participation strategy. Nonetheless, PP should proactively involve all interested parties at an early stage when it is still possible to alter the strategy. This could bring significant benefits, given that water users would thus assume more ownership and responsibility in the search for comprehensive solutions.

To address one of the previously mentioned key technical deficiencies found in the 2018 GRB DMP, **a practical and robust streamflow forecasting tool** was developed to forecast monthly and annual streamflows within the current hydrological year. This innovative, user-guided, and low-cost procedure combines the use of well-known regression analysis techniques, the two-parameter Gamma continuous cumulative probability distribution function and the Monte Carlo method. The results obtained from this model have demonstrated to be sufficiently reliable and robust to support strategic water decisions and build drought risk-reduction strategies. Additionally, this new tool is simple and can be easily used by non-technical experts such as authorities, decision-makers, managers or even water users. Therefore, it overcomes one of the major limitations associated with the use of this type of models.

Another significant obstacle to achieving an efficient and sustainable use of water resources in Spain was the lack of transparency in water-cost recovery calculations (highlighted in the fourth European Commission report in 2015). **A hydro-economic method has been developed to increase transparency in the water cost recovery calculations and identify potential cross-subsidies among water users.** This has been applied to the Upper Genil River case in the GRB. A tool has been created that calculates the Canon of Regulation (CR) for any year of the historical series under different assumptions. The results revealed that the household user pays an additional average annual cost of approximately €6,863 per cubic hectometre for having the theoretical priority of water use over the agricultural water user. However, this additional cost does not translate into a significant increase in the guarantee of water supply.

The results obtained in this PhD thesis could be useful to water authorities, decision-makers, managers, policy-makers and water users in other similar drought-prone and water-scarce basins. These could also be considered during the revision of the WFD and Spanish Water Legislation, as well as in the development of the 3rd cycle RBMPs in the EU.

RESUMEN

Las sequías son fenómenos climáticos naturales que afectan a países de todo el planeta, aunque de manera desigual. Su duración, magnitud y frecuencia son específicas de cada región y determinarán el impacto causado a los recursos hídricos, y en última instancia, el grado de afección al resto de esferas (económicas, sociales y medioambientales) que dependen directa o indirectamente del suministro de agua. Según las proyecciones del cambio climático, se espera que las sequías sean cada vez más frecuentes e intensas conforme avance el siglo XXI.

Esta tesis doctoral evalúa y propone diferentes herramientas para mejorar la gestión de sequías y situaciones de escasez, a través de: (1) una revisión crítica de la legislación y políticas de planificación del agua europeas y españolas; (2) un análisis crítico de las limitaciones e implicaciones prácticas de la aplicación del Plan Especial de Sequía (PES) de la Demarcación Hidrográfica del Guadalquivir (DHG) adoptado en 2018; (3) una evaluación crítica de la influencia real que tuvieron las alegaciones presentadas por las partes interesadas en el PES-DHG 2018; (4) una herramienta práctica de predicción de aportaciones mensuales y anuales dentro del año hidrológico en curso, para ayudar en la toma de decisiones estratégicas; y (5) una evaluación hidro-económica que aporta transparencia en los cálculos de recuperación de los costes del agua a nivel de sub-cuenca, así como ayuda a identificar la eficiencia económica en la asignación del recurso hídrico y la posible existencia de subsidios cruzados entre los distintos usuarios de un sistema.

A nivel europeo, los fenómenos de sequías se tratan de manera muy superficial en la Directiva Marco del Agua (2000/60/CE). De hecho, no fue hasta 2007, con la publicación del comunicado europeo *"Afrontar el desafío de la escasez de agua y la sequía en la Unión Europea"*, cuando se introduce a título de recomendación la elaboración de Planes de Sequía. Por otro lado, a pesar de la mejora significativa en el desarrollo de herramientas de predicción y monitorización de sequías (EDR, EDII, EDO, WEI +, etc.), todavía existen desafíos clave relacionados con la aplicación práctica e integración a nivel de cuenca, así como su mantenimiento y actualización (para que se pueda maximizar su uso).

En España, la elaboración de Planes de Sequía es obligatoria (art.27 de la Ley 10/2001, de 5 de julio, del Plan Hidrológico Nacional). Los primeros PES para las demarcaciones hidrográficas de ámbito intercomunitario fueron aprobados en 2007. Diez años más tarde, aquellos PES han sido actualizados y finalmente adoptados en diciembre de 2018. Se han integrado aspectos innovadores importantes, como la clara diferenciación entre sequías (fenómenos climáticos naturales) y situaciones de escasez (debido a la interacción antrópica con los recursos hídricos) al establecer un sistema de diagnóstico (indicadores, umbrales y fases) y medidas diferentes para gestionar cada fenómeno por separado. La gran ventaja de este sistema global común de indicadores es que los resultados son comparables entre las diferentes sub-cuencas de la misma o distinta demarcación hidrográfica y, por tanto, las medidas deberían ser similares. Esto pone en relieve no solo los importantes avances realizados por todas las Confederaciones Hidrográficas en España hacia la armonización de los procedimientos técnicos, sino también una coordinación intergubernamental efectiva entre todas las organizaciones y procesos involucrados a nivel político, técnico e institucional. Sin embargo, se observan aspectos metodológicos importantes prácticamente idénticos a los que ya se aplicaban hace más una década en los primeros PES-2007, como es la metodología para calcular los umbrales de escasez de agua.

Se han detectado deficiencias importantes en la **revisión crítica del PES DHG 2018**: (i) no se utilizan modelos de predicción de aportaciones para mejorar la gestión de sequía y escasez; (ii) no se aporta evaluación técnica, ambiental y económica para justificar las medidas y actuaciones propuestas; (iii) no se incluye una evaluación sólida del cambio climático. Se ha propuesto una metodología alternativa para calcular los umbrales de escasez y se han analizado las mejoras en la gestión que supondría la integración de modelos predictivos.

La **evaluación crítica del proceso de participación pública (PP)** asociada con el desarrollo del PES DHG 2018 ha mostrado que solo un 8% del número total de comentarios recibidos fueron aceptados. De este pequeño porcentaje, la mayoría correspondía a errores de tipo conceptual o de cálculo, mientras que una minoría estaba relacionada con mejoras en la estrategia de gestión propuesta. Se ha integrado una parte reducida del conocimiento y la experiencia local, revelando la ausencia de una estrategia de participación inclusiva. Esto sería contrario a lo que verdaderamente se pretende con un proceso real de participación pública, en el cual debería involucrarse de manera proactiva a todas las partes interesadas suficientemente temprano en el proceso de diseño de estrategias y toma de decisión (cuando aún hay opciones para alterar la estrategia propuesta si así fuera necesario). De esta manera, los usuarios podrían posiblemente asumir un mayor grado de interés y responsabilidad en la búsqueda de soluciones integrales.

Se ha desarrollado una **herramienta práctica de predicción de aportaciones** mensuales y anuales dentro del año hidrológico en curso. Es una metodología innovadora, guiada por el usuario y de bajo costo, que combina el uso de técnicas de análisis de regresión, la función de distribución de probabilidad continua Gamma de dos parámetros y el método Monte Carlo. Los resultados obtenidos han demostrado ser lo suficientemente fiables y robustos para respaldar la toma de decisiones estratégicas y desarrollar estrategias de reducción del riesgo. Además, el modelo creado es relativamente sencillo y puede ser utilizado fácilmente por técnicos (no necesariamente especialistas en modelos) como autoridades, gerentes o incluso los mismos usuarios de agua. Por lo tanto, se supera una de las principales limitaciones asociadas al uso de este tipo de modelos.

Se ha realizado una **evaluación hidro-económica que aporta transparencia en los cálculos de recuperación de los costes del agua a nivel de sub-cuenca**, así como permite identificar la eficiencia económica en la asignación del recurso hídrico y la posible existencia de subsidios cruzados entre los distintos usuarios de un sistema. Se ha aplicado al caso de estudio del sistema mixto del Alto Genil (en el cual co-existe la prioridad del abastecimiento urbano con los derechos históricos de los regantes). Se ha desarrollado una herramienta que permite calcular el Canon de Regulación (CR) para cualquier año de la serie histórica y bajo diferentes hipótesis de cálculo, así como evaluar objetivamente el impacto de la mayoración que se aplica a la demanda urbana de abastecimiento frente a las demandas de riego. Los resultados han revelado que el abastecimiento urbano paga un coste adicional medio anual de

aproximadamente € 6,863 por hectómetro cúbico de agua consumida por tener la prioridad teórica del uso del agua sobre el regadío. Sin embargo, este coste adicional en realidad no se traduce, necesariamente, en un aumento significativo en la garantía del suministro de agua para abastecimiento urbano durante situaciones de escasez.

Los resultados de esta tesis doctoral podrían ser de utilidad para autoridades, gestores y usuarios del agua en otras cuencas similares propensas a la sequía y escasez de agua. Pueden tener una aplicación práctica en la revisión de la Directiva Marco del Agua y la Legislación Española del Agua, así como en el desarrollo de los Planes Hidrológicos de cuenca de tercer ciclo (actualmente en desarrollo).

ABBREVIATIONS

AEMET	Spanish Meteorological Agency (‘*Agencia Estatal de Metereología*’)
CEDEX	Spanish Centre for Public Works Studies and Experimentation (‘*Centro de Estudios y Experimentación de Obras Públicas*’)
CR	Canon of Regulation (‘*Canon de Regulación*’) defined in the Spanish Water Legislation (art.114.1 of TRLA and art. 296.1 of RDPH)
DGW	Spanish Directorate-General for Water of the Ministry for the Ecological Transition (‘*Dirección General del Agua del Ministerio para la Transición Ecológica*’)
DMP	Drought Management Plan
EC	European Commission
EDII	European Drought Impact Report Inventory
EDO	European Drought Observatory
EDR	European Drought Reference
EEA	European Environment Agency
Emasagra	Local Water and Sewage Company of Granada and metropolitan area
EU	European Union
GRB	Guadalquivir River Basin
GRBA	Guadalquivir River Basin Authority
GRwaterDSS	Research Project: Decision Supporting System for the Upper Genil River Water Resources Management (Granada, Spain)
GW	Groundwater
H	Hypothesis
ha	hectare (1ha=10,000 m^2)
hm^3	cubic hectometre ($1hm^3 = 10^6 m^3$)
IPH	Spanish Instruction for Hydrological Planning (‘*Orden ARM/2656/2008, de 10 de septiembre, por la que se aprueba la Instrucción de Planificación Hidrológica*’)
IWD	Irrigation Water Demand
JRC	Joint Research Centre of the European Commission

MITECO	Spanish Ministry for the Ecological Transition (‘*Ministerio para la Transición Ecológica*’’)
NHP	Spanish National Hydrological Plan (‘*Ley 10/2001, de 5 de julio, del Plan Hidrológico Nacional*’)
PP	Public Participation
RBA	River Basin Authority
RBD	River Basin District
RBMP	River Basin Management Plan
RD	Royal Decree (Spain)
RDPH	Spanish Regulation of the Hydraulic Public Domain (‘*Real Decreto 849/1986, de 11 de abril, por el que se aprueba el Reglamento del Dominio Público Hidráulico’*)
SAIH	Spanish Automatic Hydrological Information System (‘*Sistema Automático de Información Hidrológica*’)
SDGs	17 Sustainable Development Goals (United Nations, 2015)
SPI	Standardized Precipitation Index
SW	Surface Water
TMU	Territorial Management Unit
TRLA	Spanish Recast Text of the Water Act (‘*Real Decreto Legislativo 1/2001, de 20 de julio, por el que se aprueba el texto refundido de la Ley de Aguas*’)
UWSD	Urban Water Supply Demand
WEI+	Water Exploitation Index Plus
WFD	Water Framework Directive (European Union Directive 2000/60/EC)
WMO	World Metereological Organization
WUT	Water Use Tariff (‘*Tarifa de Utilización del Agua’*) defined in the Spanish Water Legislation (art.114.2 of TRLA and art. 296.2 of RDPH)

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1. INTRODUCTION

1. INTRODUCTION

This Section presents the overall context of the research area, its importance and need for research, together with the structure of this doctoral thesis.

1.1 Background: Problem definition and need for research

Life (as we know it today) depends on a scarce and irreplaceable natural resource, water.

Therefore, the protection of water resources is essential to ensure that enough good quality water is available at the required time and space, and at reasonable costs for water users without compromising the environmental needs. This is a considerably challenging task if we consider the significant pressures currently being exerted on water resources.

On the one hand, the main non-climatic stressors are the population growth, urbanization, economic development and unsustainable land use practices. These are generally leading to an increase in the water consumption and decrease in water quality (due to water pollution), resulting in an overall reduction in the availability of renewable water resources for human consumption [1].

On the other hand, climate change is projected to increase the frequency of severe droughts in most of Europe, especially in southern and south-eastern Europe ([2], [3]). This is particularly important in the Mediterranean region, which has been highlighted "*as a climate change hotspot, both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature increase*" [4] and in relation to "*robust increases in the probability of occurrence of extreme droughts at 2 °C vs. 1.5 °C global warming*" [5].

This overall situation is leading to fiercer competition among water users by exacerbating conflicts over water, especially in those *drought-prone* and *water-scarce* regions.

Droughts are natural phenomena caused by a deficiency in precipitation (i.e. droughts form part of the climatic variability of a specific area). *Water scarcity* episodes occur when the water consumption is greater than the renewable available water resources, resulting in overexploited water resources [6]. This means that water scarcity could be triggered (apart from a natural drought event) by other anthropogenic factors such as excessive water demands, water losses, water pollution or inefficient drought management protocols.

The magnitude of this issue across Europe is not to be overlooked. Water scarcity and droughts affect around one third of the European territory and over 100 million people [7]. It is estimated that between 1976 and 2006 the economic impacts of droughts in Europe were approximately 100 billion euros [8]. Hydrological assessments have also shown that "*there was a 24% decrease in renewable water resources per capita across Europe between 1960 and 2010, particularly in southern Europe*" [9].

Presently, not only is this situation placing pressure on Governments and water institutions to work towards the development of effective drought risk-based management approaches, but also on water managers, and water users who are competing for an increasingly scarcer, more vulnerable and valuable resource.

Traditionally, droughts have been dealt with as a crisis situation (via applying emergency procedures and urgent measures). However, this approach has shown to be inefficient and risky, especially in this ever-growing context of uncertainty, complex water interactions and climate extremes.

Consequently, during the last decades we are witnessing a paradigm shift from the traditional "*reactive*" management approach to a "*proactive*" drought risk-reduction management strategy in many regions of the world, especially, in drought-prone countries such as Australia, South Africa, and the United States [10]. This evolution is reflected in the academic work, political agenda, and policy-making process.

This is why the development of strategic tools for drought management and water cost recovery (that encourage an efficient and sustainable water use) is receiving ever-increasing attention, especially in *drought-prone* and *water-scarce* regions.

This need was clearly exemplified in the research project named "*GRwaterDSS Decision Supporting System for the Upper Genil River Water Resources Management*" (hereinafter referred as to GRwaterDSS). This project was commissioned by Emasagra (Local Water Authority of Granada and metropolitan area) to the University of Granada in collaboration with CETAQUA (*Fundación Centro Andaluz de Investigaciones del Agua*).

The aim of GRwaterDSS was to develop a series of tools to support strategic water decision-making processes and improve the efficiency of the existing water resource management strategy for the Upper Genil river sub-basin located in the upper catchment of the Guadalquivir River Basin (GRB), in the area of Granada in southern Spain. The results obtained from this doctoral thesis have been applied to GRwaterDSS (where required).

Shortly after starting work for this research project, we realised the considerable complexity associated with the management of droughts and water scarcity situations. There were important knowledge gaps, water policy deficiencies and limitations at different levels of drought management, which needed to be addressed. These issues were coming to light, especially, during the most critical moments of droughts.

Firstly, it was necessary to bridge the knowledge gap and understand the main driving forces in water legislation and planning policies at different management levels: Europe, Spain, river basin and sub-basin scales. Therefore, a **critical review of the evolution and the current status of European and Spanish water legislation and drought management planning policy framework** was undertaken in order to assess whether within the current water policy context, an effective drought risk-based management approach might be easily implemented.

At the same time that this research was being developed, all the strategic Drought Management Plans (DMPs) in Spain for the inter-community River Basin Districts (RBDs) were revised by the relevant River Basin Authorities (RBAs) in December 2017 and these were finally adopted in December 2018. The DMPs established the framework for the drought management approach at the river basin and sub-basin scales, defined droughts and water scarcity indicators and their thresholds, early warning systems, and measures to be applied progressively during each drought/water scarcity phase. Therefore, this fact had a direct implication in the research work that was being carried out.

It was essential to **understand and evaluate the practical implications of applying the most recent 2018 GRB DMP, especially in relation to the effectiveness in identifying a real drought or water scarcity situation and the proposed measures**. The methodological approach (zoning, characterisation, diagnosis and risk evaluation) and the operational framework (in terms of the proposed measures responding to drought and water scarcity) were critically assessed and consequently, a set of recommendations and improvements were also provided.

Equally interesting was the fact of participating in the public consultation process (PP) associated with the elaboration of the 2018 GRB DMP (which took place from December 2017 to March 2018). Once this process was finished, it was considered important to **analyse whether and to what extent the contribution provided by the different stakeholders and interested parties (during the PP) actually led to a significant change and had a real influence on the approved drought management strategy established in the 2018 GRB DMP.**

One of the key deficiencies found in the most recent 2018 GRB DMPs (highlighted during the public consultation process) was the absence of using streamflow forecasting models to improve drought management. Given the extensive archive of available local hydrological information (including previous droughts events) for the Upper Genil River sub-basin, it was considered necessary to investigate the historical relationship between rainfall and streamflow. Based on that, **a practical streamflow forecasting tool to support strategic water management decisions could be developed.**

Another significant obstacle in achieving an efficient and sustainable use of water resources in Spain was the lack of transparency in economic assessments (as highlighted in the fourth European Commission report in 2015). Therefore, as part of this research, **it was found**

relevant to develop a hydro-economic evaluation focused on assessing the contribution to the recovery of the raw water service costs from each water user of the Upper Genil River system (GRB).

In summary, this doctoral thesis assesses different (legislative, management, public participation, technical and economic) instruments and proposes a set of improvements and tools in the area of drought management.

1.2 Structure

This doctoral thesis consists of eleven Sections, as detailed below and shown in **Figure 1**:

- **Section 1: Introduction.** This provides the background information and justifies the need for research.
- **Section 2: Aim and Objectives.** This presents the targets of this research.
- **Section 3: Methodology.** This outlines the overall methodological approach since the detailed materials and methods are contained in each Article (I-V).
- **Sections 4-8: Articles I-V.** These sections contain the five articles prepared in the framework of this PhD.
- **Section 9: Results and Discussion.** This highlights the key research findings and how they respond to the research objectives.
- **Section 10: Conclusions, Recommendations and Lines of Future Research.** This draws the main conclusions, recommendations and possible future research lines.
- **Section 11: References.** This includes the list of references used across the thesis.

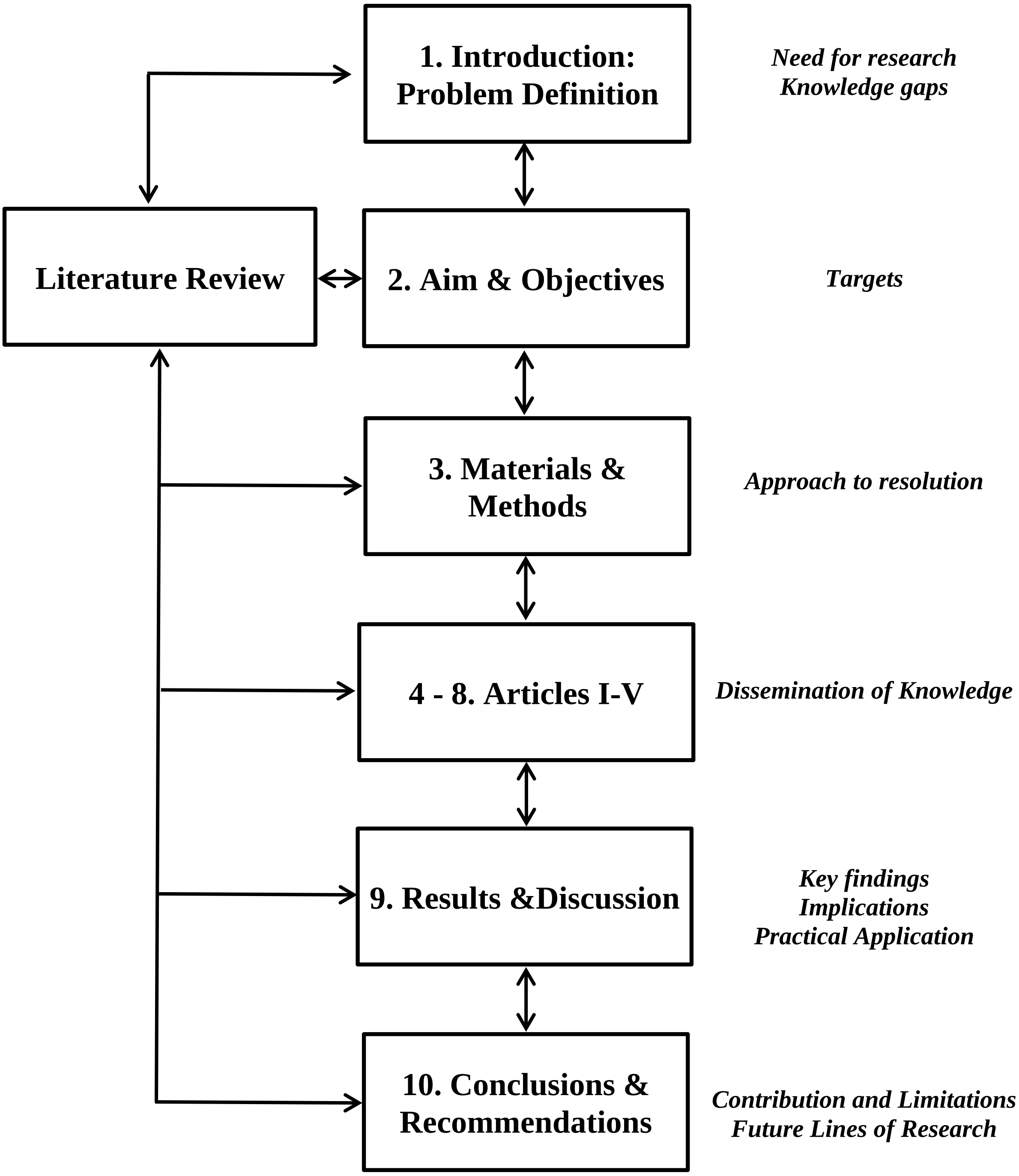


Figure 1: Structure of the thesis and research stages.

2. AIM AND OBJECTIVES

2. AIM AND OBJECTIVES

This Section sets out the aim and the specific objectives that are addressed by this doctoral thesis.

2.1 Aim

The aim of this doctoral thesis was to build further integrated knowledge and develop practical tools, which could contribute towards enhancing the management of droughts and water scarcity situations, including cost recovery methods.

2.2 Specific Objectives

After identifying the key elements concerning the research topic and conducting the review of the existing literature, it was deemed necessary to expand the knowledge in certain subjects and contribute towards filling some existing knowledge gaps.

The definition of the specific objectives was also influenced by the fact that the strategic DMPs for all inter-community river basins in Spain were being revised by the relevant RBAs at the same time that this research was being conducted.

The following research questions were proposed, which guided the formulation of the specific objectives:

1. *From the planning policy perspective, are we really prepared to efficiently deal with droughts and water scarcity events in Europe, and particularly in the Mediterranean countries such as Spain (identified as a climate change hotspot)?*

Objective 1: To critically review the evolution of European and Spanish water legislation and drought management planning policy framework, and assess whether an effective drought risk-based management approach might be promoted within the current water policy context.

2. *Do the most recent Spanish 2018 DMPs integrate a practical and proactive risk-based management approach based on the newest scientific advances?*

Objective 2: To critically analyse the methodological approach and operational framework set out in the 2018 GRB DMP, and propose improvements (where needed).

3. *How important is the process of Stakeholder Participation in current water governance issues? Are the outcomes from that process efficiently incorporated in water management tools, decisions, practices and policies?*

Objective 3: To critically assess the real influence of the public participation and stakeholder involvement process in the approved 2018 GRB DMP.

4. *Could a simple, low-cost and user-friendly forecasting methodology be created to improve water resource management decisions?*

Objective 4: To develop a practical streamflow forecasting tool whose results can support strategic water management decisions.

5. *Are the water cost-recovery methods equitable or are there cross-subsidies among the main competing water users, which might be interfering in achieving an efficient and sustainable water use?*

Objective 5: To develop a practical tool which can provide transparency in the water cost recovery calculations and help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users (Case of Study: Upper Genil River system, GRB, Spain).

The research work has led to the following published scientific articles:

- Hervás-Gámez, C.; Delgado-Ramos, F. Drought Management Planning Policy: From Europe to Spain. *Sustainability* 2019, *11*, 1862, doi: 10.3390/su11071862 (2018 JCR Journal Impact Factor 2.592, Quartile Q2, Rank 105/251 in Environmental Sciences);
- Hervás-Gámez, C.; Delgado-Ramos, F. Are the Modern Drought Management Plans Modern Enough? The Guadalquivir River Basin Case in Spain. *Water* 2020, *12*, 49. https://doi.org/10.3390/w12010049 (2018 JCR Journal Impact Factor 2.524, JIF Percentile 68.681, Quartile Q2, Rank 29/91 in Water Resources, and 2018 SJR Factor 0.634, Quartile Q1 Geography, Planning and Development);

- Hervás-Gámez, C.; Delgado-Ramos, F. Critical review of the Public Participation Process in Drought Management Plans. The Guadalquivir River Basin Case in Spain. *Water Resour Manage* 2019, doi: 10.1007/s11269-019-02354-0 (2018 JCR Journal Impact Factor 2.987, JIF Percentile 80.769, Quartile Q1, Rank 18/91 in Water Resources);
- Delgado-Ramos, F.; Hervás-Gámez, C. Simple and Low-Cost Procedure for Monthly and Yearly Streamflow Forecasts during the Current Hydrological Year. *Water* 2018, *10*, 1038, doi:10.3390/w10081038 (2018 JCR Journal Impact Factor 2.524, JIF Percentile 68.681, Quartile Q2, Rank 29/91 in Water Resources, and 2018 SJR Factor 0.634, Quartile Q1 Geography, Planning and Development).

The following article (Article V included in **Section 8**) is currently under *Water Resources Manage*ment (Q1 in Water Resources) review:

- *Cross-subsidies between water users in Spain: The Guadalquivir River Basin Case.*

3. METHODOLOGY

3. METHODOLOGY

This Section outlines the overarching methodology followed in this doctoral thesis to achieve the specific objectives (set out in **Section 2**).

Sections 4-8 (Articles I-V) contain the articles that have been prepared in the framework of this PhD. Each of them describes in detail the specific methodology, materials and methods applied to address each individual objective.

3.1 Overview

The philosophy underpinning this research work was aimed at building integrated knowledge and developing practical tools, which can contribute positively towards enhancing the management of drought and water scarcity situations, including cost recovery methods.

The rationale behind the design of each method was tailored to address each of the targeted objectives. It was an iterative process based on the findings from the literature review (existing theory and methodologies), the targeted objective and discussions with the supervisor of the thesis.

A mixture of research methods were used depending on the specific purpose to be addressed. Most of them were numerical and evidence-based methods, although qualitative research was also applied. The main methods were: i) quantitative; ii) systematic documentary analysis; iii) critical technical assessment; and iv) examination of detailed case studies.

Numerical data (where required) was collected from publically available official and reliable online sources. A wide range of different documents were also reviewed, including legislation, planning policies, drought management plans, recently developed scientific and technical advances, technical guidance documents, and an extensive number of journal papers.

It should be noted that the selection of case studies (Europe / Spain / Guadalquivir River Basin and the Upper Genil River) was influenced by diverse factors such as: a) the specific objective to be addressed (i.e. the research question to be answered); b) the availability of good quantity and quality data (so that robust results could be achieved); c) the complexity and interest of the particular case of study; d) the possibility of applying the results to other similar regions; and e) the latest updates and advances made in the area of drought management.

3.2 Summary of methodological approach

Table 1 shows a summary of the general methodological approach, materials and methods to achieve each specific objective 1-5 (detailed in Articles I-V).

Figure 2 shows the overall context in which each specific objective (Obj. 1-5) sits:

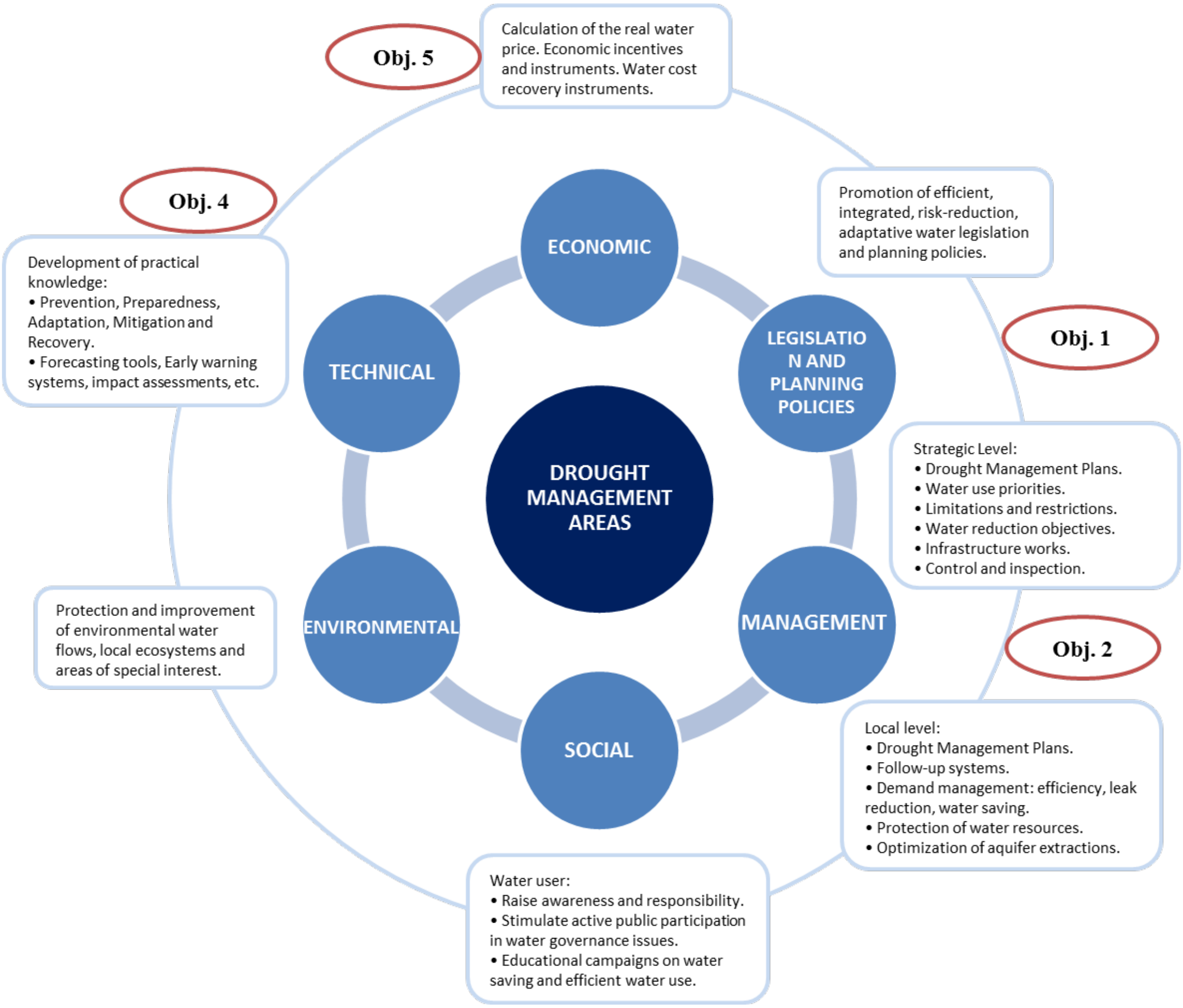


Figure 2: Context of application of each specific objective.

Table 1: Methodological Approach.

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
Specific Objective:	**To critically review the evolution of European and Spanish water legislation and planning policy framework, and assess whether an effective drought risk-based management approach might be promoted within the water policy context.**	**To critically analyse the methodological approach and operational framework set out in the 2018 GRB DMP, and propose improvements (where needed).**	**To critically assess the real influence of the public participation (PP) and stakeholder involvement process in the approved 2018 GRB DMP.**	**To develop a practical streamflow forecasting tool whose results can support strategic water management decisions.**	**To develop a practical tool which can provide transparency in the water cost recovery calculations and help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users.**
Knowledge Gap	Very few recent studies which critically assessed in detail the current water legislation and drought management planning policy framework at European and national level. Particularly, no earlier review of the most recent 2018 Spanish DMPs (approved in the context of the EU WFD) had been published at that time.	No specific technical, environmental, and economic evaluations provided to support the proposed drought management measures of the 2018 GRB DMP. It was therefore required to understand and assess the practical implications of applying the 2018 GRB DMP.	Very few recent and detailed studies that assessed the real influence of stakeholder participation in water governance matters. Particularly, no earlier review of this aspect had been published for the 2018 GRB DMP at that time.	Despite the considerable advances in streamflow forecasting models, these still remain under-used by many water decision-makers (e.g. the Guadalquivir RBA). These have not been integrated in the latest drought management instruments published in Spain (2018 GRB DMP).	The lack of transparency in economic assessments and water cost recovery calculations, and potential cross-subsidies among the main competing water users were highlighted in the fourth European Commission report in 2015. Particularly, no earlier review of this aspect had been published for the specific Upper Genil River.
Case of Study	Europe and Spain.	GRB - Upper Genil River sub-basin.	GRB.	GRB - Upper Genil River sub-basin (Canales and Quéntar reservoirs).	GRB - Upper Genil River sub-basin.
Methodology	Critical evaluation of European and Spanish water legislation, drought management planning policy and recently developed scientific and technical advances.	Critical technical assessment of the most recent 2018 GRB DMP, with a special focus on the methodological approach and operational framework.	Review of the information supplied by the Guadalquivir RBA as part of the public participation process. Review and classification of comments raised by participants and critical analysis of the written responses provided by the RBA.	The methodology is to predict the monthly and annual streamflows during the current hydrological year.	A hydro-economic evaluation at the river sub-basin scale was undertaken. Critical evaluation of the economic contribution to the recovery of the raw water service costs from each water user.

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
Methodology	It places special interest in the critical evaluation of the key elements of the latest Spanish (2018) DMPs.	Comparative assessment to evaluate how a water scarcity situation would have been managed (i) following the 2018 GRB DMP protocol, and (ii) using a streamflow forecast model in combination with the proposed alternative water scarcity thresholds.	Assessment of the PP process in terms of transparency, efficiency, real influence, and recommendations were provided on aspects that could be improved in future PP processes.	It is based on a probabilistic comparison of the progression of the current hydrological year (in terms of cumulative monthly precipitation or cumulative monthly streamflow) with the historical data series.	Assessment of the historical fees paid by the water users of the surface water regulation infrastructures to contribute towards the recovery of the financial costs supported by the State.
Method	Systematic documentary analysis and critical technical assessment.	Modelling and technical analysis of the practical implications of applying the 2018 GRB DMP to a specific sub-basin area. Proposals for improvement (where needed).	Collection, classification, review and basic descriptive statistical analysis. Critical evaluation of results.	Regression analysis, two-parameter gamma continuous cumulative probability distribution function and Monte Carlo simulation.	Modelling of the water allocated to each water user. Calculation of the total surface water and groundwater annual contribution costs by each user and historical series used. Critical assessment of results, conclusions and recommendations.
Materials	European and Spanish water legislation, planning policies, recently developed scientific and technical advances, technical guidance documents, and an extensive number of journal papers.	2018 GRB DMP, drought management instruments, journal papers, etc.	Publicly available information subject to public consultation process (i.e. the draft 2017 GRB DMP and accompanying appendices). No surveys or interviews undertaken as part of this study.	Historical hydrological data obtained from freely available official online websites.	Historical monthly streamflow data series and (surface water and groundwater) costs, obtained from official sources.

4. ARTICLE I

4. ARTICLE I: DROUGHT MANAGEMENT PLANNING POLICY: FROM EUROPE TO SPAIN

This Chapter has been published in *Sustainability* (2018 Journal Impact Factor 2.592, Quartile Q2, Rank 105/251 in Environmental Sciences), full reference as follows:

- Hervás-Gámez, C.; Delgado-Ramos, F. Drought Management Planning Policy: From Europe to Spain. *Sustainability* 2019, *11*, 1862, doi: 10.3390/su11071862.

4.1 Abstract

Climate change is anticipated to exacerbate the frequency, the intensity, and the duration of droughts, especially in Mediterranean countries. This might lead to more serious water scarcity episodes and fiercer competition among water users. Are we really prepared to deal efficiently with droughts and water scarcity events? This paper sheds light on this question by reviewing the evolution of European drought management planning policy, recently developed scientific and technical advances, technical guidance documents, and an extensive number of journal papers. More specifically, Spain presents an ideal context to assess how drought risk has been historically addressed because this country has periodically suffered the impacts of intense droughts and water scarcity episodes, and has developed a long track record in water legislation, hydrological planning, and drought risk management strategies. The most recent Drought Management Plans (DMPs) were approved in December 2018. These include an innovative common diagnosis system that distinguishes droughts and water scarcity situations in terms of indicators, triggers, phases, and actions. We can conclude that DMP should be a live and active document able to integrate updated knowledge. The DMP needs also to set out a clear strategy in terms of water use priorities, drought monitoring systems, and hierarchy of measures in each river basin in order to avoid generalist approaches and possible misinterpretation of the DMP that could lead to increase existing and future water conflicts.

Keywords: drought; water scarcity; drought management plan; European Union; Spain.

4.2 Introduction

Worldwide, we are already experiencing the impacts of climate change such as the increase in frequency and magnitude of extreme weather events such as droughts, floods, heat waves, wildfires, rising sea levels, and biodiversity loss. These events, especially when they occur in cascade, can significantly harm people's lives in terms of damage to health, economic losses, labour productivity, housing, critical infrastructures, as well as disruption of basic services and social networks [5].

The latest IPCC (Intergovernmental Panel on Climate Change) Special Report on Global Warming of 1.5 °C predicts even worse future wide-ranging climate change impacts up and until 2100: "*Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5 °C and increase further with 2 °C*" [11].

In response to this, great international efforts are being made to agree on commitments towards greenhouse gas emission reductions, integration of sustainable development, as well as fostering climate resilience, adaptation, and disaster risk-reduction strategies [12]. An example of this collaborative work is the *2030 Agenda for Sustainable Development* and the *17 Sustainable Development Goals* [13], which stresses the importance of adaptive and resilient strategies to climate-related hazards and disasters. Other examples in relation to risk-reduction and disaster management are the *Hyogo Framework for Action: Building the resilience of nations and communities to disasters* [14] and *Sendai Framework for Disaster Risk Reduction* 2015–2030 [15].

In this complex scenario, water plays a critical role as it is intricately linked to health and well-being, food security, energy, critical infrastructures, economy, and the environment. The water management sector is threatened by climate change and other significant pressures such as population growth, urbanization, and socio-economic activities. If action is not taken to mitigate climate change impacts, a considerable fraction of the world population will be exposed to absolute or chronic water scarcity [16].

Whilst water users, managers, and policy-makers generally agree on the importance of protecting water resources to ensure that enough good quality water is available for its long-term use, this is not always reflected on how water resources are actually planned, managed, and used at local, regional, and national scales. Indeed, Rosenzweig [17] highlights that at local scale, cities and municipalities are key players at the frontline of adaptation.

As a result, many regions in the world suffer from an imbalance between water demands and available water resources, especially in arid and semi-arid basins. Additionally, changes in rainfall and temperature patterns are affecting the hydrological water cycle (timing, seasonality, intensity, duration, and spatial distribution) at local and global scales, and therefore, the water availability. This adds further uncertainty and difficulty in predicting and planning water resources.

At the European Union (EU) level, substantial progress and efforts have been made in terms of developing policy instruments, research projects, and non-legally binding technical guidance documents to deal with droughts and water scarcity. The most important and ambitious piece of European water and environmental legislation was introduced with the adoption of the *Water Framework Directive* (WFD) in 2000. Whilst one of the purposes of the WFD is the mitigation of drought impacts (Art.1 (e)), droughts are only succinctly dealt with within the WFD, and the development of Drought Management Plans (DMPs) is not compulsory.

Another key milestone in terms of European drought-risk management was set by the 2007 EC Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*" and the publication of the technical guidance "*Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects*" [18].

This first one presented an initial set of seven policy instruments for tackling water scarcity and drought issues at European, national and regional levels. These included options in relation to '*putting the right price tag on water'*, '*allocating water more efficiently*', and '*fostering water efficient technologies and practices*'. The Communication also recommended the development of DMPs, as supplementary documents of the River Basin Management Plans (RBMPs) in line with art. 13(5) of the WFD. The EU has adopted other instruments to identify and deal with droughts and water scarcity such as the internet-based interactive map European Drought Observatory (EDO) and the water exploitation index plus (WEI+).

The second one provided methodological guidance on the development and implementation of DMPs in terms of their content, the drought indicator system, thresholds and recommended measures, as well as other key elements such as the consideration of "*prolonged drought*" and consequences of climate change.

Recent studies highlight the Mediterranean area "*as a climate change hotspot, both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature increase"* [4] and equally in relation to "*robust increases in the probability of occurrence of extreme droughts at 2 °C vs. 1.5 °C global warming*" [5].

Spain is a Mediterranean country that presents an ideal context to assess how drought risk has been historically addressed. This country has periodically suffered the devastating consequences of intense droughts and water scarcity episodes. Spain is also one of the pioneering EU Member States along with the longest track record in water legislation and hydrological planning. As many other European countries, Spain has moved from the traditional emergency drought management approach towards a drought risk-reduction management, as this was reflected in the most recent DMPs approved in December 2018.

This paper provides a review on the evolution of European drought management planning policy, recently developed scientific and technical advances, technical guidance documents, and an extensive number of journal papers. Then, the case of Spain is studied in detail in relation to how drought risk has been historically addressed and in particular, how the most recently adopted DMPs deal with drought and water scarcity. The key innovative aspect introduced in the DMPs is the delivery of a common diagnosis system that distinguishes droughts from water scarcity situations (using different indicators, triggers, and phases), recommending a different set of actions to deal with each phenomenon. This has not only shown the significant strides made by all River Basin Authorities (RBAs) in Spain towards the harmonization of technical procedures across all the basins but also an effective intergovernmental co-ordination between all the organizations and processes involved at the political, technical, and institutional levels.

4.3 Droughts and Water Scarcity

4.3.1. Overview

The terms of drought and water scarcity are sometimes used indistinctly. However, it is important to differentiate them in terms of underlying causes and consequences, so they can be monitored, diagnosed, and dealt with accordingly.

Droughts are defined as natural phenomena caused by a deficiency in precipitation, which represents a certain statistical anomaly with respect to the long-term average over a certain period of time and specific area. In contrast, water scarcity episodes occur when the water consumption is greater than the renewable available water resources, resulting in overexploited water resources [6].

When a drought event strikes, not only the water quantity is likely to be affected (depletion in the available water resources) but also the water quality might be seriously compromised (less dilution and higher concentration of contaminants). This would reduce, even more, the volume of water that is suitable for human consumption, while making its treatment more costly and difficult.

Water scarcity might be triggered by a drought event (depending on the duration and magnitude). However, water scarcity can be also triggered or aggravated by other pressures such as unsustainable or inefficient water usage and water pollution.

Depending on the robustness and resilience of the water infrastructures in a determined water system, water scarcity might lead to water restrictions (irrigated crops, industrial and touristic activity, environmental flows, urban and household water uses) and increased competition and conflicts among water users.

Therefore, the social, economic and environmental consequences of water scarcity episodes can be substantial and will depend on the drought magnitude and resilience of the affected area (adaptation and mitigation strategies in place) [19]. These will be more severe in water-scarce basins [6], regions lacking water storage infrastructures [20], or in the absence of contingency plans [21].

4.3.2. Drought Management

Droughts have been traditionally managed only as a crisis situation, by implementing emergency procedures and urgent measures. However, that approach usually failed in achieving the most sustainable and cost-efficient solutions in the long-term. Consequently, this led to a paradigm shift towards applying drought risk-reduction management strategies that are reflected in the academic work, political agenda, and policy-making process. This latter approach has received substantial attention, especially, in drought-prone countries such as Australia, South Africa, and the United States [10].

In this context, DMPs represent key strategic tools to support sustainable water resources management and build resilience to drought extremes. DMPs should define relevant drought and water scarcity indicators and their thresholds, provide robust early warning systems, and establish priorities among water users together with a clear action roadmap to be followed during each drought phase. In order to be effective tools and provide reliable support to water decision-makers, DMPs should promote simple, practical, and scientifically sound approaches, based on technical evidence, the latest engineering and scientific knowledge, as well as the integration of lessons learned from historical droughts.

Although the organizational and institutional framework of each country is different, three drought management levels can be pointed out: Strategic, Operational, and Contingency (or Emergency). For example, in Spain each RBA is the competent authority responsible for not only preparing the Strategic DMP at the river basin scale, but also its management, monitoring, control, and follow-up. The ultimate approving body is the Spanish Directorate General for Water (DGW) of the Ministry for the Ecological Transition (MITECO). Additionally, water companies should elaborate Operational and Contingency DMPs for urban water supply systems serving more than 20,000 people in order to ensure water services under drought situations in accordance with the directions provided in the Strategic DMPs.

At the strategic level, using reliable and accurate drought forecasting tools is crucial to inform the preparation of preventive drought-risk management strategies. However, forecasting the key drought elements (onset, end, severity, thresholds, drought phases, affected area and users, direct droughts impacts, etc.) is a considerably complex task. Unlike other natural disasters (such as floods and earthquakes), droughts do not occur suddenly and therefore, it is difficult to define exactly when the drought begins. Additionally, the duration of droughts might vary from months to years. In terms of the affected area, it is not easy to delimit the exact area (unlike floods), the interaction between droughts, and the propagation mechanisms.

Different drought indicators have been developed to target different types of droughts. Among the most common indices are the Palmer Hydrological Drought Index [22], the Standardized Precipitation Index [23], the Drought Frequency Index [24], and the Reconnaissance Drought Index [25]. Tsakiris [26] and Rossi and Cancelliere [19] provide a comprehensive, helpful and comparative critical review of the different drought indices.

Mishra and Singh [27] classified droughts into four categories: (i) meteorological defined as "*a* *lack of precipitation over a region for a period of time*"; (ii) agricultural defined as a "*period with declining soil moisture and consequent crop failure without any reference to surface water resources*"; (iii) hydrological defined as "*a period with inadequate surface and subsurface water resources for established water uses of a given water resources management system*" and (iv) socio-economic drought defined as "*a failure of water resources systems to meet water demands and thus associating droughts with supply of and demand for an economic good (water)*".

Rossi and Cancelliere [19] also provide a classification of the main drought risk-management areas: planning, monitoring, implementing planned measures, managing emergency situations and recovery. These authors also highlight that the strategic measures "*for improving drought preparedness are generally more complex, since the spectrum of potential long-term actions is large*". They also stated that "*the operational measures, to be implemented once a drought begins, require an adaptive response to the dynamic character of drought*" (due to the uncertainty in evolution, duration, and severity).

4.4 Droughts and Water Scarcity in Europe

4.4.1 Overview

In Europe, water scarcity and droughts are increasingly frequent and widespread phenomena that affect over 100 million people and around one third of the European territory [7]. It is estimated that between 1976 and 2006 the economic impacts of droughts in Europe were approximately 100 billion euros [8]. Hydrological assessments have shown that "*there was a 24% decrease in renewable water resources per capita across Europe between 1960 and 2010, particularly in southern Europe*" [9].

Recent studies highlight the Mediterranean area "*as a climate change hotspot, both in terms of projected stronger warming of the regional land-based hot extremes compared to the mean global temperature increase*" [4] and equally in relation to "*robust increases in the probability of occurrence of extreme droughts at 2 °C vs. 1.5 °C global warming*" [5]. Climate change is projected to increase the intensity, the duration, and the frequency of severe droughts in most of Europe, especially in southern and south-eastern Europe, which will lead to greater water scarcity issues ([2], [3]). This situation is placing emphasis not only on Governments and institutions to work towards an effective drought risk-based management approach but also on water users who increasingly compete for a scarce, vulnerable, and valuable resource. In particular, the agriculture sector, especially in Mediterranean countries, has been in the spotlight over the last few years as well as the water governance ability to promote water saving policies and efficiently assign water resources.

4.4.2 Legislative Framework, Policy Context, and Technical Guidance

The most important and ambitious piece of water and environmental legislation in terms of the protection and improvement of all surface waters, transitional waters, coastal waters, and groundwater was introduced with the adoption of the WFD [28] by the European Parliament and Council in 2000. This provides the common legal framework to assess, manage, safeguard, and enhance the quality of water resources across Europe. The key pioneering elements of the WFD were the introduction of an ecological dimension and economic instruments within a comprehensive river basin-wide management scale, facilitating the tools for transboundary cooperation and stakeholder involvement.

The backbone of the WFD is to achieve and maintain the "*good status*" for all waters within a fixed timescale based on an integrated river basin water management approach. The RBMPs are the key instruments to reaching those environmental goals (protection of drinking and bathing waters, aquatic ecosystems, groundwater resources, etc.) set out in the WFD. These documents present the proposed detailed strategy to achieve the environmental objectives established for all water bodies by a set deadline.

The EU Member States publish their RBMPs on a six-years planning cycle. The first RBMP cycle was 2009–2015 and the second one 2015–2021. The third RBMP documents (2021-2027) are being prepared. Following the submission of the RBMPs, the European Environment Agency (EEA) assesses and reports the status of EU waters. The latest report was published in 2018 [29]. This report informs the European Commission (EC) about the assessment of the second RBMPs in line with the requirements set out in the WFD.

Droughts are only succinctly dealt with within the WFD. These are only mentioned in Art. 1(e) in relation to mitigating drought effects: "*The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater which: (e) contributes to mitigating the effects of floods and droughts"* and Art. 4.6 in relation to prolonged drought: "*Temporary deterioration in the status of bodies of water shall not be in breach of the requirements of this Directive if this is the result of circumstances of natural cause or force majeure which are exceptional or could not reasonably have been foreseen, in particular extreme floods and prolonged droughts*".

Unlike floods, for which a specific Directive was adopted in 2007 (Directive 2007/60/EC), droughts are not yet the subject of EU law [20]. The development of DMPs is not compulsory. The DMPs are however recommended to be prepared as supplementary documents to RBMPs (in line with art. 13.5 of the WFD). The link between RBMPs (and Programme of Measures) and DMPs has not yet been defined [20].

Water scarcity is not explicitly dealt with within the WFD. Nevertheless, Article 9 enables Member States to implement incentive and transparent water pricing policies to attain water efficiency and foster improved water allocation strategies, thus putting a price on a scarce resource whilst helping to reduce water scarcity problems. Certainly, the critical role played by water quantity in ensuring good water quality and thus, good ecological and chemical status has already been recognized by the EC. In this respect, the WFD can positively contribute towards preventing and managing drought and water scarcity management [18].

After the devastating economic, environmental, and social impacts from the 2003 drought in

Europe, droughts and water scarcity were considered as a major challenge afflicting the European territory. Consequently, a number of policy mechanisms as well as extensive non-legally binding technical guidance documents to deal with droughts and water scarcity were developed in the EU.

From 2007 to the present, the European policy development on water scarcity and droughts includes three main water policy documents: (i) the 2007 Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*" [30]; (ii) the Follow-Up Reports which periodically assess the implementation of the WFD ([31]–[33]), and (iii) the 2012 Policy Review "*Review of the European Water Scarcity and Droughts Policy*" [34].

These documents, among others, informed the major assessment of water resources and thorough policy review on water scarcity and droughts across Europe completed in 2012 with the publication of the "*Blueprint to Safeguard Europe's Water Resources*" [35].

The 2007 Communication [30] presented an initial set of seven policy instruments for tackling water scarcity and drought issues at European, national, and regional levels. These included options in relation to '*putting the right price tag on water*', '*allocating water more efficiently*', and '*fostering water efficient technologies and practices*'. The Communication also recommended the development of DMPs, as supplementary documents of the RBMPs (art. 13(5) of the WFD) in order to move from the traditional crisis (or reactive) approach to a drought risk-based (or proactive) management approach. The proposed water hierarchy considered additional water supply as the last resort option, only to be pursued once water saving, water-efficiency, water pricing policy, and cost-effective alternative solutions had been exhausted.

The EC undertakes annual Follow-up Reports that evaluate the implementation of the above policy options throughout the EU. So far, three Follow-up Reports ([31]–[33]) have been completed. The last and final report of 2011 identified aspects to be improved, and confirmed that water scarcity and drought episodes affect not only Mediterranean basins but all of Europe.

Following that, the 2012 Policy Review [35] carried out a thorough evaluation of the first cycle 2009 RBMPs to assess whether and to what extent the 2007 Communication policy options had been applied, as well as to identify any potential gaps in the EU drought and water scarcity policy. The overall conclusion of this study was that the objective of the 2007 Communication (i.e. to revert trends) had not been achieved. A stronger focus was required on quantity issues as well as further integration with sectorial policies in the implementation of the next WFD cycles.

The identified policy gaps and specific solutions were addressed in the EC Communication '*Blueprint to Safeguard Europe's Water Resources*' [35]. The aim was to identify the difficulties and set out actions to be undertaken by policy-makers and water managers to protect European water resources in the long-term. Some of these include a better implementation and integration of European water legislation as well as specific actions towards “*improving land use, addressing water pollution, increasing water efficiency and resilience*”, as well as “*improving governance by those involved in managing water resources*”. It is expected that the Blueprint will lead to the EU water policy development path in the long term.

Additionally, no legally-binding but technical guidance documents have been published in the context of the WFD to support the Member States in the transition towards a planned drought risk-based management approach. For example, the “*Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects*” [18] or “*Guidelines for preparation of the Drought Management Plans*” [36]. These provide methodological guidance on the development and implementation of DMPs in terms of its content, the drought indicator system, thresholds and required measures, as well as other key elements such as the consideration of “*prolonged drought*” and consequences of climate change. That said, there is no common agreed system of indicators to be used throughout the EU.

4.4.3 Elaboration of DMPs in different EU Member States

The development of DMPs (or similar tools) is receiving increasing attention by the Member States. Up to 78 River Basin Districts (RBDs) (42%) have implemented DMPs (or similar tools) or have planned them in the framework of the Programme of Measures, while other 89 RBDs (48%) show no explicit intention in this regard, though may count on some simpler drought management tools. Finally, results in the same report concluded that in 19 RBDs (10%), the available information was still not sufficient to assess [37].

For example, in Cyprus the DMPs are included as an Annex of the RBMP while in Spain the latest approved DMPs have been developed as supplementary documents of the RBMPs in the middle of the RBMP cycle. In contrast, in the UK the private water supply companies are required to develop Water Resources Management Plans (“*strategic plan setting out the planned investments required over a 25 year planning horizon to demonstrate their ability to ensure sufficient supply to meet anticipated demand*”) and DMP (“*describes the company’s tactical and operational responses during a drought event*”) [38]. France and Netherlands have their own drought operative management tools. Other countries have tools focused on emergency management or specific early warning systems [37].

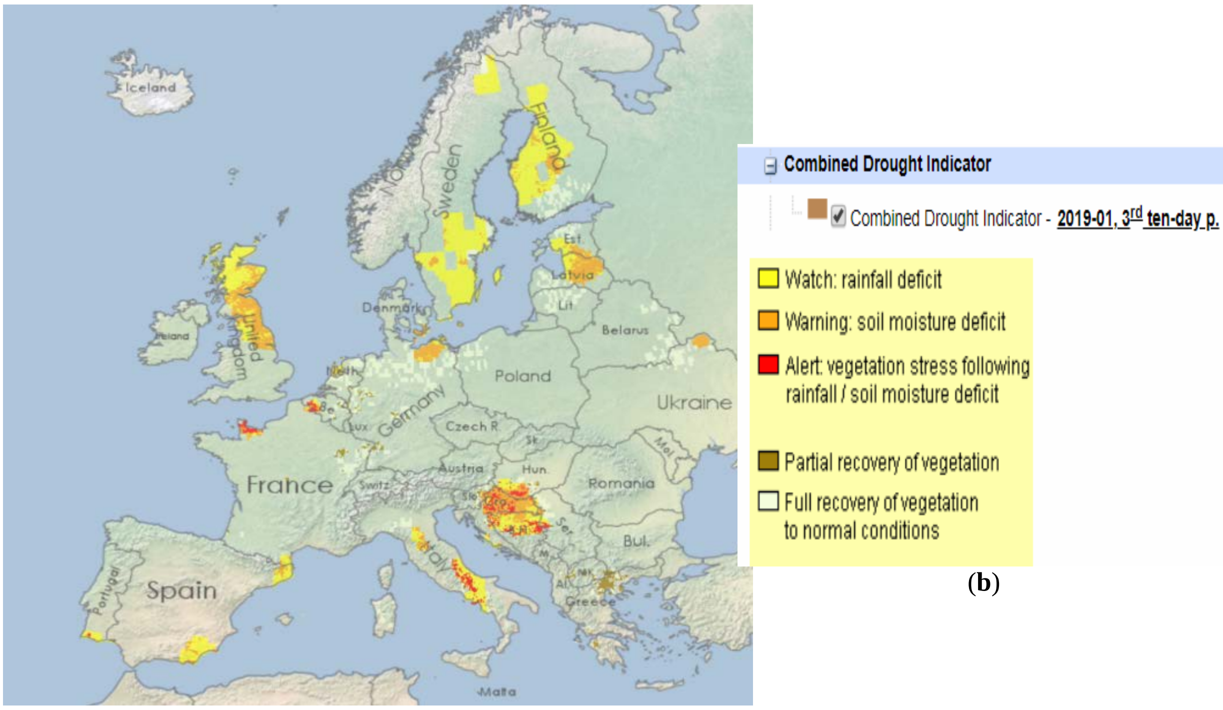
4.4.4 Research Projects, Scientific and Technical Advances

At the EU level, substantial efforts and progress have been made in terms of developing policy instruments, research projects, and non-legally binding technical guidance documents to deal with droughts and water scarcity

Important European research projects in this area are: INDRO (anticipated to finish in April 2019, Remote Sensing Indicators for Drought Monitoring), DrugCrops (anticipated to finish March 2019, Drought discovery to improve drought tolerance in crops), WATER INCENT (May 2017, Economic Instruments for Sustainable Water Management in Water Scarce and Drought Prone Irrigated Areas), MARSOL (November 2016, Demonstrating Managed

Aquifer Recharge as a Solution to Water Scarcity and Drought), TransDRiM (September 2015, Transboundary Drought Risk Management—an Application to the Guadiana River Basin), DROP (September 2015, Benefit of Governance in Drought Adaptation), DROUGHT-R&SPI (March 2015, Fostering European Drought Research and Science-Policy Interfacing), EPI-WATER (December 2013, Evaluating Economic Policy Instruments for Sustainable Water Management in Europe), DMCSEE (March 2012, Drought Management Centre for South East Europe), XEROCHORE (April 2010, an Exercise to Assess Research Needs and Policy Choices in Areas of Drought), PRODIM (June 2008, PROactive Management of Water Systems to face Drought and Water Scarcity in Islands and Coastal Areas of the Mediterranean), MEDROPLAN (July 2007, Mediterranean Drought Preparedness and Mitigation Planning, guidelines for drought preparedness plans and to set up a Network for drought preparedness in Mediterranean countries).

The EU has adopted other practical instruments to identify and deal with droughts and water scarcity such as the EDO interactive map [39]. This was developed by the Joint Research Centre (JRC) of the European Commission and is an interactive tool that provides a considerable amount of drought information and indicators at different scales. The user can choose the location, time series (the starting year depends on the selected information), drought indicator (Standardized Precipitation Index, Standardized Snowpack Index, Soil Moisture Anomaly, Anomaly of Vegetation Condition, etc.), as well as precipitation and soil moisture forecasts for 3 months. For each index, a detailed factsheet is provided to support and build the knowledge of the user. An example of the information provided is shown in **Figure 3**.



(b)

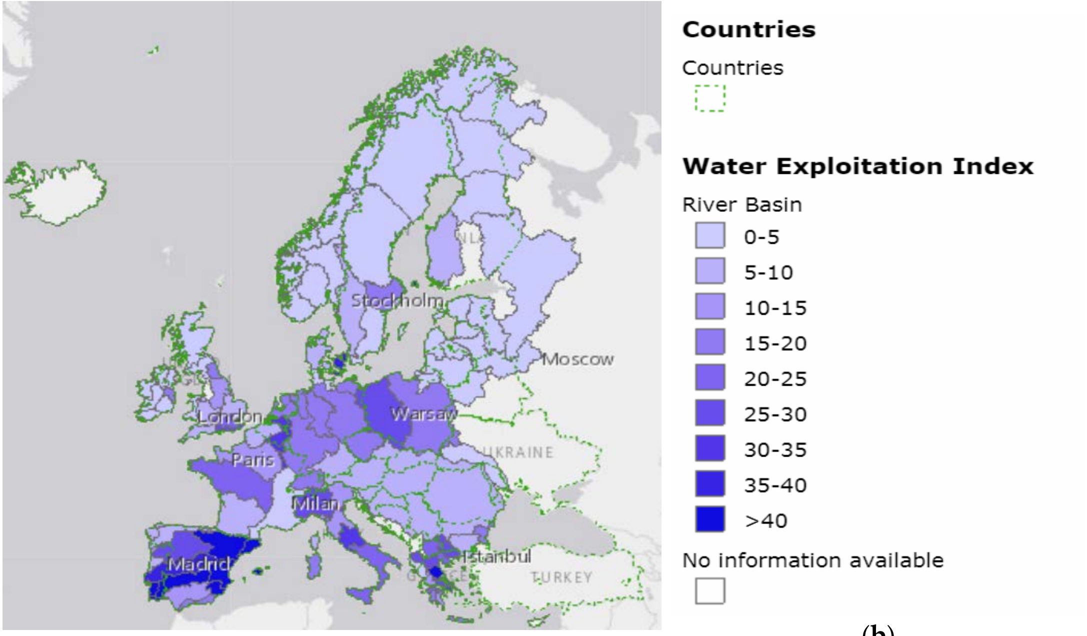
(a)

Figure 3: Combined Drought Indicator in the European Union (Source: EDO webpage, [39]): (a) EDO interactive map viewer; (b) Legend.

The EDO acts as an early-warning system to increase drought preparedness, providing Member States with robust and valuable technical information and support to easily integrate drought risk-reduction management strategies in their national planning policies and decision-making processes. Since January 2018, the EDO forms part of the Copernicus Emergency Management System. This is an integrated internet-based tool that provides emergency response information for different types of disasters (floods, tsunamis, earthquakes, landslides, humanitarian crises, etc.).

Equally, the *water exploitation index plus*, WEI+ [40], for the pressures caused by water abstractions [26] has been used. The WEI+ represents the percentage used of the total renewable freshwater resources available in a defined territory (basin, sub-basin, etc.) for a given time step (e.g., seasonal, annual). It is an interactive map that presents the evolution over time (1990-2015) in water abstraction by source, water use by sector, and water stress level at sub-basin or river basin scale (**Figure 4**).

An example of the information provided is shown in **Figure 4**:



(**a**) (**b**)

Figure 4: Water Exploitation Index July 2003 (Source: WEI webpage, [40]): (a) WEI interactive map viewer; (b) Legend.

Additionally, there is an important publically available European database called "*European Drought Reference database*" (EDR) and the "*European Drought Impact Report Inventory*" (EDII) which provides considerable information about historical drought events in Europe [41].

Even though there has been a significant improvement in developing drought data and management tools (EDR, EDII, EDO, WEI+, etc.) which are very instructive and informative, there are still key challenges related to the practical integration and application of this information as well as its periodic upgrade (so that EU members could maximise their use in practice).

Despite all the aforementioned development, there is still further research required to better understand and manage droughts and water scarcity issues. For example, Rossi and Cancelliere [19] suggests that “*a better coordination of drought-preparedness planning tasks, adaptive operation of water supply systems to prevent severe shortages, and more extensive use of early drought warning systems are needed*”. Stahl [42] highlights that “*systematic quantitative knowledge on the environmental and socioeconomic impacts of drought, however, is often the missing piece in drought planning and management*”.

4.5 Droughts and Water Scarcity in Spain

4.5.1 Overview

Spain is characterized by a highly irregular spatial and temporal rainfall distribution. The annual average rainfall varies from 2200 mm in the northern mountainous areas (Serra do Gerês, Navarra and in some areas of Galicia) to below 300 mm in the southeast (Almeria, Murcia, Alicante). **Figure 5** shows the mean annual precipitation in the Iberian Peninsula (1971–2000).

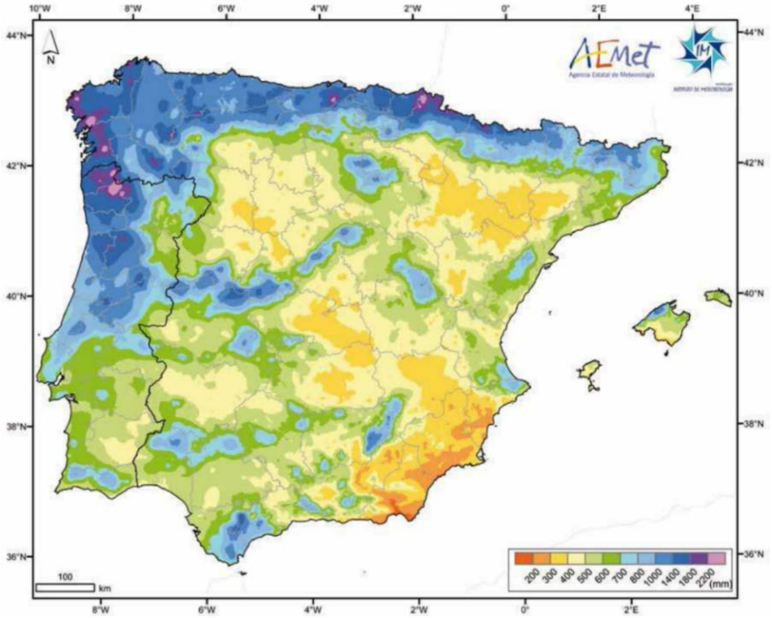
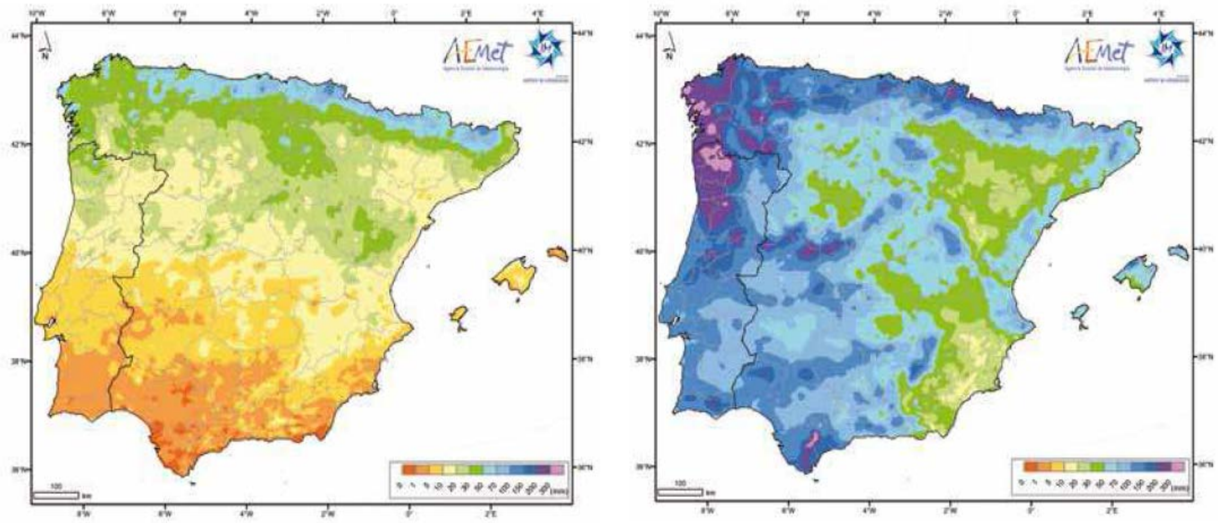


Figure 5: Mean Annual Precipitation 1971–2000 (Source: AEMET Atlas, [43]).

There is also a notable seasonality throughout the year, especially stronger in the southern half of the Iberian Peninsula (**Figure 6**). Indeed, a considerable reduction in rainfall is produced during the summer months, July being the driest month of the year [43]. The total long-term average annual renewable water resources in Spain are about 111,500 hm^3/year. The regulation capacity provided by dams and reservoirs in Spain provides approximately 53,810 hm^3/year of regulated surface water resources [44].

Spain already suffers from, on the one hand, large increases in temperature, heatwaves, and high evaporation rates (which translate into greater crop water demands) and on the other hand, decreases in precipitation and river flows, thus further reducing available water resources [2]. Additionally, it is important to note that Spain is a drought-prone country (especially, the southern and south-eastern regions). Spain has historically suffered from intense drought episodes, some of the most notorious ones in terms of impact were produced during the periods: 1941–1945, 1979–1983, 1991–1995 and 2004–2007 [45]. These precipitation deficit episodes, especially during the 90s drought, resulted in important water scarcity problems and significant economic, social, and environmental consequences (harvest losses, severe water restrictions to all users, disruptions to services, drinking water deterioration, very low river flows, contamination issues, etc.).



(**a**) (**b**)

Figure 6: Seasonal variability: (**a**) July Mean monthly precipitation 1971–2000, (**b**) December Mean monthly precipitation 1971–2000 (Source: AEMET Atlas, [43]).

The observed temperature change in Europe (1976–2006) showed significant warming in Spain when compared with the rest of the EU, particularly in summer and the south-eastern region of Spain. The average temperature rise in Spain was 1.2–1.5 °C compared with 1 °C in Europe and 0.8 °C globally. The observed changes in annual precipitation (1961–2006) show a reduction of precipitation in southern Spain of around 23%. This reduction is greatest in the northwest and lowest in the east [46].

Climate models for Spain show a general trend towards further increases in temperature and decreases in precipitation, with "*severe impacts expected in arid and semi-arid areas (approximately 30% of the national territory), where water yields may decrease by 50%. Hydrological variability will increase in the Atlantic basins, while more irregularity is expected in flood patterns of the Mediterranean basin*" [47].

Particularly, climate change is projected to reduce natural resources between 3%–12% up to 2033 (in relation to the control series 1960/1961 to 1990/1991, [48]), thus posing a substantial risk in maintaining the integrity of water-dependent systems (such as human health, river ecology, and socio-economic activities).

In terms of water demands, approximately 68.19% of the total water used in Spain is consumed by agriculture, in contrast with the 17.59% and 14.21% used by the industry and household sectors, respectively [44]. In fact, Spain leads water consumption in the agriculture sector (25.47×10^9 m^3/year) in Europe in absolute terms. In relative terms, Spanish agricultural water consumption (68.19%) is only exceeded by Greece (82.24%), and Portugal (95.85%) [49]. Based on the information provided on the Statistical Office of the EU [50], a reduction can be seen in the total gross water abstraction from 2007 (259.4 million m^3) to 2014 (192 million m^3).

The economic productivity of the agriculture sector is especially relevant in intensive-irrigated areas in the southern (driest) part of the Iberian Peninsula. For example, there are 861,065 ha irrigated in the region of Andalusia, which represents approximately 24% of the total national sector [44]. Paneque [51] states that agriculture use reaches 81.2% of water use compared to 15% for domestic use and 3% for industrial use.

Additionally, the greatest agricultural water demand occurs precisely when the temperature and evaporation are higher and precipitation is lower (usually, from April to September). This puts large amounts of pressure on water resources (quantity and quality) combined with the fact that the tourism sector is mainly concentrated in coastal areas during summer months. This makes the Spanish water scenario unique in its complexity.

Even without the occurrence of a drought event, water demands cannot be met during the summer months of a normal hydrological year using exclusively natural available water resources. Many rivers and streams dry out completely during summer due to the excessive surface and underground water abstractions.

In response to that, the Spanish Water legislation and Hydrological Planning have been historically based on implementing resilient infrastructures to better manage the temporal and spatial irregularity in precipitation in relation to the demand pattern, as well as to deal with the effects of extreme hydrological and climate phenomena (flood protection and drought preparedness).

This philosophy has mainly resulted in the construction of 1172 large dams combined with the use and development of alternative (non-conventional) water supply technologies, such as desalinated water in the Mediterranean coast and the Balearic and Canary Islands (100.2 hm^3) and treated wastewater (496 hm^3/year) [44].

Groundwater is also strategically used to increase water resources in those dry and water-scarce areas, and especially to alleviate the effects of droughts [52]. Direct use of groundwater in Spain is approximately 6,884 hm^3 [44], but the water quality is easily deteriorated due to point-source pollution or diffuse pollution caused by agricultural and livestock activities [53].

Apart from these, it is important to highlight that substantial efforts have been made in recent years across all Spanish river basins in terms of improving water efficiency, water tariffs, and water management strategies.

Water scarcity problems are related to climate (availability of renewable water resources) and water use (demand patterns related to population and socio-economic trends). Therefore, based on the above climate change forecasts, it is anticipated that water scarcity problems in Spain will increase as the 21st century advances [54].

4.5.2 Legislative Framework, Policy Context, and Technical Guidance

Spain is one of the countries with the longest track record in water legislation and hydrological planning all over the world. The following facts are proof of that: (i) the first water law was implemented in 1879; (ii) the "*Confederaciones Sindicales Hidrográficas*" (later on the RBAs) and basin management concept were firstly established in 1926 [55]; (iii) the RBMPs have been mandatory since 1985 (15 years earlier than the WFD 2000) and the (iv) the first formal RBMPs were finished 1998–1999 (20 years earlier than the first RBMPs in Europe).

The 1978 Spanish Constitution is the supreme law of the Spanish legal system which defines the competences of the State and the different Autonomous Communities that form Spain. There are 16 Autonomous Communities in Spain (in addition to Navarra, Ceuta, and Melilla) and these are administrative entities with specific legislative, executive and administrative autonomy. The rivers that flow completely within the territory of one Autonomous Community are exclusive competence of the Autonomous Community (called "*intra-community basins*"), while those catchments which are shared by more than one Autonomous Community, are exclusive competence of the State (called "*inter-community basins*").

The Spanish Water Act of 1985 objectives were set at "*meeting of water demands, balancing and harmonising the regional and sectoral development by increasing the availability of the resource, protecting its quality, making its use sustainable and rationalising its use while respecting the environment and other natural resources*" (Art. 38).

Apart from the preparation of individual hydrological management plans at the river basin scale, a National Hydrological Plan (NHP) was required. The NHP has higher legal status and authority than individual hydrological management plans, since its main purpose is precisely to address water management issues which cannot be resolved at the river basin scale (such as the water transfers between river basins). The first RBMPs in Spain were adopted in 1998 by the Government (Royal Decree 1664/1998, of 24 July) while the NHP was approved in 2001 (Act 10/2001, of 5 July, on the NHP).

At the same time, the WFD (Directive 2000/60/EC) was approved by the European Parliament and the Council of the EU. Member States were required to transpose it into their own national legislation by 2003. In Spain, this was transposed into Spanish legislation on 31 December 2003 by amending the 'Real Decreto Legislativo 1/2001' (which amended the Water Act 1985).

A number of additional regulations were approved to enable the planning process to commence. The Regulation of Hydrological Planning (Real Decreto 907/2007, de 6 julio, BOE 07- 07- 2007 and its subsequent modification by RD 1161/2010 de 17 de septiembre), the definition of the limits of RBDs (by RD 125/2007, de 2 de febrero, artículo 16 bis 5 del TRLA) as well as the definition of Competent Authorities (RD 126/2007, de 2 de febrero, artículo 36 bis del TRLA) [56].

The Hydrological Planning Instruction (ORDEN ARM/2656/2008, de 10 de septiembre) is a complementary intra-ministerial regulation instrument. Given the intrinsic heterogeneous nature of the Spanish river basins, the aim of this Instruction was to provide a common technical and methodological approach to prepare the RBMPs and for general hydrological planning processes in line with the most recent legislation and scientific advances. The Instruction is only compulsory for inter-community river basins, although it is generally followed by all river basins in Spain. The Instruction details the common procedure in relation to the general description of the river basin, identification of the significant anthropic uses and pressures, protected areas, the state of water bodies, the environmental objectives, regimen of ecological flows, cost recovery, program of measures, etc.

Although the underlying principles and objectives of the Spanish Water Act 1985 remained practically the same after transposing the WFD into the Spanish legislation, the key new concept was the "*environmental objective*" to achieve the "*good status*". In fact, the amended Water Act included as the first objective: "*achieving good status and protection of the hydraulic public domain*". The introduction of this concept required a management change in the traditional Spanish hydrological planning process along with a behavioral change in water users.

The hydrological planning shifted from the historical water-quantity management approach to a more integrated water quantity, quality, and environmental protection. To fill this gap, the concept of the 'ecological flow' was introduced in the Spanish legislation, defined as: "*The regime of ecological flows will be established in such a way as to sustainably maintain the functionality and structure of aquatic ecosystems and associated terrestrial ecosystems, contributing to achieve good status or ecological potential in rivers or transitional waters*". It is also important to note that droughts form part of the regular climatic variability which also affects the development of local ecosystems.

For each specific river system, the ecological flow regime is composed of minimum and maximum flows as well as a specific temporal distribution (seasonality), together with induced flood flows and sediment control patterns. The ecological flows in Spain are not considered as a water demand but a water restriction (or water constraint). This means that ecological flows must be satisfied in the first instance prior to meeting the water demands of the system in all situations, except when there is a prolonged drought situation. In this state, urban water supply has the highest priority of water use. The legal compliance of ecological flows in Spain is currently a real challenge in practice, due to the complex management, monitoring, and inspection processes.

The efficient allocation of scarce water resources to comply with environmental needs and meet water demands is not an easy task. In some instances, the pressure on water resources raises hot conflicts between water users, water managers, and authorities.

4.5.3 Drought Management Approach Evolution

As many other European countries, Spain has traditionally managed droughts as a crisis situation only, by applying emergency procedures and urgent measures (through the adoption of Emergency Drought Orders or Decrees). However, the experience and lessons learnt have demonstrated how that approach failed in achieving the most sustainable and cost-efficient solutions in the long-term. It was precisely after the devastating environmental, social, and economic consequences of the 1991–1995 drought period, that a paradigm shift towards a drought risk-reduction management approach in Spain was necessary.

The NHP was approved in 2001 (Act 10/2001, of 5 July, on the NHP) and sets out the basic principles for managing droughts for inter-community basins (art. 27).

Section 1 of the art. 27 requires the MITECO to establish a global system of hydrological indicators in order to identify early enough and foresee drought situations, thus supporting the RBAs when declaring formal drought and water scarcity situations. In compliance with this legal requirement, the National Drought Indicator was set up which provides drought monitoring and diagnosis for all the inter-community basins on a monthly basis (providing a summary report and is freely available at refs.: [57] , [58]).

Section 2 of the same art. 27 requires the RBAs to prepare DMPs, which will be submitted to the MITECO for approval. Section 3 requires water companies or municipalities to elaborate Operational and Emergency DMPs for local urban water supply systems serving more than 20,000 people in order to ensure water services under drought situations and following the principles set out in the DMPs. General Guidance Documents have been developed by the MITECO in Spain to facilitate the process of developing these plans [59].

The first DMPs for all inter-community river basins were developed by the RBAs in compliance with the art.27 of the NHP and approved in 2007 (Orden MAM/698/2007 de 21 de marzo). A global system of hydrological indicators was set up that monthly diagnosed the situation and the information was publicly made available in the National Drought Indicator webpage.

Even though the DMPs were not approved until 2007, the 2004–2007 drought was already managed in accordance with those principles established in the DMPs. These proved to be effective strategic management tools which positively contributed to avoid public supply restrictions, reduced and mitigated drought impacts, and highlighted the importance of involving the relevant stakeholders and interested parties (including the general public) in the decision-making processes associated with drought planning [60].

Since the first DMPs were approved in 2007, two planning cycles (2009–2015 and 2015-2021) have been completed in compliance with the WFD. During the review process corresponding to the second planning cycle, it was found necessary to update the 2007 DMPs, so that they were in line with the most recent planning framework. The objectives of this review were to: (i) adapt the DMPs to the latest information included in the hydrological plans (in terms of resources, demands, ecological flows, rules of operation, etc.), and

(ii) distinguish droughts (as a natural phenomenon independent of the use of water by humans) and water scarcity (related to temporary problems to meet the existing demands for different socio-economic uses of water).

The experience gained during more than a decade of application of the first 2007 DMPs showed the importance of having common criteria (including a global system of hydrological indicators) to avoid heterogeneities in the diagnosis and the nature of the actions and measures to be applied in the different scenarios [60].

Based on this, the Royal Decree 1/2016 instructed the revision of all the previous 2007 DMPs for the inter-community RBDs in accordance with the technical instructions provided by the MITECO named *"Technical Instruction for the Elaboration of the Special Drought Plans and the definition of the global system of indicators of prolonged drought and scarcity"*. These instructions established a common methodology to be applied among all the RBAs in Spain when diagnosing drought and water scarcity situations as well as for implementing actions and measures of similar type and nature.

The RBAs are the competent authority responsible for not only preparing the DMPs in accordance with the Spanish Law 10/2001 NHP (art. 27) and European WFD (Directive 2000/60/CE–Art. 4.6) but also its management, monitoring, control, and follow-up. The ultimate approving body is the DGW of the MITECO.

4.6 Newest Drought Management Plans (December 2018)

4.6.1 Overview

The draft versions of the newest DMPs were published on 21 December 2017 in accordance with the NHP art. 27.1 Law 10/2001 and following the methodological guidance provided by the MITECO Technical Instructions. These draft plans were then subject to a three-month public consultation period (from 21 December 2017 to 21 March 2018).

As part of the public consultation process, different queries were raised by relevant stakeholders and interested parties (water companies, irrigation associations, ecologist groups, and public institutions). In response to this, each RBA prepared a Statement of Response containing each concern and associated response, together with the revised version of the DMP, which were then published in May 2018. The final adopted DMPs were approved by the DGW in December 2018. **Figure 7** shows the development process of the 2018 DMPs in Spain.

The adopted 2018 DMPs supersede the previous 2007 DMPs (Orden MAM/698/2007 de 21 de marzo). The 2018 DMPs were developed in the context of the WFD, as supplementary documents to the RBMPs. The adopted 2018 DMPs integrated the latest information included in the already approved 2nd RBMP cycle (2015–2021) in terms of resources, demands, ecological flows, climate change conditions, etc.

The goal is to periodically update the DMPs every six years, two years after the end of every RBMP cycle (in the middle of every RBMP cycle). These will be based on the information published in the last approved RBMP.

4.6.2 Aim and Key Elements of the Newest DMP

The aim of the 2018 DMPs in Spain is to minimize the environmental, economic, and social impacts of possible drought episodes (in accordance with the NHP art. 27.1 Law 10/2001).

For example, the Guadalquivir River Basin Drought Management Plan (the largest river basin in the south of Spain) establishes the following specific objectives: (a) *guarantee sufficient water availability to ensure population life and health (while minimising negative effects of droughts and water scarcity on the urban water supply)*, (b) *avoid or minimise the negative drought effects on the water status (those situations of temporary deterioration or less stringent minimum ecological flows will be only associated with natural situations of prolonged drought)*, and (c) *minimise negative effects on economic activities, according to the prioritisation of uses established in the water legislation and River Basin Management Plans*.

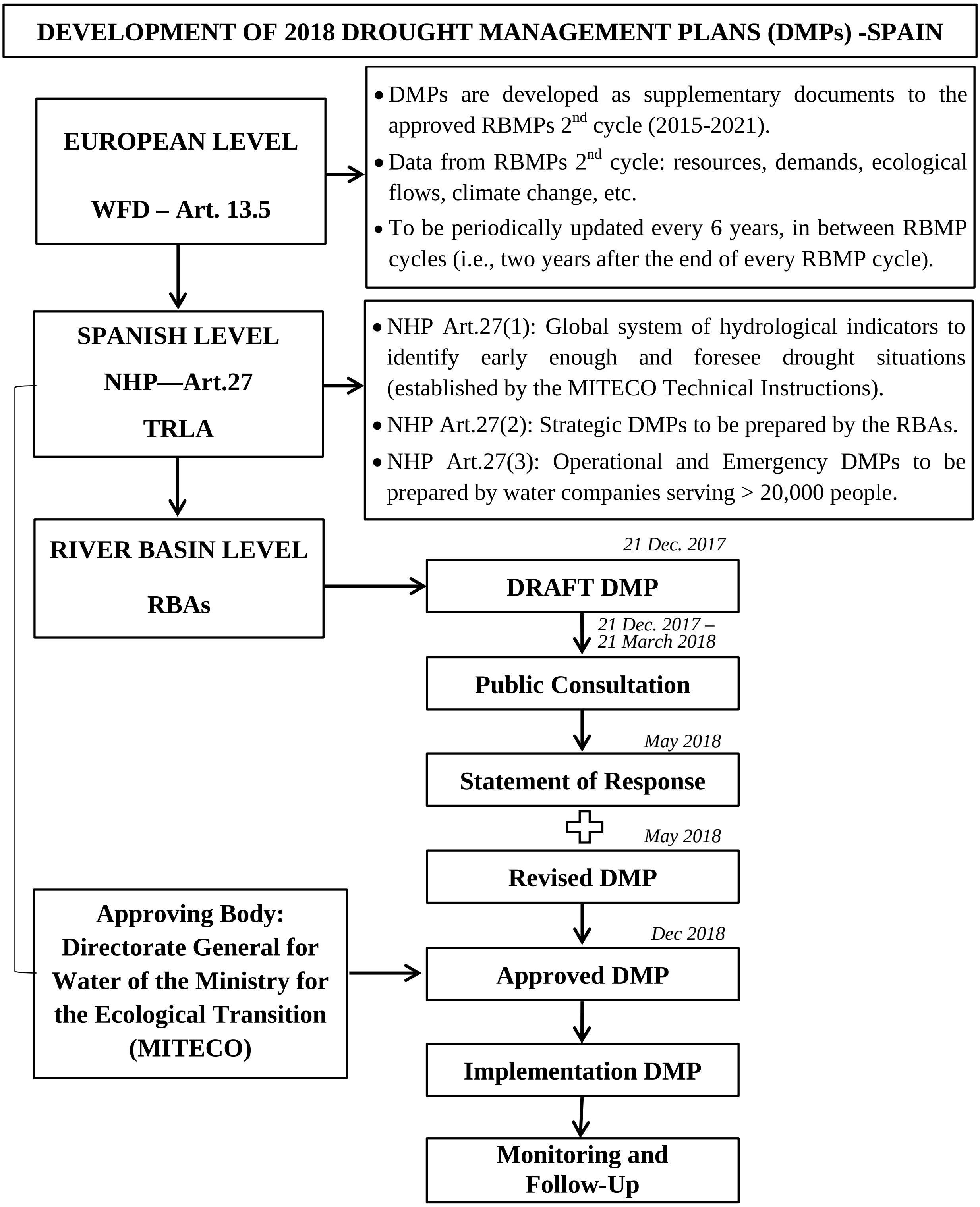
At the same time, the following instrumental or operational objectives are proposed in the same document: (a) *define mechanisms to detect as early as possible, and assess, situations of prolonged drought and water scarcity*; (b) *define the prolonged drought scenario*; (c) *set scenarios to determine the severity of water scarcity episodes*; (d) *define the actions to be applied in the scenario of prolonged drought and the corresponding measures in each water scarcity phase*; (e) *ensure transparency and public participation in the development of the plans.*

4.6.3 Content of the DMP

The MITECO Technical Instruction [61] required the DMPs to be formed in a main report, accompanied by the necessary annexes, in which at least the following contents are developed:

1. Description of the basin and identification of territorial units for analysis of the prolonged drought and water scarcity.
2. Detailed description of territorial water scarcity units and information on water demands, ecological needs, and resources.
3. Record of historical droughts and climate change.
4. Definition of the system of indicators.
5. Diagnosis procedure.
6. Actions to be applied in scenarios of prolonged drought.
7. Measures to be applied in scenarios of water scarcity.
8. Public information measures.

9. Measures of administrative organization in a situation of drought.
10. Criteria for the preparation of impact assessment reports and post-drought reports.
11. Strategic environmental report.
12. Emergency Plans for systems serving more than 20,000 inhabitants.
13. Process of monitoring and review of the DMPs.



- DMPs are developed as supplementary documents to the approved RBMPs 2nd cycle (2015-2021).
- Data from RBMPs 2nd cycle: resources, demands, ecological flows, climate change, etc.
- To be periodically updated every 6 years, in between RBMP cycles (i.e., two years after the end of every RBMP cycle).

- NHP Art.27(1): Global system of hydrological indicators to identify early enough and foresee drought situations (established by the MITECO Technical Instructions).
- NHP Art.27(2): Strategic DMPs to be prepared by the RBAs.
- NHP Art.27(3): Operational and Emergency DMPs to be prepared by water companies serving > 20,000 people.

Figure 7: Development process of the 2018 DMPs in Spain for the inter-community RBDs.

4.6.4 Drought Management Approach

Unlike the previous 2007 DMPs, the current 2018 DMPs differentiate drought events from water scarcity episodes in terms of root causes, consequences, and required actions to deal with each phenomenon. A drought is defined as "*a natural phenomenon produced by the reduction of rainfall and natural run-off, which occurs independently of anthropic action*". Water scarcity is defined as "*the temporary problem of a determined area to meet the water demands for the different socio-economic uses*" [61].

It is important to note that the DMPs distinguish two different water scarcity situations: "*temporary*" (or operational) and "*permanent*" (or structural). The DMPs only deal with "*temporary*" water scarcity situations associated with temporary problems of meeting the water demands, even when the guarantee criteria established in the RBMP are met. This means that, those water demands can be met from the hydrological planning perspective but there are operational risks which the DMP tries to identify, prevent (where possible) and mitigate. On the other hand, the "*permanent*" water scarcity situation is associated with permanent problems of meeting the water demands, and therefore it is not the result of a temporary situation caused by a deficiency in rainfall. This should be analyzed, valued, and solved through ordinary hydrological planning, i.e. addressed in the RBMPs [62].

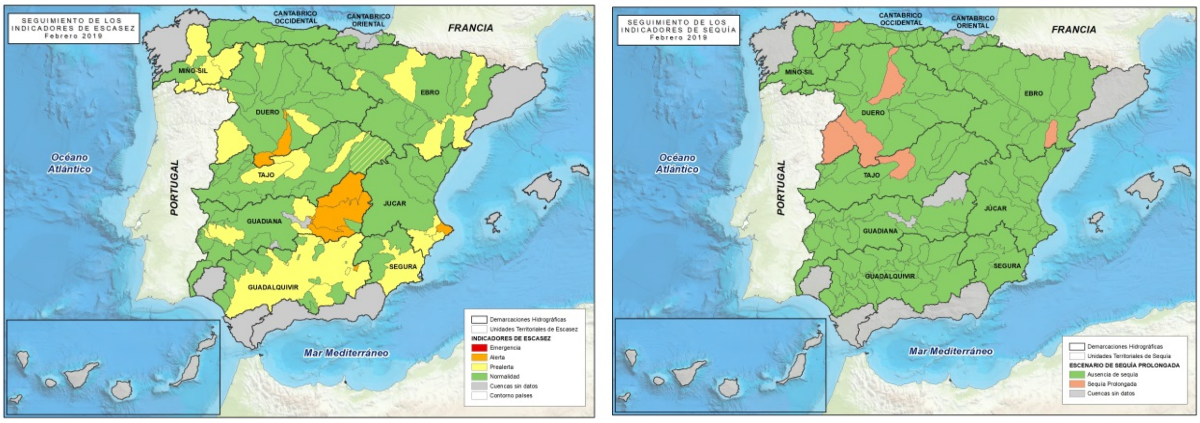
One of the objectives of the newest DMPs in Spain is to manage separately situations of prolonged drought and water scarcity. To achieve this, different territorial management units (TMUs) were identified to characterize the drought and water scarcity phenomena.

On the one hand, the "*prolonged drought TMUs*" are related to homogeneous hydrogeological areas in terms of water resources generation (including all watersheds and groundwater recharge areas according to the RBMP). The "*water scarcity TMUs*" are on the other hand related to the water demands (or consumption points) and associated ecological systems (according to the water exploitation systems established in the RBMPs). Overall, the "*prolonged drought TMUs*" are equal or greater in size than the "*water scarcity TMUs*". This is, a "*prolonged drought TMU*" is composed by one or more "*water scarcity TMUs*". For example, the Guadalquivir RBD in southern Spain includes 25 "*prolonged drought* TMUs" and each of these is formed by one or more "*water scarcity TMUs*" [62].

The purpose of the diagnosis system is to establish different drought and water scarcity triggers and phases that could lead to activating or deactivating determined actions and measures for each specific territorial management unit. A global system of hydrological indicators was established in order to identify early enough and foresee drought and water scarcity situations (in compliance with NHP art.27 paragraph 1). The methodology consisted of the following steps:

First, the most representative hydrological variable (precipitation, reservoir inflow, reservoir storage, groundwater level, etc.) is selected. For example, the precipitation was selected for characterizing the drought events in all "*prolonged drought TMUs*" of the GRB and the reservoir storage volume has been selected for all "*water scarcity TMUs*" of the GRB except for one (in which precipitation has been used). Second, the relevant hydrological variables time series are prepared (Oct 1980 – Sept 2012). Third, the indicators are calculated based on the sub-basin specific data, scaled between the values of 0 and 1, weighted and finally validated with historical data. According to the indicator status value and thresholds, a progressive implementation of actions and measures is defined in the DMPs.

Figure 8 shows the National drought and water scarcity indicator system in February 2019 and **Figure 9** shows the evolution of the water scarcity indicator in the Guadalquivir river basin (southern Spain) for the available 2006–2018 period:



(**a**) (**b**)

Figure 8: National indicator system February 2019 [57]: (**a**) Water Scarcity indicator system (normal, pre-alert, alert, and emergency); (**b**) Drought indicator system (absence of prolonged drought in green and prolonged drought in red).

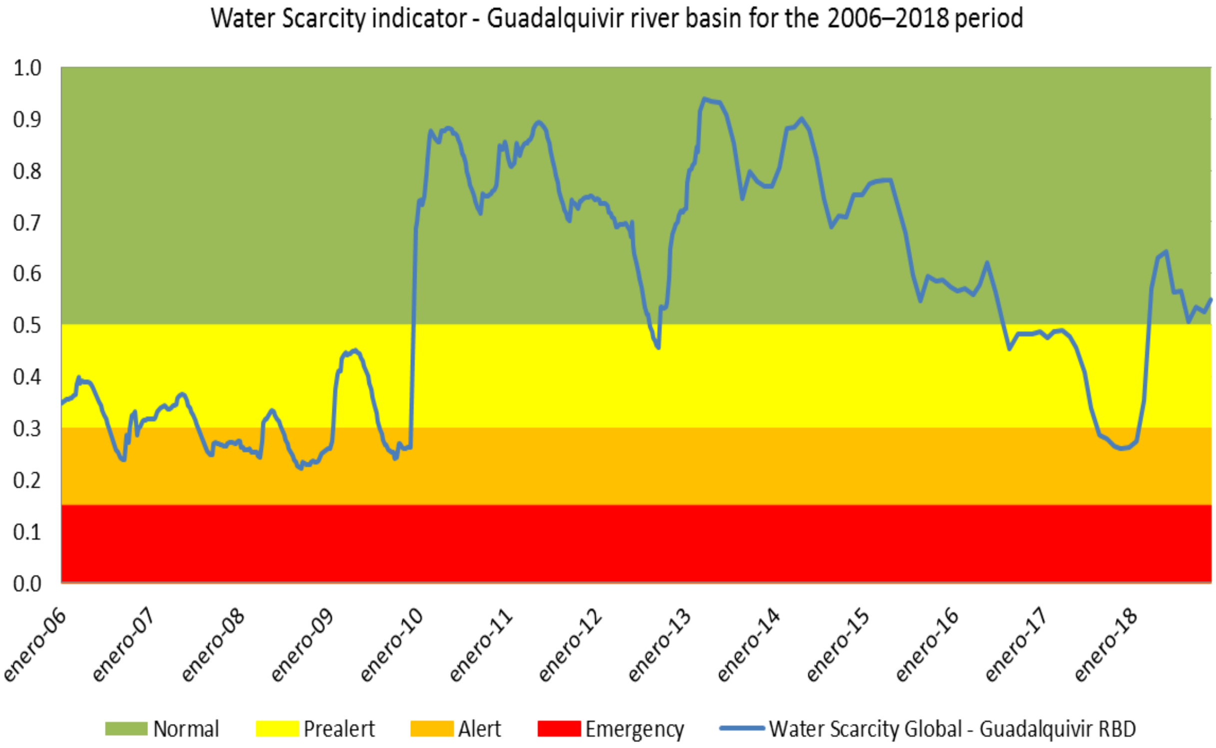


Figure 9: Evolution of Water Scarcity indicator in the Guadalquivir River Basin for the 2006-2018 period (elaborated with data taken from the Indicator System of the Guadalquivir RBA).

In each drought and water scarcity phase, a set of different measures is proposed (refer to **Table 2** and **Table 3**). For example, during a water scarcity situation, the progressive implementation of measures can vary from strategic planning and monitoring (absence of water scarcity or normal situation); water saving, monitoring and public awareness (pre-alert situation); demand and supply management, monitoring and control (alert), and intensification of actions and possible exceptional actions (emergency). Finally, a monitoring and follow-up system to evaluate the implementation of the DMP is included.

Table 2: Measures to be applied during the different drought scenarios (data from the MITECO Technical Instructions, [61]).

Prolonged Drought	**Definition**	Reduction in precipitation that considerably affects the available natural water resources (superficial or groundwater). It does not depend on the existing water demands.	
	Impacts	It can naturally produce a significant reduction in water quantity and deterioration of water quality.	
	Types of variables	Precipitation and streamflow in natural regime.	
	Global Indicator Value	0.3–1	0–0.3
	Scenario	Absence of prolonged drought	Prolonged drought
	Type of actions	Control and monitoring. No temporal deterioration. Comply with ecological flows.	Possibility of justifying a temporal deterioration of water status and adoption of less stringent ecological flow regime.
	Objective	To limit the temporary deterioration of the water status as well as the less stringent ecological flow regime (set out in the RBMP) to natural situations of prolonged drought only (not related to scarcity problems).	

Table 3: Types of measures to be applied during the different water scarcity scenarios: *normal*, *pre-alert*, *alert*, and *emergency* (data from the MITECO Technical Instructions, [61]).

Operational Water Scarcity	**Description**	Reduction in available water resources that could risk meeting the existing socio-economic water demands.			
	Impact	Socio-economic impacts due to the limitation in available water resources for water uses (which could be otherwise addressed in a normal situation)			
	Type of variable	Storage volume, reservoir inflow, streamflows, snow storage, groundwater level, etc.			
	Indicator	To detect the impossibility of meeting the water demands in a specific sub-basin.			
	Global Indicator Value	1–0.5 Absence	0.3–0.5 Moderate	0.15–0.3 Severe	0–0.15 Extreme
	Scenario	Normal	Pre-alert	Alert	Emergency
	Type of actions and measures to be activated	General Planning and monitoring.	Public Awareness, water saving and monitoring.	Management (demand/supply), control and monitoring (art. 55 TRLA).	Intensify actions already considered in Alert Scenario. Possible adoption of Extraordinary Measures (art. 58 TRLA).
	Objective	Progressive establishment of measures in order to delay or avoid the entrance in the most severe phases of scarcity, mitigating their negative consequences on socio-economic uses			

The great advantage of this common indicator system is that despite the diverse climatic, geographical or water demand specific conditions, the diagnosis and results are comparable among all the different sub-basins in Spain. This common indicator system allows a homogeneous treatment among all the different sub-basins in Spain. This means that if a similar (drought or water scarcity) indicator value is found in two different sub-basins, the (drought or water scarcity) situation is expected to be similar. Therefore, actions and measures to be taken are expected to be of the same type and nature.

This highlights substantial efforts and significant strides made by all RBAs in Spain towards the harmonization of technical procedures across all the basins. This system will not only provide support to the RBA decision-making processes (especially when declaring formal drought situations) but also when disseminating information to stakeholders and interested parties (including water users and the general public). This also demonstrates how a similar common indicator system could be implemented at the EU level.

Despite the doubtless advantages of having a global indicator system, site-specific peculiarities relevant to each sub-basin cannot be ignored since ad-hoc solutions might be required. This is especially important in those basins characterized by complex conflict resolution, for example, where fierce competition exists among water users who share scarce water resources.

Ortega-Gómez [63] recommends using a global indicator system together with a distributed drought map to better understand if there are any areas with specific problems. Additionally, González-Hidalago [64] recommends further understanding in spatial propagation gradients of droughts, as well as the onset of a drought. This study found that: "*events at different temporal scales can overlap in time and space. Spatially, the propagation of drought events affecting more than 25% of the total land indicates the existence of various spatial gradients of drought propagation, mostly east–west or west–east, but also north–south, have been found*".

One of the key deficiencies in the current DMPs is the absence of using streamflow forecast models or seasonal climate forecasts. The water scarcity thresholds and critical decisions on controlled released outflows from reservoirs are based on streamflow and historical probabilistic precipitation information only. Given the improvements in the accuracy and reliability of advanced hydrological information and streamflow forecasts, it is considered essential to use predictive models (at least for the current hydrological year) to anticipate and evaluate future impacts of a drought, as well as to take adequate and proportionate actions in each situation ([65],[66]).

Therefore, the DMP should be a live and active document able to integrate the most updated knowledge that is relevant, credible, and delivered in a timely manner. Effective management of water resources starts with planning in advance in the long, medium and short term. The most important elements of a DMP are: i) the identification of the risk and its characterization (indicators/indexes and different thresholds or trigger curves) and the actions or measures to manage that risk before, during and after the event (preparedness and prevention, mitigation and emergency actions, response and recovery). The DMP also needs to set out a clear strategy in terms of water use priorities and hierarchy of measures in each drought or water scarcity phase and for each river basin in order to avoid generalist approaches and possible misinterpretation of the DMP that could lead to increasing existing and future conflicts.

4.7 Conclusions

Traditionally, droughts were only managed as a crisis situation, by implementing emergency procedures and urgent measures. However, that approach usually failed in achieving the most sustainable and cost-efficient solutions in the long-run. Consequently, this has led in the last decades to a paradigm shift towards applying drought risk-reduction management strategies which are reflected in academic work, the political agenda, and the policy-making process.

Although the terms of drought and water scarcity are sometimes used indistinctly, it is nonetheless important to differentiate them (underlying causes and consequences) in order to appropriately diagnose them, and with that to prevent (where possible) and manage their impacts. Droughts are defined as natural phenomena (i.e. a regular climate feature) caused by a deficiency in precipitation, which represents a certain statistical anomaly with respect to the long-term average over a certain period of time and specific area. In contrast, water scarcity occurs when the water consumption is greater than the renewable available water resources.

In this context, DMPs represent key strategic tools to support sustainable water resource management, build resilience to drought extremes and reduce vulnerability. In order to be effective tools and provide reliable support to water decision-makers, DMPs should promote simple, practical but scientifically sound approaches (based on technical evidence, the latest engineering and science knowledge) and by integrating learned lessons from historical droughts (especially, past socio-economic and environmental impacts).

At the EU level, substantial progress and efforts have been made in terms of developing policy instruments and technical guidance to deal with droughts and water scarcity. The most important and ambitious piece of European water and environmental legislation was introduced with the adoption of the WFD in 2000. However, water scarcity issues are not addressed and droughts are only succinctly dealt with within the WFD (Art. 1e and Art.4.6). In fact, the elaboration of the DMPs is currently not compulsory.

After the important economic, environmental, and social impacts from the 2003 drought in Europe, droughts and water scarcity were considered as a major challenge afflicting the European territory. A key milestone in terms of European drought-risk management approach was set by the 2007 EC Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*". This presented an initial set of seven policy instruments for tackling water scarcity and drought issues at European, national, and regional levels. These included options in relation to '*putting the right price tag on water*', '*allocating water more efficiently*', and '*fostering water efficient technologies and practices*'. The Communication also recommended the development of DMPs (as supplementary documents of the RBMPs in line with the Art. 13(5) of the WFD).

The EU has adopted instruments such as the EDO internet-based interactive map and the WEI+ to identify and deal with droughts and water scarcity. Additionally, there is an important publically available European database called "*European Drought Reference database*" (EDR) and the "*European Drought Impact Report Inventory*" (EDII) which provide considerable information about historical drought events in Europe. These tools are very instructive and informative as starting point, but there are still key challenges related to the practical integration and application of this information as well as its periodic upgrade (so that EU members could maximise their use in practice).

Spain is one of the EU Member States with the longest track record in water legislation and hydrological planning. Proof of this is the fact that the 1985 Water Act already introduced the innovative concept of river basin management approach (which would be incorporated 15 years later in the WFD 2000), all the RBAs were established between 1926 and 1961 [55] and the first RBMPs were finished 1998-1999 (20 years earlier than the first RBMPs in Europe).

Possibly, the reason for this might be that Spain has historically and periodically suffered the consequences from severe droughts and water scarcity episodes. Some of the most notorious ones in terms of impacts were produced during the periods: 1941–1945, 1979–1983, 1991–1995 and 2004–2007 [45]. Additionally, the economic productivity of the agriculture sector is especially relevant and the greatest agricultural water demand occurs precisely when the temperature and evaporation are higher and precipitation is lower (usually, from April to September).

In response to this, Spanish water legislation and hydrological planning has been historically based on implementing resilient water infrastructures (such as providing water storage infrastructures) to better manage the spatial and temporal irregularity in precipitation in relation to the demand pattern, as well as to deal with the effects of extreme hydrological and climate phenomena (floods and droughts).

As many other European countries, Spain has traditionally managed droughts as a crisis situation only by applying emergency procedures and urgent measures (through the adoption of Emergency Drought Orders or Decrees). However, the experience and lessons learnt after the devastating environmental, social, and economic consequences of the 1991–1995 drought, demonstrated that a paradigm shift towards a drought risk-reduction management approach in Spain was required.

In Spain, the preparation of DMPs is compulsory in line with art. 27 of Law 10/2001, of July 5, of the National Hydrological Plan. The first DMPs in Spain were developed by the RBAs and approved in 2007. At this time, a common National Drought Indicator had already been established. Even though the DMPs were not approved until 2007, the 2004–2007 drought period was already managed in accordance with those principles established in the DMPs. These proved to be effective strategic management tools which positively contributed to avoid public supply restrictions, reduced and mitigated drought impacts, and highlighted the importance of involving the relevant stakeholders and interested parties (including the general public) in the decision-making processes associated with drought planning [60].

After the experience and lessons learnt during ten years of applying the first 2007 DMPs and 2 RBMPs cycles (2009-2015 and 2015-2021), it was found necessary to update the first 2007 DMPs. Hence, the latest DMPs were approved in December 2018 as supplementary documents to the 2nd RBMPs (Art. 13(5) of the WFD). These set out the framework for a drought risk-reduction management approach by defining relevant droughts and water scarcity indicators and their thresholds, early warning systems, and measures to be applied progressively during each drought phase. Important innovative aspects have been integrated such as a clear differentiation between drought events and water scarcity episodes in terms of different conceptual definition, diagnosis and indicator systems, as well as measures to deal individually with each phenomenon.

A common global indicator system has been set out across all the river basins, which allows comparable diagnosis and results among all the different river sub-basins in Spain. This means that if a similar (drought or water scarcity) indicator value is found in two different sub-basins, the (drought or water scarcity) situation is expected to be similar. Therefore, actions and measures to be taken are expected to be of the same type and nature.

This highlights that there have been significant strides made by all RBAs in Spain towards the harmonization of technical procedures across all the basins. This shows also that there has been an effective intergovernmental coordination between all the organizations and processes involved at the political, technical, and institutional levels. The above demonstrates how a common global indicator system and methodology could be also implemented at the EU level.

Based on the review carried out, it can be concluded that it is necessary to build further knowledge in the following areas:

- phenomenon of drought (spatial and temporal propagation and interaction, impact of global climate patterns);
- further integration of the drought monitoring tools and drought forecasting models into water planning approaches;
- economic, environmental and social impacts of droughts in different water sectors as well as drought impact forecasting;
- further involvement of all interested parties and the public during the consultation period.

Therefore, the DMP should be a live and flexible document able to integrate the most updated knowledge that is relevant, credible, and delivered in a timely manner. Effective management of water resources starts with planning in advance, in the long, medium and short term. The most important elements of a DMP are: i) the identification of the risk and its characterization (indicators/indices and different thresholds or trigger curves), ii) the actions or measures to manage that risk (before, during and after the event) by applying preparedness and prevention, mitigation and emergency actions, response and recovery, and iii) a system or methodology to monitor the effectiveness of those measures. The DMP also needs to set out a clear strategy in terms of water use priorities and hierarchy of measures in each drought or water scarcity phase and for each river basin to avoid generalist approaches and possible misinterpretation of the DMP that could lead to increasing existing and future conflicts.

5. ARTICLE II

5. ARTICLE II: ARE THE MODERN DROUGHT MANAGEMENT PLANS IN SPAIN MODERN ENOUGH? THE GUADALQUIVIR RIVER BASIN CASE IN SPAIN

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5.1 Abstract

Droughts and water scarcity events are predicted to be more frequent and intense in the future, especially in Mediterranean countries. However, are the most recent Drought Management Plans (DMPs) built on the latest technical, engineering, and scientific knowledge, as well as the learning experiences from managing historical droughts? The most significant challenge that surfaces, when a new drought event strikes, is the difficulty in predicting its duration (which can vary from months to years), the severity (or degree of affection to water resources), and the potential environmental, economic, and social impacts. Hence, there is an importance of integrating reliable forecasting and modelling tools in the development of modern DMPs, so the potential risk can be assessed under a range of possible drought scenarios. This will ensure that the proposed measures and actions of the DMP are sufficiently robust and proportionate to the drought and water scarcity situation. This paper provides a critical assessment of the core technical concepts and principles to be taken into consideration when developing the methodological and operational framework of a DMP. The case of study chosen is the Guadalquivir River Basin (GRB) in southern Spain, which presents one of the most complex and paradigmatic cases in this regard. This region suffers recurrent episodes of drought and water scarcity, together with fierce competition among water users. Recently, a new strategic DMP has been approved and adopted in December 2018. The implications of applying the 2018 GRB DMP in practice during a drought period have been also evaluated. This study draws important lessons learned that could be applied in other areas suffering from water scarcity and droughts.

Keywords: drought management plan; drought; water scarcity; Guadalquivir River; Spain.

5.2 Introduction

Global warming and its consequent extreme climate-related events affect, to a greater or lesser extent, the entire planet. The latest IPCC (Intergovernmental Panel on Climate Change) Special Report on Global Warming of 1.5 °C predicts even worse future climate-change wide-ranging impacts up and until 2100 [11].

Droughts are natural phenomena that affect worldwide although unevenly. The characteristics of droughts (duration, magnitude, and frequency) are specific to each climate region and will determine the degree of stress caused to water resources (in terms of reduction in the soil moisture, low river flows and groundwater levels, drop in reservoirs storage water levels, etc.), and ultimately, the degree of affection to the rest of spheres of society.

However, the impact of a drought event on the economy, environment, and society will depend on - apart from the inherent characteristics of the drought event - diverse site-specific circumstances, including (i) the resilience and efficiency of the existing water infrastructures, (ii) the existing drought management protocols in place, (iii) existing socio-economic factors (such as if there is a fast-growing population, the water use patterns, urbanization, economic development, agricultural irrigation practices, etc.), and (iv) environmental water constraints (e-flows). In contrast, water scarcity episodes occur when water consumption is greater than the renewable available water resources, resulting in overexploited water resources [6].

The magnitude of this issue across Europe is not to be overlooked. Water scarcity and droughts affect around one third of the European territory and over 100 million people [7]. Climate change is projected to increase the intensity and the frequency of severe droughts in most of Europe, especially in Mediterranean countries (arid and water-stressed basins) [2], [3]. A comprehensive critical review of the historical drought management planning policy evolution in Europe and Spain is presented in Hervás-Gámez and Delgado-Ramos [67].

The occurrence of droughts cannot be avoided as they are a feature of any climate. Thus, efforts should be focused on improving the preparedness, risk-reduction based strategies and progressive adaptation in order to avoid (where possible), minimise and manage the potential negative consequences of drought events. It is therefore necessary to apply rational methodologies, which can help water decision makers to find the right and proportionate balance among technically feasible, environmentally sensible, economically efficient and socially acceptable measures to deal with droughts.

However, the major challenge when dealing with a new drought event resides in predicting its duration (which can vary from months to years), the severity (or degree of affection to water resources), and the potential impacts. Hence, there is an importance of integrating reliable forecasting and modelling tools in the development of modern Drought Management Plans (DMPs), so the potential risk can be assessed under a range of possible drought scenarios. This will ensure that the proposed measures and actions are sufficiently robust and proportionate to the real drought and water scarcity situation.

In this context, DMPs are key strategic decision-making tools to build resilience to drought extremes for use by water authorities. DMPs should define relevant drought and water scarcity indicators and their thresholds, provide reliable early warning systems, and establish priorities among water users together with a clear action roadmap to be followed during each drought phase. In order to be effective tools and provide consistent support to water decision-makers, DMPs should be based on technical evidence, the latest engineering and science knowledge combined with learning experiences from historical droughts [67]. Despite their importance, the Water Framework Directive (WFD, Directive 2000/60/EC, [28]) does not explicitly require the elaboration of DMPs by Member Estates. This has been however highly recommended by EU water policies ([30]–[35]) and a wide range of European non-legally binding technical guidance documents ([18], [36]). The DMPs can be prepared as supplementary documents to the River Basin Management Plans (RBMPs) along with art. 13.5 WFD. So, the DMPs should be developed and implemented according to the WFD requirements.

In Spain, as in many other EU countries, droughts have traditionally been managed as a crisis-driven response only, by applying emergency procedures and urgent measures. However, the lessons learned from past droughts have demonstrated that these are usually hasty, costly, and inefficient solutions in the long-run. It was precisely after the devastating environmental, social, and economic consequences of the 1991–1995 drought period that a paradigm shift towards a drought risk-reduction management approach in Spain was deemed necessary.

The first DMPs for all inter-community river basins in Spain (i.e., rivers that flow across more than one autonomous community) were developed by the River Basin Authorities (RBAs) and approved by the Directorate-General for Water (DGA) of the Spanish Ministry for the Ecological Transition (MITECO) in 2007 (Orden MAM/698/2007 de 21 de marzo).

Even though the DMPs were not approved until 2007, the 2004–2007 drought was already managed in accordance with those principles. This certainly contributed to avoiding public supply restrictions, reducing and mitigating drought impacts, and stressed the importance of public participation in the decision-making process for drought events [60].

Since the first DMPs were approved in 2007, two planning cycles (2009–2015 and 2015-2021) have been completed in compliance with the WFD. The experience gained during more than a decade of implementing the DMPs across Spain has shown the importance of applying common criteria (including a global system of hydrological indicators) to avoid heterogeneities in the diagnosis and the nature of the actions and measures to be applied in the diverse scenarios and different basins [60].

Based on this, the Royal Decree 1/2016 instructed the revision of all DMPs for all the inter-community River Basin Districts in agreement with the technical instructions provided by the MITECO before the 31 December 2017. The MITECO prepared the "*Technical Instruction for the Elaboration of the Special Drought Plans and the definition of the global system of indicators of prolonged drought and scarcity*" [61] in order to ensure that a common methodology was applied among all the RBAs in Spain when diagnosing drought and scarcity situations and implementing the same type and nature of actions and measures.

The RBAs are responsible for their elaboration, management, monitoring, control, and follow-up at the river basin scale (i.e., strategic DMPs). The approving body is the DGA of the MITECO.

The Guadalquivir is the main river in southern Spain (**Figure 10**) that periodically suffers the consequences of drought events and water scarcity episodes. There is also fierce competition among water users for this scarce water resource in this basin. Therefore, this river basin presents an ideal context to assess how drought risk is ultimately managed according to the recently adopted 2018 Guadalquivir River Basin (GRB) DMP.

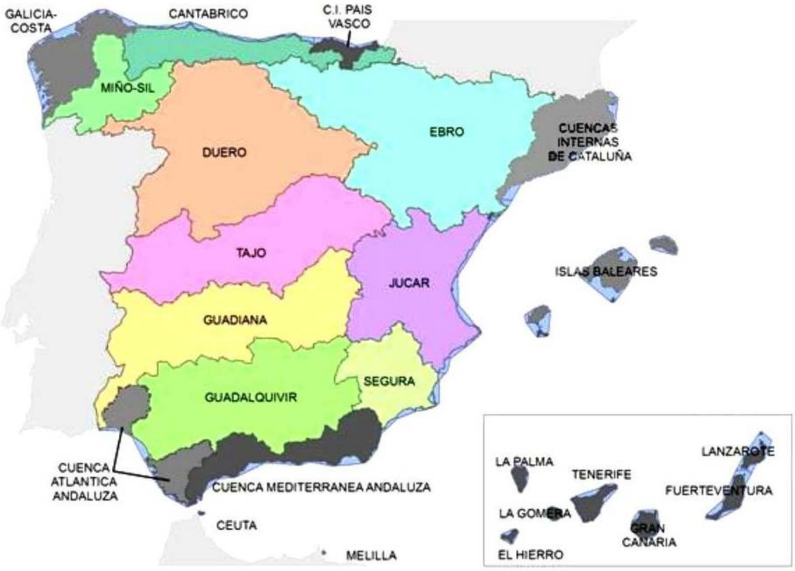

Figure 10: River basins in Spain (source: [68]).

This paper provides a critical assessment of the core technical concepts and principles to be taken into consideration when developing the methodological and operational framework of a DMP. In particular, this paper provides a critical technical assessment of the recently published 2018 GRB DMP. It is evaluated whether and how the proposed drought risk management approach (indicators, thresholds, and measures) would efficiently contribute towards a proactive risk-based management strategy.

Section 5.3 provides a critical review of the key aspects of the 2018 GRB DMP in terms of: (i) the methodological (technical) approach in terms of hydrological data sources, reference series, zoning, characterization, diagnosis, and risk evaluation, and (ii) the operational framework in terms of the measures responding to drought and water scarcity. The adopted 2018 GRB DMP (subject to this assessment) is publicly available at the GRBA (Guadalquivir River Basin Authority) webpage [62].

Section 5.4 presents a technical analysis of the practical implications of applying the 2018 GRB DMP to a specific river sub-basin (i.e. the Upper Genil River) of the GRB and a set of proposals for improvement are provided.

Section 5.5 outlines the conclusions and recommendations to enhance future preparedness to drought.

5.3 Critical Review of the Key Aspects of the 2018 Guadalquivir River Basin Drought Management Plan

5.3.1 Study Area Description

The Guadalquivir is the main river in southern Spain (**Figure 10**) that provides water to a total population of over four million people and over eight hundred thousand hectares for irrigation purposes. This system is currently formed by an interconnected system of 64 large functioning dams [69]. Although there are alternative water resources from aquifers, springs, and water re-use schemes, nowadays, reservoirs are the essential infrastructure to efficiently deal with spatial and temporal climate irregularities distinctive of this catchment area [65].

The Guadalquivir River has a total contributing catchment area of 57,527 km^2 and is delimited by Sierra Morena to the north, the Betic mountain to the south, and the Atlantic Ocean. The altitude at the mountainous borders varies between 1000 m above mean sea level (AMSL) and 3480 m AMSL, which contrasts with the lower altitudes of the Guadalquivir River valley. The climate is Mediterranean, which is defined by the warm temperatures (16.8 °C annual average) and the irregularity of precipitations (550 mm annual average rainfall, oscillating between 293 mm and 1321 mm).

The GRB periodically suffers the consequences of drought events and water scarcity episodes. One of the most recent and notorious drought and water scarcity episode was produced during the 1991–1995 drought period. For the Iberian Peninsula, this event was identified with an approximate 200-year return period and a 5-year duration [70]. The DDF (deficit, duration, frequency) curves developed by the CEDEX are based on 82-year long time series (1930/31-2010/11).

This event resulted in important water scarcity problems and significant economic, social, and environmental consequences (important harvest losses, severe water restrictions to all users, disruptions to services, drinking water deterioration, very low river flows, contamination issues, etc.) [67].

Additionally, the long-term impacts (up to 2100) of climate change predict an increasing frequency in drought events as the 21st-century advances and, consequently, an increase in water scarcity problems due to the forecasted depletion in water resources [54].

The GRBA is responsible for preparing the DMPs in accordance with the Spanish Law 10/2001 National Hydrological Plan and European WFD (Directive 2000/60/CE –Art. 4.6). The final version of the GRB DMP was adopted in December 2018 (*Orden TEC/1399/2018, de 28 de noviembre*). This framework establishes the general management principles and course of action for different drought and water scarcity scenarios and in each sub-basin.

It is important to highlight that updating a DMP for such an extensive, varied, and intricate river basin is undoubtedly a considerably complex task. The substantial efforts and technical work undertaken by the GRBA during the elaboration of the 2018 GRB DMP should, therefore, be acknowledged.

The case of study is the GRB; however, the implications of applying in practice the 2018 GRB DMP have been assessed for the particular river sub-basin case, the Upper Genil River. For this particular case, the Canales and Quéntar reservoirs form the key water infrastructures that serve water for urban and irrigation purposes. Urban water consumers are up to 300,000 inhabitants, and traditional irrigations cover over 4000 hectares. This system is supplemented by a network of groundwater wells [65]. The system uses an increasing hierarchy of surface water (SW) resources and then, groundwater (GW) resources to meet the demand.

The total annual urban water demand is 37.52 hm^3, and the total annual irrigation water demand is 25.90 hm^3 (established in the Guadalquivir RBMP 2015–2021). During years of average precipitation, water demands can be met with SW resources from the reservoirs. However, in years of below-normal precipitation, typically higher GW volume extractions and/or reductions in per right allocation are required. Strategic water decisions are made by the GRBA on the controlled released outflows from the Quéntar-Canales system. These are critical before the intensive irrigation campaign starts (usually in April) when the water authorities must make responsible management decisions about the best allocation of the available water volume between different water consumers and environmental needs for the rest of the current hydrological year [65].

5.3.2 Overview of the 2018 GRB DMP

The key elements of a DMP in accordance with the MITECO Technical Instructions [61] and the European technical document “*Drought Management Plan Report Including Agricultural, Drought Indicators and Climate Change Aspects*” [18] are:

a) a diagnosis system, including the definition of territorial units and environmental characterization;
b) the definition of a common global indicator and thresholds system (establishing onset, ending, and severity levels of the exceptional circumstances);
c) actions and measures to be taken in each phase; and
d) organizational framework: monitoring and follow-up system to deal with drought and subsequent revision and updating of the existing DMP.

Albeit a lengthy document, the 2018 GRB DMP is a well-structured report that contains the aforementioned elements (assessed further in the following Sections).

5.3.3 Diagnosis System: Definition of Territorial Units and Environmental Characterization

One of the key objectives of the 2018 DMPs was to clearly differentiate droughts events (defined as "*a natural phenomenon produced by the reduction of rainfall and natural run-off, which occurs independently of anthropic action*") from water scarcity episodes (defined as: "*the temporary problem of a determined area to meet the water demands for the different socio-economic uses, and therefore it is dependent on human intervention in relation to its use of resource*") [62].

Consequently, this conceptual differentiation led to defining different territorial management units (TMUs) in terms of water resources to adequately characterize the drought and water scarcity phenomena.

On the one hand, the "*prolonged drought TMUs*" are related to homogeneous hydrogeological areas in terms of water resources generation (including all watersheds and GW recharge areas according to the RBMP). Therefore, the indicators to be used will be related, principally, with precipitation or streamflow in the natural regime [62].

The "*water scarcity TMUs*" are, on the other hand, related to the water demands (or consumption points) and associated ecological systems (according to the water exploitation systems established according to the RBMP). Therefore, the indicators to be used will be related, principally, with meeting the water demands. Generally, the reservoir storage volume is used (for example, this applies to the Upper Genil River, as shown in **Section 5.4**) [62].

The GRB includes 25 "prolonged drought TMUs", and each of these is formed by one or more "water scarcity TMUs".

This system is considerably efficient in terms of clearly differentiating droughts from water scarcity episodes. This is important because their underlying causes and consequences are different. This system allows these events to be monitored, diagnosed, and managed differently, with a different set of actions and measures for each specific territorial management unit.

5.3.4 Definition of a Common Global Hydrological Indicator

A global system of hydrological indicators was established in the 2018 GRB DMP so that drought and water scarcity situations could be identified early enough and foreseen. The methodology followed was:

1. Firstly, the most representative hydrological variable was selected. For example, the precipitation was selected for characterizing the drought events in all "*prolonged drought TMU*". One variable or a combination of them (precipitation, reservoir inflow, reservoir storage, GW level, etc.) could be selected for characterizing the water scarcity phenomenon in each "*water scarcity TMU*";

2. Secondly, the relevant hydrological time series (Oct 1980 – Sept 2012) were prepared;
3. Thirdly, the indicators were calculated using the sub-basin specific data;
4. Finally, the numerical values obtained were then scaled (between 0 and 1), weighted, and validated using the observed historical series.

This common indicator system allows a homogeneous treatment not only of the entire GRB but among different basins in Spain. The great advantage of this system is that despite the diverse climatic, geographical, or water demand specific conditions, diagnosis results are comparable across different sub-basins. This means that if a similar indicator value is found in two different sub-basins, the drought or water scarcity situation is expected to be similar. Therefore, actions and measures are expected to be of the same type and nature. **Table 4** and **Table 6** show the common progressive measures to be applied across the GRB according to the drought and water scarcity status, respectively.

This highlights significant strides made by all RBAs in Spain towards the harmonization of technical procedures across all the river basins. This system will not only provide support to the RBA decision-making processes to justify actions and measures (especially when declaring formal drought situations) but also when disseminating information to stakeholders, interested parties, and the general public. This example demonstrates how a common indicator system could be implemented at the EU level.

It is important to highlight that despite the undoubted advantages of having a global indicator system, the DMP should be sufficiently flexible to allow actions and measures to be tailored to respond (as required) to specific sub-basin needs. This is paramount in those sub-basins characterized by complex water conflict resolution. For example, in those mixed water systems where there is fierce competition among historical water users (agriculture) and priority water users (households) who share scarce water resources.

Therefore, the DMP should also set out a clear strategy in terms of water use priorities and hierarchy of measures (supply or demand side) in each drought phase and each TMU in order to avoid possible misinterpretation of the DMP that could lead to a potential increase in existing and future conflicts.

5.3.5 Streamflow Forecasting Models

Despite the improvements in the accuracy and reliability of advanced hydrological information and streamflow forecasts, these still remain underused by many water authorities and water decision-makers. Their decisions on how to best allocate the available water resources between the different water users and environmental needs are crucial, especially in water-stressed regions, where there is strong competition for scarce water resources.

In this context, risk-based streamflow forecasts can provide consistent support to water authorities to adopt efficient water resources management strategies and actions, as well as the opportunity to assess in advance the potential environmental and socio-economic consequences. For this study, efficient strategies and actions are those that contribute towards optimizing the use of available water resources to meet the water demands of the system while minimizing environmental impacts (reduction of carbon footprint, the satisfaction of ecological flows, etc.) and reducing costs.

In Spain, for example, the GRBA is responsible for taking the strategic decisions on controlled released outflows from reservoirs in the GRB. However, they still do not rely on streamflow forecasting models to support their strategic decisions but their long-track experience in dealing with historical droughts and managing water resources in this region. The critical decisions on controlled released outflows from reservoirs and water allocation to downstream users are usually taken in the middle of the hydrological year (just before intensive irrigation campaigns commence, usually in April) [65].

The absence of using streamflow forecast models (at least, during the current hydrological year) is not justified. Drought risk-based management decisions should be informed by science and engineering knowledge that is relevant, credible, and delivered in a timely manner. In Spain, the Spanish meteorological agency (Agencia Estatal de Metereología) provides seasonal climate forecasts. Additionally, streamflow forecast models have already been developed and proven to be sufficiently robust and accurate for headwater catchments, such as the Upper Genil River [65].

The use of reliable forecasting models (at least for the current hydrological year) is essential to anticipate, assess risk, plan, and evaluate potential impacts of a drought, as well as to take adequate and proportionate actions. This is critically analysed in **Section 5.4**.

The methodology used in the 2018 GRB DMP for the calculation of the water scarcity thresholds (that ultimately defines the activation of measures) is based on the assumption that for the next three years, the reference drought event will occur. That is, the 100-year return period drought event for urban water supply systems, the 20-year return period drought event for irrigation water systems, and an intermediate return period drought event for mixed systems (usually, the 20-year return period for all cases except when the urban water supply represents more than 50% of the total water demand in which case the 100-year return period is used).

The approach followed in the 2018 GRB DMP is considered very conservative, especially when strategic decisions are taken in the middle of the current hydrological year. At that critical decision point (March–April), there is a considerable amount of hydrological information available, which should not be ignored.

For example, if the first 6 months of the hydrological year (from October to March) have been humid and wet, it is unlikely that the 100-year return period drought event will suddenly happen for the next 6 months of the same hydrological year. This is even less likely in catchments with snow storage and melting processes.

This "*worst-case*" approach has led to undertaking many actions and measures, which later, with the benefit of hindsight, were completely unnecessary or disproportionate. For example, the mobilization of strategic water resources or non-conventional water resources, some restrictions to water demands, etc. with associated negative economic, environmental, and societal consequences, which rarely the water authority would directly assume. This is critically analysed in **Section 5.4**.

5.3.6 Reference Period Used

The diagnosis system established in the 2018 GRB DMP is based on the short hydrological monthly time series (from October 1980 to September 2012, i.e., 32 years).

However, at least a monthly precipitation sample size of 30 years, with 50–60 years (or more) being optimal, is recommended to calculate rainfall statistics ([71], [72]). The current WMO (World Meteorological Organization) climatological standard normal is calculated every 10 years for 30-year periods at the start of every decade from the year ending with digit 1 (1981-2010, 1991–2020, etc.). The WMO has recently recognized [73] that "*the optimal period for precipitation is often substantially greater than 30 years*" and that "*the most recent 5- to 10-year period of record has as much predictive value as a 30-year record*". In this respect, it is also important to highlight that the most recent 6-year period of historical hydrological data records is not included in the latest 2018 DMP.

The European water scarcity and drought expert group strongly recommended using the period January 1971 to December 2010 as the reference period for the calculation of the SPI (Standardized Precipitation Index). Only in the case that a lack of data would significantly restrict the number of rainfall stations to be used, a shorter reference period may be used (e.g., 1981–2010).

An extremely humid or dry period within that short reference period (32 years) might have an impact on the short-term average and standard deviation hydrological values and associated statistical indicators. The degree of affection will depend on the duration and magnitude of the extreme event. This would, therefore, distort a proper comparison with current hydrological values and not allow a sound statistical comparison of wetter and drier climates.

The direct consequences of using the short reference period (instead of the long reference period) are presented in **Section 5.4**.

5.3.7 Climate Change Assessment

The GRB is a drought-prone and water scarce basin that has historically suffered from intense drought episodes (**Table 5**). Climate change is projected to reduce natural resources in the GRB between 3%–12% up to 2033 (in relation to the control series 1960/1961 to 1990/1991, [48]), and severe droughts are expected to become more frequent and intense as the 21st century progresses [54].

It is acknowledged that Strategic DMPs are built on a relatively short-time horizon (compared to the climate change projections) and the intention is to update them every 6 years. It is also recognised that the Strategic DMPs have been developed as supplementary documents to the RBMPs.

However, the 2018 GRB DMP does not clearly establish the link to the Programme of Measures of the RBMP nor does it refer to a long-term planning framework strategy (say up to 25–50 years in future) to cope with the key global challenges affecting drought management in the GRB (impacts of climate change, environmental and economic pressures, water pollution and water demand growth).

Given the anticipated significant impacts that higher temperatures and evapotranspiration rates could have together with the reduction of precipitation in the GRB [54], it is considered fundamental to include an evaluation of the resilience of the system to potential changes in climate (including droughts worse than historical ones), so that an adaptation programme could be accordingly prepared and gradually implemented.

A combination of different water availability and water demand growth scenarios should be tested taking into account the data uncertainty. This will not only help to quantify the future supply-demand balance and assess the potential future drought/water scarcity risk under different scenarios, but will also provide an opportunity to enhance the preparedness strategy, ease the adaptation to climate change and build resilience to droughts.

5.3.8 Drought Management Measures: Prolonged Drought

The 2018 GRB DMP defines "*prolonged drought*" as "*the drought produced by exceptional circumstances or that could not reasonably have been foreseen. The identification of these circumstances is done through the use of indicators related to the lack of precipitation during a period of time and taking into account aspects such as intensity and duration (according to definition no. 63 of the Ministerial Order for Hydrological Planning (ORDEN ARM/2656/2008 sobre Instrucción de Planificación Hidrológica (IPH))*".

The 2018 GRB DMP also establishes a system to objectively identify the indicator and thresholds of the exceptional circumstances in relation to a prolonged drought situation. The prolonged drought situation is formally declared when the drought indicator value (based on precipitation) is equal or lower to 0.3. This value has been assigned to that situation in which the natural streamflow regime cannot meet the minimum e-flows (ecological flow regime).

The WFD states in article 4.6: "*temporary deterioration in the status of water bodies shall not be in breach of the requirements of the Directive when resulting from natural or force majeure cause, or in case of a reasonably unpredictable event such as "exceptional floods" or "prolonged droughts", or due to reasonably unforeseeable accidents, when all of the established WFD conditions have been met*".

It is important to highlight that 4.6 (a) of the WFD states that "*all practicable steps are taken* *to prevent further deterioration in status and in order not to compromise the achievement of the objectives of this Directive in other bodies of water not affected by those circumstances*".

The proposed measures in the 2018 GRB DMP to deal with prolonged drought are to (**Table 4**):

i) justify a temporary deterioration of the state of water bodies due to exceptional natural causes;

ii) apply a less stringent ecological flow regime.

However, these proposed measures are not "*strictly measures*" but the consequences of a prolonged drought situation.

It is considered that these measures do not "*prevent further deterioration*" (as required by the WFD).

The DMP should be a proactive management instrument to implement preventive measures in the first instance (when and where possible), minimize and then mitigate the effects of prolonged droughts. For example, the DMP could include measures to promote water-saving or minimize the water pollution applied to all water-dependent sectors (agriculture, urban development, industry, energy, tourism, transport).

Table 4: Prolonged drought: Types of measures to be applied during the different drought scenarios (own elaboration, data from 2018 GRB DMP).

Definition	Reduction in precipitation that considerably affects the available natural water resources (superficial or groundwater). It does not depend on the existing water demands.	
Impacts	It can naturally produce a significant reduction in water quantity and deterioration of water quality.	
Indicator	Precipitation and streamflow in natural regime.	
Global Indicator Value	0.3–1	0–0.3
Scenario	Absence of prolonged drought	Prolonged drought
Type of Actions	Control and monitoring. No temporal deterioration. Comply with ecological flows.	Possibility of justifying a temporal deterioration of water status and adoption of less stringent ecological flow regime.
Objective of DMP	To limit the temporary deterioration of the water status as well as the less stringent ecological flow regime (set out in the RBMP) to natural situations of prolonged drought only (not related to scarcity problems).	

5.3.9 Water Scarcity: Indicator and Thresholds

The water scarcity thresholds are calculated for each specific water scarcity TMU by selecting the most representative variable in terms of resource availability evolution (precipitation, reservoir storage volume, reservoir inflow, GW level, etc.).

In the case of the GRB, the reservoir storage volume has been selected for all TMUs except for one (in which precipitation has been used). In those systems with irrigation demands, two different periods have been analysed: from October to March and from April to September (when the irrigation campaigns generally occur).

The water scarcity thresholds are defined in the DMP by "*the capacity of a specific territorial management unit to face or minimize the impacts of a possible drought event*". The model used to define the thresholds is based on a volumetric balance using a monthly time step, taking into account the inputs, available storage volume, and outputs for the next three years. The calculation methodology used to determine the water scarcity thresholds is presented in Equation (1):

$$\begin{gathered}\text{Stored Volume} + \text{Streamflow Contribution} - \text{Evaporation} - \text{Ecological Flows} \\ \geq \text{Water Demand} + \text{Strategic Water Reserves}\end{gathered} \tag{1}$$

Based on the results from applying Equation (1) to each water system, the following water scarcity thresholds have been defined:

- Pre-alert: there is available water supply to meet the water demand for the next three years (in compliance with the guarantee criteria established in the RBMP).
- Alert: there is available water supply to meet the water demand for the next two years (in compliance with the guarantee criteria established in the RBMP).
- Emergency: there is available water supply to meet the water demand for the next year (in compliance with the guarantee criteria established in the RBMP).

Given the high inter-annual climate variability within the GRB, reservoirs have traditionally been designed to store three times the water demand of the system. The GRB DMP states that based on existing drought records, a three-year drought prevention period should be used. However, this has been shown to be insufficient since the worst and most recently recorded drought event was the 1990/91–1994/95 (5-year duration, **Table 5**).

In fact, the serious consequences of this drought event led to the GRBA to undertake a wide range of strategic and emergency works across the whole GRB to ensure new water supply sources (new river catchments, water transfers among sub-basins, GW wells), apart from severe water demand restrictions (which had considerable social, environmental and economic consequences).

It can be seen from **Table 5** that long-term droughts of 3 years duration (or longer) occur almost every decade, so they are not rare events in this river basin. In the last decade (2010-2019), however, there have been dry spells consisting of a single season or multiple seasons (usually a dry summer followed by a dry autumn, for example, during July 2015-January 2016 and May 2017–November 2017). Additionally, the Mediterranean area is very sensitive to climate change, and it is predicted that future droughts events might be worse than historical droughts. That is, the return periods might be lower (or higher frequency of occurrence) while the duration and deficit might be higher.

Table 5: Main recent historic droughts with duration 2 years or longer on record in the GRB (own elaboration, data from 2018 GRB DMP).

Hydrological Year (from Oct. to Sept.)		**Duration**	**Total Deficit**	**Mean Annual Deficit**	**Maximum Annual Deficit**
Start	**End**	**(Years)**	**(mm)**	**(mm)**	**(mm)**
1971/72	1976/77	6	276	55	101
1979/80	1982/83	4	591	148	204
1985/86	1986/87	2	68	34	41
1990/91	1994/95	5	744	149	270
1998/99	1999/2000	2	334	167	280
2004/05	2007/08	4	81	27	44

Therefore, the 2018 GRB DMP should demonstrate that the current system is resilient, at least, to the most recent worst historic drought on record (i.e., the 1990/91–1994/95 drought event).

This means that if that event was to occur again given the current water demands of the system and available water resources options, the adoption of Emergency Drought Orders or Decrees would not be required.

In fact, strategic DMPs should also consider what would mean in practice the climate change predictions that future droughts might be worse than historic droughts. Nonetheless, it should be acknowledged that designing for an improved level of resilience to droughts conditions, considerably worse than those already experienced, might lead to unaffordable or disproportionate costs together with the exposure to an unknown area due to the lack of experience dealing with this severity level. These situations could be dealt with the use of Emergency Drought Orders or Decrees.

This highlights again the need for a long-term planning approach as part of a strategic DMP, including the modelling of a range of drought scenarios and providing a sound climate change assessment.

5.3.10 Water Scarcity Management: Measures

The standard progressive measures to be applied across the GRB according to the water scarcity status are shown in **Table 6**.

Despite the potential economic, environmental, and social wide-ranging impacts, the actions and measures to deal with droughts and water scarcity have been selected without providing a sound multi-criteria study to justify that the proposals are technically feasible, economically efficient, socially acceptable, and environmentally sustainable.

Tsakiris [74] highlighted that "*The selection of measures should always start with the scenario of business as usual, followed by the easiest and low-cost actions, and then* *gradually moving to more expensive and difficult to implement actions. Priority should be given to reallocation of water resources and water saving activities. Priority also should be given to the temporary measures which will not remain when the situation comes back to normal. We should have in mind that drought is a temporary phenomenon and can be dealt with temporary measures. Costly permanent structural measures are not generally in the centre of the scope of drought management plans. However, they can be selected only if it is deliberately proved that the suffering systems have quite inadequate capacity to face even usual drought years*".

This was also highlighted by Estrela, T. [20] in relation to the 2007 DMP: "*One of the deficiencies of the DMPs from 2007, still in force, is that they do not appropriately contemplate drought impacts on different economic sectors. For this reason, the afore-mentioned technical instruction will include criteria to evaluate these impacts in the different river basin districts. This means that the plans to be approved in 2017 will probably contain a homogeneous and adequate estimation of the economic impacts of droughts in the whole Spanish territory*". This is still one of the key deficiencies of the 2018 GRB DMP.

Table 6: Operational water scarcity: Types of measures to be applied during the different water scarcity scenarios (own elaboration, data from 2018 GRB DMP).

Description	Reduction in available water resources that could risk meeting the existing socio-economic water demands of the specific water system.			
Impact	Socio-economic impacts due to the limitation in available water resources for water use (which could be otherwise addressed in a normal situation).			
Indicator	Storage reservoir volume, reservoir inflow, streamflows, snow storage, groundwater level, etc.			
Global Indicator Value	1–0.5 Absence	0.3–0.5 Moderate	0.15–0.3 Severe	0–0.15 Extreme
Scenario	Normal	Pre-alert	Alert	Emergency
Type of Actions and Measures to Be Activated	General planning and monitoring	Public awareness, water-saving, and monitoring	Management (demand/supply), control, and monitoring	Intensify actions already considered in the alert scenario. Possible adoption of extraordinary measures
Objective	Progressive establishment of measures in order to delay or avoid the entrance in the most severe phases of scarcity, mitigating their negative consequences on socio-economic uses.			

Another difficulty is that the hierarchy and priority assigned to each type of measure within each water scarcity scenario is not provided (which should be the core of the DMPs' scope). There are a set of measures that could be applied in each water scarcity zone, but the order of application is not given. There is also ambiguity on the priority of use among water users and environmental needs. This undermines the definition of the adequate measures to be undertaken and the achievement of environmental objectives in line with the WFD.

Although it is acknowledged that specific actions would be dependent on site-specific circumstances (nature of the supply and demand system, time of year, precedent conditions, climatic predictions, etc.), the Strategic DMP does not provide a clear sequence of drought trigger intervention responses to be followed during each water scarcity phases, with generalist measures to be applied.

In Spain, water companies elaborate operational and contingency DMPs for urban water supply systems serving more than 20,000 people in order to ensure water supplies under drought situations.

Therefore, the Operational DMPs will detail the specific measures to be applied in the particular water system, in accordance with the directions provided in the Strategic DMP. However, at the moment, the Operational and Strategic DMPs are not prepared in parallel. This fact sometimes leads to the mismatch between the overarching principles set out in the Strategic DMPs and the specific assessments of the Operational DMPs. In order to ensure that both are completely aligned, it is fundamental that these (Strategic and Operational) are prepared together or, at least, with the required levels of interaction/liaison with third parties.

It is also considered necessary to relate each measure not only with the water scarcity indicator but also with the drought indicator.

A crucial aspect of any program of measures is that: "*their action methods and established measures must be applied once the interested parties have agreed upon them: administrations, civil society, scientific community, NGOs etc.*" [20]. This aspect should also be improved in the next revision of the GRB DMP.

5.4 Practical Implications and Limitations when applying the 2018 GRB DMP. Proposed Improvements.

5.4.1 Overview

After reviewing the key elements of the 2018 GRB DMP and identifying the main strengths and weaknesses, a technical analysis of the practical implications of applying the 2018 GRB DMP to a specific sub-basin area (the Upper Genil River) has been undertaken, and a set of proposals for improvement has been provided.

The following aspects have been assessed:

a) Implications of using the short reference period (instead of the long reference period) to calculate the drought indicator system (Standardized Precipitation Index) and water scarcity indicator system.

b) Limitations of using the 2018 GRB DMP water scarcity thresholds and proposed alternative methodology to calculate the water scarcity thresholds.

c) Use of streamflow forecast models to improve drought management during the current hydrological year. The forecast model used for this assessment is AQUAFOR (a simple and robust monthly and yearly streamflow forecasting model developed by the University of Granada [65]).The results obtained from using AQUAFOR forecast model (in combination with the aforementioned proposed alternative water scarcity thresholds) were compared with the outcomes from managing a drought event following the 2018 GRB DMP protocol of action. The efficiency in optimising the use of the available water resources to meet the existing water demands of the system was compared. The potential cost implications and environmental impacts were also discussed.

5.4.2 Implications of the selected Reference Period on the Drought Indicator System (Standardized Precipitation Index)

As mentioned in **Section 5.3.6**, the diagnosis system established in the 2018 GRB DMP is based on the short hydrological monthly time series (from October 1980 to September 2012, i.e., 32 years), and this has a series of limitations.

A comparative assessment has been undertaken to show the differences in the SPI calculation using the short and long reference periods and, based on that, what that would actually mean in terms of diagnosing the drought situation and the response.

The aim of the SPI is to objectively identify the variation in the total precipitation (associated with a specific number of months) compared with the long-term average historical precipitation (for the same period). The reduction in precipitation in comparison with the long-term average historical precipitation is the key driver to identify a drought situation. Therefore, negative SPI values mean drier periods than normal. The intensity of the event is given by the absolute value of the SPI [23].

Figure 11 shows a comparative analysis of the SPI for six cumulative months (SPI-6m) using both the short and the long reference series for the Canales and Quéntar reservoirs (Upper Genil River sub-basin) within the GRB.

The average annual precipitation values for Canales and Quéntar reservoirs are 1109.54 mm (using the most recent 31-year short reference period, Oct 1988 - Sept 2019) and 1184.04 mm (using the long time series, Oct-1951-Sept 2019). This means approximately a 6.3% reduction in precipitation when using the short time series.

Figure 11 shows how the most severe drought events (e.g. 1991-1995, 2004-2007) are characterised with lower SPI absolute values when using the short reference period (i.e. lower return period and greater probability of occurrence). This means that an extreme/severe drought event (1991-1995, 2004-2007) would be identified as "*more normal*" or moderate event using the short time series than using the long time series.

This is because one of the most severe recently recorded drought events occurred from 1991 to 1995 (**Table 5**). This 5-year period of intense drought had a total rainfall deficit of 744 mm (mean annual deficit of approximately 149 mm). Logically, an event of these characteristics has a considerable impact on the mean and standard deviation values of precipitation over a short period of time.

This means that extreme (humid or dry) events might not be adequately depicted using the short reference period to efficiently inform the early warning system. Consequently, the statistical indicator (SPI) might not be adequately representative of the event since there is not a sufficiently long record of data. An incorrect diagnosis of the situation could lead to activate drought measures at the wrong time, with the associated environmental, social and economic consequences.

It is, therefore, recommended that the long-term historical precipitation and streamflow series are used for the correct characterization of drought events. The 2018 GRB DMP justifies the use of the most recent short reference period because it reflects better the most recent changes in climate in comparison with the long-term data series. However, the historical data sets provide important information for adequate probabilistic treatment, and cannot be ruled out. An alternative option could be to use a weighting system so that the most recent years are assigned a greater weight compared to previous years.

5.4.3 Implications of the selected Reference Period on the Water Scarcity Indicator System

The aim of the water scarcity indicator system is to objectively identify the potential temporal difficulty in meeting the water demands of a specific water system. The streamflow time series are the input data used to calculate the water scarcity thresholds (refer to Equation 1).

The difference in the total renewable average annual streamflow for the entire GRB, using the long-time series (Period 1940/41–2011/12) in contrast to the short-time series (Period 1980/81-2011/12) is 1168 hm^3/year (according to the data provided in the 2018 GRB DMP) [1].

Therefore, using the lower contribution inputs in the system (i.e. the short-time series) will mean higher water scarcity threshold values. That is, under the same water demand circumstances, the water system will enter earlier and more often into the water scarcity thresholds using the short time series compared with the long-time series. This could lead to activate "*more extreme*" measures and earlier than actually required, with the associated environmental, social, and economic consequences. This is demonstrated in **Sections 5.4.4 and 5.4.5.**

It is thus considered that the length of the historical time-series used (i.e., 32 years) in the 2018 GRB DMP generates uncertainty to (i) adequately depict and characterize the extreme climate-related events, (ii) define adequately the drought and water scarcity indicators, and (iii) provide a reliable early warning system. Extreme event strikes are the result of stochastic processes with usually much larger time horizons than the baseline reference period against which risk is assessed.

It is, therefore, recommended that the long-term historical precipitation and streamflow series are used for the correct characterization of drought and water scarcity episodes.

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[1] Note: The SI unit of volume is the cubic meter (m^3). In this article, the cubic hectometer unit (hm^3) has been used. That is, 1 $hm^3 = 10^6$ m^3.

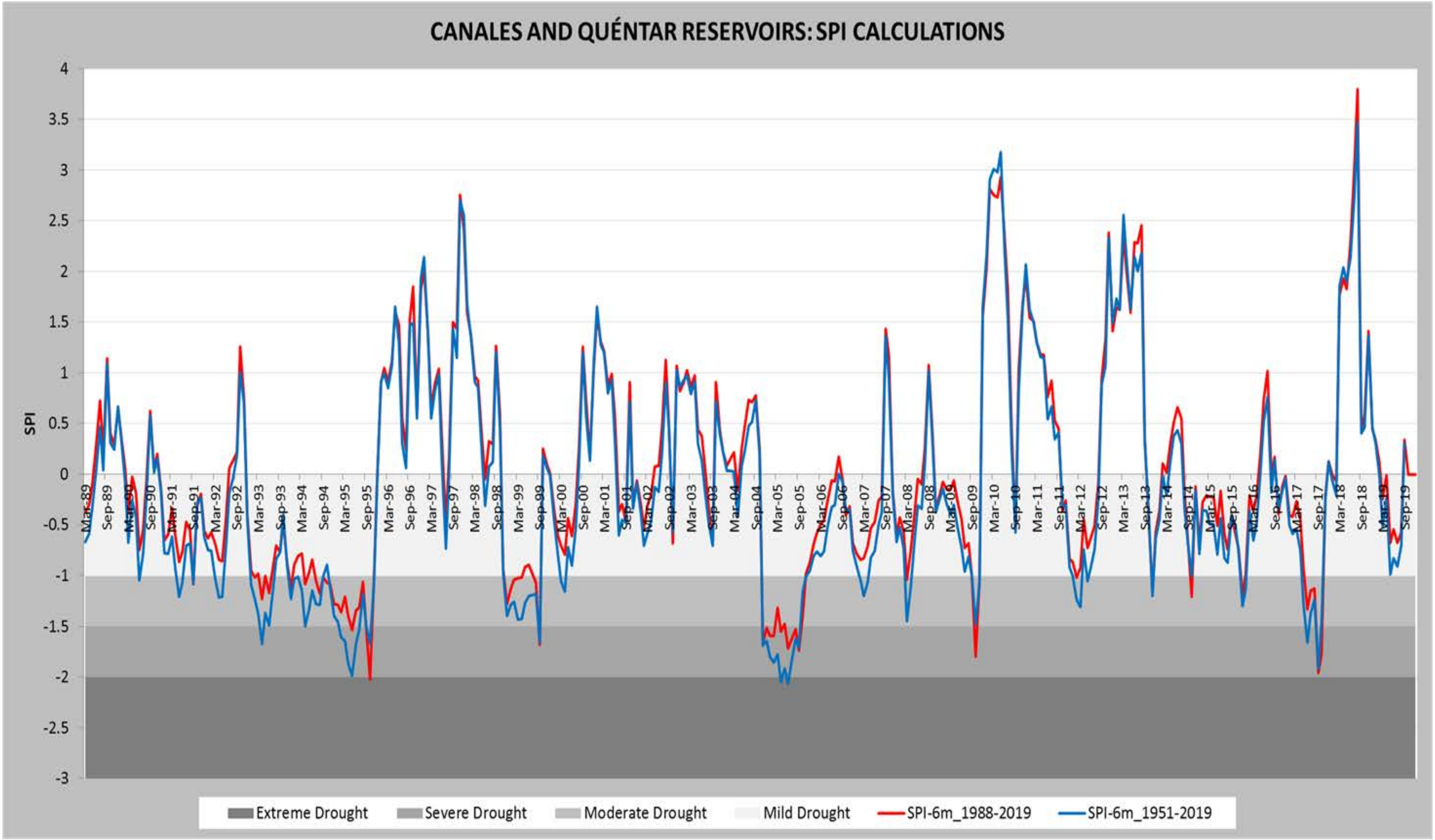


Figure 11: SPI using the short and long-term time series for the Canales and Quéntar reservoirs (Upper Genil River sub-basin, GRB).

5.4.4 Limitations of using the 2018 GRB DMP water scarcity thresholds and proposed alternative water scarcity thresholds

For the Upper Genil River sub-basin (known as the "Canales and Quéntar reservoirs water system"), the water scarcity values set out in the 2018 GRB DMP are shown in **Table 7**.

Table 7: Canales and Quéntar reservoirs stored volume water scarcity thresholds (from 2018 GRB DMP).

Scenario	2018 GRB DMP Water Scarcity Thresholds Stored Volume Canales and Quéntar Reservoirs (hm^3)											
	Oct	**Nov**	**Dc**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**August**	**Sept**
Pre-alert	65	65	65	65	65	65	51	51	51	51	51	51
Alert	43	43	43	43	43	43	37	37	37	37	37	37
Emergency	15	15	15	15	15	15	16	16	16	16	16	16

It can be observed that the values are constant from October to March, and from April to September (period that correspond to the irrigation campaign).

Figure 12 shows the 2018 GRB DMP water scarcity thresholds, the historically observed reservoir stored volume records from October 1999 to September 2019. This period of time corresponds to the available observed data obtained from the "*Automatic Hydrological Information System*" (known as SAIH [75]), as well as the long-term average monthly reservoir stored volume values.

The critique of this system is presented below:

a) It is unclear why the thresholds values are constant (from October to March and from April to September). This is not representative of the normal reservoir storage operating curve. The thresholds should vary monthly, depending on the intrinsic characteristics of the system and the stored volume expected for that time of the year.

   For example, at the beginning of the hydrological year (October–November), the stored volume values are expected to be at their lowest values of the year. After the summer months and the irrigation campaign from the previous hydrological year (April to September), the reservoir is sufficiently empty to provide its water storage and flood protection functions for the winter months.

b) Pre-alert monthly value of 65 hm^3 (from October to March): This value is relatively high since it represents 78% of the total storage capacity of the system (83.6 hm^3, 70 hm^3 Canales reservoir and 13.6 hm^3 Quéntar reservoir). Additionally, this value represents 81% of the mean annual contribution to the reservoirs (80.42 hm^3 for Canales and Quéntar).

   Figure 12 shows how, for the historical average year, the system would enter into the pre-alert scenario from October to March (which is not logical). In fact, looking at the historical data set presented in **Figure 12** the system is always in pre-alert at the beginning of the year except in two occasions: October 2010 (when the stored volume was 69.6 hm^3) and October 2018 (when the stored volume was 66.3 hm^3), slightly higher than 65 hm^3.

One of the measures sets out in the 2018 GRB DMP for the pre-alert scenario is the possibility of mobilizing strategic GW resources (up to 8 hm^3 / year). However, if the strategic GW wells are activated and later on these were not actually required, it is important to consider the unnecessary socio-economic and environmental consequences. This is demonstrated in **Section 5.4.5**.

c) Emergency threshold value of 15 hm^3 (October - March) and 16 hm^3 (April - September): these values are relatively low in comparison with the annual household and irrigation water demands of this this system (37.52 hm^3 and 25.90 hm^3, respectively as described in **Section 5.3.1**). These values are also relatively low in comparison with the historical minimums recorded in this system. This means that if we face a severe drought situation (similar to the 1991-1995 drought), this would be identified as an "*Emergency*" situation, considerably late.

d) The alert and emergency thresholds hardly offer any relevant information, as shown for example during the 2004–2007 drought period.

The aforementioned remarks demonstrate that the 2018 GRB DMP water scarcity thresholds are not representative of a real water scarcity situation of this system. Incorrect scarcity thresholds (pre-alert, alert, and emergency) might lead to the activation of inadequate or disproportionate actions at the incorrect time, with potential negative economic, energetic, social, and environmental impacts. This is demonstrated in **Section 5.4.5**.

Table 8 shows the proposed alternative water scarcity thresholds, and **Figure 13** shows these in relation to the mean historical year and observed storage volume values.

Table 8: Canales and Quéntar reservoirs: Proposed stored volume water scarcity thresholds (own elaboration).

Scenario	**Proposed Water Scarcity Thresholds Stored Volume Canales and Quéntar Reservoirs (hm^3)**											
	Oct	**Nov**	**Dc**	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**August**	**Sept**
Pre-alert	42	42	41	42	44	46	50	53	57	55	49	44
Alert	32	32	32	33	35	37	41	43	48	46	39	34
Emergency	20	19	21	22	25	26	29	31	36	34	27	22

The purpose was to identify early enough the onset, severity and end of the different phases of water scarcity representative of the intrinsic operation of this particular water system, and based on that, identify proportionate measures to be progressively implemented and avoid entering into more severe phases.

The proposed pre-alert scenario indicates a slight deviation from the modelled average year, so within this scenario, measures such as raising public awareness, promoting water savings and efficiency, as well as monitoring the key hydrological variables should be implemented. Therefore, this is one of the key differences with respect the 2018 GRB DMP, which in the pre-alert scenario establishes the possibility of mobilising strategic GW resources (described further in **Section 5.4.5).**

The proposed alert and emergency scenarios show greater deviations from modelled average year, respectively. These phases indicate the time at which demand/supply management measures need to be activated such as applying progressive water restrictions to irrigation and households, mobilizing additional conventional or non-conventional sources, as well as facilitating and optimizing trading assignments in water right markets. It is important to highlight that bottom-up approaches, such as demand management first, are also recognized as critical factors to resilience planning alongside more traditional supply-side management [76].

The proposed water scarcity thresholds (**Table 8**) have been calculated using the software MODSIM-DSS from the University of Colorado [77], and all the input data is described in **Appendix A**. The evolution of the reservoir storage volume (for Canales and Quéntar reservoirs) has been modelled based on the historically observed streamflow data series (Oct 1988-Sept 2019) and the projected water demands (households and irrigation) set out in the Guadalquivir RBMP (2015-2021). The initial storage volume (Oct 1988) to start the simulation has been set at the historical mean storage volume corresponding to October (as there was no available observed storage volume data).

In order to define the water scarcity thresholds (**Table 8**), only the primary water resources of the system (i.e., regulated SW resources from Canales and Quéntar reservoirs) have been included in the model. This is because the use of alternative or complementary strategic water resources or application of water restrictions will be activated only when the water system moves away from its “normal” operation and enters into more severe scarcity phases.

From the modelling results, the modelled average reservoir storage volume year and the standard deviation (STD) have been calculated. The different thresholds have been set out by evaluating the modelled water scarcity thresholds in relation to the historical droughts and reservoir storage data. Then, the values at which it is necessary to activate alternative water resources (and quantity) or/and apply water demands reductions have been determined. Hence, the pre-alert, alert, and emergency scenarios have been estimated as the modelled average reservoir storage volume values minus 0.3 × STD, 0.7 × STD, and 1.2 × STD, respectively.

To validate the proposal, the alternative or strategic water resources of the system were then added to the model and the operating rules were established in such a way that the measures are only activated when the reservoir storage volume reaches the proposed scarcity values.

Figure 13 shows the proposed water scarcity trigger curves obtained following the abovementioned methodology.

The alternative water scarcity thresholds address the aforementioned shortcomings of the 2018 GRB DMP. It can be appreciated how the proposed water scarcity thresholds are more representative of this particular water system since they depict considerably well the onset, severity level, and end of historical water scarcity situations (for example, the drought 2004-2007).

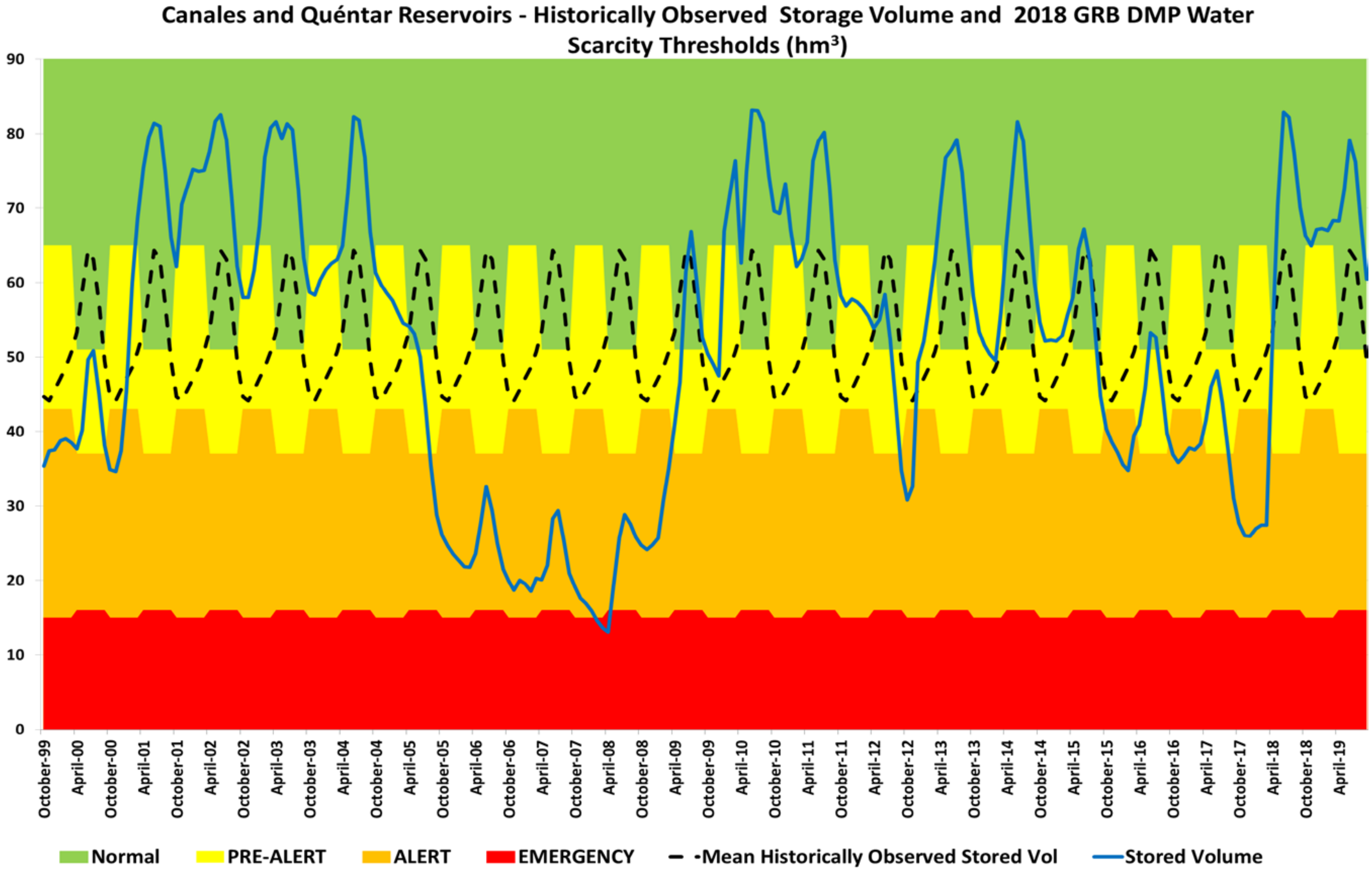


Figure 12: Canales and Quéntar reservoirs: Historically observed stored volume, Mean historically stored volume, and 2018 GRB DMP trigger curves (own elaboration).

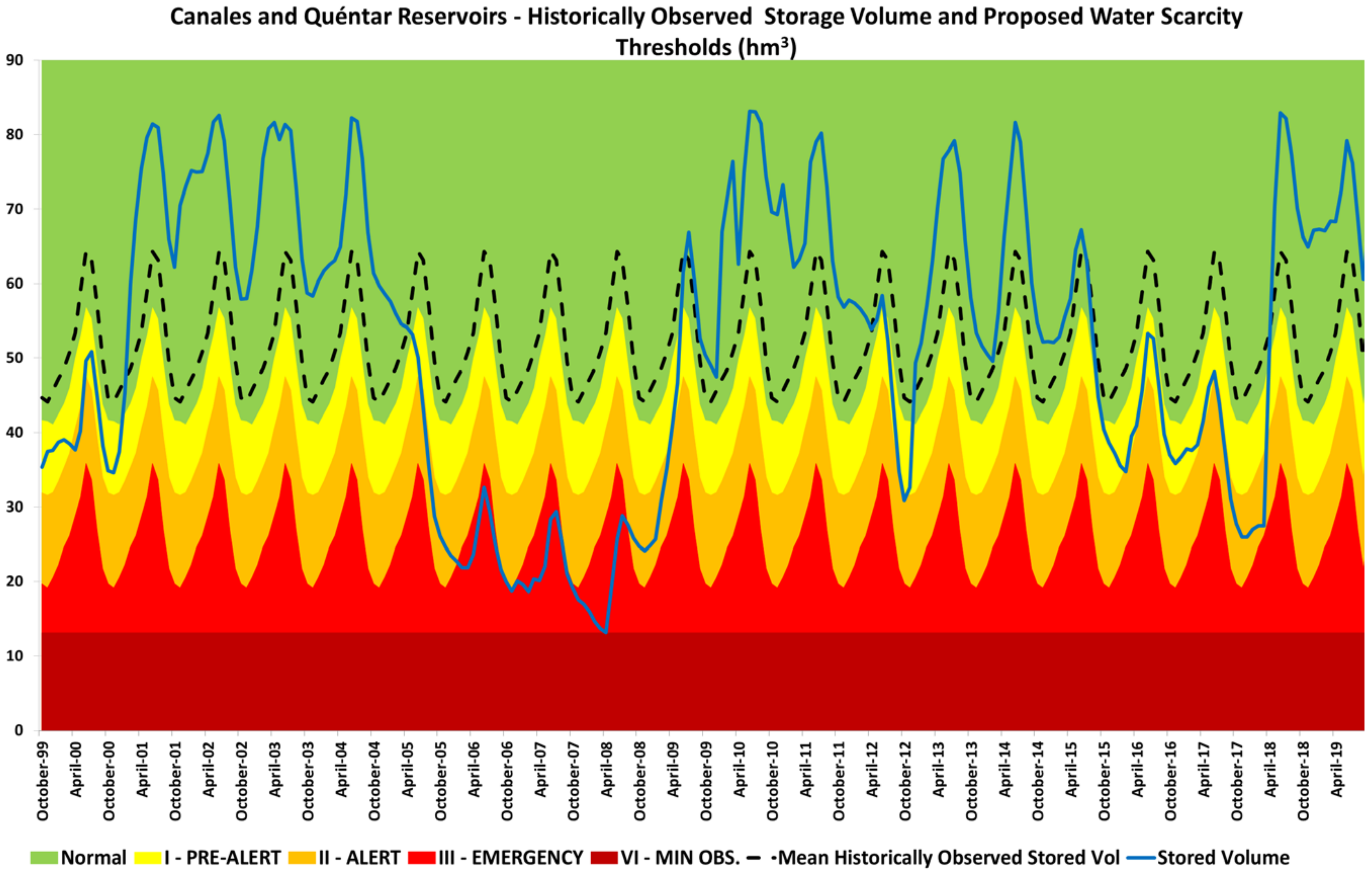


Figure 13: Canales and Quéntar reservoirs: Historically observed stored volume, Mean historically stored volume, and proposed trigger curves (own elaboration).

5.4.5 Use of Streamflow Forecast Models to Improve Drought Management During the Current Hydrological Year

Usually, it is easy to look back to evaluate historical drought events (when all the relevant information is available) and then identifying when, how, and what specific actions should have been undertaken by who, so the potential negative drought impacts might have been minimized. Indeed, important lessons can be learned from managing historical drought events, but the reality is that there are not two completely equal drought events.

When we face a new drought episode, the major challenge is precisely identifying and characterizing the type of event we will be dealing with, in terms of its duration (which can vary from months to years), its severity (or degree of affection to available water resources), and the potential economic, social, and environmental effects. If this information were known in advance, it would be much easier to activate the required preventive, adaptive, and proportionate actions at the right time to cope with the real situation, in addition to keeping all interested parties well-informed.

Whilst establishing relevant water scarcity thresholds may be an approach to identify a water scarcity situation and the type of measures to be applied, these trigger curves alone are not sufficient to ensure the most appropriate response to a potential water scarcity situation. The water scarcity curves need to be looked at in combination with using forecasting tools. This is especially important during the current hydrological year, when there is a considerable amount of relevant information as the the number of observed months increases, which should not be dismissed.

A comparative assessment has been carried out to assess how a water scarcity situation had been managed in the following scenarios:

i) Scenario I (S-I): Following the 2018 GRB DMP protocol of action;
ii) Scenario II (S-II): Using a streamflow forecast model in combination with the proposed alternative water scarcity thresholds described in **Section 5.4.4**.

The forecast model used for this assessment is AQUAFOR (a simple and robust monthly and yearly streamflow forecasting model developed by the University of Granada, Spain [65]). The model outputs three probabilistic forecasts: optimistic or upper streamflow forecast (this corresponds to the 90th percentile), mean streamflow forecast (that correspond to the average forecast), and pessimistic or lower streamflow forecast (this corresponds to the 10th percentile). For this comparative assessment, the mean streamflow forecast has been chosen. However, water authorities can make use of the upper and lower risk-based streamflow forecasts to assess different future water scenarios and adopt risk-based management decisions.

For the particular case of application, the Upper Genil River (like many other Mediterranean basins where the agriculture sector plays a key role), the critical decision point is in the middle of the hydrological year (just before intensive irrigation campaigns commence, usually in April). At this time, the GRBA decides on controlled released outflows from reservoirs and water allocation to downstream water users. To inform these decisions, an assessment of the current hydrological year (in terms of precipitation, reservoir storage volume, and streamflow) in relation to the mean historical year is undertaken by the GRBA. The type of actions and measures to be applied in order to ensure water supplies to the urban water supply-demand (UWSD) and irrigation water demand (IWD) will depend on the reservoir storage volume and water scarcity scenario (normal, pre-alert, alert, and emergency), as identified in the 2018 GRB DMP (**Appendix B**).

The 2004–2008 drought period has been selected for this comparative assessment because this is sufficiently recent, long, and severe event to show the implications of applying the 2018 GRB DMP in practice. **Figure 14** shows the observed precipitation, streamflow, and reservoir storage during the 2004–2008 drought period for the system of study, compared with the historical mean values.

It can be observed how the initial storage volume was higher than the average year and then the streamflow and precipitation began to be below the average year, which caused the storage volume to fall.

It is also important to consider that during the 2004/05-2008/09 period, approximately 46 hm^3 in total were extracted from the GW wells (2.30 hm^3 in 2004/05, 10.79 hm^3 in 2005/06, 8.83 hm^3 in 2006/07, 16.68 hm^3 in 2007/08 and 7.35 hm^3 in 2008/2009) to serve the UWSD, with a monthly maximum of 2.44 hm^3 in June 2008. The activation of the strategic GW resources helped to recover the reservoir levels at the end of the drought period. There is no record of the real water reductions applied to the UWSD and IWD during that period.

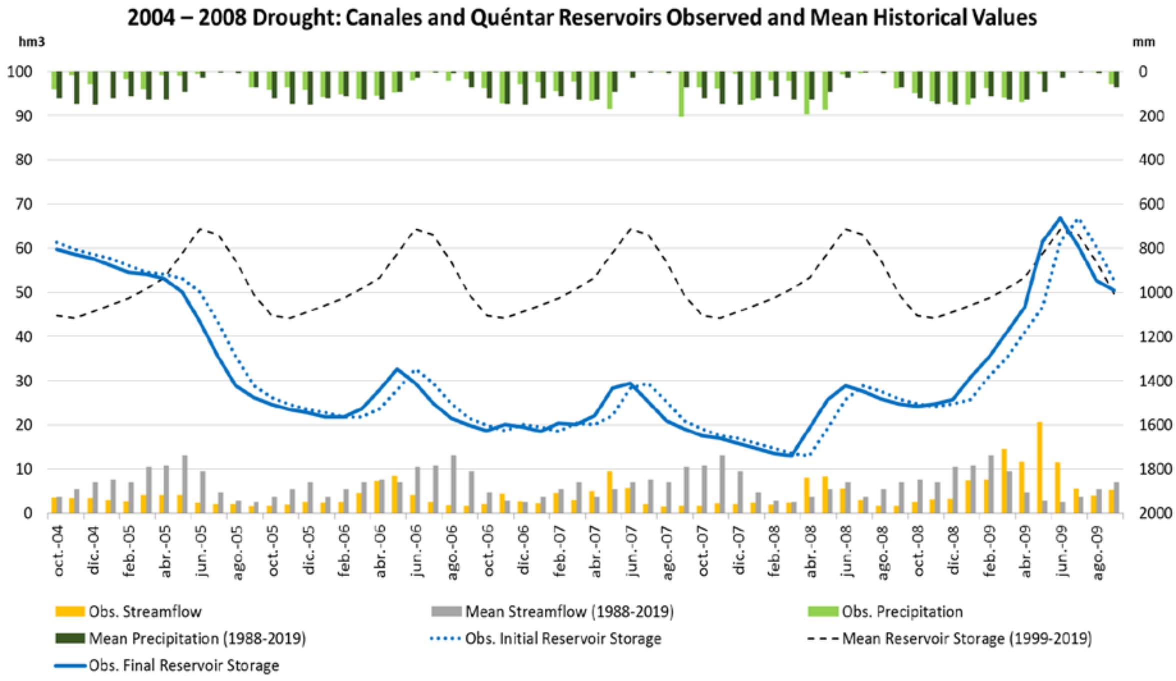


Figure 14: 2004–2008 drought: Canales and Quéntar reservoir observed and average precipitation, streamflow, and reservoir storage values (own elaboration).

For the comparative assessment, it has been modelled the actions that would have been taken on the 1st April each hydrological year using (i) the 2018 GRB DMP (i.e., based on the reservoir storage volume and no information about the future), and (ii) AQUAFOR (i.e., using the mean streamflow forecast for the current hydrological year) in combination with the proposed water scarcity thresholds (described in **Section 5.4.4**). Then, at the end of each hydrological year (1st October) when all the information is available, it has been assessed whether the measures activated back in April were actually required or not.

For this study, efficient strategies and actions are those that contribute towards optimizing the use of available water resources to meet the water demands of the system while minimizing environmental impacts (reduction of energy consumption and carbon footprint, the satisfaction of ecological flows, etc.) and reducing costs.

The Upper Genil River system uses an increasing hierarchy of SW resources and then, GW resources to meet the demand. Strategic GW resources are mainly used to satisfy the UWSD. In this particular sub-basin, the regulated SW resources from Canales and Quéntar reservoirs (from Sierra Nevada mountains) are of higher water quality than the GW volume extracted from the aquifer "*Acuífero de la Vega de Granada*". Additionally, regulated water does not require any pumping system up to the potable water treatment plant. Therefore, in principle, minimizing the use of GW resource will minimize the energy consumption (and carbon footprint) and energetic costs (associated with the pumping system as well as the higher water treatment requirements).

show the graphical monthly results, while **Table 9** shows a summary of the main annual results in terms of (i) the volume of water consumed by each water user (in this case, the UWSD and the IWD) and from each available water source (in this case, from regulated SW resources and strategic GW volume), and (ii) the water deficits (when the demand cannot be met) for each year of the historical data series used.

In both scenarios, the UWSD has been modelled with priority of water use over the IWD (in line with current the Spanish Water Legislation). The software used, input data, sources, and parameters of modelling are described in **Appendix A**.

If the results from S-I and S-II are compared, it can be appreciated how the optimal use and management of the existing available water resources of the system during a drought period that provides the greatest guarantee of supply for both, the UWSD and IWD, is achieved by using streamflow forecast tools (in this case, S-II Using AQUAFOR).

Indeed, the water deficits of the system are considerably reduced (up to 37% for the IWD), and the use of strategic GW resources is minimized (up to 9%). There is no water deficit for the UWSD in the whole drought period for S-I and S-II (since the UWSD has priority of water use). The IWD benefits from a mean annual water deficit of 10% for S-II in comparison with the 30% for S-I.

So, thanks to the better use of the existing SW resources (as shown in S-II):

- The carbon footprint can be minimized. A decrease in the GW volume consumed would, in principle, imply a reduction in the carbon footprint and economic costs (lower energy consumption due to the pumping requirements from the wells to the potable water treatment plant, as well as lower energy consumption for the potable water treatment requirements).
- Compliance with the ecological flow regime: The S-II model has been set out to satisfy the ecological flows before trying to meet the water demands of the system. Following the 2018 GRB DMP, there is the possibility of justifying a temporal deterioration of the water status when applying less stringent ecological flow regime during a *prolonged drought situation* (for the particular case of study, this corresponds to the SPI-6month value lower than -1.49). Under this exceptional circumstance, the e-flows could be slightly reduced, and the urban water supply (households) has the highest priority of water use over any other water uses.
- Social consequences and economic losses due to the unnecessary water restrictions to the IWD can be avoided or, at least, considerably minimized.

Table 9: Volume (hm^3) of water used and efficiency in satisfying the water demands.

Hydrological	**S-I: Using the 2018 GRB DMP**						**S-II: Using AQUAFOR (Mean Streamflow Forecast)**					
Year	**UWSD**				**IWD**		**UWSD**				**IWD**	
	SW	**GW**	**Total**	**Deficit**	**SW**	**Deficit**	**SW**	**GW**	**Total**	**Deficit**	**SW**	**Deficit**
2004/05	35.46	2.06	37.52	**0.00**	25.90	**0.00**	37.52	0.00	37.52	**0.00**	25.90	**0.00**
2005/06	25.14	12.38	37.52	**0.00**	9.16	**16.74**	22.14	15.38	37.52	**0.00**	21.44	**4.46**
2006/07	23.14	14.38	37.52	**0.00**	14.88	**11.02**	19.14	18.39	37.52	**0.00**	14.74	**11.16**
2007/08	19.14	18.39	37.52	**0.00**	11.39	**14.51**	18.14	19.39	37.52	**0.00**	14.74	**11.16**
2008/09	26.14	11.38	37.52	**0.00**	25.90	**0.00**	37.52	0.00	37.52	**0.00**	25.90	**0.00**
Total	**129.02**	**58.60**	**187.62**	0.00	**87.25**	**42.27**	**134.46**	**53.16**	**187.62**	0.00	**102.73**	**26.79**
Mean	***25.80***	***11.72***	***37.52***	***0***	***17.45***	***8.45 (33%)****	***26.89***	***10.63***	***37.52***	***0***	***20.55***	***5.36 (21%)****
Comparison (%)							4%	**−9%**	0%		18%	**−37%**

(*) Mean annual water deficit for the IWD in relation to the total annual IWD of 25.904 hm^3 as established in the Guadalquivir RBMP 2015–2021. IWD: irrigation water demand; UWSD: urban water supply-demand.

The results from S-I show how the strategic GW water resources are activated much earlier in 2004/05 (shown in **Table 9**, **Figure 15** (a) and **Figure 15** (b)) than for S-II (shown in **Table 9**, **Figure 16** (a) and **Figure 16** (b)). Even after that, there are still considerable water deficits the following year (2006) in the IWD (16.74 hm^3, approximately 65% of the total annual IWD), as shown in **Figure 15** (c) and **Figure 15** (d).

It is important to note that before the drought event started (2004/05), the reservoir storage volume was relatively high in comparison with the mean historical year (as shown in **Figure 14**) and even in that situation, strategic GW resources would have been mobilized following the 2018 GRB DMP protocol.

The results from S-I show how the strategic GW water resources would have been activated all years (**Figure 15** (a)-(j)), in comparison with the results from S-II (**Figure 16** (a)-(j)) where the first and last year GW resources would have not been activated (**Figure 16** (a) and **Figure 16** (i)).

Equally important was the return-to-normal conditions (2008/09). The reservoir storage volume was relatively low (after the drought period); which was followed by an increasing level of rainfall. However, the 2018 GRB DMP would have been very slow in recognizing this positive change in the situation. Thus, even after months of rain, still, strategic GW resources would have been used (**Figure 15** (i)).

Although for the purposes of this comparative assessment, only the Mean Streamflow Forecast for the 1st April has been used, it is important to note that the AQUAFOR forescasting model provides monthly and yearly streamflow forecasts starting the forecasts from 1st January and then, monthly for the rest of the hydrological year. This can help improving the preparedness, prevention and planning the drought response, as well as to adapt to the dynamic nature of the drought event as this evolves in time by verifying (on a monthly basis) what measures are required to be mobilised. So, in comparison with the 2018 GRB DMP, the use of forecasting models help in dealing with drought and water scarcity situations dynamically (say, every month the situation can be assessed), rather than statically (by deciding on April what is going to be done for the rest of the year).

Therefore, using streamflow forecasting models can help detecting the onset of the drought, the severity, the duration and return-to-normal conditions. This allows a better identification of when, how and what specific actions should be undertaken during a drought event, apart from providing more time to liaise with the required parties.

It is important to highlight that the 2018 GRB DMP water scarcity thresholds and actions have been established based on the 100-year return period drought event. Therefore, it is a relatively conservative plan, which might work well during severe and extreme drought events but less well during mild and moderate drought events (which are more frequent events). As shown in the comparative assessment, the 2018 GRB DMP is slow in identifying “positive” changes in the system (increasing rainfall) that leads to the end of a drought event or return-to-normal conditions. This means that during mild and moderate drought events, conservative measures could be applied (such as water restrictions to the IWD or mobilization of GW resources), that would not be actually required. These will have associated economic, environmental, and social consequences.

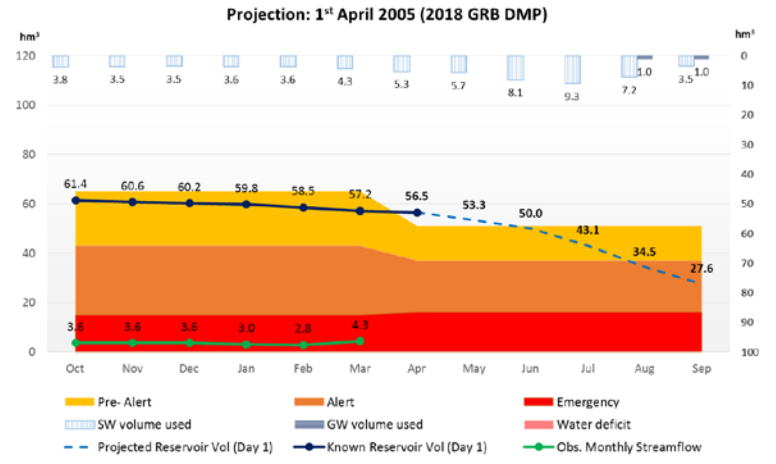
The results from S-II show how the use of streamflow forecast models can help with the early detection of droughts and water scarcity situations, identifying the adequate timing to activate and deactivate strategic water measures to ensure water supplies while minimizing social, environmental, and economic impacts. Therefore, the use of streamflow forecast models can support strategic and sustainable water management strategies when deciding on optimum water allocation to achieve resource and cost-efficient strategies.

If droughts (and their severity) are anticipated, it is more likely that sensible management strategies are designed by testing different risk scenarios, and consequently, optimal actions can be implemented (following, for example, a phased approach as the drought evolves). The risk-based forecast outputs can be also helpful to all water users and stakeholders involved in the planning, management, and decision-making processes.

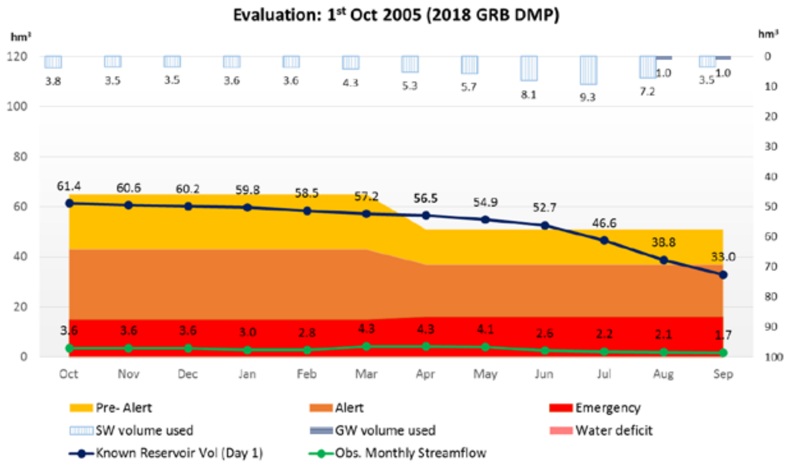
Projection: April

Evaluation: October

2005

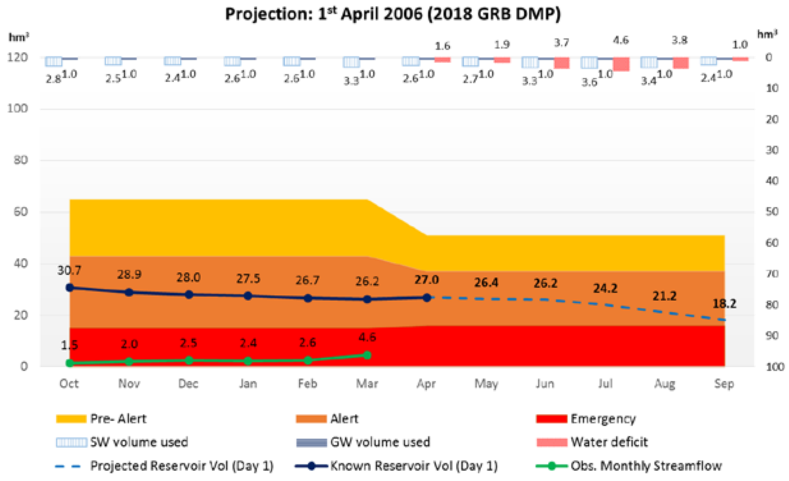


(a)

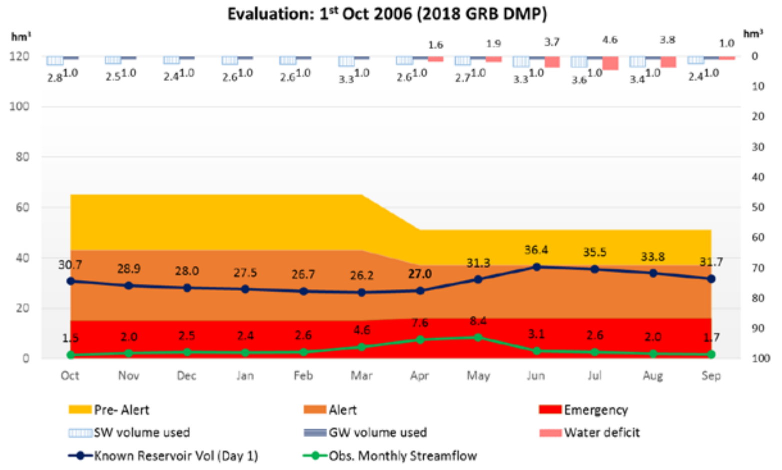


(b)

2006



(c)

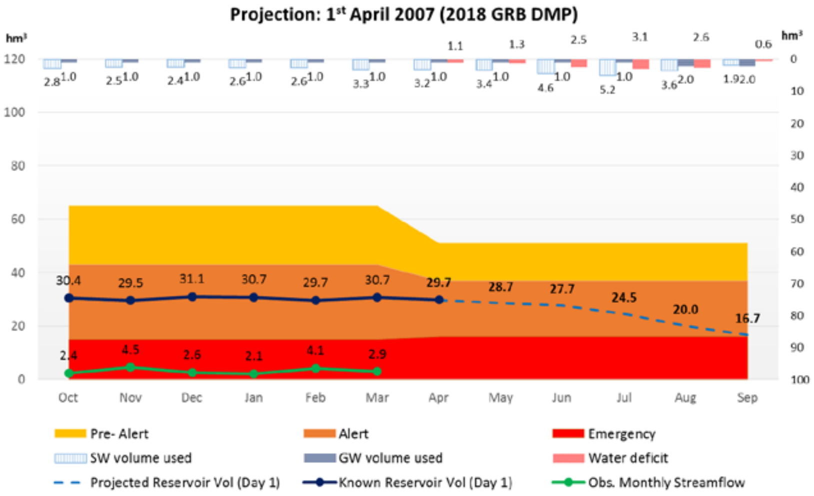


(d)

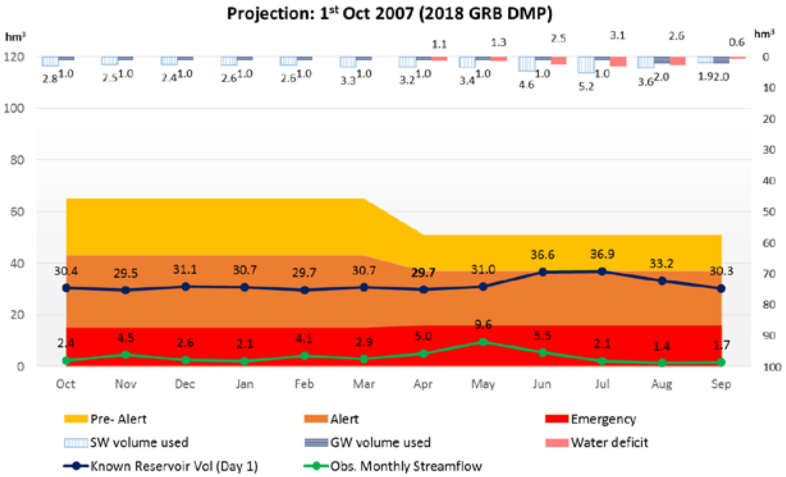
Projection: April

Evaluation: October

2007

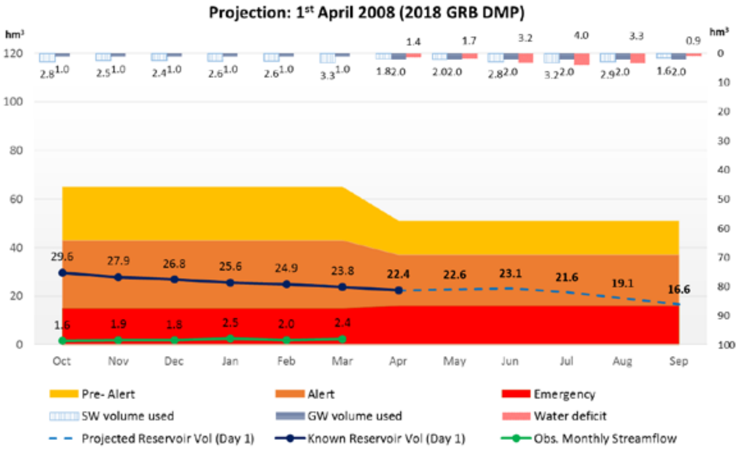


(e)

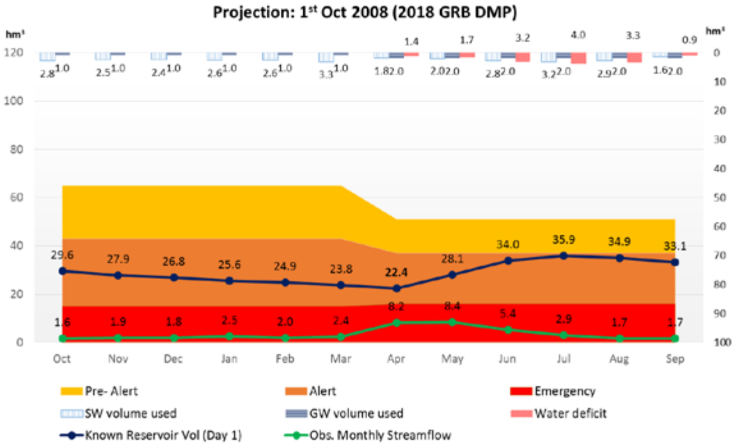


(f)

2008



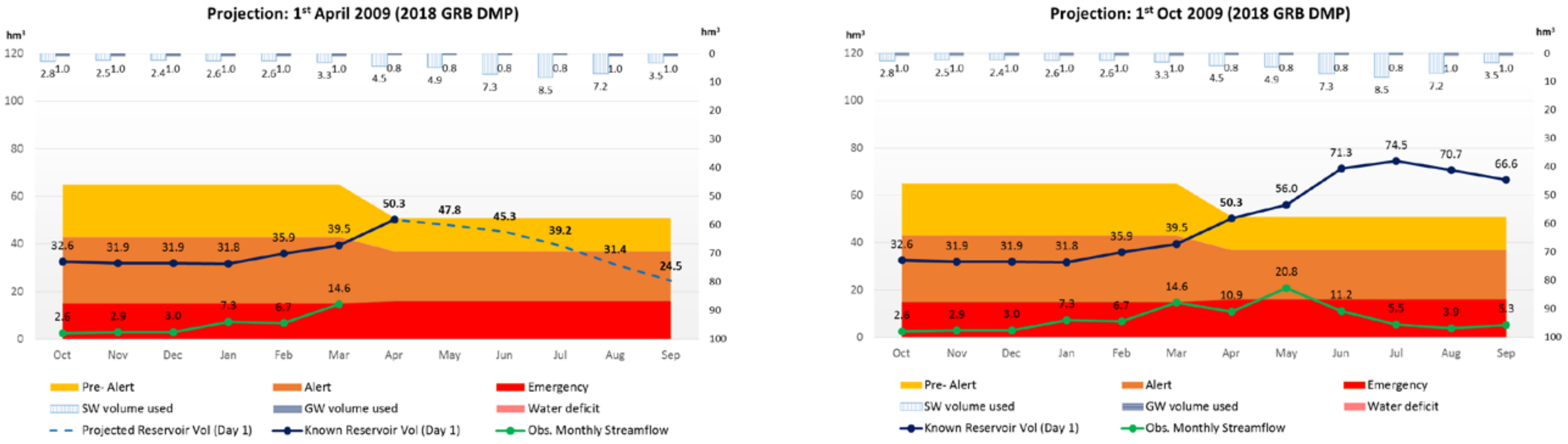
(g)



(h)

Projection: April **Evaluation: October**

2009



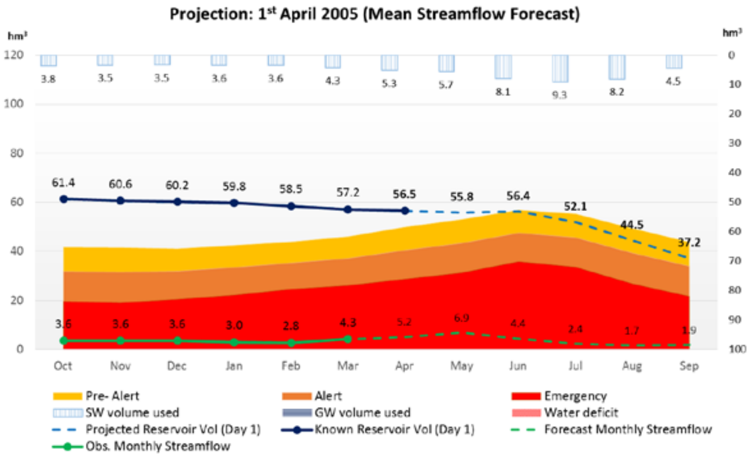
(i) (j)

Figure 15: 2018 GRB DMP: Measures taken in April (a, c, e, g, i) and evaluation of the real situation made in October (b, d, f, h, j).

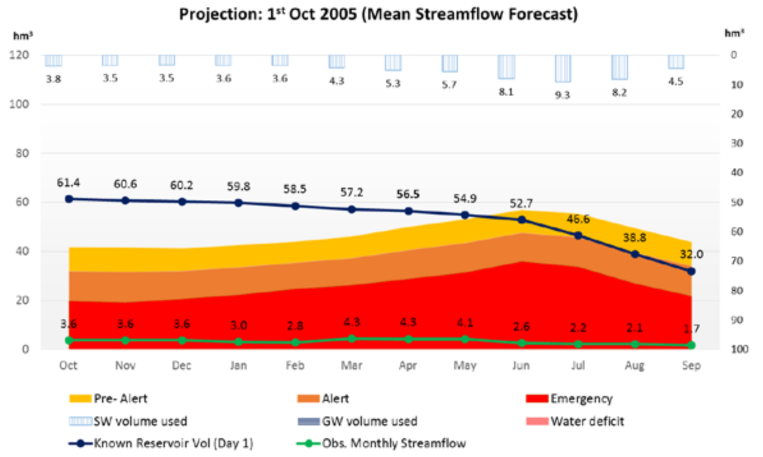
Projection: April

Evaluation: October

2005

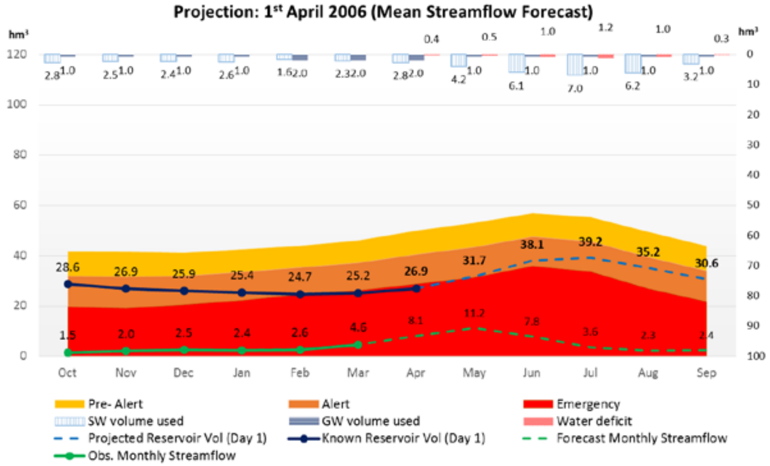


(a)

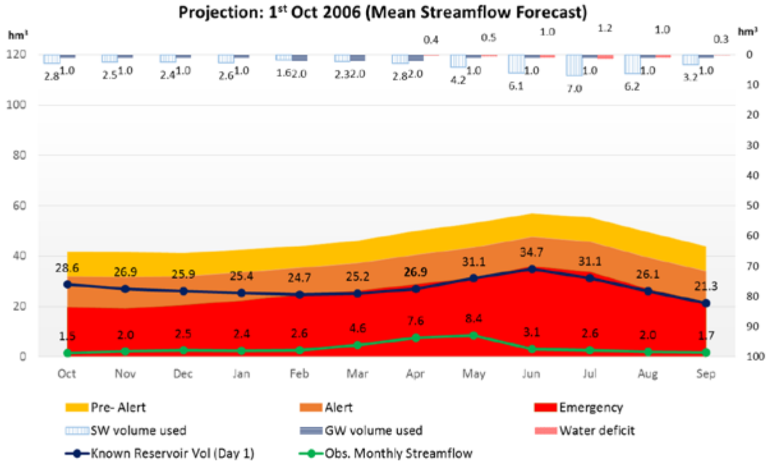


(b)

2006

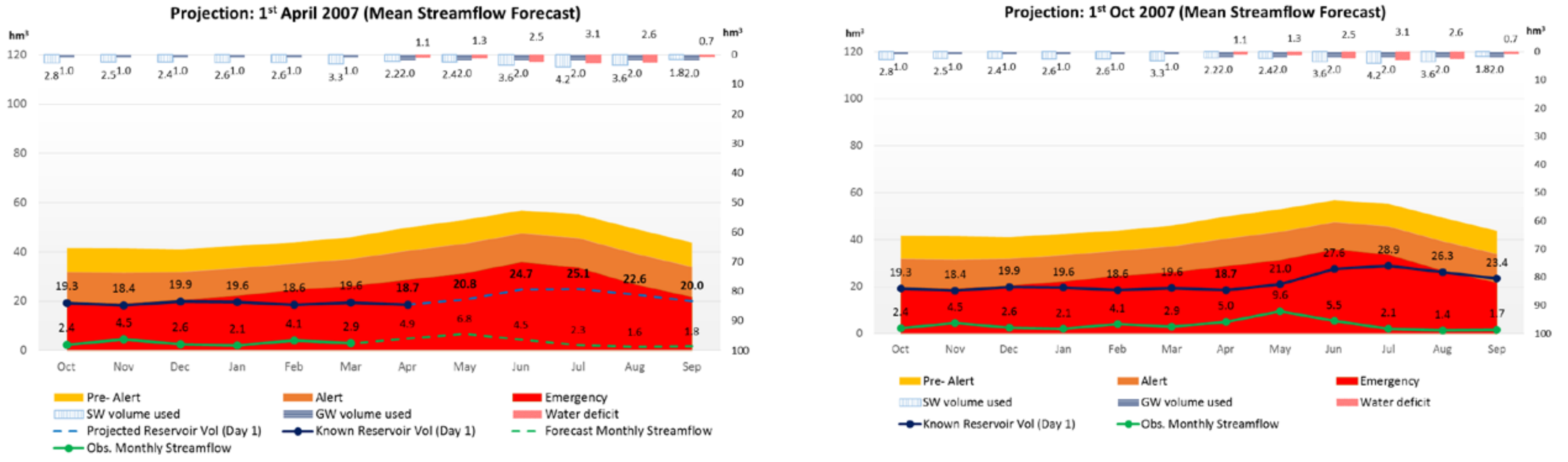


(c)



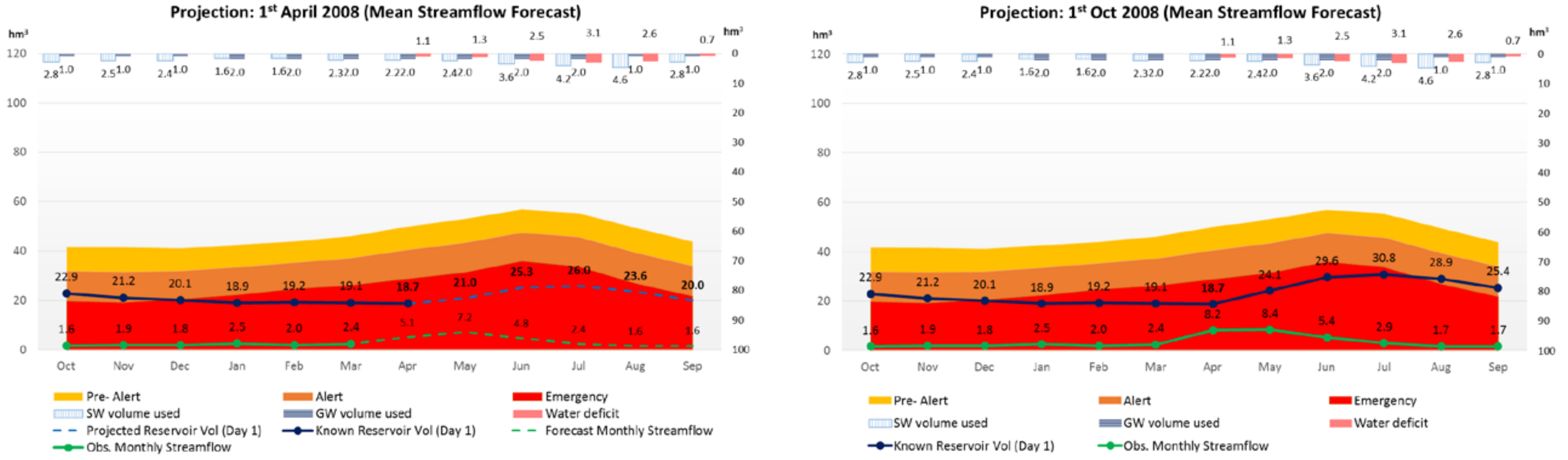
(d)

2007



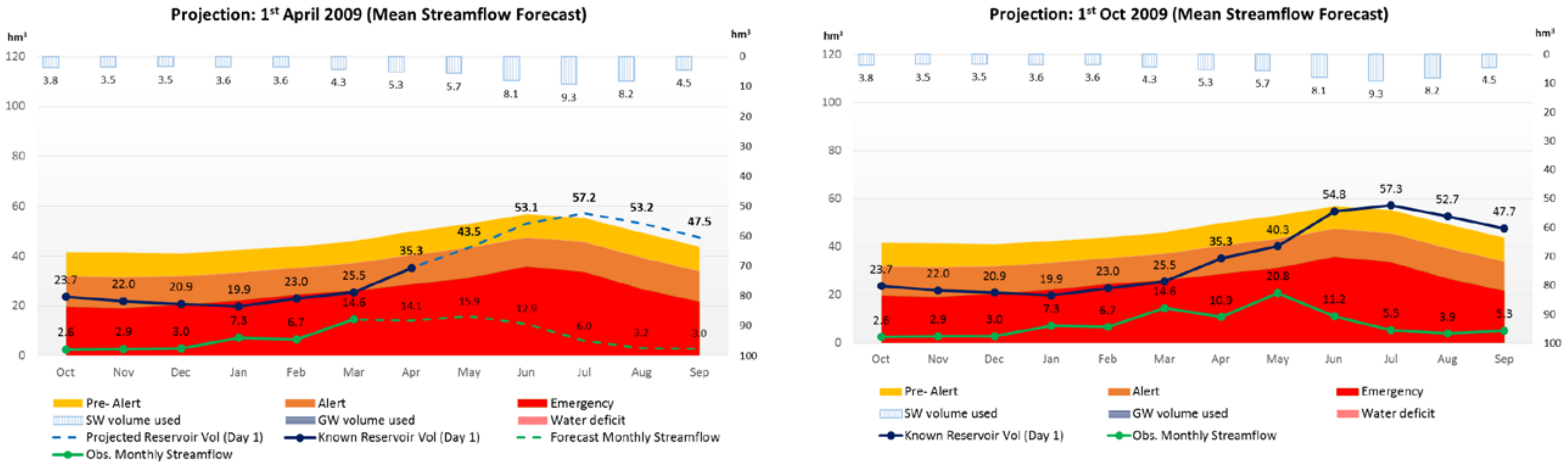
(e) (f)

2008



(g) (h)

2009



(i) **(j)**

Figure 16: Using streamflow forecast models (in this case, AQUAFOR): Measures taken in April (a, c, e, g, i) and evaluation of the real situation made in October (b, d, f, h, j).

5.5 Concluding Remarks

In Spain, the RBAs updated the DMPs in December 2017 (adopted in December 2018) at the river basin scale in the context of the WFD, as reported in the supplementary documents of the RBMPs (art. 13(5) WFD).

The Guadalquivir is the main river in southern Spain, which periodically suffers the consequences of drought events and water scarcity episodes. One of the most pressing problems in this basin is precisely the fierce competition among water users for the scarce water resource.

The 2018 GRB DMP establishes the general drought-risk management principles, as well as the progressive implementation of actions based on the drought and water scarcity scenario. It is a well-structured report that contains the key elements of a DMP: (a) diagnosis system: territorial units and environmental characterization; (b) definition of a common global indicator and thresholds system (establishing onset, ending, and severity levels of the exceptional circumstances); (c) actions and measures to be taken in each phase; (d) organizational framework: monitoring and follow-up system to deal with drought and subsequent revision and updating of the existing DMP [18].

The 2018 GRB DMP clearly distinguishes drought events from water scarcity events, by setting out a different diagnosis system and measures to deal with each phenomenon separately. In fact, a common hydrological indicator system has been established to identify early enough and foresee the drought or water scarcity situations. This is to be applied in all river basins in Spain in compliance with the Spanish legislation.

This has helped to apply a consistent approach in terms of diagnosing a drought/water scarcity situation and provide clarity in terms of the type of actions to be taken to manage a drought and water scarcity situation. This highlights the important strides made by all the Spanish RBAs towards harmonization of technical procedures across all the river basins. This will not only provide support to the RBA decision-making processes (especially, when declaring formal drought situations) but also it will be very instructive when disseminating drought information to the general public. This demonstrates how a common indicator system at the EU level could be also possible.

Yet, doubts exist on a number of issues about the real effectiveness of the 2018 GRB DMP.

Firstly, general management measures proposed in the DMP should not disregard the inherent heterogeneity among the different water systems within the same basin (especially in those basins with historical and complex water rights interactions). Secondly, the proposed actions and measures are not supported by any technical, environmental, or economic assessments. These are fundamental to any DMP, so it can be demonstrated that the proposed actions and measures are sufficiently robust to achieve optimal use of existing water resources during a drought event that meets the water demands of the system while minimizing the economic, social, and environmental impacts of these actions.

Thirdly, the absence of using streamflow forecast models and seasonal climate forecasts is one of the greatest deficiencies in the current DMPs. The water scarcity thresholds and critical decisions on controlled released outflows from reservoirs are based on streamflow and precipitation probabilistic historical information only. Given the improvements in the accuracy and reliability of advanced hydrological information and streamflow forecasts, it is considered essential to use predictive models (at least for the current hydrological year) to anticipate and evaluate future impacts of a drought, as well as to take adequate and proportionate actions in each situation ([65], [66]).

A comparative assessment has been carried out to assess how a water scarcity situation had been managed (i) following the 2018 GRB DMP protocol, and (ii) using a streamflow forecast model in combination with the proposed alternative water scarcity thresholds. The results show how the optimal use and management of the existing available water resources of the system during a drought period that provides the greatest guarantee of supply is achieved by using streamflow forecast tools. Indeed, the water deficits of the system are considerably reduced (up to 37%), and the use of strategic GW resources is minimized (up to 9%).

So, thanks to the better use of the existing SW resources using streamflow forecast tools: i) the carbon footprint can be minimized, ii) the compliance with the ecological flow regime can be better guaranteed and managed, and iii) social consequences and economic losses due to the unnecessary water restrictions can be avoided or, at least, considerably minimized.

The results have shown that the 2018 GRB DMP is a relatively conservative plan, which might work well during severe and extreme drought events but less well during mild and moderate drought events (which are more frequent events). The 2018 GRB DMP is very slow in identifying the "positive" change in the system (increasing rainfall) that leads to the end of a drought event or return-to-normal conditions. This means that during mild and moderate drought events, conservative measures could be applied (such as water restrictions to the IWD or mobilization of GW resources), that would not be actually required. These will have associated economic, environmental, and social consequences.

The use of streamflow forecast models can help with the early detection of droughts and water scarcity situations, identifying when and how actions should be implemented (timing to activate and deactivate strategic water measures) to ensure water supplies while minimizing social, environmental, and economic impacts. If droughts (and their severity) are anticipated, it is more likely that sensible management strategies are designed by testing different risk scenarios, and consequently, optimal actions can be implemented.

The lessons learned could be applied to tackle water scarcity in other water-scarce and drought-prone basins.

Appendix A. Upper Genil River sub-basin (Guadalquivir River Basin): Modelling Process, Input Data, Sources, and Limitations

Appendix A.1. Input Data

All the input data used to inform this study is publically available and described below.

Surface Water Resources

The '*Automatic Hydrological Information System* (SAIH)' is a free and public online portal maintained by the GRBA in Spain [75]. The SAIH offers information, such as streamflow, rainfall, temperature, reservoir inflows, outflows, storage volume, and water level, for up to 57 reservoirs, 52 non-regulated rivers, 20 canals, and 10 hydropower plants. Other information on rain, snow, and temperature gauging stations across the basin is also offered. The available temporal data sets vary depending on the specific sub-catchment area. The information can be downloaded in an hourly, daily, or monthly time step or requested directly via an online application form or email to the SAIH contact details provided on the webpage.

The historical monthly streamflow data series for Canales (from October 1988 to present) and Quéntar (from October 1977 to present) have been obtained via an online request on the SAIH webpage. The common historical data set period for both reservoirs (1988/1989–2018/2019, 31 years) has been used in the modelling (included below for information).

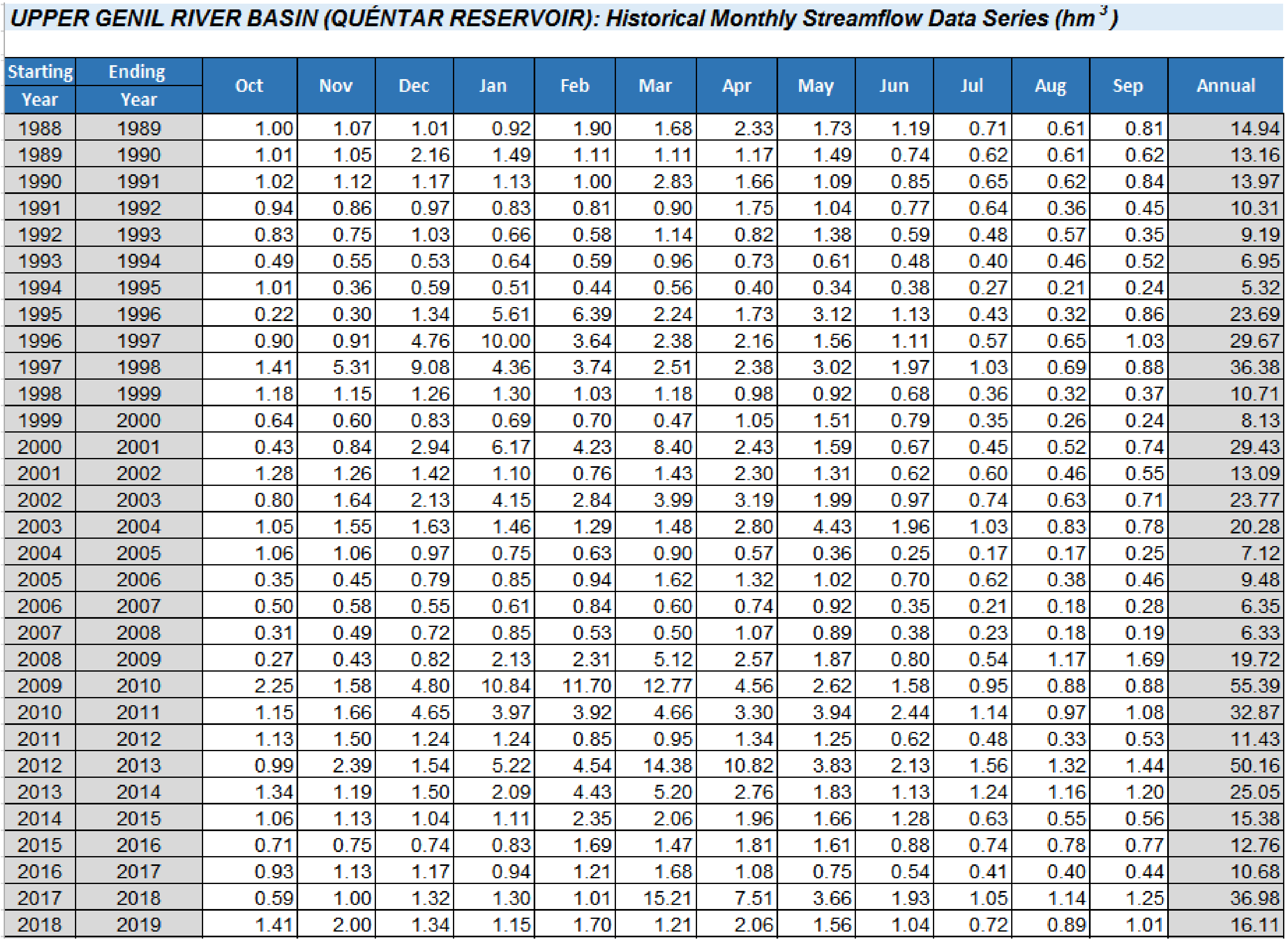
From the data set used, we would draw attention to the historical intense drought episodes: 1991–1995 and 2004–2008.

Historical monthly streamflow data series (hm^3) for Canales and Quéntar reservoirs (October 1988–September 2019):

Groundwater Resources

For the chosen case of study, the GW resources relate to the available abstraction capacity of the existing network of operating wells located in the upper area of the Vega de Granada aquifer (known as "*Pozos de la Ronda Sur*"). This source supplements the regulated SW resources and is normally used to supply the UWSD of Granada and its metropolitan area. The maximum extraction capacity is 2 hm^3/month.

Although the technical pump capacity of the wells is slightly greater than 2 hm^3/month, this amount has been set out as the maximum value for modelling purposes (and to be used only when needed). The two reasons that support this assumption are: (i) a maximum abstraction capacity of 2 hm^3/month is in line with the protocol of actions and measures during drought and water scarcity situations established by the recently approved in December 2018 GRB Drought Management Plan (DMP) [62]; (ii) this value is validated with the historical monthly maximum abstraction of 2.44 hm^3/month (June 2008) and the annual historical maximum of 18 hm^3/year (2008).



UPPER GENIL RIVER BASIN (QUÉNTAR RESERVOIR): Historical Monthly Streamflow Data Series (hm^3)

Starting Year	Ending Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Annual
1988	1989	1.00	1.07	1.01	0.92	1.90	1.68	2.33	1.73	1.19	0.71	0.61	0.81	14.94
1989	1990	1.01	1.05	2.16	1.49	1.11	1.11	1.17	1.49	0.74	0.62	0.61	0.62	13.16
1990	1991	1.02	1.12	1.17	1.13	1.00	2.83	1.66	1.09	0.85	0.65	0.62	0.84	13.97
1991	1992	0.94	0.86	0.97	0.83	0.81	0.90	1.75	1.04	0.77	0.64	0.36	0.45	10.31
1992	1993	0.83	0.75	1.03	0.66	0.58	1.14	0.82	1.38	0.59	0.48	0.57	0.35	9.19
1993	1994	0.49	0.55	0.53	0.64	0.59	0.96	0.73	0.61	0.48	0.40	0.46	0.52	6.95
1994	1995	1.01	0.36	0.59	0.51	0.44	0.56	0.40	0.34	0.38	0.27	0.21	0.24	5.32
1995	1996	0.22	0.30	1.34	5.61	6.39	2.24	1.73	3.12	1.13	0.43	0.32	0.86	23.69
1996	1997	0.90	0.91	4.76	10.00	3.64	2.38	2.16	1.56	1.11	0.57	0.65	1.03	29.67
1997	1998	1.41	5.31	9.08	4.36	3.74	2.51	2.38	3.02	1.97	1.03	0.69	0.88	36.38
1998	1999	1.18	1.15	1.26	1.30	1.03	1.18	0.98	0.92	0.68	0.36	0.32	0.37	10.71
1999	2000	0.64	0.60	0.83	0.69	0.70	0.47	1.05	1.51	0.79	0.35	0.26	0.24	8.13
2000	2001	0.43	0.84	2.94	6.17	4.23	8.40	2.43	1.59	0.67	0.45	0.52	0.74	29.43
2001	2002	1.28	1.26	1.42	1.10	0.76	1.43	2.30	1.31	0.62	0.60	0.46	0.55	13.09
2002	2003	0.80	1.64	2.13	4.15	2.84	3.99	3.19	1.99	0.97	0.74	0.63	0.71	23.77
2003	2004	1.05	1.55	1.63	1.46	1.29	1.48	2.80	4.43	1.96	1.03	0.83	0.78	20.28
2004	2005	1.06	1.06	0.97	0.75	0.63	0.90	0.57	0.36	0.25	0.17	0.17	0.25	7.12
2005	2006	0.35	0.45	0.79	0.85	0.94	1.62	1.32	1.02	0.70	0.62	0.38	0.46	9.48
2006	2007	0.50	0.58	0.55	0.61	0.84	0.60	0.74	0.92	0.35	0.21	0.18	0.28	6.35
2007	2008	0.31	0.49	0.72	0.85	0.53	0.50	1.07	0.89	0.38	0.23	0.18	0.19	6.33
2008	2009	0.27	0.43	0.82	2.13	2.31	5.12	2.57	1.87	0.80	0.54	1.17	1.69	19.72
2009	2010	2.25	1.58	4.80	10.84	11.70	12.77	4.56	2.62	1.58	0.95	0.88	0.88	55.39
2010	2011	1.15	1.66	4.65	3.97	3.92	4.66	3.30	3.94	2.44	1.14	0.97	1.08	32.87
2011	2012	1.13	1.50	1.24	1.24	0.85	0.95	1.34	1.25	0.62	0.48	0.33	0.53	11.43
2012	2013	0.99	2.39	1.54	5.22	4.54	14.38	10.82	3.83	2.13	1.56	1.32	1.44	50.16
2013	2014	1.34	1.19	1.50	2.09	4.43	5.20	2.76	1.83	1.13	1.24	1.16	1.20	25.05
2014	2015	1.06	1.13	1.04	1.11	2.35	2.06	1.96	1.66	1.28	0.63	0.55	0.56	15.38
2015	2016	0.71	0.75	0.74	0.83	1.69	1.47	1.81	1.61	0.88	0.74	0.78	0.77	12.76
2016	2017	0.93	1.13	1.17	0.94	1.21	1.68	1.08	0.75	0.54	0.41	0.40	0.44	10.68
2017	2018	0.59	1.00	1.32	1.30	1.01	15.21	7.51	3.66	1.93	1.05	1.14	1.25	36.98
2018	2019	1.41	2.00	1.34	1.15	1.70	1.21	2.06	1.56	1.04	0.72	0.89	1.01	16.11

Ecological Flows (e-flows)

Ecological flows have been taken from the Guadalquivir RBMP (2015–2021) [62], as shown in Table A1.

Table A1. Ecological flows.

Reservoir	**Volume (hm^3)**												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**TOTAL**
Canales	0.308	0.298	0.388	0.388	0.351	0.388	0.376	0.295	0.285	0.295	0.295	0.285	3.952
Quéntar	0.134	0.130	0.134	0.134	0.121	0.134	0.130	0.134	0.130	0.134	0.134	0.130	1.577

(*) Note: the number of decimal places shown in Tables A1–A4 is in accordance with the Guadalquivir RBMP (2015–2021) from Guadalquivir RBMP (2015–2021).

In Spain, the Q eco is not considered as a water demand but as a water restriction (or water constraint). This means that ecological flows must be satisfied in the first instance prior to meeting the water demands of the system in all situations, except when there is a prolonged drought scenario (for the particular case of study, this corresponds to SPI's 6-month values lower than 1.49). Under this exceptional circumstance, the e-flows could be slightly reduced, and the urban water supply (households) has the highest priority of water use over any other water uses.

Established Water Demands (UWSD and IWD)

For modelling purposes, the water demands established in the Guadalquivir RBMP (2015-2021) have been taken, as shown in Table A2. It is important to note that these water demands are not real water consumption values but estimations made by the RBA.

The UWSD is named as "*UDU 06A01 Área Metropolitana Granada Genil*" and is formed by Granada city and its metropolitan area (14 towns). The established total annual UWSD is 37.524 hm^3, with a constant monthly UWSD of 3.13 hm^3.

The IWD is named as "*06D02—Regadíos Vega Alta río Genil*" and is formed by various irrigation communities with a total irrigated land of approximately 3800 ha (according to the Guadalquivir RBMP (2015–2021)). The established annual water demand is 25.9 hm^3, with the peak water demand in summer months (June, July, and August).

In this case, it is important to highlight that there has been a progressive reduction in the total irrigated land during the past decades, mainly due to urban development and new infrastructures. However, this reduction in the irrigated land (and a corresponding reduction in water demand) has not been integrated yet in the water demands estimations made by the GRBA.

Table A2. Established water demands from Guadalquivir RBMP (2015–2021).

Name (*from the Guadalquivir RBMP*)	Water Demand (hm^3)												
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	TOTAL
UDU 0601 Área Metropolitana de Granada-Genil	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	37.524
UDA 06D02. Regadíos Tradicionales Vega Alta río Genil	0.658	0.391	0.338	0.507	0.507	1.181	2.134	2.578	4.997	6.129	5.106	1.378	25.904

(*) Note: the number of decimal places shown in Tables A1–A4 is in accordance with the Guadalquivir RBMP (2015–2021) from Guadalquivir RBMP (2015–2021).

The peak water demand occurs in summer months, when the temperature is higher, evaporation is higher, and precipitation is lower. This puts large amounts of pressure on water resources (quantity and quality) and highlights the relevance of reservoirs to better manage the irregularity in precipitation in relation to the demand pattern (as well as to deal with the effects of extreme hydrological and climate phenomena).

Minimum and Maximum Storage Volume Reservoirs

This information has been also taken from the Guadalquivir RBMP (2015–2021) and shown in Table A3 and Table A4.

The maximum storage volume is related to the maximum storage capacity of reservoirs (October–November, and May–September) and the flood protection function of reservoirs (from December to April).

Table A3. Minimum monthly reservoir storage volume requirements from Guadalquivir RBMP (2015-2021) (*).

Reservoir	Volume (hm^3)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Canales	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Quéntar	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

(*) Note: the number of decimal places shown in Tables A1–A4 is in accordance with the Guadalquivir RBMP (2015–2021) from Guadalquivir RBMP (2015–2021).

Table A4. Maximum monthly reservoir storage volume from Guadalquivir RBMP (2015–2021) (*).

Reservoir	Volume (hm^3)											
	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Canales	70.0	70.0	59.4	58.6	57.9	61.5	68.6	70.0	70.0	70.0	70.0	70.0
Quéntar	13.6	13.6	11.4	11.3	11.1	11.8	13.2	13.6	13.6	13.6	13.6	13.6

(*) Note: the number of decimal places shown in Tables A1–A4 is in accordance with the Guadalquivir RBMP (2015–2021) from Guadalquivir RBMP (2015–2021).

Appendix A.2. AQUAFOR: Streamflow Forecast Model [65]

This is a simple, novel, user-guided, and low-cost methodology to forecast streamflows within the current hydrological year. It can be easily used by non-technical experts, such as water authorities, water managers, or water users. Therefore, it overcomes one of the major traditional limitations associated with the use of this kind of model.

The methodology was successfully applied to two headwater reservoirs within the Guadalquivir River Basin in southern Spain, achieving an accuracy of 92% and 80% in March 2017.

The model outputs are the probabilistic mean annual and monthly streamflows along with the 10th and 90th percentiles (which can be easily modified by the user, if needed).

The model results have been compared with the most recent ARIMA model results (for example, those shown in Myronidis et al. [78] and similar works cited by the same author). It has been found relevant that in average terms, our model performed similarly or even slightly better at providing results for even a longer forecasted period (for up to nine months in advance), using a much simpler methodology.

Appendix A.3. AQUASPREAD: Model Simulation Process and Outcomes

AquaSpread modelling software (developed by the University of Granada) has been used. This performs a volumetric balance on a monthly basis based on the headwater inflows, the reservoir storage volume variation, and the water outputs, such as the evapotranspiration, the environmental restrictions (e-flows), the water demands (urban water supply, irrigation, industry, energy), and the controlled released flood flows (where required). It also takes into account the available alternative water resources in the specific water exploitation system.

The model has been set out to satisfy the ecological flows of the system before trying to meet the water demands. Then, the model takes into account the priority of water use order assigned to each water user, as well as the preference order of the available water sources to serve each water demand.

The main outcomes from this modelling exercise are: (i) the volume of water consumed by each water user and from each available water source and (ii) the water deficits (when the demand cannot be met) for each month of the historical data series used.

Appendix B – 2018 GRB DMP – Proposed measures to be applied to the Upper Genil River sub-basin

Table B1. Upper Genil River System: Specific actions and measures proposed in the 2018 GRB DMP to be applied in each water scarcity scenario (own elaboration, data from 2018 GRB DMP).

Water Scarcity Scenario	Type of measure to apply	Time	Authority
Normal	Track and monitor the water scarcity index.	Monthly	GRBA
Pre-Alert	Track and monitor the water scarcity index.	Any month	GRBA
	Raise awareness campaigns and promote voluntary actions of temporary water savings.	Any month	GRBA and Local Water Authority
	Inventory, updating and maintenance of specific infrastructures to deal with a potential water scarcity situation. Inspection and adaptation of existing groundwater intakes.	Any month	GRBA and Local Water Authority
	Assess the possibility of providing up to 8 hm^3 / year (distributed in at least 6 months) to supply the UWSD from the strategic underground wells.	Any month	GRBA and Local Water Authority
	Assess the opportunity to advise crops with lower water demands.	October-March	GRBA
Alert	Track and monitor the water scarcity index.	Any month	GRBA
	Apply water reduction measures to the UWSD (goal: 5%). Activation of water savings plans for large urban consumers and water restrictions on non-essential urban water uses (garden irrigation, street cleaning activities, etc.).	Any month	GRBA and Local Water Authority
	Activate education and water saving awareness campaigns.	Any month	GRBA and Local Water Authority
	Verificate that the *Alert* level of the Operational and Contingency DMPs for urban water supply systems has been activated.	Any month	Local Water Authority
	Increase the control of the piezometric levels as well as the Deifontes Spring flows.	Any month	GRBA
	Mobilise strategic GW resources: - Up to 12 hm^3 / year to supply the UWSD - Up to 2.5 hm^3 / year year to supply the IWD	Any month	GRBA and Local Water Authority
	Recommendation to the Exploitation Service to assess whether it may be convenient to reduce the water volume allocated to the IWD to face the irrigation campaign. The objective is to schedule the reservoir outflow releases to achieve a minimum reservoir volume at the end of the irrigation campaign of at least 16 hm^3 in Quéntar and Canales reservoirs, and of at least 6 hm^3 in Cubillas and Colomera reservoirs.	October to March	GRBA

Water Scarcity Scenario	Type of measure to apply	Time	Authority
Alert	Ask the Water Commission and the Exploitation Service to maintain special vigilance for water flow detractions for irrigation.	April to September	GRBA
	Assess the option to reduce unregulated irrigation water demands and reduce the use of GW resources for irrigation. The objective will be to maintain a strategic groundwater reserve for possible mobilizations if necessary.	April to September	GRBA
Emergency	Track and monitor the water scarcity index.	Any month	GRBA
	Intensify education and water saving awareness campaigns.	Any month	GRBA and Local Water Authority
	Mobilise strategic GW resources: - Up to 24 hm^3 / year to supply the UWSD; - Up to 5 hm^3 / year to supply the IWD.	Any month	GRBA and Local Water Authority
	Intensify water reduction measures to the UWSD (minimum 5%, and goal 10%).	Any month	GRBA and Local Water Authority
	Verificate that the *Emergency* level of the Operational and Contingency DMPs for urban water supply systems has been activated.	Any month	Local Water Authority
	Increase the control of the piezometric levels as well as the Deifontes Spring flows.	Any month	GRBA
	Enable the Exploitation Service to reduce the water volume allocated to the IWD to face the irrigation campaign. The objective is to schedule the reservoir outflow releases to achieve a minimum reservoir volume at the end of the irrigation campaign of at least 16 hm^3 in Quéntar and Canales reservoirs, and of at least 6 hm^3 in Cubillas and Colomera reservoirs.	October to March	GRBA
	Water restrictions to irrigation, except in exceptional cases, with the objective of reaching a volume greater than 16 hm3 in Quentar and Canales reservoirs, and a volume greater than 6 hm^3 in Cubillas and Colomera reservoirs.	April to September	GRBA
	Ask the Water Commission and the Exploitation Service to maintain special vigilance for water flow detractions for irrigation.	April to September	GRBA
	Assess the option to reduce unregulated irrigation water demands and reduce the use of GW resources for irrigation. The objective will be to maintain a strategic groundwater reserve for possible mobilizations if necessary.	April to September	GRBA

6. ARTICLE III

6. ARTICLE III: CRITICAL REVIEW OF THE PUBLIC PARTICIPATION PROCESS IN DROUGHT MANAGEMENT PLANS. THE GUADALQUIVIR RIVER BASIN CASE IN SPAIN

This Chapter has been published in *Water Resour Manage* (2018 JCR Journal Impact Factor 2.987, JIF Percentile 80.769, Quartile Q1, Rank 18/91 in Water Resources), full reference as follows:

- Hervás-Gámez, C.; Delgado-Ramos, F. Critical review of the Public Participation Process in Drought Management Plans. The Guadalquivir River Basin Case in Spain. *Water Resour Manage* 2019, doi: 10.1007/s11269-019-02354-0

6.1 Abstract

In an ever-growing environment of uncertainty, complex interactions and climate extremes, the effective implementation of Public Participation (PP) into water management is sought as a key step to address water challenges and achieve holistic solutions. This requirement was already set out in the EU Water Framework Directive (Art. 14) twenty years ago. However, is PP successfully implemented in water management decisions, practices and policies nowadays? The literature review has revealed that there are few recent and detailed studies that assess this issue at the river basin scale. The aim of this paper is to contribute towards building evidence base on this topic. The learnings could be applied during the current consultation and development of the 3rd cycle River Basin Management Plans across EU. This study presents the complex and paradigmatic case of the Guadalquivir River Basin (GRB) in southern Spain. This work evaluates the real influence of PP on the most recent (2018) GRB Drought Management Plan (DMP) and draws important conclusions and recommendations in this regard. The findings showed that PP had, actually, a negligible influence in shaping the final (2018) GRB DMP. In fact, there was a very limited incorporation of the local knowledge and experience received from participants, highlighting the absence of a truly inclusive participation strategy. In contrast to this, PP should proactively involve all interested parties at an early stage when there are still opportunities to alter the strategy. This could bring significant benefits such as taking more ownership and responsibility by water users.

Keywords: Public Participation; drought; water scarcity; Drought Management Plan; Guadalquivir River; Spain

6.2 Introduction

Public participation (PP) is defined as "*allowing people to influence the outcome of plans and working processes. It is a means of improving decision-making, to create awareness of environmental issues and to help increase acceptance and commitment towards intended plans*" [79].

Implementing effective PP processes into water management is required by Art. 14 (Public information and consultation) of the EU Water Framework Directive (WFD): "*Member States shall encourage the active involvement of all interested parties*" [28].

Furthermore, this is highly encouraged and supported by European water policies and best practice technical documents: "*Fostering public participation processes are essential to obtain all interested parties (water users, stakeholders and general public) opinions, prior to the decision-making process, being able to influence in the final decision process. Active participation processes represent an opportunity to solve differences and achieve agreements between different affected parties sufficiently early in the DMP process*" [18].

In the same vein, a large number of authors (for example, [20], [58], [80]) consider that the key elements to achieving successful DMPs are: i) ensuring transparent public and active participation processes, ii) promoting agreements among the interested parties, iii) encouraging collaboration among the water administrations at the different scales to integrate local knowledge and, iv) supporting the use of adaptive governance.

Nonetheless, moving from the theoretical approach to the practical and collaborative implementation of PP into water management is not an easy task. Moreover, the application of different levels of PP (information supply, consultation and active participation as considered in the WFD) depends on aspects such as the type of democracy and the cultural context established in each country [81].

Ruiz-Villaverde and García-Rubio [82] provide a robust literature review of PP implementation examples across EU countries and the case of Spain. The same paper also concludes that the democratic situation of the country is one of the most relevant factors to determine the degree of PP that can be achieved. In relation to PP processes in Spain, it is stated that "*public participation is being introduced in a more visible way, but not necessarily effective*" and "*only in those cases where there has been strong support from the public authorities have higher levels of participation been achieved*".

According to the requirements set in the Spanish Law 10/2001 National Hydrological Plan, the River Basin Authorities (RBAs) are responsible for not only the preparation but also the implementation, maintenance and follow-up of the DMPs at the river basin scale.

In 2007, the first DMPs for all River Basins were approved in Spain. These strategic instruments contributed considerably towards improving drought preparedness and impact mitigation, highlighting the relevance of PP in the decision-making process for drought events [58] . The 2007 DMPs were revised ten years later in 2017 and the final adopted DMPs for all inter-community river basins (those in which the river flows through more than one Autonomous Community) were approved in 2018.

The Guadalquivir River Basin (GRB), as shown in **Figure 17,** is located in the southern part of Spain and covers a total area of 57,196km^2. The Guadalquivir is the main river formed by 25 sub-basins that flow to the south-west into the Atlantic Ocean. It serves a total population of 4,480,321 people (approximately 10% of the total Spanish population, 98% settled in the region of Andalusia) and 856,429 hectares for irrigation purposes. The total annual precipitation is 582 mm (based on the reference period 1940/41–2011/12), oscillating between maximum annual values of 1321 mm for the wet years and 293 mm for the dry years [83].

Drought and water scarcity are frequent phenomena in this area due to climate conditions and existing water management practices. This situation generates a significant competition among the existing water users (mainly irrigators and urban water supply), especially during water scarcity episodes. This highlights the importance of establishing robust, rational and efficient drought risk-reduction and management strategies in this territory.

The draft GRB DMP was published on 21st December 2017 and was subject to a three-month public consultation period. This paper provides a critical review of the recently approved (2018) GRB DMP, in terms of the effectiveness and real influence of PP in the elaboration of the GRB DMP. The learnings from this experience could be applied during the current consultation and development of the 3rd cycle River Basin Management Plans (RBMPs) across EU.

Section 6.3 describes the methodology, **Section 6.4** summarises the main outcomes and **Section 6.5** concludes.

Figure 17: River basins in Spain (source: [68]).

6.3 Methodology

The aim was to critically assess whether and to what extent the contribution provided by stakeholders and interested parties - during the public consultation period of the recently adopted 2018 GRB DMP - actually meant a significant change and a real influence on the approved drought management strategy established in the 2018 GRB DMP.

The methodology followed consisted of the following steps:

1. Preliminary review of the information supplied by the Guadalquivir RBA as part of the PP process (i.e. the draft 2017 GRB DMP and accompanying appendices);
2. Classification of comments raised by participants (based on the type of water user, topic of concern, etc.);
3. Critical analysis of the written responses provided by the RBA (in terms of adequacy, level of detail, rationale, etc.);
4. Critical assessment of the overall PP process in terms of information transparency, communication efficiency and real influence of the public involvement in shaping the drought management strategy;
5. Recommendations on possible aspects that could be improved in future PP processes.

The publicly available information subject to public consultation and assessed as part of this study is available at the Guadalquivir RBA webpage [62]:

6.4 Critical review of the public information and participation processes during the elaboration of the GRB DMP

6.4.1 Overview

The draft GRB DMP was published on 21st December 2017 and was subject to a three-month public consultation period (from 21st December 2017 to 21st March 2018). There was a significant interest among the public and stakeholders, reflected on their willingness to actively take part in the PP. As a result, a wide range of technical, economic, environmental and social concerns were raised by all interested parties (water companies, irrigators, ecologist groups and institutions).

There were 19 contributions in total and similar participation from the different water user groups (**Table 10**): 4 urban water supply companies, 4 irrigation associations, 5 ecologist groups and 6 institutions (including scientific/technical groups and government authorities).

There were a total of 157 comments, observations or suggestions: 41% made by the environmental groups, 24% made by the urban water supply groups, 18% made by the irrigation groups and 17% made by the institutions, as shown in **Figure 18**.

In response to this, a written Statement of Response together with the revised GRB DMP were published in May 2018. The final GRB DMP was approved in December 2018. This document establishes the general management principles and course of action for different drought and water scarcity scenarios and in each sub-basin of the GRB [67].

Table 10: Water users who took part in the PP process of the draft (2017) GRB DMP (Own elaboration, data from: '*Plan Especial De Sequía, Demarcación Hidrográfica del Guadalquivir, Informe de Observaciones y Sugerencias, 30* de *Mayo de 2018'*, [62]).

Water users who provided input in the PP process of the draft (2017) GRB DMP

Group	Name	Description
(A) Local Water and Sewage Authorities	**1** Emasagra	Local Water, Drainage and Sewage Company - Granada City and Metropolitan Area
	2 Aguas de Sierra Elvira	Local Water, Drainage and Sewage Company - Various municipalities (Granada metropolitan area)
	3 Emasesa	Local Water, Drainage and Sewage Company - Sevilla City and Metropolitan Area
	4 Aljarafesa	Local Water, Drainage and Sewage Company - Various municipalities (Sevilla area)
(B) Irrigation/ Agricultural Groups	**5** UPA	Unión de Pequeños Agricultores y Ganaderos de Andalucía (approximate translation: "Union of Small Farmers and Ranchers of Andalusia")
	6 COAG	Coordinadora de Organizaciones de Agricultores y Ganaderos (approximate translation: "Coordinator of Farmers and Ranchers Organizations")
	7 FERAGUA	Asociación de Comunidades de Regantes de Andalucía (approximate translation: "Association of Andalusian Irrigation Communities")
	8 CR Canal del Guadalmellato	Comunidad de Regantes del Pantano del Guadalmellato (approximate translation: "Guadalmellato Reservoir Irrigation Community")
(C) Ecologist Groups	**9** FNCA	Fundación Nueva Cultura del Agua (approximate translation: "New Culture of Water Association")
	10 WWF	World Wildlife Fund - ONG
	11 PDRC	Plataforma en Defensa del Río Castril (approximate translation: "Platform in Defense of the Castril River")
	12 SEO Bird Life	Sociedad Española de Ornitología (approximate translation: "Spanish Society of Ornithology")
	13 Various	Aeopas, CCOO, COAG, Ecologists in action, Facua, FNCA, SEO bird life, UGT, UPA, WWF
(D) Government institutions and scientific organisations	**14** Junta de Castilla La Mancha	Political Government Institution of the Autonomous Community of Castilla la Mancha
	15 Junta de Andalucía	Political Government Institution of the Autonomous Community of Andalusia
	16 Ayuntamiento de Castril	Local Council of Castril (Granada)
	17 IGME	Instituto Geológico y Minero Español (approximate translation: "Spanish Geological and Mining Institute")
	18 ICOGA	Ilustre Colegio Oficial de Geólogos de Andalucía (approximate translation: "Illustrious Official College of Geologists of Andalusia")
	19 AEH	Asociación Española de Hidrogeólogos (approximate translation: "Spanish Association of Hydrogeologists")

6.4.2 Consultation period

The GRB DMP was prepared and published in the context of the WFD (according to Art. 13.5), as supplementary documents to the already approved 2nd cycle (2015-2021) Guadalquivir River Basin Management Plan (RBMP).

The draft GRB DMP was subject to a three-month public consultation period (from 21st December 2017 to 21st March 2018). However, Art. 14 of the WFD states that: "*Member States shall allow at least six months to comment in writing on those documents in order to allow active involvement and consultation*".

Given the strong interrelation between the Guadalquivir RBMP and DMP, as well as to ensure that all water users were fully aware of the key drought management issues and potential (social, economic and environmental) consequences, a minimum period of six months should have been allowed in this process.

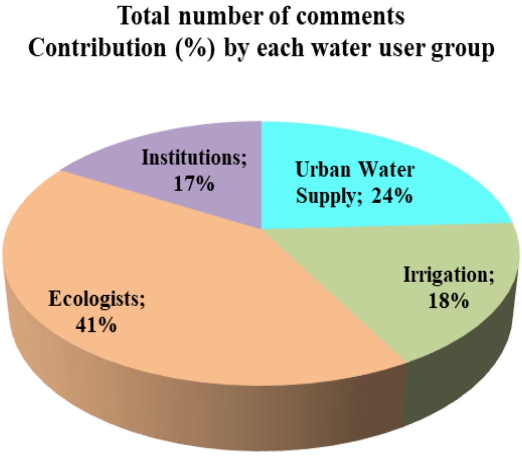


Figure 18: Percentage (%) of comments made by each water user group during the PP.

6.4.3 Overlapping consultation periods

The common methodological approach for preparing the DMPs of the Spanish River Basin Districts (RBDs) was set out by the Spanish Government Ministry for the Ecological Transition (MITECO) Technical Instruction [61].

Remarkably, the draft GRB DMP was published before the MITECO Technical Instruction was even approved. In fact, these two key documents were simultaneously subject to public consultation (approximately two months overlapping period): the GRB DMP from 21st December 2017 to 21st March 2018 and the MITECO Technical Instruction from 28th November 2017 to 28th February 2018.

It is logical to think that the "*common*" methodological framework should have been subject to public consultation and approved before releasing the draft GRB DMP. This is, all interested parties should have had the opportunity to be involved in the process sufficiently early and comment on the methodology first, and then, once approved, comment on the specific river basin DMPs.

6.4.4 Information Supply

6.4.4.1 Dissemination

The draft (2017) GRB DMP was composed by the main report and two appendices. These documents were disseminated mainly through the GRBA website [62].

Apart from the information supplied on the internet, and limited workshops (with practically no advertisement and limited access to the general public), there was no real effort to attain an efficient involvement and active participation from the public during the 3 month period of public consultation process.

In future, a wider range and more effective communication methods could be applied, such as involving mass media, leaflets, advertising campaigns, direct emails (for example to the relevant representatives from the different water groups), etc.

PP could be also further improved by convening informative and interdisciplinary discussion meetings, where interaction, constructive dialogue and mutual learning are sought. Technical experts, decision-makers and the relevant representatives from all water sectors (water supply companies, farmers and irrigators, industry, environmental groups, authorities and general public) should be invited. Or, if there are specific topics/conflicts to be addressed that affect to particular water groups, then target the invitations to the relevant interested parties. The meetings should be aimed at dealing with specific objectives at the sub-basin spatial unit (rather than the complete basin scale).

The benefits of this approach are multiple. On the one hand, this offers the possibility to directly inform people about the key drought management issues, the risk management strategy as well as the potential (economic, social and environmental) impacts. On the other hand, it gives the opportunity to exchange different insights and opinions, which can help to improve the strategy along with building new constructive relationships. This promotes transparency and genuine participation, as well as efficiency in managing expectations and establishing agreements between water users (for example, for the water allocation conflict).

6.4.4.2 Compliance with the EU WFD requirements

The draft (2017) GRB DMP was published approximately one year before the beginning of the period to which the plan refers to. This is in accordance with Art. 14(1c) of the WFD.

Nonetheless, a timetable, work programme for the production of the plan as well as an interim overview of the significant water (drought) management issues were not provided as per the requirements of Art. 14(1a and 1b) of the WFD.

6.4.4.3 Quantity and Quality

Despite the large extent of the main report (470 pages), the input data sources are not easily traced. The memory report provides general references to online resources, webpages, the Guadalquivir RBMP 2nd cycle and a general description of the methodology.

However, access to all the supporting background documents, the detailed methodological description and complete numerical information were not provided by the RBA (despite the fact that various water users specifically requested these during the public consultation process).

For example, it is notorious that there is an absence of important numerical information such as: i) the Standardized Precipitation Index (SPI) calculations (only the final graphical results are provided), ii) the 100-yr and 20-yr return period reference drought events (key numerical data used to estimate the water scarcity thresholds) and iii) modelling input data or results are not provided.

This information is fundamental not only for the PP process (to ascertain that the calculations are correct) but also and most importantly, for the actual operation and implementation of the DMP (during the next 6 years). So that, the water users can estimate the relevant drought and water scarcity indicators without depending on the RBA to publish these on their website on a monthly basis.

It is also noteworthy that the 2018 GRB DMP is a highly technical document and thus, inaccessible to most of the public (as the relevant expert knowledge is required). In order to achieve an informed and meaningful engagement, the GRBA should be committed to adapting the specialised language to ensure that the “*key messages*” are fully understood by all the interested parties and general public.

Finally, it is worth mentioning that the data used to elaborate the 2018 GRB DMP was not the most updated one. The adopted 2018 GRB DMP integrated the approved information included in the 2nd RBMP cycle (2015-2021) in terms of resources, demands, ecological flows, climate change, etc. The reference period was Oct 1980 – Sept 2012, and therefore, the most recent years were not used. The most updated information and planning framework is contained in the draft 3rd RBMP (2021-2027) documents, to be published by the end of 2021.

6.4.5 Type of comments raised by interested parties

A comprehensive variety of technical, economic, organizational, environmental and social concerns were raised by stakeholders and interested parties. It must be highlighted the difficulty of classifying those under one single criterion, given their diverse, interrelated and sometimes complex nature.

While the comments and suggestions were varied in nature, the main issues raised by the participants were related to the core principles of the DMP, such as the:

a) use of the short-term reference hydrological period from October 1980 to September 2012 (instead of the long reference period) for the: i) calculation of drought indices and ii) integration of climate change impacts.

b) drought and water scarcity definitions;

c) methodology applied to determine the drought and water scarcity indicators and their thresholds;

d) actions and measures to be activated during a prolonged drought situation (as these do not seem to contribute towards the prevention or mitigation, required by the art.4.6 of the WFD) as well as the uncertainty in terms of application, management and control of the ecological flow regime (especially in situations of prolonged drought);

e) actions and measures to be applied during each water scarcity scenario. In particular, emphasis was placed on the nature of the measures and when to apply them (hierarchy of measures) and the ambiguity in the priority of water use among water users and environmental needs;

f) other specific comments related to particular sub-basins.

Figure 19 shows the classification of the comments by type of water user and section of the DMP to which they refer.

Even though most of these comments are related to the operation and management of specific sub-basins, overall, the suggestions given by the water users to the RBA were to:

a) establish a clear and transparent strategy, including site-specific actions and governance rules during each drought and water scarcity phase (i.e. avoiding the possibility of different interpretations and reducing potential conflict between different water users);

b) clearly set out the priority of water users (during an ordinary and prolonged drought situation);

c) describe in detail the ecological flow regime strategy plan (how and when these are applied);

d) study in more detail the possible alternative use of underground resources in some sub-basins and other alternative resources for irrigation, such as the re-use of treated water;

e) update the register of abstractions and review water concessions (i.e. to adapt them to real needs);

f) ensure further control, inspection and monitoring of illegal water abstractions;

g) encourage and facilitate the transfer of rights or public banks of water to promote efficiency in use.

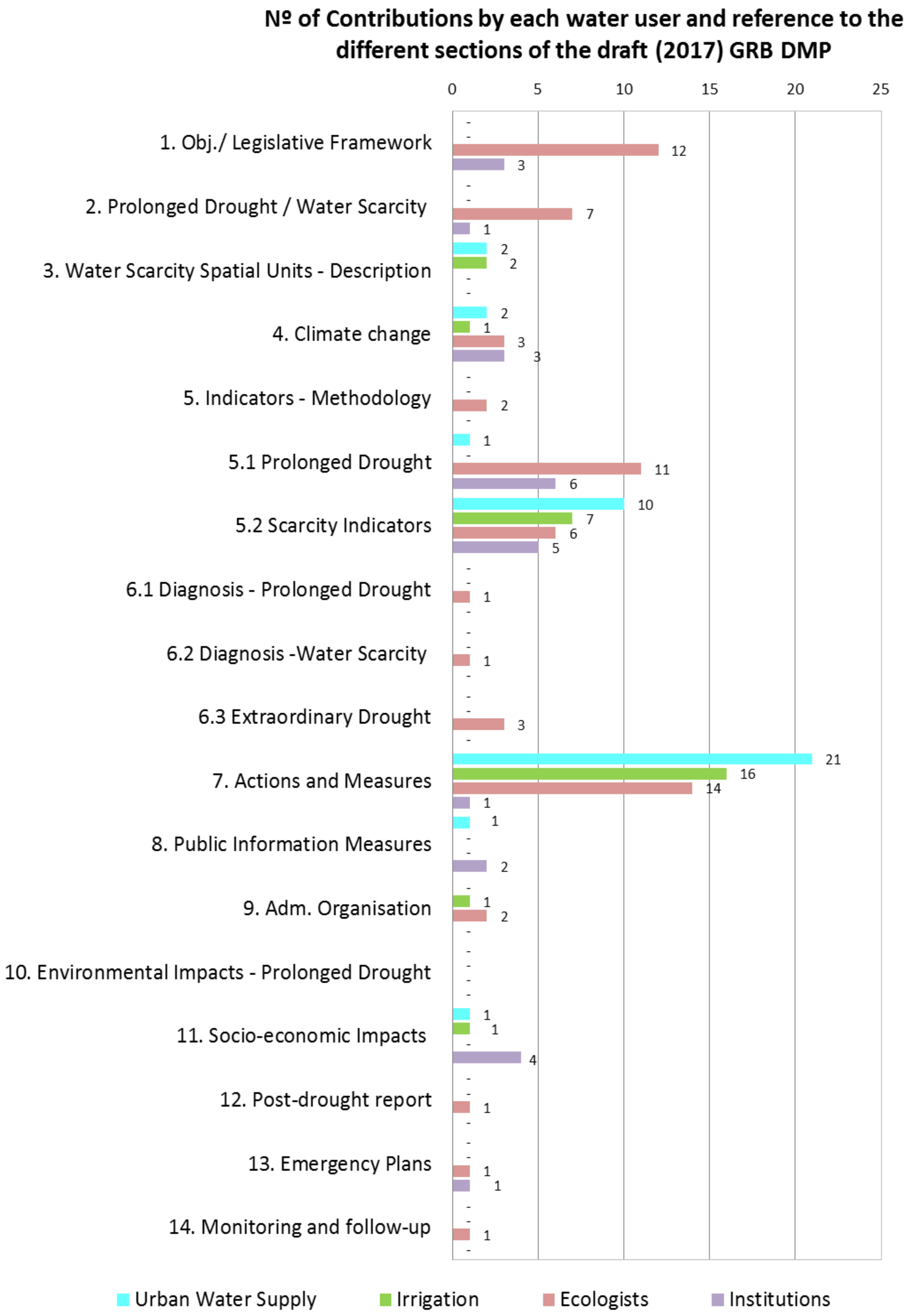


Figure 19: Classification of comments by type of water user and topic (Section of the GRB DMP).

6.4.6 Responses provided by the Guadalquivir RBA

In response to the comments received, a written Statement of Response (containing each concern and associated response) together with the revised GRB DMP were published in May 2018.

While the participants generally provided evidence to support their comments, the Guadalquivir RBA did not offer the same level of detail in their responses. In fact, most of the responses were "*standard answers*".

From these results, the participants could have interpreted that their input to the process was not taken properly into consideration by the water authorities or sufficiently important to the authorities, resulting in disappointment and discouraging them to be involved in any future PP process (as it takes time and effort).

6.4.7 Real Influence of PP process

While some modifications were introduced as a result of the public consultation process, the revised GRB DMP remained essentially the same as the first draft. Only 8% of the total number of comments (157) received were actually accepted. These were integrated totally or partially into the updated documents (**Figure 20**).

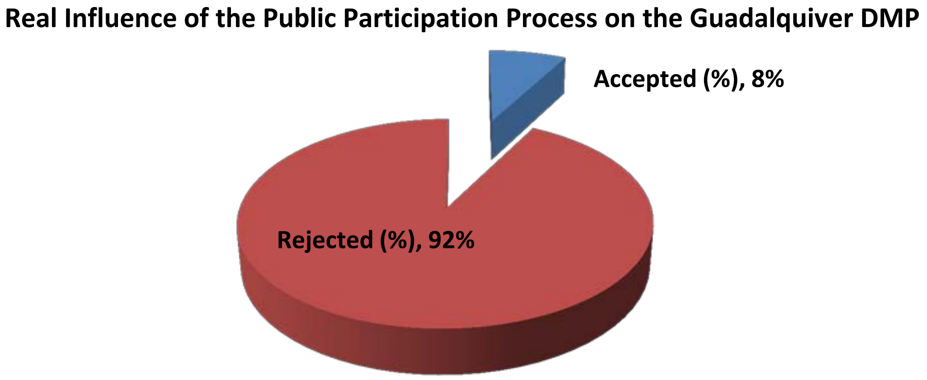


Figure 20: Percentage of comments accepted and rejected during the revision of the draft (2017) GRB DMP.

From this small proportion of accepted comments (8%), the majority corresponded to typo, conceptual or calculation errors, while only a minority of the accepted comments were related to improvements in the drought management strategy.

Important aspects were left unresolved such as the absence of: i) using streamflow forecast models, ii) technical, socio-economic and environmental assessments to provide evidence to support the proposed drought management actions and measures, and iii) assessment of climate change impacts.

In future events, it would be recommended to follow the advice provided by Paneque et al. [51] highlighted that "*water-governance models must take into consideration different alternative management measures and the degree of social approval of each alternative*".

A leading example in terms of public information and participation process has been developed in the Júcar RBD. The Júcar RBA held two types of events to encourage active participation: a one-day workshop at the University of Valencia open to the general public and specific round tables in different cities to address particular aspects of drought management in those regions. During the one-day workshop, technical experts organized seminars where key aspects of the draft Júcar DMP were presented and discussed (the slides of these presentations are also available at [84]). During the round tables, the specific problems associated with possible measures to be implemented to minimize the impacts of drought in those territories were reviewed. They were open to different stakeholders, such as water users, administrations, non-governmental organizations, companies, associations, universities and other stakeholders). In this basin, the 60% of the total number of comments (317) were (totally or partially) integrated in the revised version of the Júcar DMP (127 comments totally accepted and 62 comments partially accepted). This is a good example of how a genuine and inclusive participation process should be [84].

6.5 Concluding remarks and recommendations

The publication of the draft (2017) GRB DMP aroused a significant interest among the public and stakeholders, that was reflected on their willingness to take active part in the PP process. During the short three-month PP period, a wide range of technical, economic, environmental and social concerns were raised by all interested parties (water companies, irrigators, ecologist groups, scientific groups and governmental institutions).

The most frequently repeated concerns among the participants were related to the proposed actions and measures to be applied during the occurrence of a drought event (i.e. the core of the drought management strategy).

In response to this, a written Statement of Response together with the revised version of the GRB DMP were published in May 2018. The final GRB DMP was approved in December 2018. While some modifications were introduced as a result of the PP process, the revised and final (2018) GRB DMP remained essentially the same as the first draft version. Only 8% of the total (157) number of comments received were accepted and integrated (totally or partially) into the updated documents.

Bearing in mind these results, it could be concluded that PP was a mere box-ticking exercise to comply with the EU WFD legal requirements rather than a real mechanism to improve the water management. PP had, in practical terms, no real influence in the decision-making for shaping the 2018 GRB DMP.

The major weaknesses were associated to the information supply (unclear and insufficient), consultation period (short) and participation approach (late involvement and lack of integration of the local knowledge and experience provided by the participants).

For future PP processes, it is recommended to involve all interested parties at an early stage (when the options are still under consideration and there are still opportunities to adjust the strategy) and extend the consultation period to a minimum of 6 months (in line with Art. 14 of the WFD).

In this respect, two elements are fundamental: i) fostering proactive involvement from all the water users and key stakeholders, and ii) working towards an effective and genuine communication method based on information transparency and collaborative programs. This could help towards integrating site-specific knowledge and achieving consensus among water users in those controversial topics.

All water users and Stakeholders should have the opportunity to provide their opinion to have a real influence on the final decision processes. It is equally important to provide access to all the supporting background documents and detailed methodological and numerical information.

A leading example in terms of public information and participation process has been developed in the Júcar RBDs. There was real engagement with all water users via different kind of meetings (which were well-published in advance) and integration of up to 60% of the total comments received during the consultation period.

These recommendations may contribute to achieving consistent, transparent and responsible drought management solutions during the entire life-cycle of a DMP (development, implementation, monitoring, control and recovery/lessons learnt). Other important benefits could be brought in, such as taking more ownership and responsibility from water users while stimulating innovation, increasing acceptance of solutions, building constructive relationships and reducing potential future water conflicts.

These learnings could help improving not only the Spanish case but also be applied during the current consultation and development of the 3rd cycle RBMPs across EU.

7. ARTICLE IV

7. ARTICLE IV: SIMPLE AND LOW-COST PROCEDURE FOR MONTHLY AND YEARLY STREAMFLOW FORECASTS DURING THE CURRENT HYDROLOGICAL YEAR

This Chapter has been published in *Water* (2018 JCR Journal Impact Factor 2.524, JIF Percentile 68.681, Quartile Q2, Rank 29/91 in Water Resources, and 2018 SJR Factor 0.634, Quartile Q1 Geography, Planning and Development), full reference as follows:

- Delgado-Ramos, F.; Hervás-Gámez, C. Simple and Low-Cost Procedure for Monthly and Yearly Streamflow Forecasts during the Current Hydrological Year. *Water* 2018, *10*, 1038, doi:10.3390/w10081038.

7.1 Abstract

Accurately forecasting streamflow values is essential to achieve an efficient and integrated water resources management strategy as well as to provide consistent support to water decision-makers. We present a simple, low-cost, and robust approach for forecasting monthly and yearly streamflows during the current hydrological year, which is applicable to headwater catchments. The procedure innovatively combines the use of well-known regression analysis techniques, the two-parameter Gamma continuous cumulative probability distribution function and the Monte Carlo method. Several model performance statistics metrics (including the Coefficient of Determination R^2; the Root-Mean-Square Error RMSE; the Mean Absolute Error MAE; the Index of Agreement IOA; the Mean Absolute Percent Error MAPE; the Coefficient of Nash-Sutcliffe Efficiency NSE; and the Inclusion Coefficient IC) were used and the results showed good levels of accuracy (improving as the number of observed months increases). The model forecast outputs are the mean monthly and yearly streamflows along with the 10th and 90th percentiles. The methodology has been successfully applied to two headwater reservoirs within the Guadalquivir River Basin in southern Spain, achieving an accuracy of 92% and 80% in March 2017. These risk-based predictions are of great value, especially before the intensive irrigation campaign starts in the middle of the hydrological year, when Water Authorities have to ensure that the right decision is made on how to best allocate the available water volume between the different water users and environmental needs.

Keywords: integrated water resources management; support to decision-making process, streamflow forecast; simple and low-cost forecasting model; Guadalquivir River Basin; Genil River.

7.2 Introduction

Nowadays, water authorities and decision-makers are facing considerable challenges in achieving a sustainable and integrated water resources management system, especially, in water-stressed areas. They must make responsible management decisions on the optimum allocation of the available water volume from a wide range of possible water sources (regulated or non-regulated rivers, groundwater resources, water re-use schemes, desalination plants, etc.) between the demands of, usually, multi-sectoral water users (urban, agriculture, industry, tourism, energy, etc.).

Not only must these decisions meet the water demands, but they must also protect this natural, essential and finite resource along with careful consideration of the environmental needs, the possible environmental impacts, the increase of legal requirements on water quality, the social equity, the costs, and the promotion of economic growth. Additionally, the effects of climate change on spatial distribution and temporal climate variability, coupled with an ever-increasing population, are altering traditional approaches to water resources planning, management, and decision processes ([85], [86]).

To cope with this situation, a wide variety of water conservation policies from water demand reduction (i.e., water use efficiency, water restrictions, pricing policies, governance, etc.) to water supply augmentation (i.e., new infrastructures, such as reservoirs, desalination plants, rainwater harvesting, grey and black water reuse schemes, water transfers, groundwater recharge, etc.) can be adopted at the basin scale [87].

Therefore, advanced hydrological information and the provision of accurate streamflow forecasts is one of the key aspects to provide consistent support to decision-makers. Short-term forecasting, such as hourly or daily forecasting, is crucial for flood warning and sediment control. Medium-term forecasting based on monthly, seasonal, or annual time scales is fundamental in deciding on critical aspects of the current hydrological year, such as reservoir outflows planning, scheduling irrigation releases, allocating water to downstream users, drought mitigation, and managing river treaties or implementing compact compliance [88]. Long-term forecasting is key for planning investment in new strategic water infrastructures (such as reservoirs or water transfers between different catchments) as well as to inform the preparation of the River Basin Management Plans (RBMPs) required by the Water Framework Directive (WFD) 2000/60/CE.

In Mediterranean countries (for example, Spain), where agriculture plays an important socio-economic role, the critical decision point is in the middle of the hydrological year just before intensive irrigation campaigns commence (usually in April [89]). Whilst typical annual precipitation peaks generally occur during the months of January, February, and March, peak agricultural water demands occur precisely during the most water-stressed months of June, July, and August [90]. Therefore, water supply infrastructures, such as reservoirs, provide an important source of water storage during the wet season and are the essential infrastructure to efficiently deal with spatial and temporal climate irregularities distinctive of the Mediterranean area.

At a seasonal level, a skilful streamflow forecast may allow for more efficient water allocation and predictable trade-offs between flows for energy, irrigation, urban water supplies, environmental services, etc. Such forecasts often allow us to address anticipated conditions and not simply react to existing conditions, potentially reducing climate-related risks and offering opportunities ([91], [92]).

The importance of achieving an adequate level of accuracy when predicting streamflows has been highlighted by many authors ([93]–[96]). There is a wide variety of methods that have been used to build streamflow prediction models. Streamflow forecasting models fall into two general categories: Process-driven and data-driven ([88], [96], [97]). Shalamu [88] and Yu et al. [97] have provided a very detailed description and review of the different models, limitations, and applications.

Conceptual hydrologic models replicating observed historical data sets have traditionally been used for predicting the future. However, some of their shortcomings might come from aspects, such as the quality, accuracy, and completeness of the input requirements. Their complexity is due to the number of required input variables, the difficulty to capture certain hydrological phenomena (such as the snow storage and melting processes), and the computational time, as well as the calibration and parameter optimization processes, which can be also challenging. Gragne et al. [98] proposed to address these difficulties by complementing conceptual models with simple error models and thus their results present more accurate inflow forecasts into hydropower reservoirs several hours ahead.

On the other hand, data-driven models can use many different methods, for example: (i) the support vector machine, genetic programming, and seasonal autoregressive techniques [99]; (ii) artificial intelligence-based rainfall–runoff models that include the Artificial Neural Network (ANN), Wavelet, and SARIMAX (Seasonal Auto Regressive Integrated Moving Average with exogenous input concepts) [100]; and (iii) high dimensional vine copulas, conditional bivariate copula simulations, and a quantile-copula function [101], etc. More recently, Myronidis et al. [78] successfully used ARIMA (autoregressive integrated moving average) models to forecast the mean monthly streamflow values for the next three months and to predict the evolution of drought indices in Cyprus.

Currently, the use of seasonal climate predictions is becoming more commonplace. For example, Khedun et al. [102] presented a copula-based precipitation-forecasting model that produces a notable improvement in simulating negative precipitation anomalies during "*La Niña*" and negative Pacific Decadal Oscillation. Also, Liu et al. [103] presented a probabilistic wavelet–support vector regression model for streamflow forecasting with rainfall and climate information input that consistently generates more reliable predictions for daily and monthly forecasts as compared with the best single-member wavelet-support vector models and the adaptive neuro-fuzzy inference system.

Nevertheless, in Spain, the level of accuracy achieved by the seasonal climate forecasts provided by the Spanish Meteorological Agency (AEMET or Agencia Estatal de Metereología [104]) for the hydrological year 2017–2018 has not been as good as expected. For example, in February 2018, AEMET predicted that, for the south-eastern quarter of Spain, March, April, and May would be much drier than average, whereas March 2018 has been the wettest month registered to date.

This research contributes towards the development of a user-guided, novel, simple, low cost, and robust methodology to forecast streamflows within the current hydrological year. This is applicable to headwater systems and can provide support to strategic water management decisions. The methodology has been successfully applied to two headwater reservoirs located at the upper area of the Genil River within the upper area of the Guadalquivir River Basin (GRB), namely, Quéntar and Canales.

The model forecast outputs are the mean monthly and yearly streamflows along with the 10th and 90th percentiles (although the model offers flexibility to easily modify the percentiles if needed). The model was first put into operation in October 2016 and the model output forecasts achieved satisfactory results, with a relative error varying from 8% (Canales) to 18% (Quéntar). These risk-based forecasts are not only useful for water reservoir operators and authorities, but also to all stakeholders involved in the planning, management, and decision-making processes. The model also has the ability to incorporate seasonal climate predictions and climate change effects.

The aim of this work was to develop a simple and low cost statistical model (data-driven) to forecast monthly and annual streamflows during the current hydrologic year. To achieve this, the specifications were set to:

- use free hydrological data sources available in the public domain (to be downloaded in an easy, free, and quick manner from a reliable and official online resource where possible);
- minimise the number of hydrological variables;
- integrate easily and regularly new observed hydrological data in the model (an automatic process where possible);
- minimise computational and simulation running times (instantaneously where possible); and
- offer a user-friendly interface.

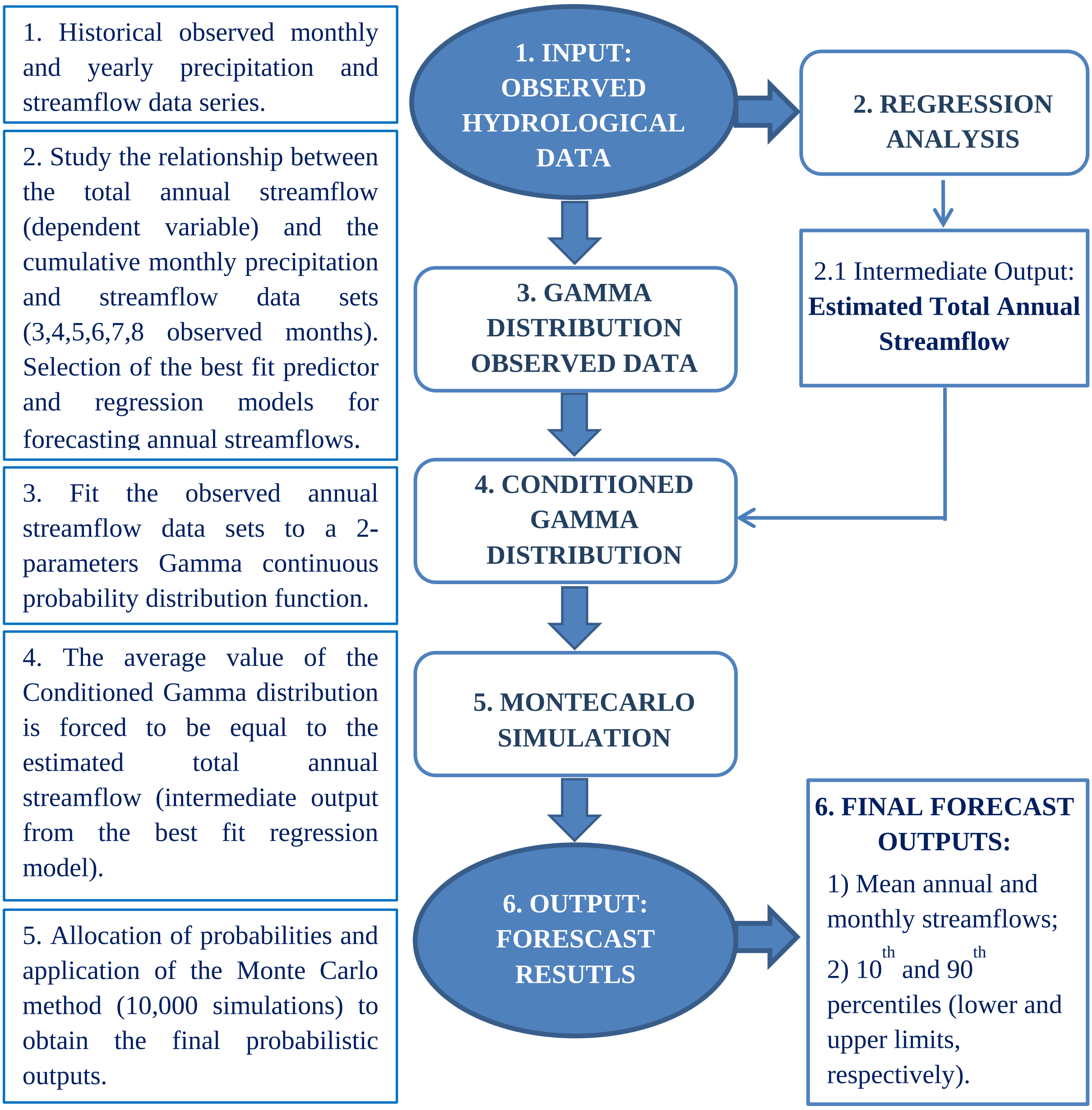
This paper is organised as follows: **Section 7.3** describes the methodology, **Section 7.4** presents the results for the two cases of study, including the description, findings, model performance tests using reliability metrics, and the discussion, and **Section 7.5** provides the concluding remarks.

7.3 Materials and Methods

7.3.1 Overview

The proposed methodology is to predict the probabilistic monthly and annual streamflows during the current hydrological year. It innovatively combines the use of well-known regression analysis techniques (between relevant hydrological variables), the two-parameter gamma continuous cumulative probability distribution function and the Monte Carlo simulation. It is based on a probabilistic comparison of the progression of the current hydrological year (in terms of cumulative monthly precipitation or cumulative monthly streamflow) with the historical data series.

Figure 21 shows the flowchart of this methodology (described in detail in the following sections and applied to two cases of study detailed in **Section 7.4**).



1) Mean annual and monthly streamflows;

2) 10th and 90th percentiles (lower and upper limits, respectively).

1. Historical observed monthly and yearly precipitation and streamflow data series.

2. Study the relationship between the total annual streamflow (dependent variable) and the cumulative monthly precipitation and streamflow data sets (3,4,5,6,7,8 observed months). Selection of the best fit predictor and regression models for forecasting annual streamflows.

3. Fit the observed annual streamflow data sets to a 2-parameters Gamma continuous probability distribution function.

4. The average value of the Conditioned Gamma distribution is forced to be equal to the estimated total annual streamflow (intermediate output from the best fit regression model).

5. Allocation of probabilities and application of the Monte Carlo method (10,000 simulations) to obtain the final probabilistic outputs.

Figure 21: Flowchart of the methodology.

7.3.2 Model Time Step, Data Sources, and Treatment

A monthly time step has been considered adequate for this work since the results are to support strategic and management decisions associated with annual or quarterly cycles.

Therefore, the predictions from the model might not be applicable to other reservoir operations (for example, hydropower plants or flood forecasting) with lower time scale data requirements (hours, days).

It is also important to understand the phenomena that will be picked up within the selected monthly time step for each particular catchment area (for example, snow storage and melting processes, subterranean inflows, etc.).

Free hydrological data sources available in the public domain have been used to inform this work. The data can be downloaded in an easy, free, and fast manner from a reliable and official online resource.

The data requirements were the historical precipitation and streamflow monthly data sets for each particular catchment of study. It is recommended to apply the methodology when there is good quality input data and at least 30 years of observed data (although 40 years would be desirable to increase the forecasts' accuracy). The minimum number of observed years should be greater in those catchments with a greater standard deviation.

From the observed data series, the cumulative precipitation and streamflow monthly time series were calculated for the first three observed months (Oct to Dic), four observed months (Oct to Jan), five observed months (Oct to Feb), six observed months (Oct to March), seven observed months (Oct to April), and eight observed months (Oct to May). The reason why the assessment starts with the first three cumulative observed months is to ensure that sufficiently good correlation coefficient values were achieved in the regression analysis.

With this input data, the model provides monthly and yearly streamflow forecasts for the rest of the current hydrological year monthly, starting the forecasts from January, as shown in **Table 11**.

Table 11: Relationship between the observed and forecasted periods.

Number of Observed Months	Observed Period	Number of Forecasted Months	Forecasted Period
3	Oct–Dec	9	Jan–Sept
4	Oct–Jan	8	Feb–Sept
5	Oct–Feb	7	Mar–Sept
6	Oct–Mar	6	Apr–Sept
7	Oct–Apr	5	May–Sept
8	Oct–May	4	Jun–Sept

7.3.3 Simple Regression Analysis and Best Fit Predictor

For the proposed methodology, we used simple regression analysis techniques. We sought to predict the total annual streamflow (hereinafter referred to as A_{annual}) from relevant hydrological descriptors. We selected the cumulative monthly precipitation (hereinafter referred to as P_{cum}) and the cumulative monthly streamflow (hereinafter referred to as A_{cum}) as the best predictors.

The analysis assumed that the hydrological cycle (from October to September) for a specific basin is in balance at the end of the hydrological year. Therefore, a greater correlation between the total annual streamflow and the cumulative monthly time sets was expected as the number of observed months increases.

The results from the regression analysis were subsequently assessed using the coefficient of determination (R^2). This allowed us to select the best fit regression model and best fit hydrological predictor (cumulative rainfall or cumulative streamflow) for each specific month of study. The estimated total annual streamflow from the regression models is an intermediary output (to be used as an input to obtain the conditioned gamma, as shown in **Figure 21**).

It is important to note that the best fit regression model and the best fit predictor do not necessarily need to be same for all the observed months of study. In fact, it might vary depending on the predominant hydrological process given at each specific month or season of the year (snow storage and melting processes, subterranean inflows, seasonal extreme, and sporadic rainfall events). In this situation, a combined regression model should be used to achieve the best correlation values and forecast results.

7.3.4 Two-Parameter Gamma Cumulative Probability Distribution Function

The next step was fitting the historical annual streamflow data series to a two-parameter gamma (α,β) cumulative probability distribution function (CDF).

There is extensive literature describing the properties, parameters estimation, and applications of the two-parameters gamma (α,β) CDF [105]. This distribution has been shown to fit well to rainfall and streamflow data sets, respectively, and, therefore, has been widely applied to hydrological data-driven models, such as those described in the studies of Buishand [106], Stephenson et al. [107], Wang and Nathan [108], Chen et al. [109], and Chowdhury et al. [110].

A random variable, X, is said to have a two-parameter gamma continuous probability density function if its distribution is given by:

$$f_X(x;\alpha,\beta)=\begin{cases}\frac{1}{\beta^{\alpha}\,\Gamma(\alpha)}x^{\alpha-1}e^{-\frac{x}{\beta}}, & x\geq 0,\ \alpha,\beta>0,\\ 0, & x<0\end{cases} \tag{1}$$

$$\Gamma(\alpha)=\int_0^{\infty}x^{\alpha-1}e^{-x}dx,\ \alpha>0, \tag{2}$$

where α and β are the shape and scale parameters, respectively.

The gamma CDF is given by:

$$P(X\leq x)=F(x;\alpha,\beta)=\begin{cases}\dfrac{1}{\beta^{\alpha}\Gamma(\alpha)}\displaystyle\int_0^x y^{\alpha-1}e^{-\frac{y}{\beta}}\,dy\,, & x>0,\ \alpha>0,\ \beta>0\\ 0 & ,\quad x\leq 0\end{cases} \tag{3}$$

The mean, E(x), and variance, V(x), are given by Equations (4) and (5), respectively:

$$E(x)=\alpha\beta \tag{4}$$

$$V(x)=\alpha\beta^2 \tag{5}$$

From Equations (4) and (5), we can estimate the mean and variance of the observed series and the parameters α and β, as follows:

$$\beta = V\ (x)/E\ (x) \tag{6}$$

$$\alpha = E(x)/\beta \tag{7}$$

This distribution provides the non-exceedance (or maximum) probability that the total annual streamflow will take a value less than or equal to a determined value as well as the maximum total annual streamflow value associated to a specific probability value.

It is important to check how well the gamma distribution fits with the observed data series of annual streamflows for each case study. **Section 7.4.4** shows that for the two case studies, the gamma CDF was found to provide a very good fit to the observed annual streamflow data series.

7.3.5 Conditioned Two-Parameter Gamma Cumulative Probability Distribution Function (Using the Output from the Regression Models)

To obtain the conditioned gamma distribution function, we determined the influence of the estimated total annual streamflow (from the regression models, **Section 7.3.3**) on the gamma CDF (fitted to the observed data, **Section 7.3.4**).

To do that, we imposed the condition that the mean value of the new conditioned gamma CDF is equal to the result obtained from the regression model (‘A_{annual}’ or estimated total annual streamflow). The value of the scale parameter, β, is kept the same as that already obtained from the gamma CDF (fitted to the observed total annual streamflow data sets).

Based on this, the shape parameter, α, of the conditioned gamma was re-calculated as follows:

$$\begin{aligned}\alpha_{\text{cond}}\ (\text{Conditioned Gamma}) &= \text{Mean (Conditioned Gamma)}/\beta = \\ &= \text{Estimated total annual streamflow (from the regression analysis)}/\beta\end{aligned} \tag{8}$$

We then estimated the conditioned gamma CDF using Equation (3) and the two-parameters (α_{cond},β).

It is important to highlight that whilst the gamma CDF is a fixed curve (since this is derived from the observed and complete hydrological years), the conditioned gamma CDF curve will vary from month to month depending on the output obtained from the regression models. In fact, the conditioned gamma CDF curve will move to the right or left of the gamma CDF, depending on whether the prediction is for a wetter or drier hydrological year than the mean historical year, respectively. If the conditioned gamma CDF is close to the observed gamma CDF this means that the current hydrological year is expected to be similar to the mean observed hydrological year.

The conditioned gamma distribution function (α_{cond},β) allowed us to assign a probability to each year of the historical series based on their total annual streamflow. Therefore, we obtained greater probabilities for those observed years whose annual streamflow is similar to the estimated annual streamflow (‘A_{annual}’) and lower probabilities for those observed years whose annual streamflow differs from the estimated annual streamflow. For each year of the historical series, we have its probability (p), given by:

$$\mathrm{P(x)} = \frac{1}{\beta^{\alpha_{\text{cond}}}\,\Gamma(\alpha_{\text{cond}})}\,\mathrm{x}^{\alpha_{\text{cond}}-1}\mathrm{e}^{-\frac{\mathrm{x}}{\beta}} \tag{9}$$

where x is the observed annual streamflow of the historical records (hm^3), α_{cond} is the shape parameter of the conditioned gamma, and β is the scale parameter of the gamma distribution (the same as per the non-conditioned gamma distribution).

7.3.6 Monte Carlo Method

The Monte Carlo Method is a numerical statistical method that allows the replication of random behaviour of real, non-dynamic systems through the generation of random numbers to which an event is assigned based on their probability distribution [111].

Our model generates 10,000 random input numbers in the interval [0,1]. Each of these random numbers is assigned to one year of the observed streamflows series according to the conditioned gamma CDF (which already integrates the output from the regression model). Therefore, we obtained 10,000 random observed years (from the historical series) according to the probability of success.

From the statistical analysis of those, we obtained three probabilistic forecasts: optimistic, average, and pessimistic. For our case study, we assigned the 90th percentile to the optimistic streamflow forecast and the 10th percentile to the pessimistic forecast, though the user can easily modify these values in the model if needed.

7.3.7 Model Running Time, Test, and Validation

The model takes just a few seconds to run the simulations and provide the forecast results. Therefore, this tool provides a significant improvement in saving simulation and computational times when compared with more complex and sophisticated models.

To verify the model performance, measure its predictive accuracy, and identify potential limitations, several metrics, including the root-mean-square error (RMSE) and determination coefficient (R^2), were used (as shown in **Section 7.4.6**).

7.3.8 Application and Limitations

The total annual streamflow was chosen as the prediction target (instead of the precipitation) to avoid the need of using an additional model to transform the precipitation into streamflow.

However, it is important to note that if there are rapid and significant land use changes within the catchment of study, these might alter the observed hydrological cycle within the basin. In this situation, the model might generate misleading streamflow forecasts. For example, a recent and rapid increase in impermeable area would generate a greater volume of surface water flows and quicker streamflow peaks than the historical observed catchment response [112]. In this case, the precipitation as the prediction target (instead of the streamflow) might be more appropriate and an additional model to transform the precipitation into the streamflow contribution might be required.

The proposed methodology does not consider the contributing inflows from upstream systems (for example, regulated outflow releases from other upstream reservoirs). Therefore, this methodology is applicable to headwater systems located at upper catchment areas only.

There is no limitation in catchment size, however, those catchments with considerable climatic irregularity or very rare seasonal sporadic rainfall events are difficult to predict and should be carefully studied prior to progressing the modelling works (since this methodology is based on a statistical treatment of the known past to predict the future).

7.4 Application to Canales and Quéntar Reservoirs (Upper Guadalquivir River Basin, Spain)

7.4.1 Study Area Description

The Guadalquivir River is the main river in southern Spain that provides water to a total population of over four million people and over eight hundred thousand hectares for irrigation purposes. This system is currently formed by an interconnected system of 64 functioning dams [113]. Although there are alternative water resources from aquifers, springs, and water re-use schemes, nowadays, reservoirs are the essential infrastructure to efficiently deal with spatial and temporal climate irregularities distinctive of this catchment area. **Figure 22** shows the location of the GRB in Spain and the area of study.

Figure 22: Location of the Guadalquivir River Basin [113] in Spain and the area of study (Latitude 37.15855 Longitude: –3.470605).

The Guadalquivir River has a total contributing catchment area of 57,527 km^2 and is delimited by Sierra Morena to the north, the Betic mountain to the south, and the Atlantic Ocean. The altitude at the mountainous borders varies between 1000 m above mean sea level (AMSL) and 3480 m AMSL, which contrasts with the lower altitudes of the Guadalquivir River valley. The climate is Mediterranean, which is defined by the warm temperatures (16.8 °C annual average) and the irregularity of precipitations (550 mm annual average). The rains are frequently torrential and occur after long periods of drought and high temperatures, with a distinct susceptibility to erosion [113]. **Figure 23** shows the mean annual precipitation and temperature, altitude, and land uses in the GRB.

The Guadalquivir River Basin Authority (GRBA) is responsible for the elaboration of the Guadalquivir River Basin Management Plan (according to the European WFD Directive 2000/60/CE) as well as the administration and control of the hydraulic public domain [113]. The GRBA published the draft version of the GRB Special Drought Management Plan (DMP) in Decemeber 2017. This document establishes the general water management principles and course of action for different drought and water scarcity threshold scenarios for each sub-catchment area [114], but does not incorporate any streamflow forecast model or procedure.

The two headwater reservoirs of study are the Quéntar and Canales, located at the upper area of the Genil River within the Granada administrative area and to the south-east of the GRB (refer to **Figure 22** and **Figure 24**).

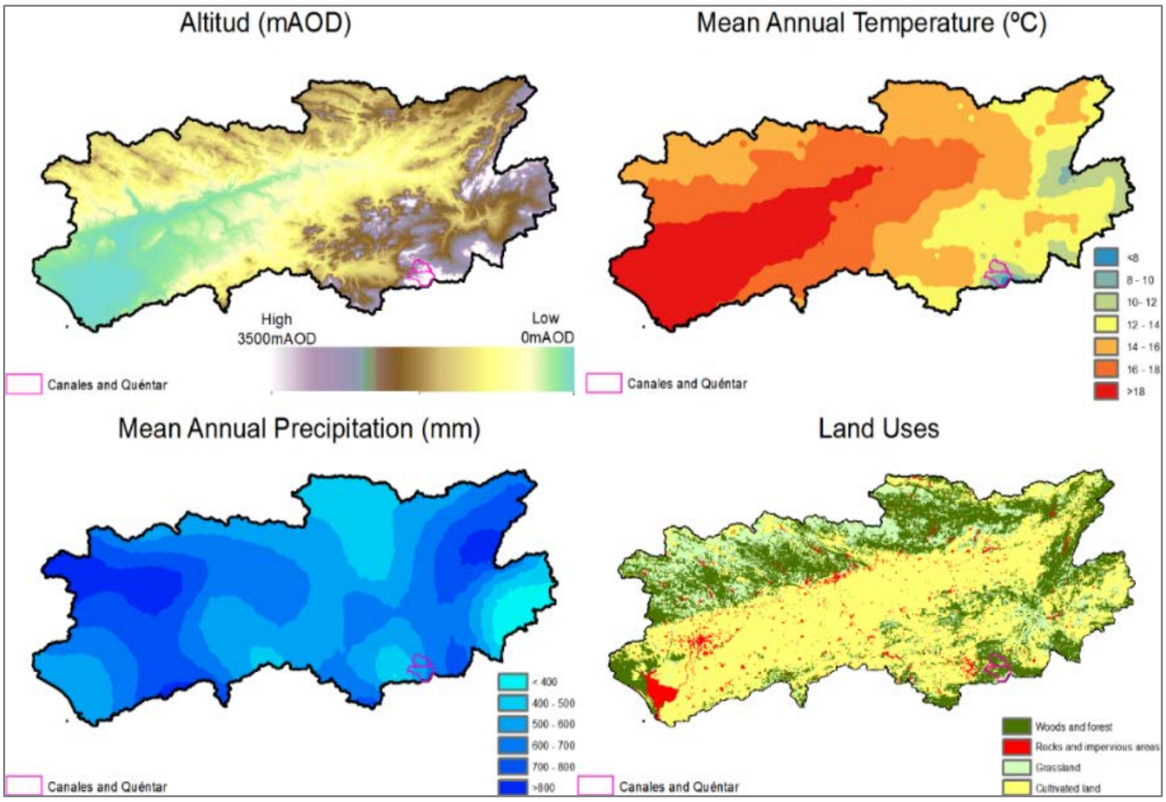


Figure 23: Guadalquivir River Basin (**a**) altitude, (**b**) mean annual temperature, **c**) mean annual precipitation, and (**d**) land uses.

The Canales reservoir is located in the upstream area of the Genil River (close to Sierra Nevada mountains), close to the village of Güejar Sierra, with a total contributing catchment area of 176.5 km^2. The dam was built in 1989 with a total capacity of 70 hm^3 and average streamflow of 66.71 hm^3/year. This catchment area is affected by snow storage and melting processes in the Sierra Nevada. The snow appears between the months of November and May, reaching the maximum accumulation of snow in March with an average water-equivalent volume of 20 hm^3 [115].

The Quéntar reservoir is located on the Aguas Blancas River (tributary of the Genil River), with a total contributing catchment area of 101.2 km^2. This dam was built in 1975 with a total volume capacity of 13.6 hm^3. The average streamflow is 21 hm^3/year. This catchment area is affected by subterranean inflows due to the aquifer and lithology present in the region.

These two reservoirs form the key infrastructure that mainly provide water for urban and irrigation purposes. Urban water consumers are formed by the Granada city and fourteen towns of its metropolitan area, with up to 300,000 inhabitants. The '*Vega Alta del Río Genil'* traditional irrigations cover over 4000 hectares and are fed by an extensive irrigation channel system that diverts water from the Genil River (downstream of the Canales and Quéntar reservoirs).

This system is currently supplemented by a network of thirteen operating underground water wells located in the upper area of the Vega de Granada aquifer (south-east of the city of Granada, on both banks of the Monachil River and the A-395 motorway). These were built by the GRBA after the serious social, economic, and environmental consequences suffered during and after the 1991–1995 drought period (during which Canales and Quéntar reservoirs were depleted). The objective of these works was to supplement the existing surface water resources (provided by the Canales-Quéntar system) with the abstraction of groundwater to serve the urban water supply demand of Granada and its metropolitan area. In 1995, the GRBA delivered this infrastructure to Emasagra (Local Water and Sewage Company) to guarantee its correct management, operation, and maintenance. Since then, Emasagra has been responsible for its management, while the GRBA is responsible for the supervision, reservoir management, and compliance with water allocation.

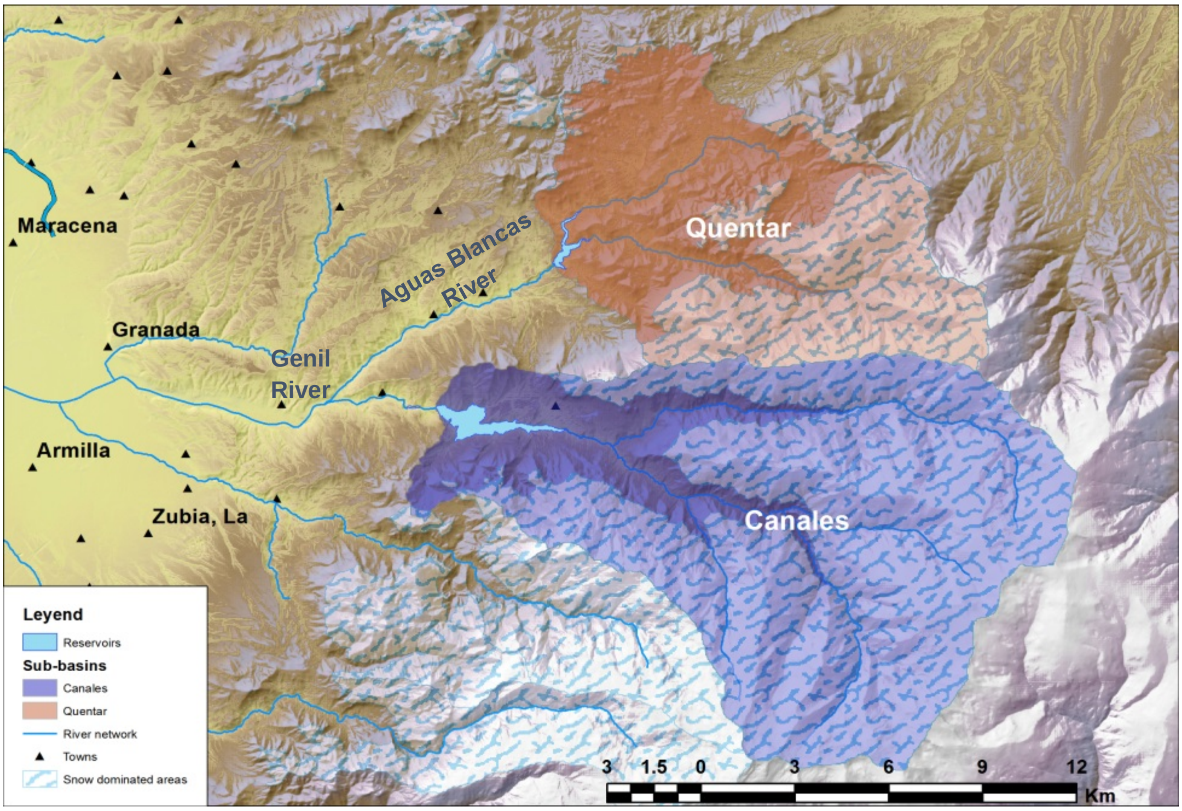


Figure 24: Location of Canales reservoir sub-basin (Latitude: 37.15855 Longitude: −3.470605) and the Quéntar reservoir sub-basin (Latitude: 37.206527 Longitude: −3.433458). Source: own elaboration.

During years of average precipitation, water demands can be met with surface water resources. However, in years of below-normal precipitation, typically higher underground water volume abstractions and/or reductions in per right allocation are required. During prolonged periods of drought and water scarcity, the urban water supply demand has theoretically been assigned priority of use over the irrigation water demand.

Strategic decisions made by the GRBA on the controlled released outflows from the Quéntar-Canales system are critical to ensure the most resource-efficient, cost-efficient, and sustainable allocation of the available water resources. These decisions are especially relevant before the intensive irrigation campaign starts (usually in April), when the water authorities must make responsible management decisions about the best allocation of the available water volume between different water consumers and environmental needs for the rest of the hydrological year.

However, despite their vital importance, decisions made by the GRBA are mainly based on the current water storage in reservoirs instead of using the results from streamflow forecast models. Therefore, we believe the proposed tool can positively contribute towards the development of a practical, quick, and reliable tool to support water authorities and managers on the strategic decision process to achieve a sustainable water resources management approach.

7.4.2 Data Sources and Treatment

The '*Automatic Hydrological Information System* (SAIH)' is a free and public online portal maintained by the GRBA in Spain [75]. The SAIH offers information, such as streamflow, reservoir outflows, rainfall, reservoir level, temperature, etc. for up to 57 reservoirs, 52 non-regulated rivers, 20 canals, and 10 hydro power plants. Other information on rain, snow, and temperature gauging stations across the basin is also offered. The available temporal data sets vary depending on the specific sub-catchment area, but usually these are available from 1989. The information can be downloaded in an hourly, daily, or monthly time step.

The historical monthly precipitation and streamflow data series for Canales (from October 1988 to present) and Quéntar (from October 1977 to present) were obtained. From this information, the cumulative precipitation and streamflow monthly time series for the first three, four, five, six, seven, and eight observed months were determined (as described in **Section 7.3.2**).

7.4.3 Regression Analysis, Correlation, and Selection of the Best Fit Estimator and Regression Model

A complete statistical study was carried out to assess the correlation between the total annual streamflow and the cumulative monthly precipitation and streamflow sets.

Figure 25 and **Figure 26** show the regression analysis for the first three, four, five, six, seven, and eight observed months for Canales and Quéntar, respectively. From a visual inspection of **Figure 25** and

Figure 26, it can easily be observed how the correlation is greater as the number of observed months increases. This is corroborated by the R^2 values shown in **Table 12** (results obtained for the Canales and Quéntar reservoirs).

The comparative critical assessment of the coefficient of determination (R^2) allowed us to select the best fit regression model and best fit hydrological predictor (cumulative rainfall or cumulative streamflow) for each reservoir and specific month of study. The estimated total annual streamflow from the regression models is an intermediary output (to be used as an input to obtain the conditioned gamma).

Table 12 shows that that the linear regression model is the best fit model for the Canales reservoir. It can be observed that the cumulative precipitation presents the best R^2 values (varying from 0.7253 to 0.9083) for the first three, four, and five observed months whilst the cumulative streamflow achieves the best R^2 values (varying from 0.9429 to 0.9839) for the six, seven, and eight observed months. This fact is considered to be due to the influence of snow storage and melting processes distinctive of this basin. The Canales catchment river hydrograph shows a pluvio-nival pattern with two flow peaks. The first one was in January and February due to the surface water runoff from rainfall events. The second one was around April and May due to snow-melt water flows from the Sierra Nevada.

Table 12: Coefficient of determination (R^2) from the regression analysis.

Period	**Canales Reservoir (R^2)**				**Quéntar Reservoir (R^2)**			
No. Observed Months	y = ax + b		$y = cx^d$		y = ax + b		$y = cx^d$	
	P cum	A cum	P cum	A cum	P cum	A cum	P cum	A cum
3 (Oct–Dec)	0.7253	0.5939	0.6353	0.6314	0.3370	0.3801	0.4100	0.5442
4 (Oct–Jan)	0.8257	0.8098	0.7453	0.7836	0.4675	0.5772	0.5653	0.7594
5 (Oct–Feb)	0.9083	0.8664	0.8567	0.8449	0.6428	0.8069	0.6714	0.8909
6 (Oct–Mar)	0.9154	0.9429	0.8366	0.8872	0.7187	0.9190	0.7341	0.9483
7 (Oct–Apr)	0.8996	0.9658	0.8656	0.9374	0.6767	0.9567	0.6724	0.9710
8 (Oct–May)	0.8736	0.9839	0.8487	0.9714	0.6479	0.9844	0.6539	0.9894

Note: P cum: cumulative monthly precipitation. A cum: cumulative monthly streamflow.

Therefore, the Canales regression model follows the equation:

$$A_{annual} = a\, x_{cum.} + b, \qquad (10)$$

where A_{annual} is the annual streamflow (hm^3), $x_{cum.}$ is the cumulative monthly precipitation (for the first three, four, and five observed months in mm) and cumulative monthly streamflow (for the first six, seven, and eight months in hm^3), and a and b are the linear regression model coefficients.

Figure 25: Canales reservoir: Regression analysis for the first three, four, five, six, seven, and eight months using the cumulative monthly reservoir inflow and precipitation (linear model regression).

Figure 26: Quéntar reservoir: Regression analysis for the first three, four, five, six, seven, and eight months using the cumulative monthly reservoir inflow and precipitation (power model regression).

Table 12 shows that the regression model (linear with logarithmic transformation) is the best fit model for the Quéntar reservoir. It can be observed that the cumulative streamflow presents the best R^2 values (varying from 0.5442 to 0.9894) for all the months of study. The most important hydrological process given within the Quéntar catchment is due to the underground aquifer flows. The snow storage and melting processes are not relevant if compared with the Canales reservoir. Therefore, the base flow contribution into the total annual reservoir inflow is important. This might be the reason why the strongest correlation is found between the cumulative monthly streamflow and the annual streamflow.

Therefore, the Quéntar regression model follows the equation:

$$A_{annual}=c\ A_{cum.}{}^{d}, \tag{11}$$

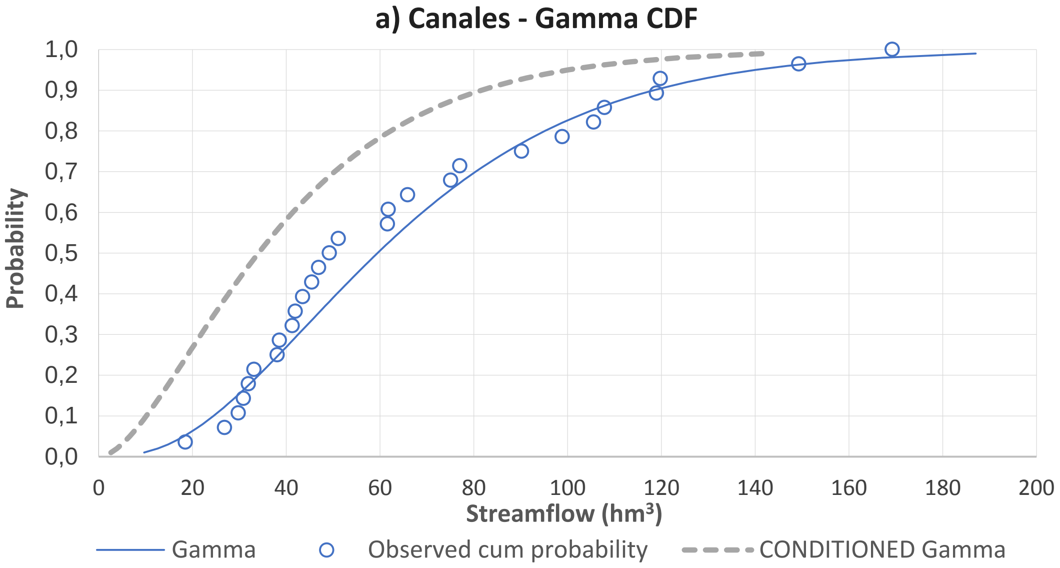
where A_{annual} is the annual streamflow (hm^3), A_{cum}. is the cumulative monthly streamflow (hm^3), and c and d are the regression model coefficients.

The estimated annual streamflow (‘A_{annual}’) can therefore be estimated from the obtained regression models for Canales and Quéntar reservoirs, which are based on complete hydrological years (from October to September, both inclusive) of observed precipitation and streamflow data. That is, the regression models should contain all the historical records up to September of the last year that is needed to be forecasted.

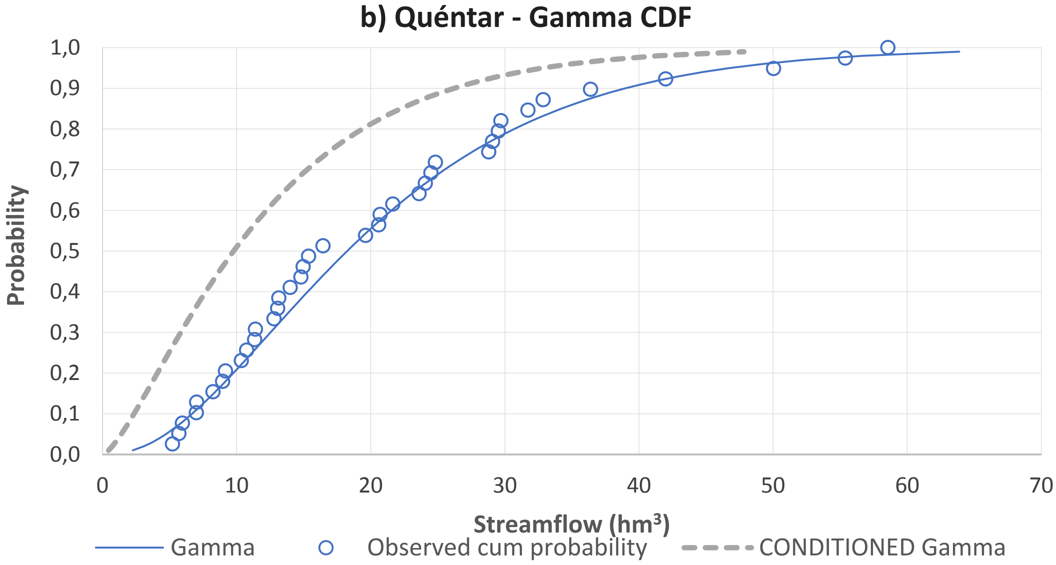
7.4.4 Two-Parameter Gamma Cumulative Probability Distribution Function (Observed Data) and Conditioned Gamma Cumulative Probability Distribution Function (Using the Output from the Regression Models)

Following the methodology described in **Sections 7.3.4** and **7.3.5**, we obtained two-parameter gamma CDF for each reservoir of study shown in **Figure 27**. It was found that the gamma distribution fits very well with rainfall in general [116] and particularly with the observed series of annual streamflows for the two reservoirs of study. We obtained a correlation coefficient (R) of 0.99 and 0.98 for Quéntar and Canales, respectively, between the observed annual streamflow series and those given by the distribution function.

It can be seen from **Figure 27** that the forecast given by the model in April 2017 for Canales and Quéntar was for a drier year than the mean historical hydrological year (since the conditioned gamma distribution was to the left side of the historical gamma CDF), which was what actually happened last year.



(**a**)



(**b**)

Figure 27: Two-parameter gamma CDF and conditioned gamma distribution—1st April 2017: (**a**) Canales reservoir (observed data Oct 1988–Sept 2016); and (**b**) Quéntar reservoir: (observed data Oct 1977–Sept 2016).

7.4.5 Assigning Probabilities and Application of Monte Carlo Method

As explained in **Section 7.3.6**, we obtained 10,000 random observed years (from the historical series) using the Monte Carlo simulation method.

From the statistical analysis, we obtained three forecasts: optimistic, average, and pessimistic. For our case study, we assigned the 90th percentile to the optimistic forecast and the 10th percentile to the pessimistic forecast, but the user can easily modify these values if needed.

Figure 28 shows, as an example, the April 2017 forecast output graph for the Quéntar reservoir model (six observed months and six forecast months). Lines in blue correspond to each observed year and the dotted red line to the historical average year. The orange line is the model average forecast output while the yellow dotted lines are the 90th and 10th percentiles forecasts (optimistic and pessimistic, respectively).

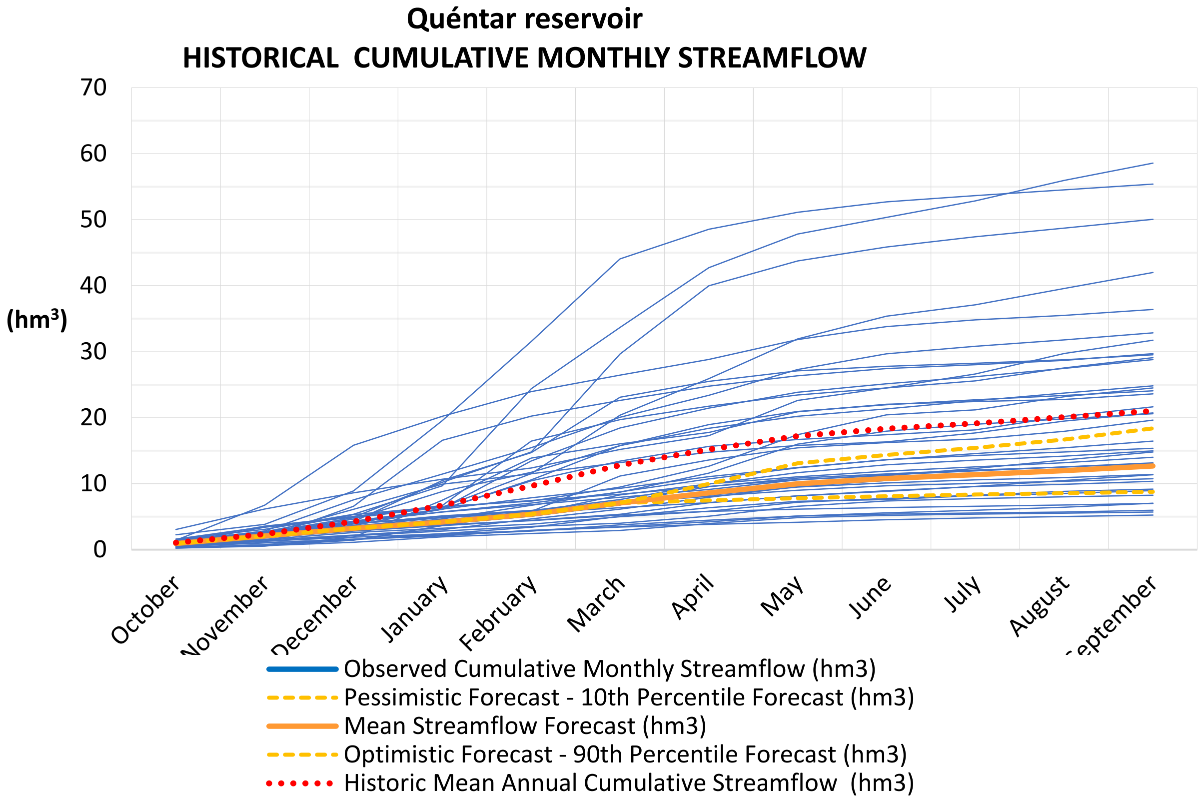


Figure 28: Example of typical model forecast outputs results compared with the historical observed streamflow data.

7.4.6 Model Validation

To verify the model performance and measure its predicting accuracy, the following metrics were applied [117]:

1. Coefficient of determination (R^2);
2. Root-mean-square error (RMSE);
3. Mean Absolute Error (MAE);
4. Index of Agreement (IOA);
5. Mean Absolute Percent Error (MAPE);
6. Coefficient of Nash-Sutcliffe efficiency (NSE); and
7. Inclusion Coefficient (IC) defined as the percentage of times that the observed streamflow falls within the 10th and 90th percentiles (our pessimistic and optimistic forecast values).

The results are listed in **Table 13** and **Table 14** for Canales and Quéntar, respectively. The performance indices presented in **Table 13** show that the model performs relatively better at forecasting annual rather than monthly streamflows. This highlights the difficulty of forecasting the monthly streamflow distribution along the hydrological year. This may be because the snow melt processes occurring in the Canales catchment area are more difficult to predict monthly (due to its variability).

The monthly forecast results achieved for the Canales reservoir (R^2 values vary from 0.53 to 0.83 and average of 0.69) are better than those found for the Quéntar reservoir (R^2 values vary from 0.23 to 0.51 and average of 0.41). The optimal results in our study are given for the Canales reservoir for the seven observed months that achieved the highest R^2 = 0.83 and lowest MAPE = 32.45.

The results also show that, generally, the model performs better as the number of observed months increases (the values of R^2, IOA, and NSE increase while the values of RMSE, MAE, and MAPE decrease). The higher values of error correspond to those observed hydrological years where hydrographs differ considerably from the mean historical observed year. Particularly, the worst MAPE value for the Canales and Quéntar reservoirs occurs in the driest years of 1994–1995 and 2004–2005.

To gain better insight into the model performance in relation to the lower and upper forecasts (i.e., 10th and 90th percentiles, respectively), the inclusion coefficient was calculated. An inclusion coefficient of approximately 80% for the monthly streamflow forecasts and higher than 80% for the annual forecasts was achieved. These results show that the 10 and 90 percentiles are representative values to support risk-based management decisions for these specific catchments.

Figure 29 and **Figure 30** present the observed and estimated monthly and yearly streamflow hydrographs (with six months of observed data) for the Canales and Quéntar reservoirs, respectively. The model predicted the entire historical set relatively well, with a tendency to slightly overestimate the flows. The error distribution suggests that the model is less likely to be more effective in forecasting hydrograph peaks (very dry or very wet years).

Myronidis et al. [78] developed ARIMA models to forecast the mean monthly streamflows for the next three months and for 10 different catchments in Cyprus, achieving moderate accuracy. The results achieved R^2 values varying from 0.10 to 0.63 (average of 0.37) and MAPE values varying from 25.02 to 1112.38. Myronidis et al. acknowledged similar results achieved by other authors also using ARIMA models. Their optimal results obtained in this study were found for catchment number 6, which achieved the highest R^2 = 0.63 and lowest MAPE = 25.02. If we compare the ARIMA model results with those achieved in this study (**Table 13** and **Table 14**), in average terms, our model performed similarly or even slightly better at providing results for a longer forecasted period (for up to nine months in advance), using a simpler methodology.

Given that the model has been developed to support management decisions associated with annual or quarterly cycles, we consider that the model presented in this paper is fit for its purpose and the results obtained are satisfactory.

Table 13: Canales reservoir: Performance test results.

		Canales Reservoir–Model Fit Statistics													
Forecast Period	**No. Observed Months**	**Monthly Series**							**Yearly Series**						
		R^2 (-)	**RMSE (hm^3)**	**MAE (hm^3)**	**IOA (-)**	**MAPE (%)**	**NSE (-)**	**IC (%)**	**R^2 (-)**	**RMSE (hm^3)**	**MAE (hm^3)**	**IOA (-)**	**MAPE (%)**	**NSE (-)**	**IC (%)**
Jan–Sept	3 (Oct–Dec)	0.53	3.75	2.26	0.83	46.72	0.53	79.01	0.70	21.56	14.82	0.89	25.32	0.69	85.19
Feb–Sept	4 (Oct–Jan)	0.59	3.51	2.08	0.86	42.46	0.59	82.87	0.82	16.69	11.53	0.94	19.83	0.82	88.89
Mar–Sept	5 (Oct–Feb)	0.64	3.37	1.91	0.88	37.34	0.64	83.07	0.88	13.87	9.21	0.96	15.42	0.87	88.89
Apr–Sept	6 (Oct–Mar)	0.75	2.69	1.63	0.92	34.18	0.75	82.72	0.95	9.26	6.74	0.98	13.23	0.94	88.89
May–Sept	7 (Oct–Apr)	0.83	2.16	1.36	0.95	32.45	0.83	81.48	0.98	6.67	5.40	0.99	10.25	0.97	88.89
Jun–Sept	8 (Oct–May)	0.79	2.01	1.19	0.93	34.24	0.79	81.48	0.99	5.08	4.08	1.00	7.49	0.98	88.89

Table 14: Quéntar reservoir: Performance test results.

		Quéntar Reservoir–Model Fit Statistics													
Forecast Period	**No. Observed Months**	**Monthly Series**							**Yearly Series**						
		R^2 (-)	**RMSE (hm^3)**	**MAE (hm^3)**	**IOA (-)**	**MAPE (%)**	**NSE (-)**	**IC (%)**	**R^2 (-)**	**RMSE (hm^3)**	**MAE (hm^3)**	**IOA (-)**	**MAPE (%)**	**NSE (-)**	**IC (%)**
Jan–Sept	3 (Oct–Dec)	0.23	1.95	1.09	0.63	69.17	0.20	82.75	0.39	10.72	7.60	0.75	39.23	0.37	84.21
Feb–Sept	4 (Oct–Jan)	0.33	1.82	0.99	0.72	62.28	0.28	78.62	0.59	8.82	5.82	0.87	27.84	0.57	86.84
Mar–Sept	5 (Oct–Feb)	0.50	1.39	0.76	0.83	53.61	0.45	79.32	0.81	6.03	4.04	0.95	18.52	0.80	89.47
Apr–Sept	6 (Oct–Mar)	0.51	0.93	0.55	0.85	46.26	0.53	78.95	0.92	3.85	2.55	0.98	11.19	0.92	84.21
May–Sept	7 (Oct–Apr)	0.48	0.71	0.46	0.88	45.21	0.62	78.95	0.96	2.78	1.73	0.99	8.03	0.96	84.21
Jun–Sept	8 (Oct–May)	0.41	0.52	0.36	0.93	44.45	0.75	77.63	0.98	1.72	1.19	1.00	5.77	0.98	81.58

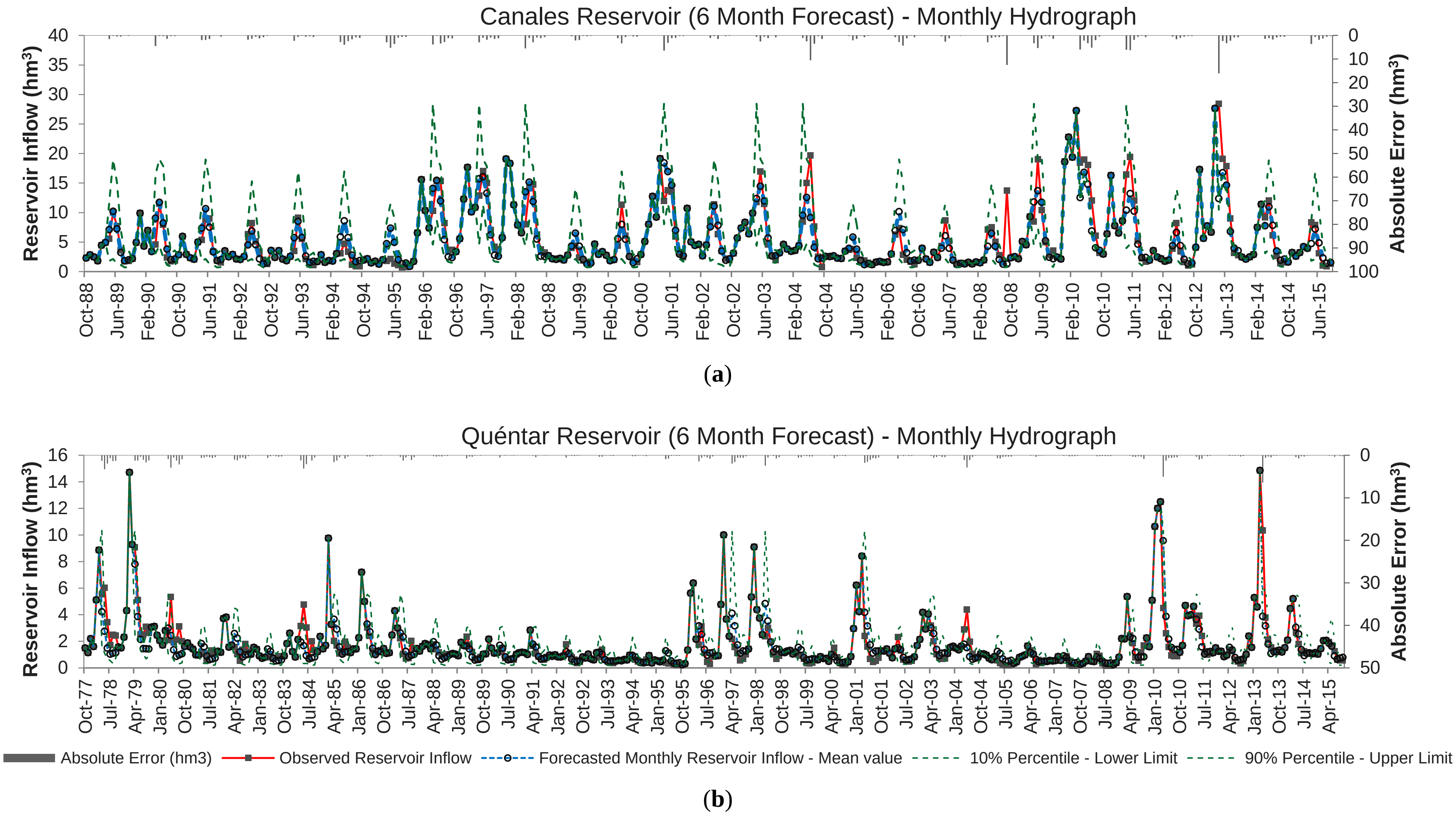


Figure 29: Observed monthly streamflows (hm^3) and predictions using the model with the first six months of observed data of the hydrological year and 10th and 90th percentiles (hm^3) of the (**a**) Canales reservoir and (**b**) Quéntar reservoir.

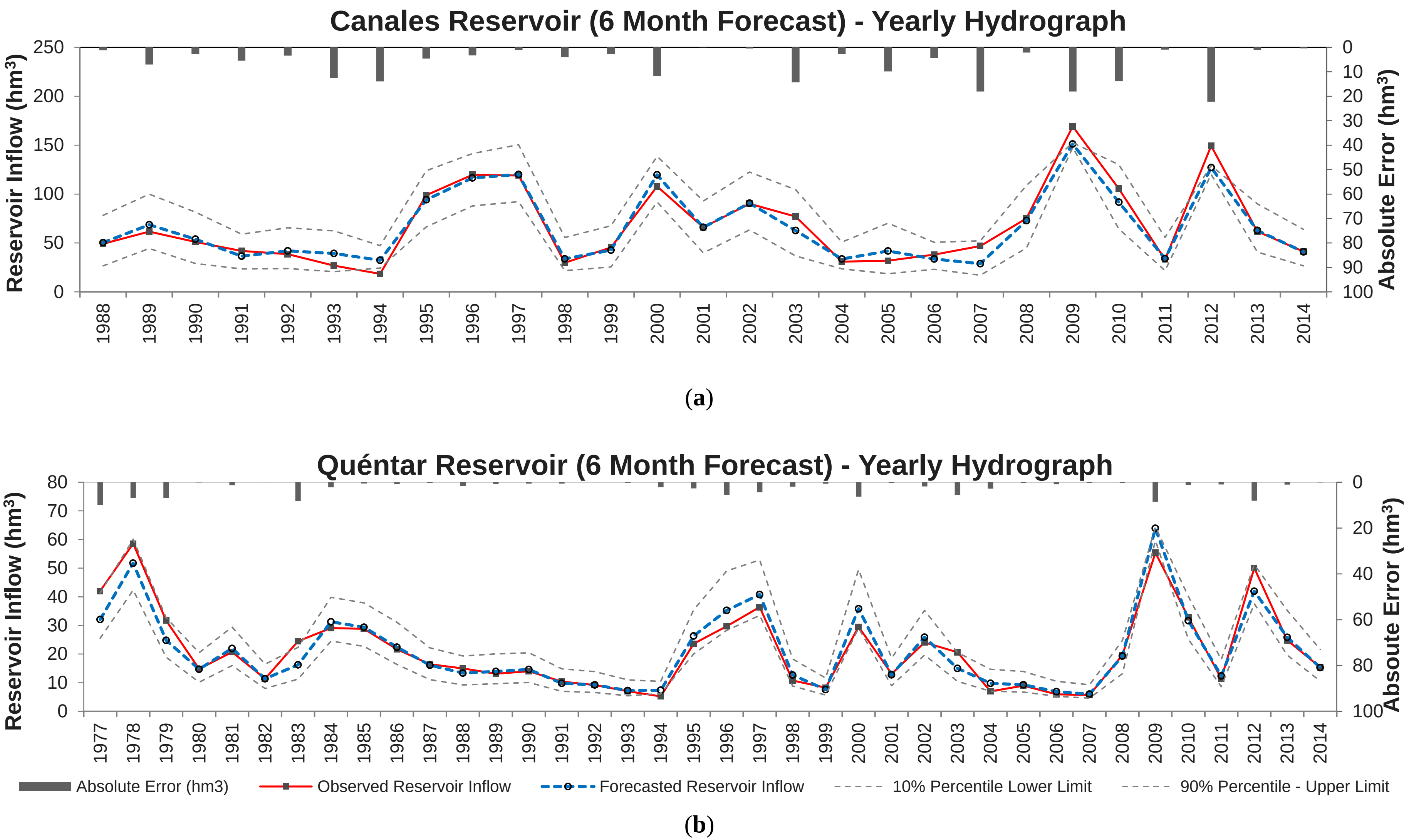
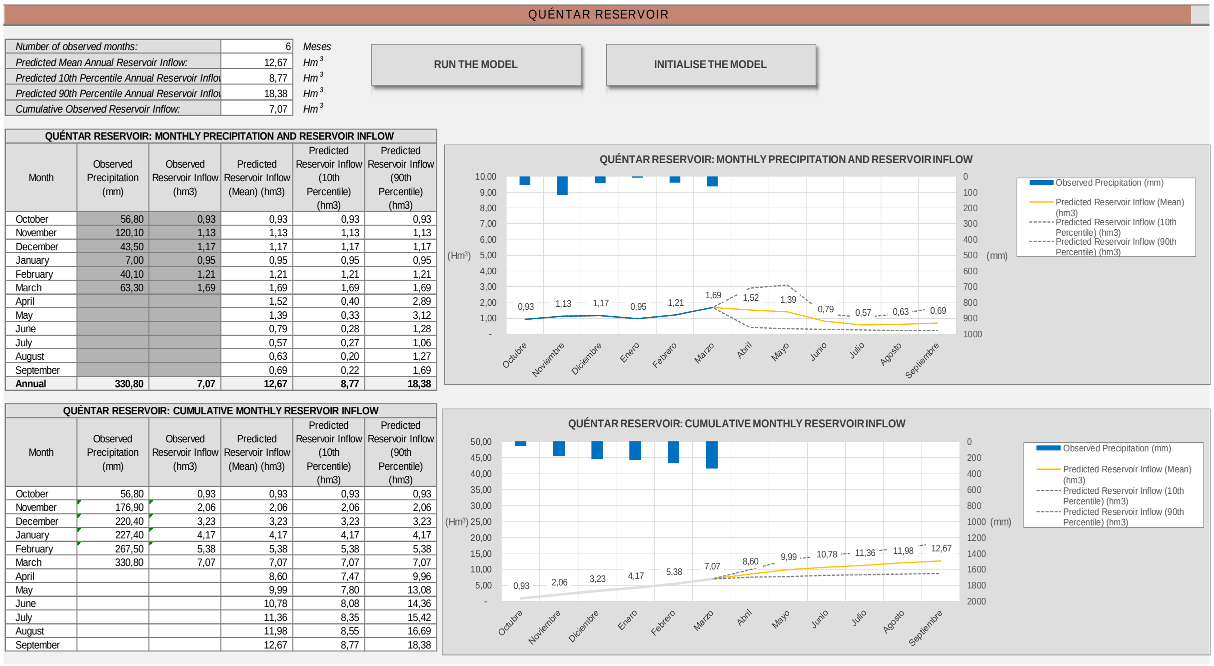


Figure 30: Observed annual streamflows (hm^3) and predictions using the model with the first six months of observed data of the hydrological year and 10th and 90th percentiles (hm^3) of the (**a**) Canales reservoir and (**b**) Quéntar reservoir.

7.4.7 Model Outputs

The proposed method can be implemented using mathematical programming software or simply using an Excel ® spreadsheet.

Figure 31 shows the user-friendly interface (taken from our model implemented in Excel). The user only needs to introduce the observed monthly rainfall and streamflow information in the dark grey columns and press the button called "*Run the model*". Almost instantly, the user can see the numerical results and associated graphs (on the right hand side of the screen) showing the probabilistic mean total annual streamflow and the monthly distribution as well as the optimistic and pessimistic forecasts.



Number of observed months:	6	*Meses*
Predicted Mean Annual Reservoir Inflow:	12,67	*Hm³*
Predicted 10th Percentile Annual Reservoir Inflo	8,77	*Hm³*
Predicted 90th Percentile Annual Reservoir Inflo	18,38	*Hm³*
Cumulative Observed Reservoir Inflow:	7,07	*Hm³*

QUÉNTAR RESERVOIR: MONTHLY PRECIPITATION AND RESERVOIR INFLOW

Month	Observed Precipitation (mm)	Observed Reservoir Inflow (hm3)	Predicted Reservoir Inflow (Mean) (hm3)	Predicted Reservoir Inflow (10th Percentile) (hm3)	Predicted Reservoir Inflow (90th Percentile) (hm3)
October	56,80	0,93	0,93	0,93	0,93
November	120,10	1,13	1,13	1,13	1,13
December	43,50	1,17	1,17	1,17	1,17
January	7,00	0,95	0,95	0,95	0,95
February	40,10	1,21	1,21	1,21	1,21
March	63,30	1,69	1,69	1,69	1,69
April			1,52	0,40	2,89
May			1,39	0,33	3,12
June			0,79	0,28	1,28
July			0,57	0,27	1,06
August			0,63	0,20	1,27
September			0,69	0,22	1,69
Annual	**330,80**	**7,07**	**12,67**	**8,77**	**18,38**

QUÉNTAR RESERVOIR: CUMULATIVE MONTHLY RESERVOIR INFLOW

Month	Observed Precipitation (mm)	Observed Reservoir Inflow (hm3)	Predicted Reservoir Inflow (Mean) (hm3)	Predicted Reservoir Inflow (10th Percentile) (hm3)	Predicted Reservoir Inflow (90th Percentile) (hm3)
October	56,80	0,93	0,93	0,93	0,93
November	176,90	2,06	2,06	2,06	2,06
December	220,40	3,23	3,23	3,23	3,23
January	227,40	4,17	4,17	4,17	4,17
February	267,50	5,38	5,38	5,38	5,38
March	330,80	7,07	7,07	7,07	7,07
April			8,60	7,47	9,96
May			9,99	7,80	13,08
June			10,78	8,08	14,36
July			11,36	8,35	15,42
August			11,98	8,55	16,69
September			12,67	8,77	18,38

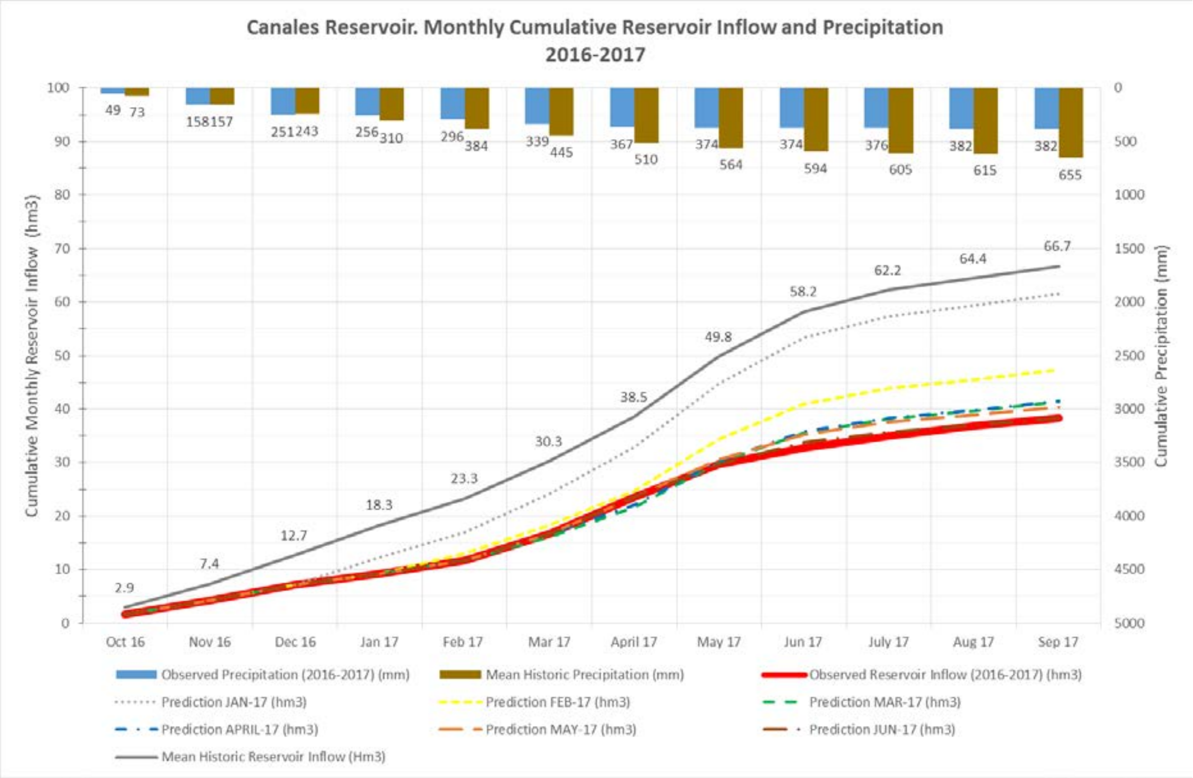
Figure 31: Example of typical model input requirements and outputs results.

Figure 28 shows the historical data set of observed years and the historical average monthly streamflow as well as the prediction. This graph helps the user to quickly see how far the current hydrological year is from the mean historical hydrological year as well as similar historical observed years.

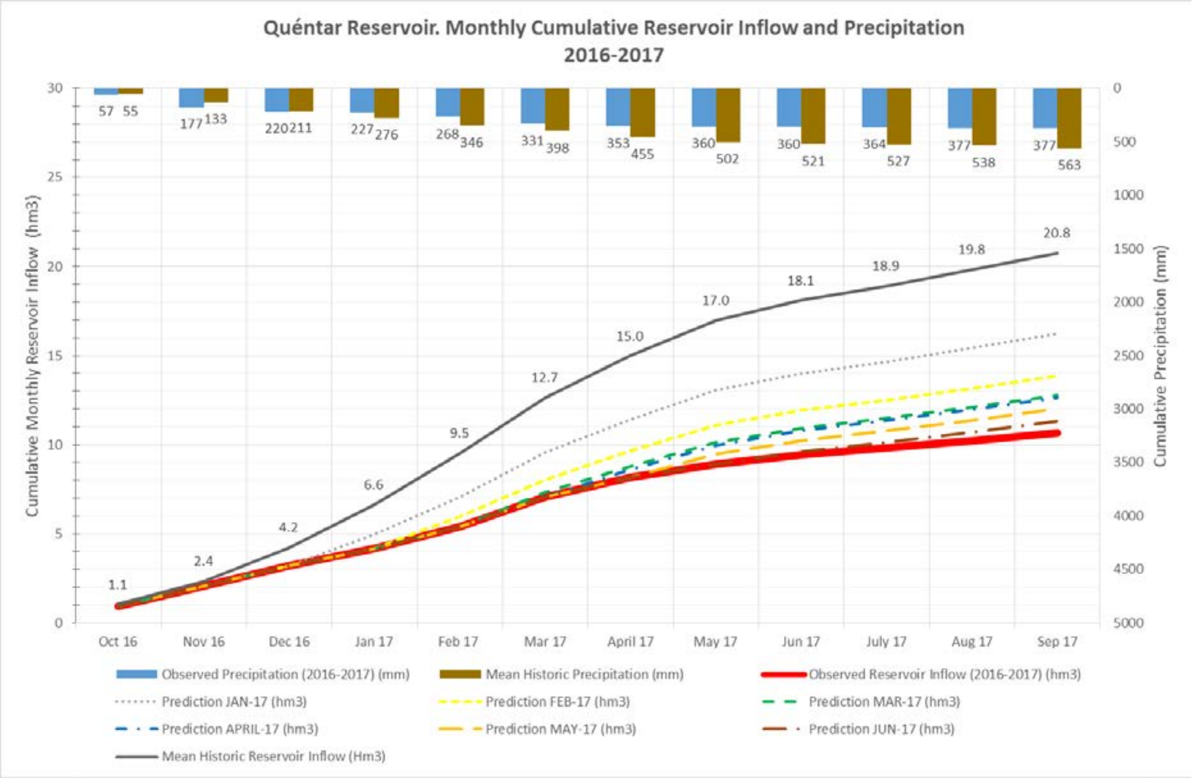
7.4.8 First Operational Year 2016–2017: Results

The model was first put into operation in October 2016. **Figure 32** presents a comparative analysis of the annual and monthly streamflow forecasts with the observed values.

It can be observed that the 2016–2017 hydrological year was predicted to be drier than the historical average year and all predictions were between the average year shown in dark grey and the observed values shown in red. It can also be appreciated that the prediction given in January was below, but closer, to the average historical year, whilst as the number of observed months increased, the predictions were getting closer to the observed data.



(a)



(b)

Figure 32: Predictions of annual and monthly cumulative streamflow (hm^3) and observed annual and monthly cumulative streamflow (hm^3) of the (**a**) Canales reservoir and (**b**) Quéntar reservoir.

It was observed for the Canales reservoir that the accuracy of the prediction output achieved in March 2017 (for the 2016/2017 total annual streamflow) was very good at approximately 92%. The forecast annual streamflow value was 41.52 hm^3 whilst the observed value was 38.34 hm^3 (compared with the observed historical mean annual streamflow of 66.71 hm^3). Logically, the prediction results improved as the number of observed months increased.

For the Quéntar reservoir, the accuracy of the prediction given in March 2017 (for the 2016/2017 total annual streamflow) was slightly lower than the Canales reservoir, thus, achieving an accuracy of 80%, which is good. The total annual streamflow forecast was 12.65 hm^3 whilst the observed value was 10.68 hm^3 (compared with the observed historical mean annual streamflow of 21 hm^3).

We investigated in more detail whether the Quéntar model could be improved. A more detailed evaluation of the behaviour and influence of the interannual underground flow in the total annual contribution to the reservoir was carried out. It was found that there is a relatively small correlation between the annual streamflow and with the previous years. It was also examined whether when applying the Monte Carlo simulation, the median value might provide better forecasts than using the mean value. Even though for the hydrological year of 2016–2017, the median provided better forecast results, when assessing the complete historical data set, the mean value provided more accurate forecast results. For this particular sub-basin, we also concluded that the minimum number of observed years (to minimise the error) should be 40 years.

The model allows for the inclusion of seasonal predictions, for example, those provided by the AEMET in Spain. The seasonal probability prediction values estimated for the next quarter of the current year assigned to each tertile (wet, normal, and dry) are applied to the model outputs by multiplying them with seasonal predictions (upper, central, and lower estimations). Equally, the model allows the integration of climate change effects by scoring and weighing recent years of the historical data.

7.5 Conclusions and Future Research Directions

In Mediterranean countries, risk-based streamflows forecasts are critical, especially, before the intensive irrigation campaign starts (usually in April). During this time, water authorities must make responsible management decisions on the best allocation of the available water volume between different water users and environmental needs.

This research contributes towards the development of a user-guided, simple, low cost, and robust procedure for forecasting monthly and annual streamflows during the current hydrological year.

The methodology is innovative because of its combination of well-known techniques and its ability to achieve satisfactory and reliable results. Firstly, regression analysis techniques were applied to obtain the relationship between the total annual streamflow and the cumulative monthly rainfall and monthly streamflow. Secondly, the historical streamflow data sets were fitted to a two-parameter gamma continuous and cumulative probability distribution function. The estimated total annual streamflow output obtained from the regression analysis was made to be equal to the mean value of a new distribution, named the conditioned two-parameter gamma cumulative probability distribution function. This new distribution allowed the allocation of the probability for each year of the historical data set based on the estimated annual streamflow (from the regression analysis) and the gamma distribution (previously fitted to the historical data set). Finally, the Monte Carlo simulation was applied to obtain 10,000 simulations. The model outputs were the probabilistic mean annual and monthly streamflows along with the 10th and 90th percentiles (which can be easily modified by the user if needed). This allows decision-makers to adopt a water resource management risk-based approach, which can be adjusted to their own needs.

The method was successfully applied to two headwater reservoirs located at the upper area of the Genil River (GRB), namely, the Quéntar and Canales. Several metrics (including MAE, MAPE, IOA, RMSE, R^2, and NSE) were used during the validation process, which showed good levels of accuracy and increased with the number of months observed. The model was first put into operation during the last hydrological year (2016–2017), obtaining accuracy levels of 92% and 80% respectively, for Canales and Quéntar, for the annual streamflow forecast given in March 2017.

The regression analysis shows that the best descriptor for forecasting the total annual streamflow for the Quéntar reservoir was the cumulative monthly streamflow (due to the influence of the subterranean flows). For the Canales reservoir, the cumulative precipitation was the best predictor for the first three, four, and five months observed whilst the cumulative streamflow was the best predictor for the six, seven, and eight months observed (due to the influence of the snow melting processes). It is important to highlight that the best fit regression model and best fit predictor may vary depending on the predominant hydrological process at each specific basin and season of the year. In this situation, a combined regression model should be used to achieve the best correlation and predictive results.

The key advantages of this procedure are: (i) the use of relatively simple algorithms and well-known techniques, which can be easily implemented in an excel spreadsheet; (ii) the use of a minimum number of hydrological variables (streamflow and precipitation); (iii) the model saves substantial computational time (the model takes just a few seconds to run the simulations); (iv) the model does not depend on other software to achieve the results; (v) the model offers an intuitive user interface, which can be easily used by anyone; and (vi) the results achieved are similar or slightly better than those achieved with other more complex models.

The method also has some limitations: (i) it is applicable to headwater systems; (ii) if there are new rapid and significant land use changes within the catchment of study (not reflected in the historical data sets), the model might not capture these changes and may generate misleading streamflow forecasts; and (iii) whilst there is no limitation in catchment size, catchments with considerable climatic irregularity or very rare seasonal sporadic rainfall are difficult to predict and should be carefully studied.

To obtain the best results, this methodology should be applied when there is good quality input data and, at least, 30 years of observed data (although 40 years would be desirable to increase the forecast accuracy). The minimum number of observed years should be greater in those catchments with a greater standard deviation. The performance of the model can be further improved (and reduce prediction errors) by increasing the number of observed years.

The model results were compared with the most recent ARIMA model results (shown in Myronidis et al. [78] and similar works cited by the same author). It was found relevant that in average terms, the model performed similarly or even slightly better at providing results for even a longer forecasted period (for up to nine months in advance), using a much simpler methodology.

Current and future research is in line with the full integration of seasonal climate predictions as well as the effects of climate change. Equally, we are working towards the integration of this model with other types of hydrological models (conceptual or distributed models) to check whether the accuracy could be further improved.

We conclude that the proposed methodology to forecast streamflows presented in this paper, although simple and of low cost, provides satisfactory, consistent, and robust results with a relatively small error margin. The outputs of this model can help with the early detection of droughts and periods of water scarcity, and support strategic water management decisions. This can improve resource and cost efficiency when deciding on optimum water allocation.

8. ARTICLE V

8. ARTICLE V: CROSS-SUBSIDIES BETWEEN WATER USERS IN SPAIN: THE GUADALQUIVIR RIVER BASIN CASE

The following article is currently under the review process of *Water Resources Management* (Q1 in Water Resources). Latest status (February 2020): One reviewer has provided comments ("*I find the study very interesting and I think it meets all the requirements for publication. Congratulations to the authors*."). The journal is waiting responses from others reviewers.

- *"Cross-subsidies between water users in Spain: The Guadalquivir River Basin Case."*

8.1 Abstract

The last 2015 European Commission report [56] highlighted that in Spain: "*there is a lack of adequate incentives for efficient use of the resource and the adequate contribution to the recovery from different users is not guaranteed*" and recommended to *"present transparently subsidies and cross-subsidies"*. This paper presents a hydro-economic methodological approach to provide transparency in the water cost recovery calculations. This can also help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users of a particular system. The chosen case study is the Upper Genil River (Guadalquivir River Basin) in southern Spain. This case presents an interesting context given its particular complexity of mix water uses that can be served from different water sources, combined with their historical water rights and priority of water use conflicts, especially during drought and water scarcity situations. The simulation results showed that the household user pays an additional average annual cost of approximately € 6,863 per cubic hectometre[2] of water consumed for having the theoretical priority of water use over the agricultural water user. However, the simulation results also show that if both water users would have the same priority of water use, the current water demands of the system would have been met in practically all months of the entire simulated 30-year period (with only a

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[2] The SI unit of volume is the cubic meter (m^3). In this article, the *cubic hectometre* unit (hm^3) has been used. This is, $1hm^3 = 10^6m^3$.

negligible water deficit in the driest year of the simulated series, i.e. in 1995). This means that despite the extra annual cost paid by the household user (recovery of financial water service costs), in practice, the priority of water use would only be patent in very extreme drought events (approximately 200-year return period) and when all the water resources of the system have been completely exhausted. It is therefore recommended to provide a transparent cost-benefit analysis when water authorities decide on the extra cost to be paid by a specific water user of a particular water system.

Keywords Recovery of the raw-water service cost; Cross-subsidies; Upper Genil River; Guadalquivir River Basin; Article 9 Water Framework Directive.

8.2 Introduction

One of the most revolutionary and interesting legal requirements introduced by the European Water Framework Directive (WFD) in December 2000 (Directive 2000/60/EC) was the use of economic principles and instruments to achieve the environmental objectives. In fact, there is not any other natural resource legislation at the EU level which integrates resource management, environmental and economic principles [118]. Those economic principles and instruments were established in Article 9 (recovery of costs for water services), Article 5 and Annex III (economic analysis of water use) of the WFD.

Particularly, Article 9 states that: *"Member States shall take account of the principle of recovery of the costs of water services, including environmental and resource costs, having regard to the economic analysis conducted according to Annex III, and in accordance in particular with the polluter pays principle"*. Member States are required to achieve this through incentive water pricing instruments and an adequate contribution of the different water uses (industry, households and agriculture) to the recovery of the costs of water services. The goal of the 'polluter pays' principle established by the WFD is to estimate costs proportionally to the damage created by each water user to the water resource and the environment.

In other words, the WFD tries to promote water pricing policies that consider not only the financial costs of providing the water service itself but also the integration of the environmental and resource costs. In doing so, adequate incentives to water users can be encouraged to promote an efficient and sustainable use of the water resource.

In order to help with the practical implementation of the economic principles set out in the WFD, a specific working group named WATECO (for WATer and ECOnomics) was formed by economists, technical experts and stakeholders from EU Member States. They developed the Common Implementation Strategy Guidance document no. 1 "*Economics and the Environment*" [119]. This is a non-legally binding and practical guidance which provides an overall methodological approach to deal with the implementation of the WFD economic elements in the broader context of integrated River Basin Management Plans (RBMPs). Whilst the concept of financial costs is generally familiar to Member States, it is not the same case for the environmental and resource costs. The definitions of the environmental and resource costs are complex and not very concise in the CIS document, let alone the assessment methodologies.

After the WATECO publication in 2003, extensive research work has been undertaken by many authors and organisations to: i) understand the definition and implications of the environmental and resource costs in line with the requirements of the WFD, and ii) establish methodologies which can help to reasonably estimate these costs ([120], [121], [122], [123],[124], [125], [126], [127], [128], [129], [130]).

Despite the substantial efforts made by the EU, policy-makers, experts and the academic world, almost twenty years after the entry into force of the WFD, there is not yet a common definition or methodology to integrate the resource and environmental costs in the cost-recovery calculations at the European level. However, the economic, social and environmental consequences of inefficient or unsustainable water pricing policies are of critical importance, especially in drought-prone and water-scarce regions such as the Mediterranean countries.

Spain is a very good example of a Mediterranean country with recurrent drought events and water scarcity episodes. This is probably the reason why there is a long track record in water legislation, hydrological planning and cost-recovery practices. However, there are still some notable deficiencies in terms of integrating a common economic approach to support the water resource, planning and management decision processes. Proof of that is the absence of a common water pricing policy and cost-recovery evaluation methods across the different river basins in Spain.

In fact, a significant obstacle to achieving an efficient and sustainable use of water resources in Spain is the lack of transparency in water-cost recovery calculations as highlighted in the fourth European Commission report in 2015 [56]: *“there is a lack of adequate incentives for efficient use of the resource and the adequate contribution to the recovery from different users is not guaranteed”* and recommended to *“present transparently subsidies and cross subsidies”*.

Far from being an isolated problem in Spain, this seems to be a widespread issue across Europe, especially in relation to irrigated land as stated by Berbel et al. (2007) [118]: *”the charges for irrigation in the EU countries, as in most other countries, have been inadequate to recover capital and operating costs. Other levels of recovery have been introduced largely in regard to the issue of allocating the water between competing uses, in particular, between human and environmental uses”* and *“irrigators have been, and still are, heavily subsidized”*.

In Spain, the raw-water cost recovery instruments for groundwater (GW) or surface water (SW) infrastructures publically built by the State (such as large dams, reservoirs, etc.) are set out in the Spanish Water Law, the Recast Text of the Water Act (TRLA, Royal Legislative Decree 1/2001, of 20 July) and the Regulation of the Hydraulic Public Domain (RDPH, Royal Decree 849/1986, of 11 April).

It is important to highlight that the Spanish Water Legislation refers to the recovery of the financial water service costs only (i.e., investment, capital, operation and maintenance costs). This is, the environmental and resource costs (required by the WFD) are not considered in the Spanish Legislation.

This research contributes towards the development of an overall hydro-economic methodological approach to provide transparency in the water cost recovery calculations. This can also help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users of a particular system. The methodology could be applied to other similar river basins, but it should be tailored to their site-specific circumstances. The learnings could be applied during the current consultation and development of the 3rd cycle RBMPs across EU to improve transparency in the economic assessments.

The chosen case study is the Upper Genil River, a sub-basin of the Guadalquivir River Basin (GRB) in southern Spain. This case presents an interesting context given its particular complexity of mix water uses that can be served from different water sources, combined with their historical water rights and priority of water use conflicts, especially during drought events and water scarcity episodes.

In fact, it is significantly notorious that, still today, litigation continues in this particular water system among the key players (i.e., the Guadalquivir River Basin Authority, the Local Water and Sewage Company and one of main the irrigation communities) after the devastating environmental, social and economic consequences of the 1991-1995 drought period. The problem aroused when the GRBA instructed in 1994 (almost at the end of that intense drought period) that all available SW volume stored in Canales and Quéntar reservoirs was to serve the household water demand of Granada city (given its priority of water use). This decision logically caused losses and economic damage to the agricultural sector of this area, which also had historical water rights for the use of the SW resources. The root cause of the issue was precisely the misunderstanding in terms of the priority of water use during droughts, the historical water rights and the economic contribution to the cost-recovery from each water user. **Annex A** describes this conflict during the 1994 drought event in this sub-basin.

The aim of this paper is therefore to assess if there is a cross-subside among the main competing water users of the Upper Genil River. This is, if some users pay part of the cost attributable to other water users, justifying it as a theoretical greater guarantee of water supply during drought events and water scarcity periods (without being accompanied by a transparent cost-benefit analysis). To shed light on this question, the economic contribution to the recovery of the raw-water service costs from each water user has been evaluated. Hence, this detailed analysis and insight at site-specific scale can help drawing conclusions applicable to other regions in Spain, other Mediterranean countries and the rest of the EU territory.

Section 8.3 outlines the Spanish water cost recovery system. **Section 8.4** details the methodology applied. **Section 8.5** describes the particular case of the Upper Genil River sub-basin, results and discussion. **Section 8.6** presents the main conclusions and recommendations.

8.3 Spanish water cost recovery system

The cost recovery instruments for groundwater (GW) or surface water (SW) infrastructures publically built by the State (such as large dams, reservoirs, etc.) are set out in the Spanish Water Law, the Recast Text of the Water Act (TRLA, Royal Legislative Decree 1/2001, of 20 July) and the Regulation of the Hydraulic Public Domain (RDPH, Royal Decree 849/1986, of 11 April).

There are two different type of levies applied to the use of water infrastructures works. The first one, known as "*Canon of Regulation*" (CR), is related to SW or GW resources regulation infrastructures. The second one, known as "*Water Use Tariff*" (WUT), is related to the use of the rest of water infrastructures such as channels, canals, etc.

According to art.114.1 of TRLA and art. 296.1 of RDPH: "*the beneficiaries of the surface water or groundwater regulation infrastructures that are totally or partially funded by the State, will pay a fee known as "Canon of Regulation" (CR or regulation levy) to contribute towards the investment, capital, operation and maintenance costs supported by the State*".

According to art.114.2 of TRLA and art. 296.2 of RDPH: "*the beneficiaries of other specific hydraulic infrastructures that are totally or partially funded by the State, including the corrective actions due to the deterioration of the hydraulic public domain, derived from its use, will pay a fee known as "Water Use Tariff" to contribute towards the investment, capital, operation and maintenance costs supported by the State*".

For the purposes of this assessment, the calculation of the WUT has been excluded because it has no relation to water resources availability. We focus on the calculation of the CR cost as this is the most significant element associated with the use of regulation water infrastructures.

In any case, it is important to highlight that the Spanish Water Legislation refers to the recovery of the financial water service costs only (i.e., investment, capital, operation and maintenance costs). However, it does not contemplate the environmental and resource costs as required by the WFD.

The CR is calculated annually by each River Basin Authority (RBA) in Spain for each River Basin District (RBD). The CR for the next year (year n+1) is estimated during the current year (year n) based on the real costs incurred during the previous year (year n-1).

The water cost recovery calculations associated with the CR consist of the following elements:

1. Volumetric balance: the total volume of water provided to each water user is quantified (based on the controlled released outflows from the reservoirs);
2. Economic valuation: the total financial costs associated with regulated water from SW reservoirs (before entering in the Potable Water Treatment Plant) are calculated. These costs are composed by three elements:

   a) operation, exploitation and maintenance costs;
   b) administrative costs incurred by the RBA, attributable to the corresponding infrastructures;
   c) 4% of the value of the investments made by the State taking into account the technical amortization period (50 years).

3. Distribution among water users: the TRLA establishes that: *“the distribution of the total Canon of Regulation amount among all the beneficiaries of the infrastructures* –dams, reservoirs, etc.- *will be carried out according to rationalization criteria in terms of water use, equity in the distribution of obligations and self-financing of the service”*.

It is important to note that the costs associated to the environmental services provided by the dams in terms of guaranteeing the provision of environmental flows (water restriction) as well as the flood flow control function are not recovered. These services are considered of general public interest and therefore, these are not attributable to water users of the particular water system but the State. The percentage of costs assumed to provide the public service of flood control by each RBA is different and may vary from 20% (for the majority of dams in Spain) to 70% of some special Mediterranean cases [120]. This shows that currently in Spain the concept of full water cost recovery is not be possible.

On the other hand, when water is abstracted directly from the environment (from unregulated rivers, springs, GW abstractions, etc.) without making use of publicly built infrastructure by the State, the water users are responsible for all the pumping, transport, maintenance and exploitation costs.

8.4 Materials and Methods

Figure 33 shows the flowchart of this methodology (described in detail in the following sections and applied to the Upper Genil River Case of Study detailed in **Section 8.5**).

The proposed methodology is to assess the economic contribution of the main competing water users to the financial cost recovery of water services. The resource, environmental and social costs have been excluded from this study (as these are not currently considered in the Spanish Water Legislation).

This study considers the financial costs corresponding to the ‘*raw or untreated*’ water. This is, the water service costs associated with the water infrastructures located upstream of the Potable Water Treatment Plant (i.e., abstraction, storage and transport up to the Potable Water Treatment Plant). The costs associated with the potable water treatment, distribution network and wastewater have been scoped out from this study (since these are directly managed by the Local Water Supply and Sewage Company in Spain, with no involvement from the RBA).

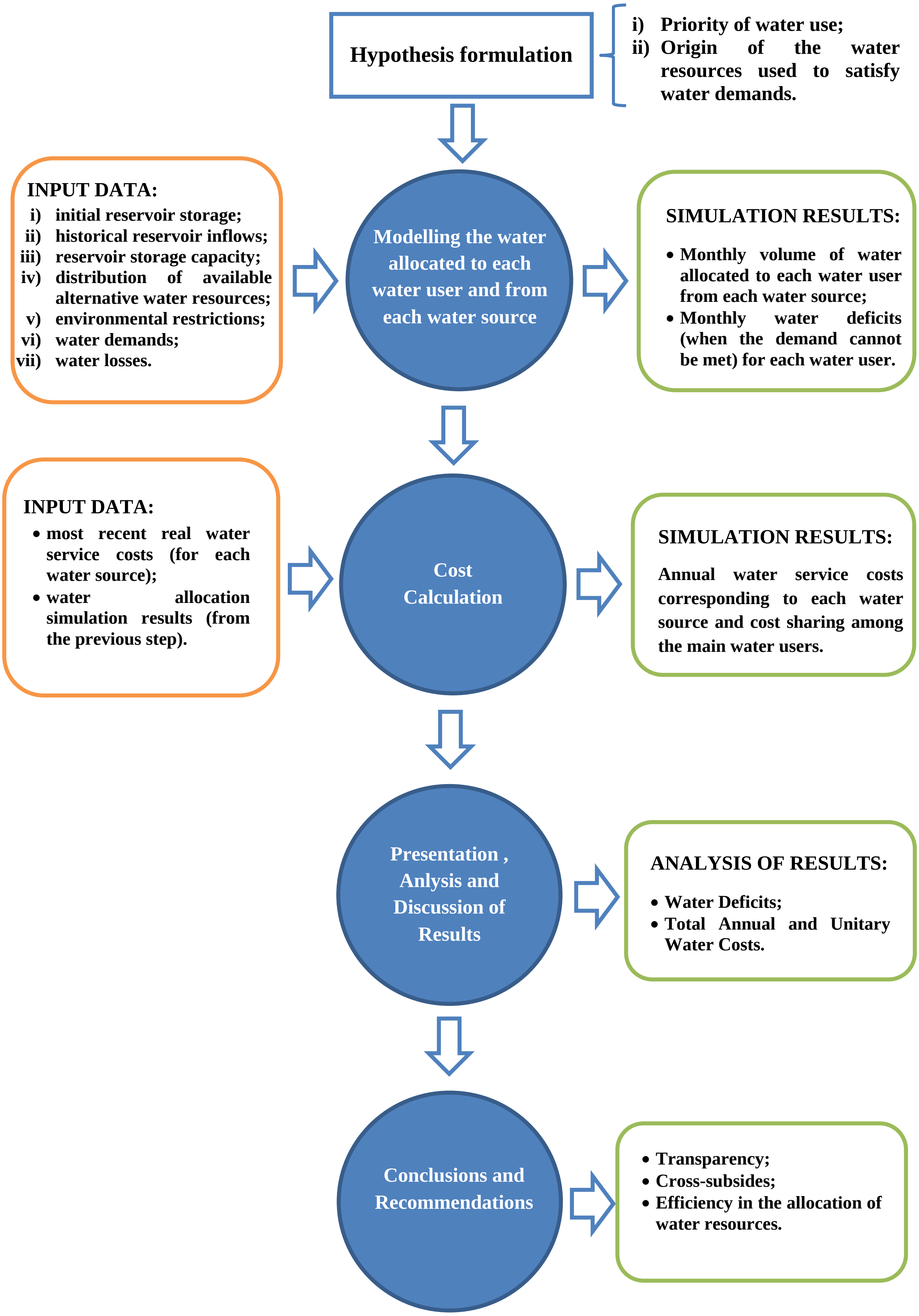


Figure 33: Flowchart of the methodology.

Particularly, the aim of this paper is to assess if there is a cross-subside among the main competing water users (i.e., households and irrigators) of the Upper Genil River. This Case of Study provides an interesting context given its particular complexity of mix water users (mainly, agriculture and urban water supply), a multi-source supply system (mainly, surface water and groundwater) combined with the historical water rights conflict among the main water users (especially during drought and water scarcity periods).

The methodology proposes an integrated evaluation of the water allocation and the operating water system (in terms of available water resources and order of use, infrastructures and operating rules, water demands and water restrictions, priority of water use, etc.), the financial water service costs (in particular, those associated to the regulated SW volume from the existing Canales and Quéntar reservoirs and the GW volume from the strategic GW wells) and cost sharing among the water users in accordance to the Guadalquivir River Basin Authority (GRBA) methodology.

8.4.1 Description

The methodology consists of three main phases (as shown in **Figure 33** and detailed below): i) modelling the water allocated to each water user based on the historical monthly streamflow data series, ii) calculation of the total annual SW and GW costs, iii) analysis of results and discussion, conclusions and recommendations. From the results, the potential existence of cross-subsidies among the water users will be analysed.

For the particular Case of Study, the main competing water users are the urban water supply demand (UWSD) and irrigation water demand (IWD).

8.4.1.1 Modelling the water allocated to each water user based on the historical monthly streamflow data series.

- Input data – Collection and preparation

  The input data requirements are: i) the initial reservoir storage volume, ii) the historical monthly headwater reservoir inflows, iii) the maximum reservoir storage capacity for each month of the year (which will vary depending on the flood control protection arrangements) and the minimum reservoir storage volume (or dead storage); iv) the distribution of available alternative water resources (e.g. GW wells, springs, water re-use, desalination, etc.); v) the environmental restrictions set out for each specific water system (e-flows); vi) the water demand patterns of the main competing water users, and vii) losses (evaporation, filtration, etc.).

  In Spain, most of this information can usually be found in the corresponding RBMPs. The site-specific input data used to inform this study is described in **Annex B**.

  A monthly time step for the simulation results has been considered adequate for this work, in line with the GRBA methodology.

- Model Simulation Process and Outcomes

AquaSpread modelling software (developed by the University of Granada) has been used. This performs a volumetric balance on a monthly basis based on the inflows, the reservoir storage volume variation, and the water outputs (water demands, environmental restrictions or e-flows, water losses and controlled released flood flows where required). It also takes into account the available alternative water resources in the specific water exploitation system and specific order of use (if any).

The model has been set out to satisfy the ecological flows of the system before trying to meet the water demands (i.e. e-flows are considered as a water restriction) in all drought circumstances (including prolonged drought). Then, the model takes into account the priority of water use assigned to each water user of the system, as well as the preference order of the available water sources to serve each water demand.

The main outcomes from this modelling exercise are: (i) the monthly volume of water allocated to each water user from each available water source and (ii) the monthly water deficits (when the demand cannot be met) for each water user.

8.4.1.2 Cost Calculation

- Calculation of the total annual SW costs

The total annual SW service costs are related to the costs of investment or capital, exploitation, operation, maintenance and administration of SW storage infrastructures (reservoirs). These annual total costs are distributed among all the water users who benefit directly from using those. This charge is known as 'Canon of Regulation' (CR), described in **Section 8.3**.

The cost contribution percentage of each water user towards the recovery of the total annual SW service costs is calculated by each RBA in accordance with the Spanish Water Law. For this particular case of study, the cost distribution among the water users has been calculated according to the GRBA methodology.

The final cost contribution percentage of each water user depends on: i) the monthly regulated SW volume provided to each water user (in relation to the volume that could have been captured directly from the rivers without the existence of the reservoirs according to their water user right); ii) the priority of water use assigned to each water user.

For the particular case of study (Upper Genil River) and in accordance with the GRBA method, a 3 to 1 increase in the contribution costs is applied to the regulated SW volume of water (from Canales and Quéntar reservoirs) consumed by the priority water user, in this case, the UWSD. This weighting system is applied to the UWSD to theoretically guarantee the water supply for the present year and the next two years. As an example, **Annex C** shows the CR calculations for 2017.

However, this cost distribution is not equitable between the different water users neither does it depends on the total volumetric consumption of the water resource.

The total raw-water service costs are shared among the water users proportionally to the "*improvement percentage or coefficient*". The monthly "*improved SW volume*" is calculated as the difference between the monthly volume of water provided to a water user from Canales-Quéntar reservoirs and the monthly volume of water that could have been captured directly from the rivers (without the reservoirs in place) according to the water user right.

The "*improvement percentage or coefficient*" is then calculated for each water user as the total annual "*improved SW volume*" divided by the total annual SW volume supplied from the reservoirs.

Then, the 3 to 1 increase in the contribution costs is applied to the volume of SW consumed by the urban water supply (i.e. volume of water coming from Canales and Quéntar reservoirs) because of its priority of water use.

- <u>Calculation of the total annual GW costs</u>

For the particular case of study, the network of strategic GW wells were built by the GRBA and delivered to the Local Water and Sewage Company (Emasagra) who is responsible for their correct operation, management and running costs.

The objective of these GW works was to supplement the existing regulated SW resources to serve the UWSD of Granada and its metropolitan area (when needed). Therefore, GW costs are only applicable to the UWSD.

The GW cost curves provided by Emasagra have been used to calculate the operation, exploitation and maintenance costs. The annual GW costs depend not only on the monthly GW volume abstracted, but also on a fixed monthly cost (due to the contracted power, maintenance, etc.), which have been included in the cost calculations.

8.5 Application to the Upper Genil River sub-basin (Guadalquivir River Basin)

8.5.1 Study Area Description

The Guadalquivir is the main river in southern Spain that provides water to a total population of over four million people and over eight hundred thousand hectares (ha) for irrigation purposes. This system is currently formed by an interconnected system of 64 functioning large dams [69]. Although there are alternative water resources from aquifers, springs, and water re-use schemes, nowadays, reservoirs represent the essential infrastructure to efficiently deal with spatial and temporal climate irregularities distinctive of this catchment area [65]. **Figure 34** shows the location of the GRB in southern Spain and Granada area (as the particular area of study).

The GRB periodically suffers the consequences from drought events and water scarcity episodes. There is also a fierce competition among the main water competing users for this scarce water resource in this basin.

The 1991-1995 drought event created the greatest impact in the GRB. This event was identified with an approximate 200-year return period and 5-year duration [70]. This resulted in important water scarcity problems and significant economic, social and environmental consequences (very low river flows, groundwater levels and reservoir storage volume, harvest losses, severe water restrictions to all water users, disruptions to services, contamination issues, drinking water deterioration, etc.).

The scarce regulated SW resources available in 1995 were destined to serve households along with the application of severe water demand reduction measures (temporary use bands, pressure reduction, rota cuts for up to 10 hours per day in important cities such as Sevilla, prohibiting the use of water for activities such as watering outdoor plants, filling swimming pools, washing non-domestic premises, cleaning vehicles, etc.) which were aimed at attaining a 30% reduction compared with the ‘normal’ water demands. At the same time, the GRBA had to carry out emergency infrastructure works to increase the water supply (new abstractions from rivers and aquifers, water transfers, etc.) [62].

The two headwater reservoirs of study are the Canales and Quéntar reservoirs, located at the upper area of the Genil River within the Granada area and to the south-east of the GRB (**Figure 34**).

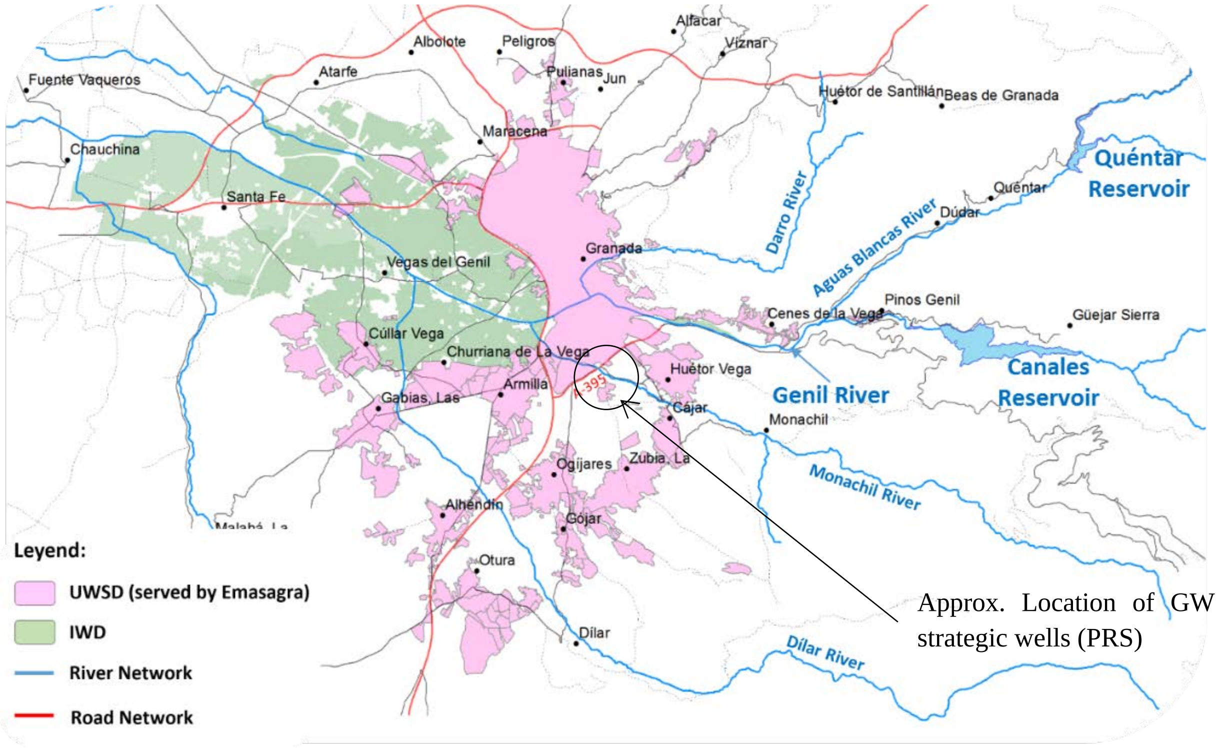
Figure 34: Location of the Guadalquivir River Basin [69] in southern Spain and the Upper Genil River sub-basin in Granada area (Latitude: 37.15855 Longitude: -3.470605).

The Canales reservoir (**Figure 35**) is located in the upstream area of the Genil River (close to Sierra Nevada), close to the town of Güejar Sierra, with a total contributing catchment area of 176.5 km^2. The dam was built in 1989 with a total capacity of 70 hm^3 and average streamflow of 66.71 hm^3/year. This catchment area is affected by snow storage and melting processes in the Sierra Nevada. The snow appears between the months of November and May, reaching the maximum accumulation of snow in March with an average water-equivalent volume of 20 hm^3 [65].

The Quéntar reservoir (**Figure 35**) is located on the Aguas Blancas River (tributary of the Genil River), with a total contributing catchment area of 101.2 km^2. This dam was built in 1975 with a total volume capacity of 13.5 hm^3. The average streamflow is 21 hm^3/year. This catchment area is affected by subterranean inflows due to the aquifer and lithology in the region.

These two reservoirs form the key water infrastructures that mainly serve *UWSD* and *IWD*. Urban water consumers are formed by the Granada city and fourteen towns of its metropolitan area, with up to 300,000 inhabitants.

The IWD is mainly formed by various irrigation communities denominated the "*Vega Alta del Río Genil*", with a total irrigated land of approximately 3,800 ha (according to the Guadalquivir RBMP 2015-2021). These irrigation communities are fed by an extensive irrigation channel system that diverts water from the Genil River (downstream of the Canales and Quéntar reservoirs).



Approx. Location of GW strategic wells (PRS)

Figure 35: Canales-Quéntar water system (Latitude: 37.15855 Longitude: −3.470605). Source: own elaboration.

This system is currently supplemented by a network of fourteen operating GW wells located in the upper area of the Vega de Granada aquifer (south-east of the city of Granada, on both banks of the Monachil River and the A-395 motorway). These are commonly known as the "*Pozos de la Ronda Sur*". These were built by the GRBA after 1991–1995 drought period, during which the storage volume of Canales and Quéntar reservoirs was depleted. The objective of these GW works was to supplement the existing regulated SW resources to serve the UWSD of Granada and its metropolitan area (when needed).

In 1995, the GRBA delivered these infrastructure works to Emasagra (Local Water and Sewage Company) in order to guarantee its correct management, operation, and maintenance. Since then, Emasagra has been responsible for managing these and its associated costs. However, these will only be put into operation under the GRBA instructions.

The GRBA is responsible for supervising and managing reservoir outflows, providing water abstraction licences and ensuring compliance with water rights and water resources allocation.

During years of average precipitation, water demands of this system can be met using regulated SW resources only. However, in years of below-normal precipitation, typically higher GW volume abstractions and/or reductions in per right allocation are required. During prolonged periods of drought and water scarcity episodes, the UWSD has theoretically been assigned priority of water use over IWD. This priority of water use assigned to the urban water supply is however not at free cost (as shown in **Section 8.5.5**).

8.5.2 Input data, sources and limitations

The site-specific input data used to inform this study is described in **Annex B**.

8.5.3 Hypothesis of Study

Four hypotheses (H-I to H-IV) have been formulated (

Table 15) based on the origin of the water resource used to meet the water demands, and the priority of water use: a) the UWSD has priority of water use over the IWD, and b) both UWSD/IWD have equal priority of water use.

Hypothesis IVa simulates the current water situation of a multi-source supply system (using both surface and groundwater sources) to serve multi-sectorial water demands (in this case, agricultural and urban water), and the UWSD as the priority water user. Hence, the analysis was mainly focused on the results obtained for Hypothesis IV.

Table 15: Hypotheses of Study.

	Origin			**Priority of Water Use**			
Hypothesis Name	**Unregulated Rivers**	**Regulated Rivers**	**Groundwater**	**UWSD Priority (a)**	**UWSD & IWD Equal (b)**	**Description of water resources used**	**Elements included in the Cost Calculation**
H-I: **No reservoirs**	×			H-Ia	H-Ib	Surface water captured directly from Aguas Blancas and Genil Rivers. It is assumed that the Canales-Quéntar reservoirs were never built and the GW wells are not used.	For the purposes of this study, the resource and environmental costs, as well as the WUT associated to water transport infrastructures are excluded (Refer to **Section 8.3**). Since there are no reservoirs or GW wells, and surface water is directly captured from rivers, the water service cost (CR) is 0.
H-II: **Only reservoirs**		×		H-IIa	H-IIb	Regulated surface water volume from Canales-Quéntar reservoirs only (i.e. without using GW wells).	In this case, the regulated SW costs apply (i.e., the Canon of Regulation, CR). Refer to **Section 8.3** and **Section 8.4.1.2**. H-IIa: As the UWSD has priority of water use, a 3 to 1 increase in the contribution costs is applied to the regulated SW volume allocated to the UWSD. H-IIb: both water users have the same priority of water use and therefore, contribute equally to the cost-recovery (i.e., a 1 to 1 increase in the contribution costs is applied).
H-III: **Only GW wells**			×	H-IIIa	*N/A*[1]	GW resources will be used to meet the UWSD only.	The cost-curves provided by the Local Water and Sewage Authority are used in to calculate the GW operational costs.
H-IV: **Reservoirs and GW wells**		×	×	H-IVa	H-IVb	Regulated Rivers and GW Resources.	The regulated SW costs (CR) and GW costs are calculated. This hypothesis is a combination of H-II and H-III.

[1] *N/A*: Not applicable. GW wells (‘*Pozos de la Ronda Sur*’) only serve the UWSD.

8.5.4 Modelling the water allocated to each water user (based on the last 30 hydrological years of historical monthly streamflow data series 1988/89-2017/18)

Table 16 shows the mean annual SW and GW volume allocated to each water user and mean annual water deficit (%) over the simulated 30-year period and for each hypothesis.

Table 16: Mean annual SW and GW volume allocated to each water user and mean annual water deficit (%) – 1988/89-2017/18.

Hypothesis Name	Mean Annual Volume (hm^3)					
	UWSD			IWD		
	SW	GW	Water deficit (*)	SW	GW	Water deficit (**)
H-Ia	30.31	0	19.34% *(7.26/37.52)*	10.22	0	60.61% *(15.69/25.90)*
H-Ib	25.54	0	32.03% *(12.02/37.52)*	14.94	0	42.35% *(10.97/25.90)*
H-IIa	37.01	0	1.38% *(0.52/37.52)*	21.43	0	17.25% *(4.47/25.90)*
H-IIb	34.99	0	6.74% *2.53/37.52*	23.95	0	7.53% *(1.95/25.90)*
H-III	0	24.00	36.14% (*13.56/37.52*)	*N/A*	*N/A*	*N/A*
H-IVa	31.61	5.91	0% (*0/37.52*)	24.31	0	6.16% (*1.59/25.90*)
H-IVb	30.94	6.51	0.20% (*0.076/37.52*)	25.50	0	1.56% (*0.40/25.90*)

(*) Mean Annual Water Deficit (%) for the UWSD in relation to the annual water demand of 37.524hm^3 as established in the Guadalquivir RBMP 2015-2021.

(**) Mean Annual Water Deficit (%) for the IWD in relation to the total annual IWD of 25.904 hm^3 as established in the Guadalquivir RBMP 2015-2021.

Figure 36, **Figure 37**, **Figure 38** and **Figure 39** show the graphical simulated monthly water deficits results for H-IV (*a* and *b*). The complete set of simulation results (for all the hypotheses) together with the modelling results for Canales and Quéntar reservoirs (H-II and H-IV) have been included in **Annex D** for information.

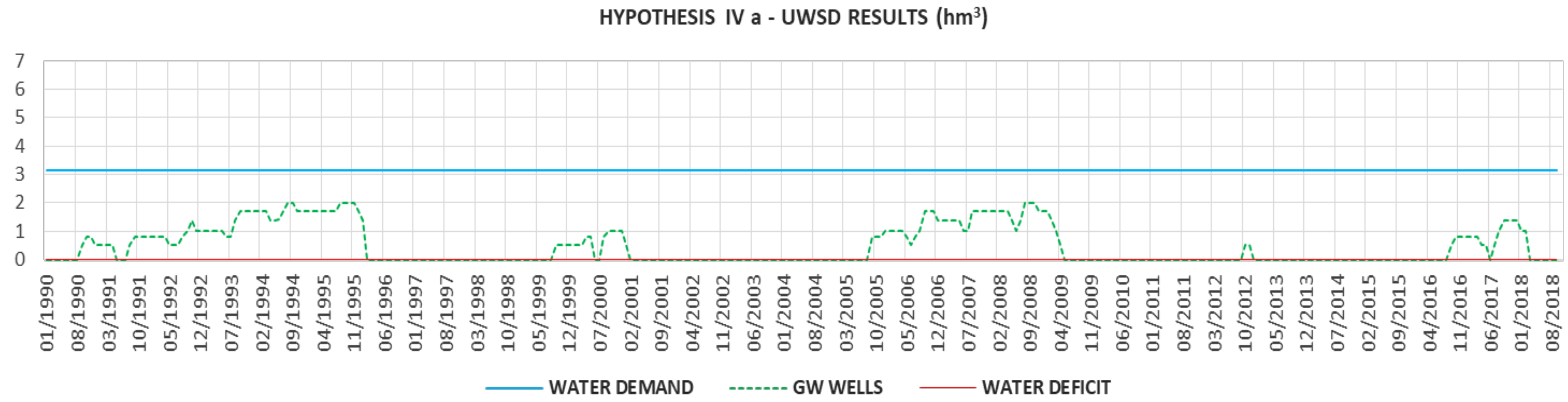


Figure 36: H-IVa (Reservoirs and GW wells – USWD priority): Simulation Results for the UWSD.

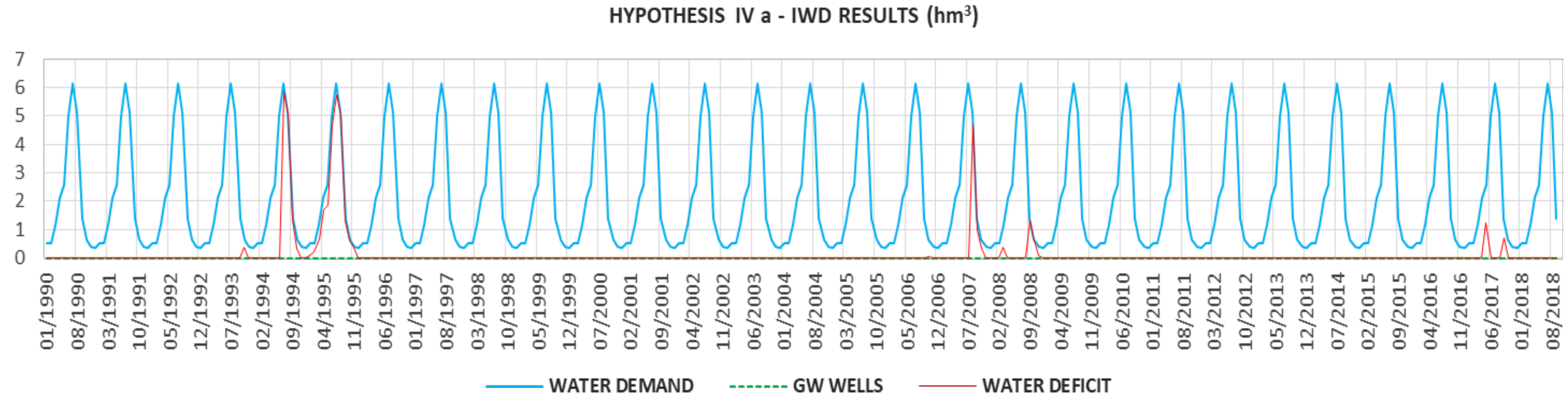


Figure 37: H-IVa (Reservoirs and GW wells – USWD priority): Simulation Results for the IWD.

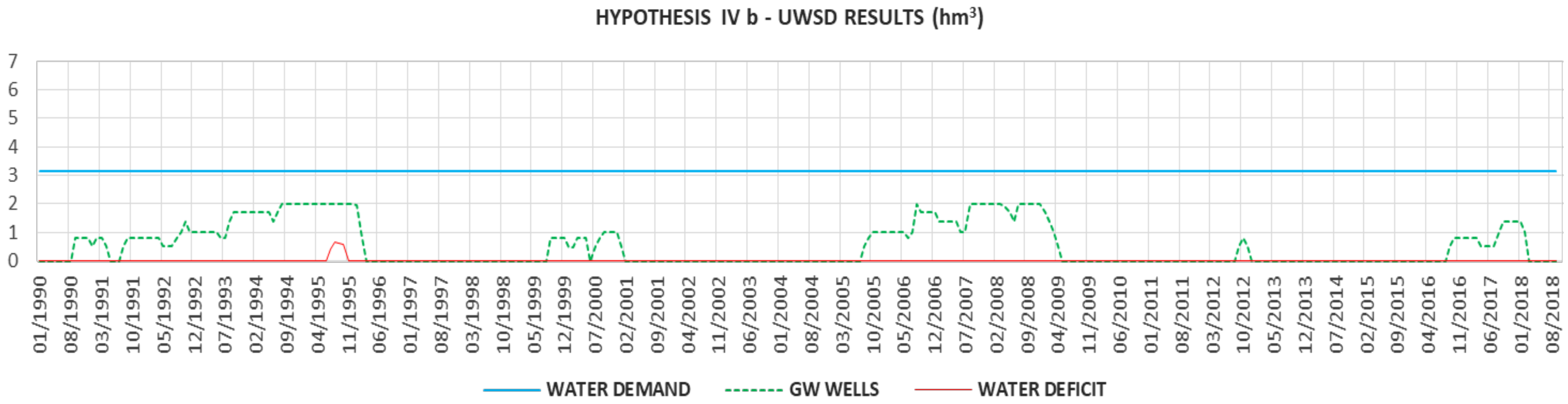


Figure 38: H-IVb (Reservoirs and GW wells – Equal priority): Simulation Results for the UWSD.

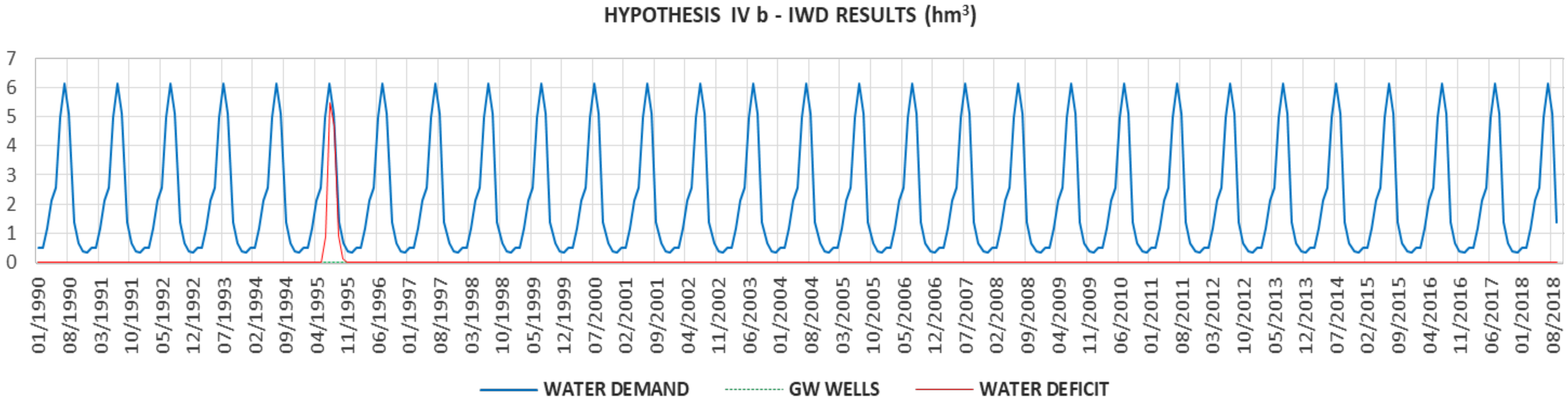


Figure 39: H-IVb (Reservoirs and GW wells – Equal priority): Simulation Results for the IWD.

Table 16 shows that the optimal water supply management strategy, which provides the greatest guarantee of supply for both, the UWSD and IWD, is achieved for H-IV. This is thanks to the use of the strategic GW wells to serve the UWSD.

If we compare the simulation results obtained from H-IVa and H-IVb for the UWSD (**Table 16**, **Figure 36** and **Figure 38**), it can be appreciated that:

- despite the loss of priority of water use (H-IVb) and thanks to the optimal use of the existing strategic GW wells, the household or uban water supply demand (UWSD) would have been met in practically all months of the simulated 30-year period, with only a negligible water deficit of 0.076hm^3 (i.e., 0.20% mean annual water deficit) in the driest year of the simulated series (1995);
- the priority of water use for the UWSD, in practice, does not translate into a significant improvement in the guarantee of water supply (or considerable reduction in water deficits). In fact, the priority of water use will be only patent in very extreme drought events (approximately 200 year return period) and when all the resources of the system have been completely exhausted and are insufficient to satisfy the water demands;
- there is a relative decrease in the mean annual SW volume allocated to the UWSD (from 31.61 to 30.94 hm^3) and a relative increase in the mean annual GW volume (from 5.91 to 6.51 hm^3). This is because when the UWSD does not have priority of water use over the regulated SW resources from the reservoirs, there will be a greater GW volume mobilised from the aquifer to meet their water demand (since the GW wells only serve the UWSD, and they will be mobilised as soon as the UWSD is on deficit).

If we compare the simulation results obtained from H-IVa and H-IVb for the IWD (**Table 16**, **Figure 37** and **Figure 39**), it can be appreciated that:

- the water deficits are reduced from 6.16% (H-IVa) to 1.56% (H-IVb). In fact, the IWD would only experience water deficit during the summer months of the driest year of the simulated series (1995) for H-IVb. This is because the earlier mobilisation of GW resources (to serve the UWSD, H-IVb) helps to have more available water storage volume in the reservoirs. Since this volume is shared equally among both water users (H-IVb), the IWD water deficits are reduced;
- the IWD would considerably benefit from having equal priority of water use in terms of availability of water resources to meet their water demands (higher in Summer). In this case, the mean water deficit would be reduced approximately by 60% (mainly due to a greater use of regulated SW volume in comparison with H-IVa).

In this particular sub-basin, the SW resources from Canales and Quéntar reservoirs (from Sierra Nevada mountains) are of higher water quality than the GW resources from the aquifer. Therefore, it is important to consider not only the satisfaction of the water demands of the system but also the sustainability of each option. In principle, the highest water quality should be allocated to the drinkable water demand (so that important carbon footprint and cost reductions might be achieved in terms of reducing abstraction, pumping, transportation and water treatment requirements). An increase in the GW volume to serve the UWSD would, in principle, imply a larger carbon footprint and economic costs.

Presently, the following options are being partly integrated and further investigated in this particular water system: i) the use the GW volume to serve the irrigated land in exchange of the same water volume from the reservoirs to serve the UWSD, and ii) the water re-use to serve the irrigated land.

8.5.5 Results obtained from the calculation of the total annual regulated SW costs (H-II and H-IV) and GW costs (H-III and H-IV)

8.5.5.1 SW costs

The results for H-II and H-IV for the UWSD are shown in **Figure 40** and **Figure 41**.

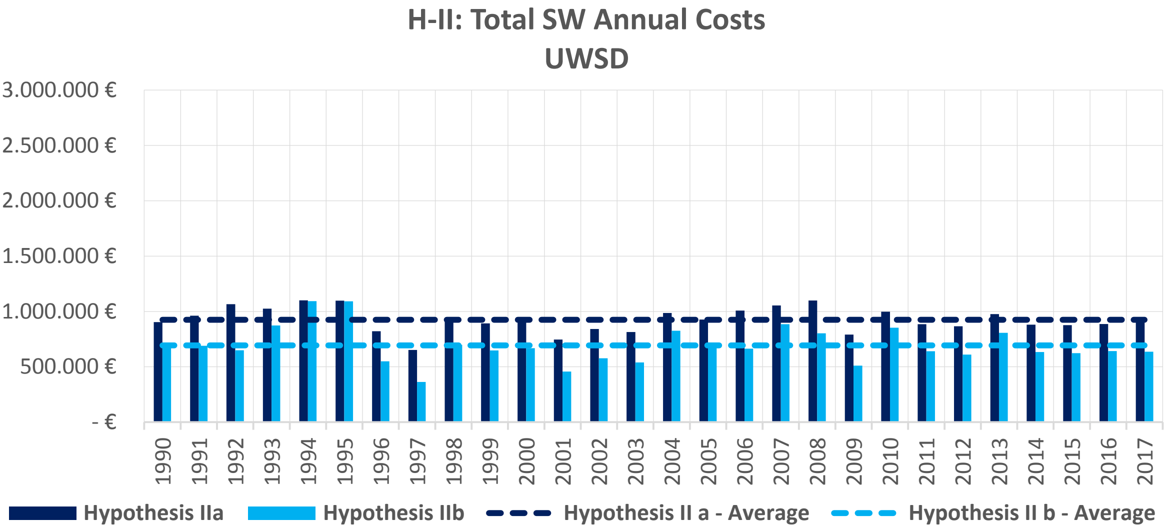


Figure 40: H-II (Only Reservoirs): Total SW Annual Costs Urban Water Supply Demand.

The cost paid by the UWSD for having the theoretical priority of water use over the IWD will be the difference between the results obtained from Hypotheses "*a (UWSD - priority of water use)*" and "*b (UWSD&IWD – equal priority)*", described below for each hypothesis.

Based on the assumption that GW resources were not used (H-II), the simulated mean annual regulated SW costs that the UWSD would pay are €925,618 (H-IIa) and €693,121 (H-IIb). This is, an average additional annual cost of €232,497 (or, €6,289 per cubic hectometre) for having the priority of water use.

Based on the assumption that GW resources were used to serve the UWSD (H-IV), the simulated mean annual regulated SW costs that the UWSD would pay are €825,163 (H-IVa) and €513,542 (H-IVb). This is, an average additional annual cost of €311,620 (or, €9,797 per cubic hectometre) for having the priority of use.

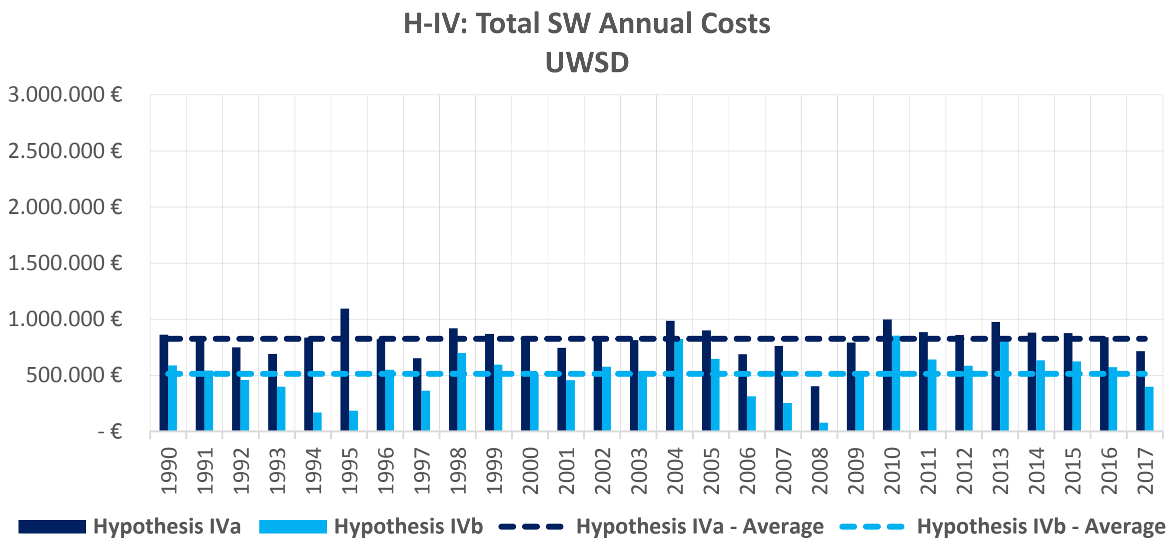


Figure 41: H-IV (Reservoirs and GW wells): Total SW Annual Costs Urban Water Supply Demand.

Figure 41 shows that the annual regulated SW costs paid by the UWSD for having the priority of water use (H-IVa) during the driest hydrological years (i.e., 1995 and 2008) are considerably higher than the costs of not having the priority of water use (H-IVb). This is because as the availability of water resources decreases during dry years and because the UWSD has the priority of water use, the "*improved SW volume*" and the "*improvement percentage or coefficient*" (**Section 8.4.1.2**) are higher and so, the contribution costs.

The mean annual regulated SW costs for the UWSD are greater for H-II than for H-IV since the SW volume allocated to the UWSD for H-II is greater than for H-IV (**Table 16**).

8.5.5.2 GW costs

Figure 42 and **Figure 43** show the total annual and mean GW costs for the UWSD (for H-III and H-IV).

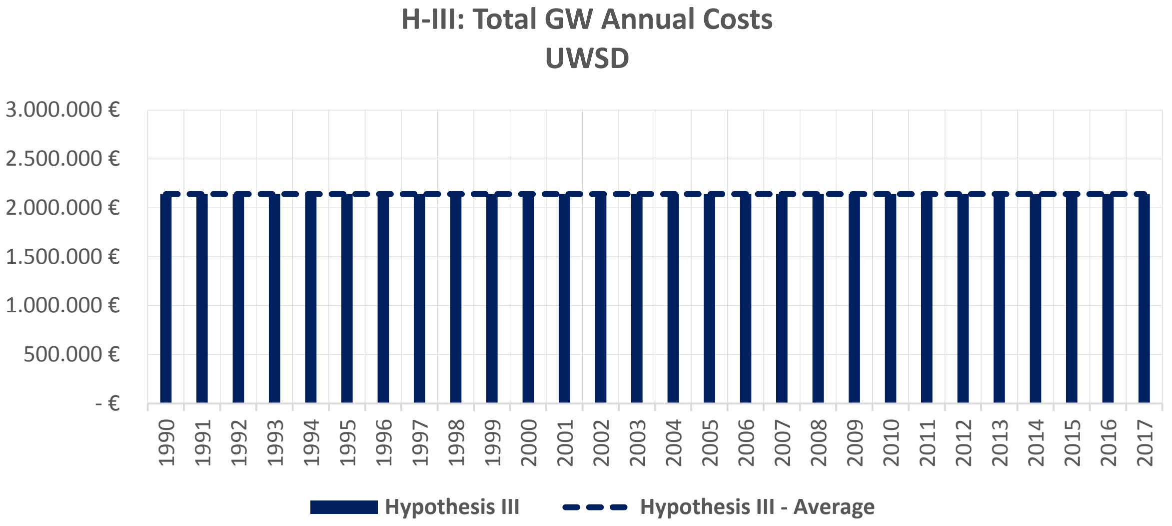


Figure 42: H-III (Only GW wells): Total GW Annual Costs Urban Water Supply Demand.

For H-III (**Figure 42)**, the total annual GW costs are constant and equal to €2,141,157. These are based on a constant monthly GW abstraction rate of 2 hm^3 (maximum abstraction capacity, see **Annex B**) to satisfy the monthly UWSD (3.127 hm^3). Since there are not any other water resources in this hypothesis, the maximum abstraction capacity will be mobilised every month (with a monthly water deficit of 1.127 hm^3).

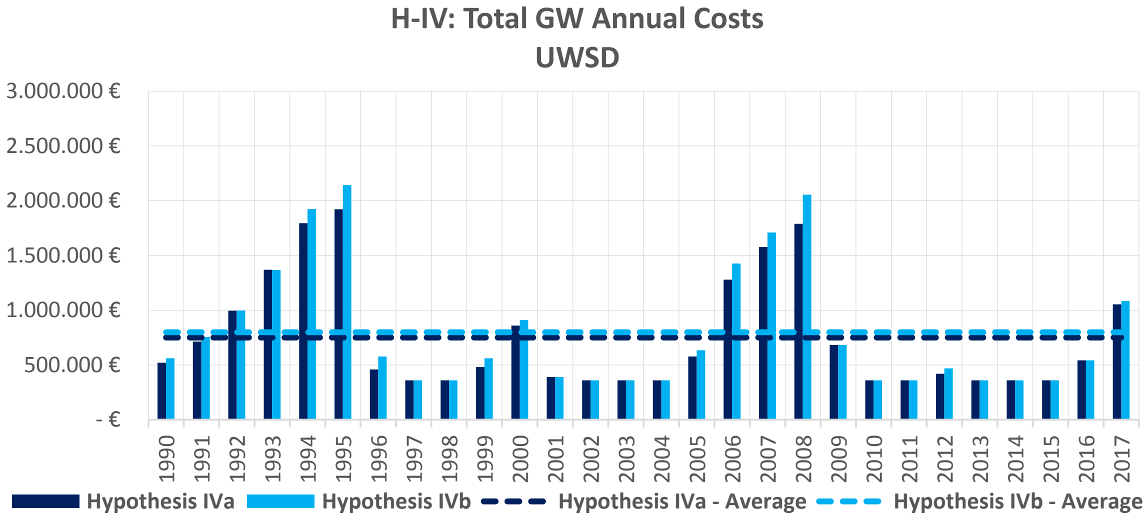


Figure 43: H-IV (Reservoirs and GW wells): Total GW Annual Costs Urban Water Supply Demand.

For H-IV **(Figure 43)**, the annual GW costs incurred by the UWSD are slightly higher for H-IVb than H-IVa. This is also reflected in the annual average GW costs €750,176 (H-IVa) and €799,111 (H-IVb). This is because there is a greater GW volume mobilised in H-IVb (equal priority of water use) in order to meet the UWSD demand (**Table 16**). This increase in costs is higher during the driest hydrological years (i.e., 1995 and 2008).

It is important to note that the GW wells, even without being used (e.g. 1997-1998, 2001-2004, 2010-2011, 2013-2015) incur in a fixed monthly cost (due to the contracted power, maintenance, etc.) of approximately € 262,450 which has also been considered in the cost calculations (**Figure 43**).

8.5.5.3 Total (SW and GW) costs

Table 17 presents a summary of the total (SW and GW) mean annual and unitary costs for the UWSD and each hypothesis, together with the mean annual water deficits and total (SW and GW) mean water volume allocated to the UWSD in each hypothesis.

Table 17: Summary of results – UWSD.

Hypothesis Name		**Priority of Water Use**		
		UWSD Priority (a)	**UWSD / IWD Equal Priority (b)**	**Difference (a)-(b)**
H-I: **No reservoirs**	**A**	19.34%	32.03%	**-12.69%**
	B	30.31 hm^3	25.54 hm^3	**4.77 hm^3**
	C	0 * (CR=0)	0 * (CR=0)	**0**
	D	0*	0	**0**
H-II: **Only reservoirs**	**A**	1.38%	6.74%	**-5.36%**
	B	37.01 hm^3	34.99 hm^3	**2.02 hm^3**
	C	€ 925,618	€ 693,121	**€ 232,497**
	D	0.0254 €/m^3	0.0220 €/m^3	**0.0034 €/m^3** **(or, 3,359 €/hm^3)**
H-III: **Only GW wells**	**A**	36.14%	*N/A*	***N/A***
	B	24.00		
	C	€ 2,044,743		
	D	0.0852 €/m^3		
H-IV: **Reservoirs and GW wells**	**A**	0%	0.2%	**-0.2%**
	B	37.52 hm^3	37.45 hm^3	**0.07 hm^3**
	C	€ 1,478,925	€ 1,216,239	**€ 262,685**
	D	0.0394 €/m^3	0.0325 €/m^3	**0.0069 €/m^3** **(or, 6,863 €/hm^3)**

* *(No reservoirs, therefore, the CR=0 and the WUT has been excluded from this study)*

A. Mean Annual Water Deficit for the UWSD in relation to the total annual UWSD of 37.524hm^{3,} established in the Guadalquivir RBMP 2015-2021 (%).

B. Mean Annual Total Water Volume (hm^3), the specific SW and GW volumes can be found in **Table 16**.

C. Mean Annual Total (SW + GW) Water Costs (€).

D. Mean Unitary Water Costs (€/m^3 and €/hm^3).

From **Table 17**, the main observations are:

- For H-II (only using SW resources from the reservoirs, without GW resources), the UWSD pays an additional average annual cost of € 232,497 (or, an approximate average cost of €3,359 per cubic hectometre of water) for having the priority of use;
- For H-IV (using both, SW resources from the reservoirs and GW resources to serve the UWSD), the UWSD pays an additional average annual cost of € 262,685 (or, an approximate average cost €6,863 per cubic hectometre of water) for having the priority of use. However, this additional cost is not reflected on a significant increase in the guarantee of supply (or reduction of water deficit) when we compare the results of H-IVa and H-IVb;
- The results for H-IV clearly show how despite the increase in the pumped volume from the aquifer to serve the UWSD (**Table 16**) and the consequent increase in the GW costs, the savings when eliminating the 3 to 1 increase in the contribution costs (due to the priority of water use related to the SW volume from Canales-Quéntar reservoirs) considerably outweighs the pumping costs.

It is important to highlight that the GW resources have been modelled to supplement the regulated SW resources (once these have been depleted). However, the proposed water scarcity measures included in the 2018 GRB DMP for this system are to mobilise the GW resources relatively soon (in relation to the reservoir storage volume of Canales and Quéntar reservoirs) to meet the water demands, so that, water deficits in this system can be avoided or minimised. This is achieved at a higher cost paid by the UWSD.

Therefore, in practice, the extra cost that the UWSD currently pays for having the priority of water use is only patent when the resources of the system have been exhausted and are insufficient to satisfy all the demands.

Figure 44 shows the evolution of the total (SW+GW) annual costs for the UWSD (H-IV):

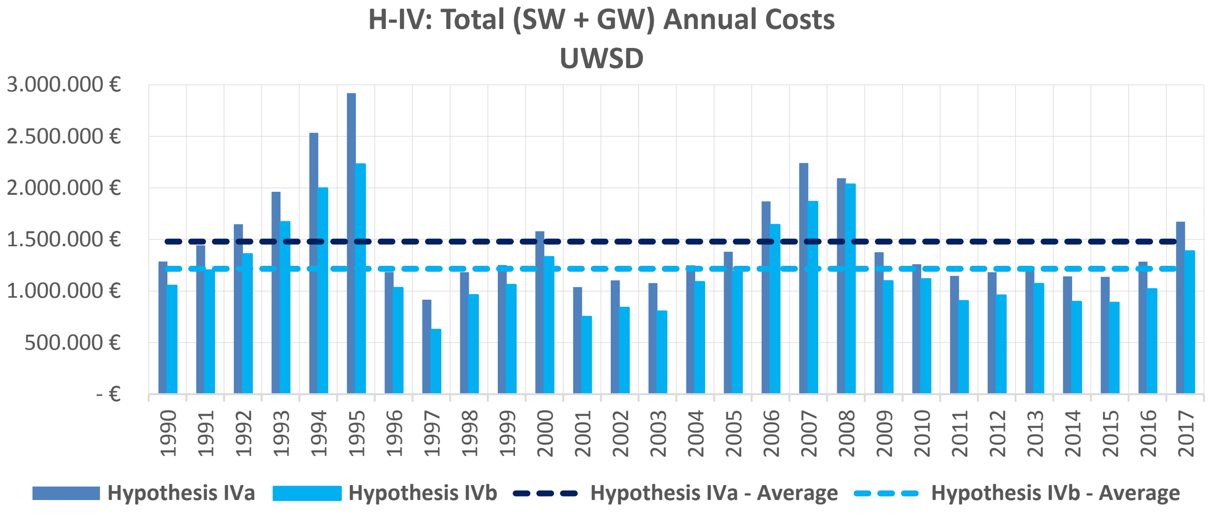


Figure 44: H- IV (Reservoirs and GW wells): Total SW and GW Annual Costs Urban Water Supply Demand.

Figure 44 shows that the annual costs paid by the UWSD for having the priority of water use (H-IVa) during dry hydrological years (1991- 1995 and 2006-2008) are considerably higher when compared with the costs for not having the priority of water use (H-IVb).

Figure 45 shows the cumulative total annual SW and GW costs for the UWSD (H-IV). It can be seen that in the period 1990- 2017, the UWSD has paid approximately 6 million euros extra for having the priority of water use.

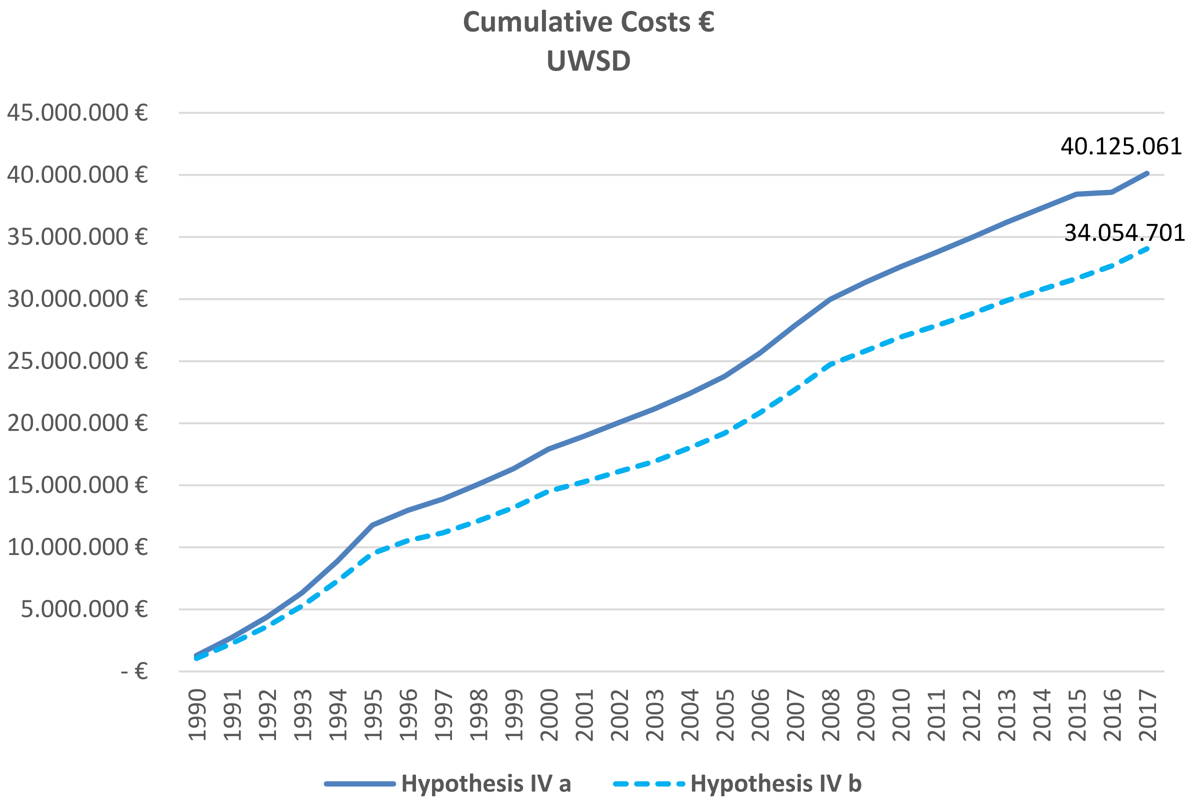


Figure 45: H-IV (Reservoirs and GW wells): Cumulative Costs Urban Water Supply Demand.

Nonetheless, it is important to note that after the severe historical 1991-1995 drought, the UWSD was requested to economically compensate the agricultural sector (IWD) for the loss of harvests during this severe drought period. This was because all the available SW resources from the reservoirs were to satisfy the UWSD (after applying as well severe demand reduction measures to the UWSD). Even after the GRBA intervention to resolve the conflict among the UWSD and the IWD, the case was taken to the courts and is still unresolved (refer to **Annex A**). The root cause of the issue was precisely due to the misunderstanding in terms of priority of water use of the UWSD, historical water rights of the IWD and contribution to the cost-recovery from each water user.

Figure 46 shows the evolution of the total SW and GW unitary costs for the UWSD (H-IV) for each year of the simulated series. It can be observed how the unitary water costs paid by the UWSD for having the priority of water use (H-IVa) during dry hydrological years (1991- 1995 and 2006-2008) are considerably higher when compared with the costs of not having the priority of water use.

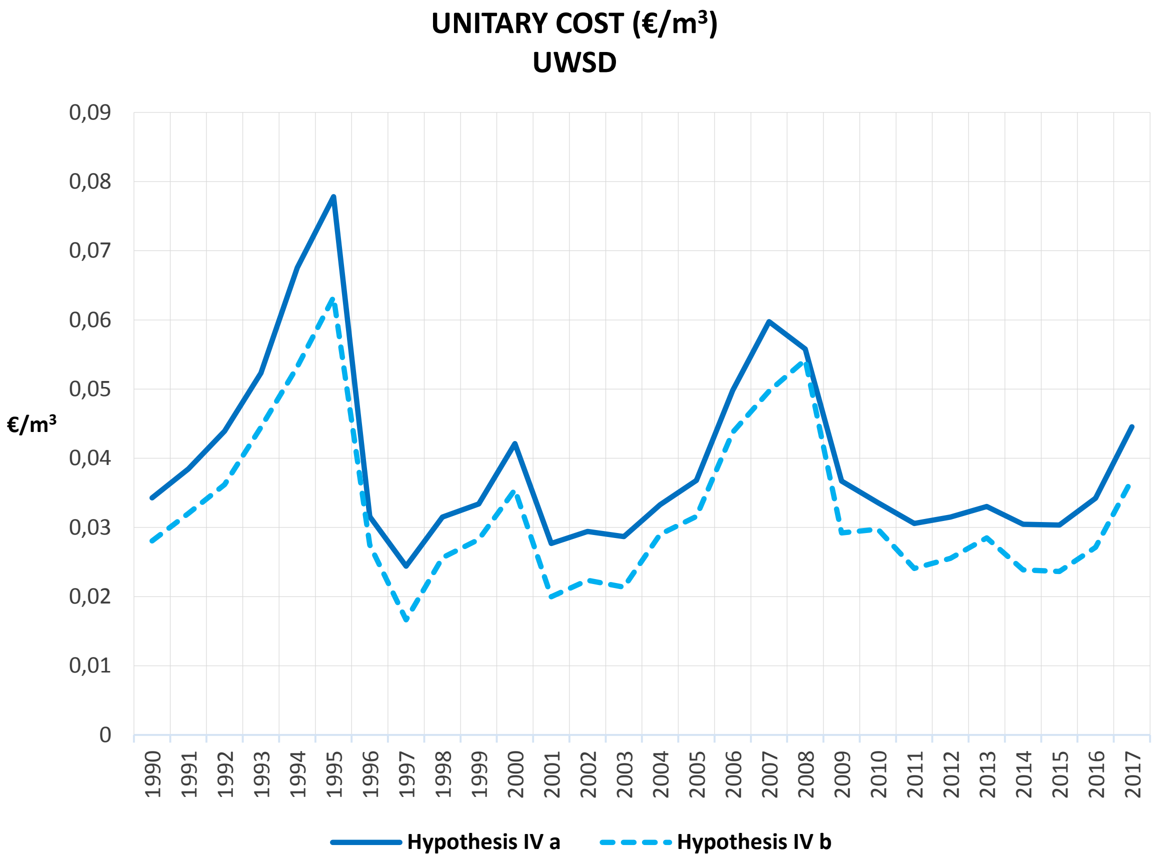


Figure 46: H-IV (Reservoirs and GW wells): Raw Water Unitary Costs for UWSD.

These results are more updated but of the same order of magnitude to those achieved in 2007 by Berbel et al. [118]: " *Average tariffs paid for irrigation water in areas where water is supplied by RBAs is €0.02/m*^{3} *, except for the agricultural users served from the Tajo- Segura Transfer who pay about €0.09/m*^{3}*, while areas that use GW pay an average of €0.04–0.07/m*^{3} *, based on extraction and other O&M costs*"

8.6 Conclusions

The results have showed that the household water user pays an additional average annual cost of approximately €262,685 (or, 6,863€ / hm^3) for having the theoretical priority of water use over the agricultural user. However, the simulation outcomes also revealed that this additional cost was, actually, not reflected on a greater guarantee of water supply for the UWSD.

In fact, the simulation outputs demonstrated that if both water users would have equal priority of water use, and with the optimal use of the existing strategic GW wells, the current water demands of the system would have been met in practically all months of the simulated 30-year period, with only a negligible water deficit in the driest year of the simulated series (1995). This means that despite the extra annual cost paid by the UWSD, in practice, the priority of water use would only be patent in very extreme drought events (approximately 200-year return period) and when all the water resources of the system have been completely exhausted.

Not only that, but it is also important to highlight that this theoretical priority of water use has not even been applied during historical drought and water scarcity situations. It was after the devastating environmental, social and economic consequences of the 1991-1995 drought period in Spain and for this particular sub-basin, that the urban water supply user was requested to economically compensate the agricultural sector for the loss of harvests during this intense drought period (since all the available SW from the two existing reservoirs was made available to the UWSD). Even after the GRBA intervention to resolve the conflict among the UWSD and IWD, the case was taken to the courts and is still unresolved. The root cause of the issue was precisely due to the misunderstanding in terms of priority of water use, historical water right and contribution to the cost-recovery from each water user.

It is therefore concluded that in Spain, greater emphasis should be placed on the critical role played by the water pricing policies as an effective and direct tool to communicate the real water service cost to the water user. What is more, the current lack of transparency in the water cost recovery calculations is one of the most important obstacles for the achievement of a rational water pricing policy consistent with the requirements of the WFD. A consequence of this is, in many cases, the existence of cross subsidies between water users of the same water system.

Annex A – 1994 Drought Event – Water Rights Conflict.

It is significantly notorious that in this system, still today, litigation continues among the key water players (i.e. the GRBA, the Local Water and Sewage Company and one of the irrigation communities) after the devastating environmental, social and economic consequences of the 1991-1995 drought period.

The problem aroused when the GRBA instructed in 1994 (almost at the end of that intense drought period) that all available SW volume stored in Canales and Quéntar reservoirs was to serve the household water demand of Granada city (given its priority of water use). This decision logically caused losses and economic damage to the agricultural sector of this area, which also had historical water rights for the use of the SW resources.

Consequently, four different irrigation collectives of this area (namely, the *Community of Irrigators of Arabuleila*, *Tarramonta*, *Santa Fé* and *Acequia Gorda del Genil*) decided to sue the GRBA. They claimed historical water rights over the SW resources and therefore, they wanted to be economically compensated for the loss of harvests during the intense drought period. The GRBA then accepted this demand from the irrigation sector and decided that the Local Urban Water Supply Company (Emasagra) should compensate the agricultural sector (since the households used all the available surface water volume during the drought period). The GRBA also instructed that both, the urban water supply and the agricultural sector, should reach a mutual agreement on the economic compensation (to be paid by the urban water supply demand to the agricultural sector).

In compliance with the aforementioned resolution, Emasagra proceeded to calculate the amount of the economic compensation and tried to reach an agreement between the parties. Three out of the four irrigation communities (the *Community of Irrigators of Arabuleila, Tarramonta and Santa Fé*) accepted and collected the economic compensation proposed by Emasagra.

Only one of the irrigation communities (the *Community of Irrigators of Acequia Gorda del Genil)* that has the greatest irrigated area rejected the proposed amount. The economic compensation requested by this Community was € 2,669,398.90 (due to the decrease in cultivated area, decrease in yields and additional pumping costs).

In the absence of agreement between the interested parties and after numerous lawsuits, the GRBA quantified the economic compensation on 238,798.00 euros (01-04-2013) to be paid by the Local Water and Sewage Company of Granada (Emasagra) to the *Community of Irrigators of Acequia Gorda del Genil* for the deprivation of water during 1994.

This resolution was appealed by both implicated parties (Emasagra and *Community of Irrigators of Acequia Gorda del Genil).* Precisely one of the arguments put forward by Emasagra was the fact that in the water service cost calculation method, the urban water supply pays an extra annual amount for having priority of water use for the present year and the next two years.

This particular case clearly shows the importance of objectively evaluating the contribution of the main competing water users to the recovery of water service cost and whether there is currently a cross-subside among water users.

Annex B – Upper Genil River sub-basin (Guadalquivir River Basin) Input data, sources and limitations.

All the input data used to inform this study is publically available and described below.

Surface water resources

The '*Automatic Hydrological Information System* (SAIH)' is a free and public online portal maintained by the GRBA in Spain [75] The SAIH offers information such as streamflow, rainfall, temperature, reservoir inflows, outflows, storage volume and water level, etc. for up to 57 reservoirs, 52 non-regulated rivers, 20 canals and 10 hydro power plants. Other information on rain, snow and temperature gauging stations across the basin is also offered. The available temporal data sets vary depending on the specific sub-catchment area. The information can be downloaded in an hourly, daily or monthly time step or requested directly via an online application form or email to the SAIH contact details provided in the webpage [75].

The historical monthly streamflow data series for Canales (from October 1988 to present) and Quéntar (from October 1977 to present) were obtained via an online request on the SAIH webpage. The common historical data set period for both reservoirs (1988/1989 – 2017/2018, 30 years) has been used in the modelling (included below for information).

From the data set used, we would draw the attention to the historical intense drought episodes: 1991-1995 and 2004-2008.

Historical monthly streamflow data series (hm^3) for Canales and Quéntar reservoirs (October 1988 - September 2018):

CANALES RESERVOIR: Historical monthly streamflow data series (hm^3)

Number of hydrological years ***30***

*** Data received from *SAIH on 04.10.2018***

Starting Year	Ending Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Annual
1988	1989	2.28	2.94	2.47	1.88	4.43	4.92	5.56	10.06	7.67	3.65	1.72	1.78	49.35
1989	1990	2.19	4.92	10.54	4.32	2.44	3.39	4.57	11.21	7.94	2.39	1.72	1.82	57.46
1990	1991	2.83	3.15	2.93	2.34	2.08	5.04	5.42	8.78	9.04	3.41	1.85	1.56	48.42
1991	1992	3.52	2.49	2.89	2.11	2.01	2.73	6.10	8.24	5.15	3.38	1.82	1.30	41.73
1992	1993	3.58	2.41	3.50	2.09	1.81	2.56	3.49	9.19	5.58	2.10	1.20	1.09	38.59
1993	1994	1.69	2.85	1.57	1.87	1.77	3.01	3.11	4.69	3.33	1.18	0.88	0.87	26.82
1994	1995	1.93	2.19	1.47	1.76	1.25	2.00	1.85	2.17	1.34	1.12	0.71	0.77	18.56
1995	1996	0.89	1.71	6.55	15.58	10.34	7.38	10.23	15.31	15.36	8.19	3.60	3.72	98.84
1996	1997	3.37	5.57	12.26	17.65	10.12	10.85	12.88	17.02	15.04	7.04	4.22	3.76	119.77
1997	1998	5.73	19.08	18.32	11.31	7.88	6.53	8.02	14.08	14.73	6.29	3.89	3.20	119.05
1998	1999	2.69	2.16	2.05	2.23	1.95	2.78	3.99	4.40	2.38	1.87	1.64	1.63	29.76
1999	2000	4.68	2.92	3.37	2.76	1.85	2.02	4.38	11.34	6.09	2.58	1.85	1.61	45.44
2000	2001	2.87	5.08	8.00	12.65	9.21	19.05	12.00	13.78	13.47	5.95	3.17	2.43	107.67
2001	2002	10.71	5.02	4.43	4.61	2.67	4.48	8.19	11.40	6.36	3.52	2.22	1.94	65.55
2002	2003	3.22	5.62	7.44	8.55	6.35	9.95	12.38	17.07	11.60	4.61	2.72	1.96	91.48
2003	2004	3.17	4.83	3.95	3.48	3.65	4.39	8.40	14.71	20.12	7.91	3.19	2.35	80.16
2004	2005	2.47	2.37	2.45	2.22	2.02	3.27	3.49	3.75	2.23	2.03	1.92	1.40	29.61
2005	2006	1.42	1.60	1.80	1.58	1.63	2.94	6.11	7.56	3.47	2.00	1.53	1.22	32.86
2006	2007	1.65	3.89	2.18	1.65	3.65	2.33	4.26	8.62	5.28	2.00	1.23	1.49	38.23
2007	2008	1.42	1.74	1.48	1.60	1.49	1.89	7.01	7.53	5.09	2.77	1.58	1.49	35.08
2008	2009	2.24	2.75	2.52	5.33	5.30	9.40	9.01	18.81	10.64	5.04	2.78	3.57	77.38
2009	2010	2.46	2.09	17.84	23.31	18.65	27.90	18.27	19.04	18.15	12.27	6.06	3.19	169.23
2010	2011	2.82	6.35	16.30	7.87	6.46	8.55	16.35	19.33	12.24	5.32	2.27	1.69	105.54
2011	2012	1.91	3.55	2.44	2.19	1.77	1.92	3.78	8.22	3.46	1.63	1.06	1.34	33.27
2012	2013	3.98	17.35	5.66	7.64	6.78	26.47	29.28	19.11	17.92	9.16	3.17	2.42	148.92
2013	2014	2.53	1.96	2.58	2.84	7.46	11.39	9.24	12.15	6.13	2.78	1.45	1.16	61.67
2014	2015	1.62	3.16	2.65	2.42	4.99	3.89	8.13	8.06	3.12	1.09	0.87	1.29	41.29
2015	2016	1.79	2.10	1.78	2.18	6.44	3.64	6.39	9.36	5.11	2.27	1.50	1.17	43.72
2016	2017	1.66	2.54	2.94	2.01	2.47	4.92	6.84	6.16	3.18	2.20	1.90	1.49	38.31
2017	2018	1.77	2.34	3.19	2.58	2.10	19.93	19.22	20.02	17.97	7.25	3.32	2.80	102.47

QUÉNTAR RESERVOIR: Historical monthly streamflow data series (hm^3) ***Number of hydrological years*** ***30***

*** Data received from *SAIH on 04.10.2018***

Starting Year	Ending Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Annual
1988	1989	1.00	1.07	1.01	0.92	1.90	1.68	2.33	1.73	1.19	0.71	0.61	0.81	14.94
1989	1990	1.01	1.05	2.16	1.49	1.11	1.11	1.17	1.49	0.74	0.62	0.61	0.62	13.16
1990	1991	1.02	1.12	1.17	1.13	1.00	2.83	1.66	1.09	0.85	0.65	0.62	0.84	13.97
1991	1992	0.94	0.86	0.97	0.83	0.81	0.90	1.75	1.04	0.77	0.64	0.36	0.45	10.31
1992	1993	0.83	0.75	1.03	0.66	0.58	1.14	0.82	1.38	0.59	0.48	0.57	0.35	9.19
1993	1994	0.49	0.55	0.53	0.64	0.59	0.96	0.73	0.61	0.48	0.40	0.46	0.52	6.95
1994	1995	1.01	0.36	0.59	0.51	0.44	0.56	0.40	0.34	0.38	0.27	0.21	0.24	5.32
1995	1996	0.22	0.30	1.34	5.61	6.39	2.24	1.73	3.12	1.13	0.43	0.32	0.86	23.69
1996	1997	0.90	0.91	4.76	10.00	3.64	2.38	2.16	1.56	1.11	0.57	0.65	1.03	29.67
1997	1998	1.41	5.31	9.08	4.36	3.74	2.51	2.38	3.02	1.97	1.03	0.69	0.88	36.38
1998	1999	1.18	1.15	1.26	1.30	1.03	1.18	0.98	0.92	0.68	0.36	0.32	0.37	10.71
1999	2000	0.64	0.60	0.83	0.69	0.70	0.47	1.05	1.51	0.79	0.35	0.26	0.24	8.13
2000	2001	0.43	0.84	2.94	6.17	4.23	8.40	2.43	1.59	0.67	0.45	0.52	0.74	29.43
2001	2002	1.28	1.26	1.42	1.10	0.76	1.43	2.30	1.31	0.62	0.60	0.46	0.55	13.09
2002	2003	0.80	1.64	2.13	4.15	2.84	3.99	3.19	1.99	0.97	0.74	0.63	0.71	23.77
2003	2004	1.05	1.55	1.63	1.46	1.29	1.48	2.80	4.43	1.96	1.03	0.83	0.78	20.28
2004	2005	1.06	1.06	0.97	0.75	0.63	0.90	0.57	0.36	0.25	0.17	0.17	0.25	7.12
2005	2006	0.35	0.45	0.79	0.85	0.94	1.62	1.32	1.02	0.70	0.62	0.38	0.46	9.48
2006	2007	0.50	0.58	0.55	0.61	0.84	0.60	0.74	0.92	0.35	0.21	0.18	0.28	6.35
2007	2008	0.31	0.49	0.72	0.85	0.53	0.50	1.07	0.89	0.38	0.23	0.18	0.19	6.33
2008	2009	0.27	0.43	0.82	2.13	2.31	5.12	2.57	1.87	0.80	0.54	1.17	1.69	19.72
2009	2010	2.25	1.58	4.80	10.84	11.70	12.77	4.56	2.62	1.58	0.95	0.88	0.88	55.39
2010	2011	1.15	1.66	4.65	3.97	3.92	4.66	3.30	3.94	2.44	1.14	0.97	1.08	32.87
2011	2012	1.13	1.50	1.24	1.24	0.85	0.95	1.34	1.25	0.62	0.48	0.33	0.53	11.43
2012	2013	0.99	2.39	1.54	5.22	4.54	14.38	10.82	3.83	2.13	1.56	1.32	1.44	50.16
2013	2014	1.34	1.19	1.50	2.09	4.43	5.20	2.76	1.83	1.13	1.24	1.16	1.20	25.05
2014	2015	1.06	1.13	1.04	1.11	2.35	2.06	1.96	1.66	1.28	0.63	0.55	0.56	15.38
2015	2016	0.71	0.75	0.74	0.83	1.69	1.47	1.81	1.61	0.88	0.74	0.78	0.77	12.76
2016	2017	0.93	1.13	1.17	0.94	1.21	1.68	1.08	0.75	0.54	0.41	0.40	0.44	10.68
2017	2018	0.59	1.00	1.32	1.30	1.01	15.21	7.51	3.66	1.93	1.05	1.14	1.25	36.98

Groundwater resources

For the chosen case of study, the GW resources relate to the available abstraction capacity of the existing network of thirteen operating wells located in the upper area of the Vega de Granada aquifer ("*Pozos de la Ronda Sur*"). This source supplements the regulated SW resources and is normally used to supply the UWSD of Granada and its metropolitan area. The maximum extraction capacity is 2 hm^3 / month.

Although the technical pump capacity of the wells is slightly greater than 2 hm^3 / month, this amount has been set out as the maximum value for modelling purposes (and to be used only when needed). The two reasons that support this assumption are: i) a maximum abstraction capacity of 2 hm^3 / month is in line with the protocol of actions and measures during drought and water scarcity situations established in the GRB Drought Management Plan (DMP) approved in December 2018 [62]; ii) this value is validated with the historical monthly maximum abstraction of 2.44hm^3 / month (June 2008) and the annual historical maximum of 18hm^3 / year (2008).

Ecological flows (e-flows)

Ecological flows have been taken from the Guadalquivir RBMP (2015-2021) [62], as shown in **Table A1**:

Table A1. Ecological flows 3 from Guadalquivir RBMP (2015-2021).

Reservoir	**Volume**(hm^3)												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**TOTAL**
Canales	0.308	0.298	0.388	0.388	0.351	0.388	0.376	0.295	0.285	0.295	0.295	0.285	3.952
Quéntar	0.134	0.130	0.134	0.134	0.121	0.134	0.130	0.134	0.130	0.134	0.134	0.130	1.577

It is important to note that the ecological flows in Spain are not considered as a water demand but as a water restriction (or water constraint).

Established water demands (UWSD and IWD)

For modelling purposes, the water demands established in the Guadalquivir RBMP (2015-2021) have been taken, as shown in **Table A2**. It is important to note that these water demands are not real water consumption values but estimations made by the RBA.

The UWSD is named as "*UDU 06A01 Área Metropolitana Granada Genil*" and is formed by Granada city and its metropolitan area (14 towns). The established total annual UWSD is 37.524 hm^3, with a constant monthly UWSD of 3.13 hm^3.

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[3] (*) Note: the number of decimal places shown in Tables A1-A4 are in accordance with the Guadalquivir RBMP (2015-2021).

The IWD is named as "*06D02 – Regadíos Vega Alta río Genil*" and is formed by various irrigation communities with a total irrigated land of approximately 3,800ha (according to the Guadalquivir RBMP (2015-2021)). The established annual water demand is 25.9 hm^3, with the peak water demand in summer months (June, July and August).

In this case, it is important to highlight that there has been a progressive reduction in the total irrigated land during the past decades, mainly due to urban development and new infrastructures. However, this reduction in the irrigated land (and corresponding reduction in water demand) has not been integrated yet in the water demands estimations made by the GRBA.

Table A2. Established Water demands (*) from Guadalquivir RBMP (2015-2021).

Name	**Water Demand (hm^3)**												
(*from the Guadalquivir RBMP*)	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**TOTAL**
UDU 0601 Área Metropolitana de Granada-Genil	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	3.127	**37.524**
UDA 06D02. Regadíos Tradicionales Vega Alta río Genil	0.658	0.391	0.338	0.507	0.507	1.181	2.134	2.578	4.997	6.129	5.106	1.378	**25.904**

The peak water demand occurs in summer months, when the temperature is higher, evaporation is higher and precipitation is lower. This puts large amounts of pressure on water resources (quantity and quality), and highlights the relevance of reservoirs to better manage the irregularity in precipitation in relation to the demand pattern (as well as to deal with the effects of extreme hydrological and climate phenomena).

Minimum and Maximum Storage Volume Reservoirs

This information has been also taken from the Guadalquivir RBMP (2015-2021) and shown in **Table A3** and **Table A4**.

The maximum storage volume is related to the maximum storage capacity of reservoirs (October-November and May to September) and the flood protection function of reservoirs (from December to April).

Table A3. Minimum monthly reservoir storage volume requirements from Guadalquivir RBMP (2015-2021) (*).

Reservoir	**Volume(hm^3)**											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Canales	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Quéntar	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Table A4. Maximum monthly reservoir storage volume from Guadalquivir RBMP (2015-2021) (*).

Reservoir	**Volume(hm^3)**											
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Canales	70.0	70.0	59.4	58.6	57.9	61.5	68.6	70.0	70.0	70.0	70.0	70.0
Quéntar	13.6	13.6	11.4	11.3	11.1	11.8	13.2	13.6	13.6	13.6	13.6	13.6

Cost information

The real costs corresponding to 2017 (publically available in the draft 2019 CR document [131] have been used to estimate the total annual SW costs for each year of the modelled series.

The GW cost curves have been provided by Emasagra (responsible for the operation, management and maintenance of the wells).

Annex C – Example of Canon of Regulation Cost Calculation for the Upper Genil River (using the Real Costs 2017)

Table A5: Cost-recovery calculations (2017 real cost data used, taken from the GRBA 2019 Canon of Regulation): Improvement Coefficient, Priority of Use Coefficient and Distribution Cost Coefficients (own elaboration, data from the SAIH and 2019 Canon of Regulation).

CALCULATION PROCEDURE - IMPROVEMENT AND DISTIBUTION COEFFCIENTS **Year** **2017**

PERIOD		RESERVOIR INFLOW			WATER RIGHT (m^3)		WATER SUPPLIED (m^3)		IMPROVEMENT VOLUME (m^3)	
Year	Month	QUÉNTAR	CANALES	TOTAL	Urban Water Supply 48% Str.	Irrigation (52% Str. + 25% UWS)	Urban Water Supply	Irrigation	Urban Water Supply	Irrigation
2017	1	945,475.20	2,011,478.40	2,956,953.60	1,419,337.73	1,892,450.30	2,605,000.00	18,748.80	1,185,662.27	-
2017	2	1,212,019.20	2,501,452.80	3,713,472.00	1,782,466.56	2,376,622.08	2,330,300.00	104,025.60	547,833.44	-
2017	3	1,687,392.00	4,930,934.40	6,618,326.40	3,176,796.67	4,235,728.90	2,479,700.00	334,800.00	-	-
2017	4	1,073,088.00	6,912,864.00	7,985,952.00	3,833,256.96	5,111,009.28	2,542,900.00	119,232.00	-	-
2017	5	744,595.20	6,085,324.80	6,829,920.00	3,278,361.60	4,371,148.80	2,876,400.00	1,309,737.60	-	-
2017	6	533,952.00	3,154,464.00	3,688,416.00	1,770,439.68	2,360,586.24	3,156,500.00	4,261,248.00	1,386,060.32	1,900,661.76
2017	7	407,116.80	2,188,252.80	2,595,369.60	1,245,777.41	1,661,036.54	3,138,400.00	5,220,201.60	1,892,622.59	3,559,165.06
2017	8	399,081.60	1,848,096.00	2,247,177.60	1,078,645.25	1,438,193.66	2,957,300.00	4,904,150.40	1,878,654.75	3,465,956.74
2017	9	445,824.00	1,521,504.00	1,967,328.00	944,317.44	1,259,089.92	2,928,400.00	1,728,864.00	1,984,082.56	469,774.08
2017	10	594,604.80	1,746,316.80	2,340,921.60	1,123,642.37	1,498,189.82	3,079,200.00	262,483.20	1,955,557.63	-
2017	11	1,021,248.00	2,472,768.00	3,494,016.00	1,677,127.68	2,236,170.24	2,706,100.00	321,408.00	1,028,972.32	-
2017	12	1,320,451.20	3,136,406.40	4,456,857.60	2,139,291.65	2,852,388.86	2,660,400.00	195,523.20	521,108.35	-
						TOTAL	**33,460,600.00**	**18,780,422.40**	**12,380,554.24**	**9,395,557.63**

IMPROVEMENT COEFFICIENT

Irrigation	0.500284681
Urban Water Supply	0.370003952

	Water Supplied	Priority of Use Coeff	Improvement Coeff	Virtual Water	Distribution Coefficient
Irrigation	18,780,422.40	1.00	0.50	9,395,557.63	0.2019
Urban Water Supply	33,460,600.00	3.00	0.37	37,141,662.72	0.7981
Total				**46,537,220.35**	**1.0000**

Annex D – Modelling Simulation Results

- Modelling Simulation Results -Historical monthly water deficits for hypothesis I, II, III and IV and both water users (UWSD and IWD).
- Modelling Simulation results for Canales and Quéntar reservoirs (Hip. II and IV).

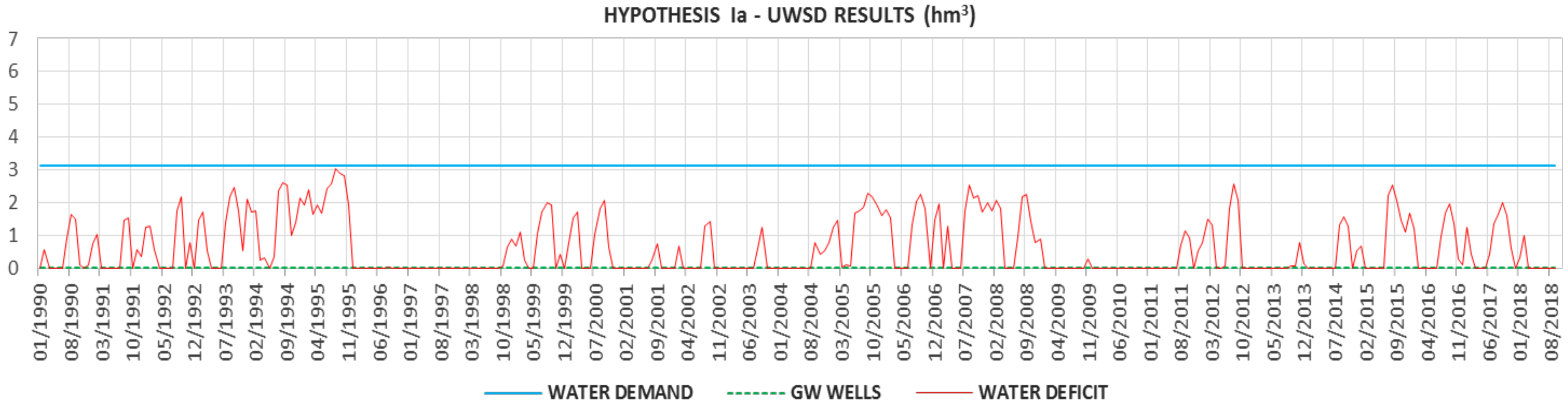

Figure A1. Hypothesis Ia (No reservoirs, no GW wells – USWD priority): Simulation Results for UWSD.

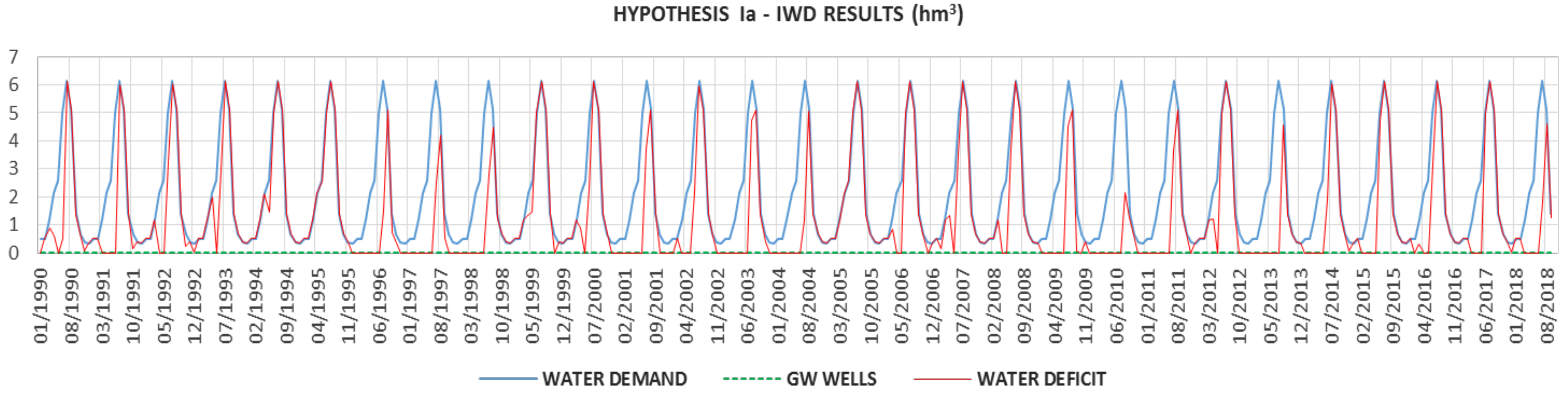

Figure A2. Hypothesis Ia (No reservoirs, no GW wells – USWD priority): Simulation Results for IWD.

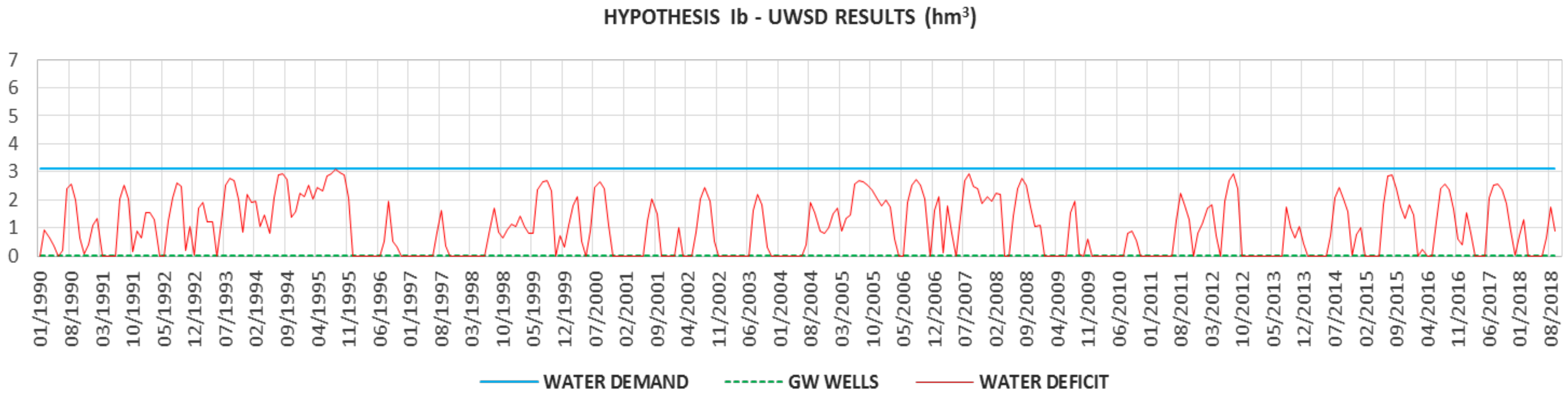

Figure A3. Hypothesis Ib (No reservoirs, no GW wells – Equal priority): Simulation Results for UWSD.

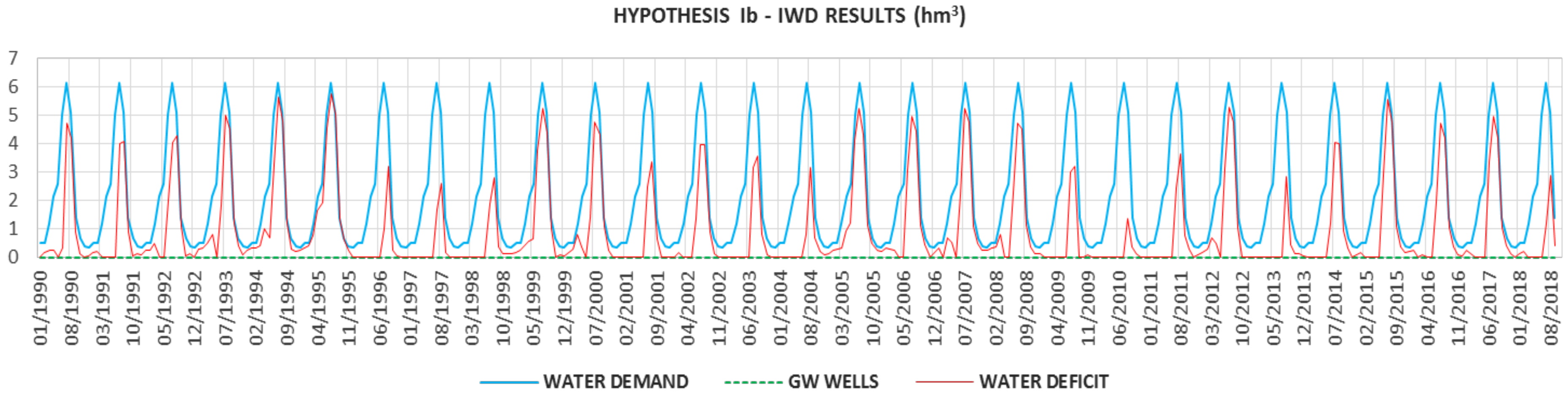

Figure A4. Hypothesis Ib (No reservoirs, no GW wells – Equal priority): Simulation Results for IWD.

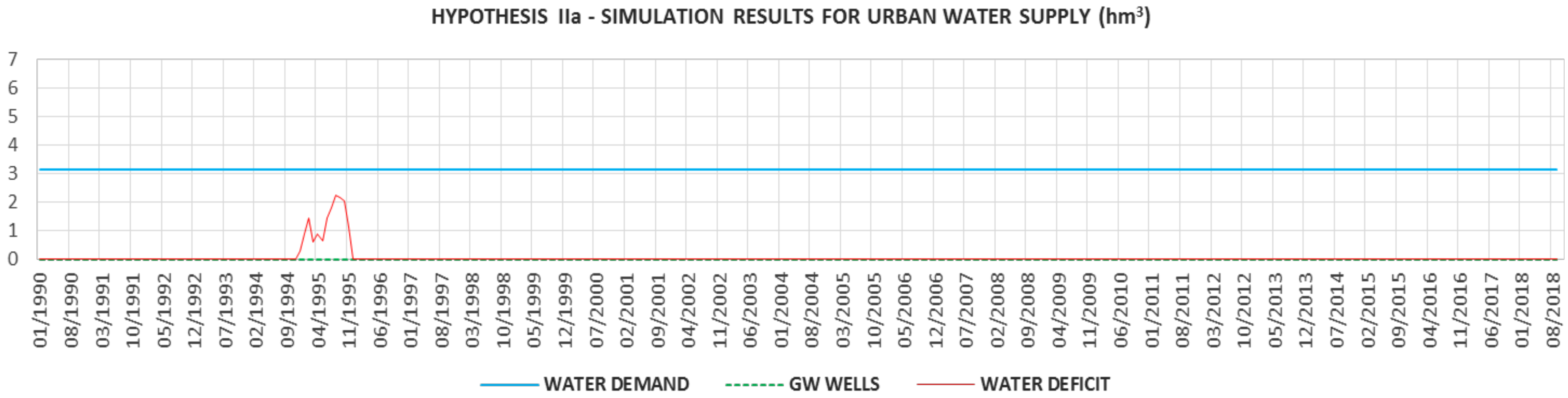

Figure A5. Hypothesis IIa (Reservoirs, no GW wells – USWD priority): Simulation Results for UWSD.

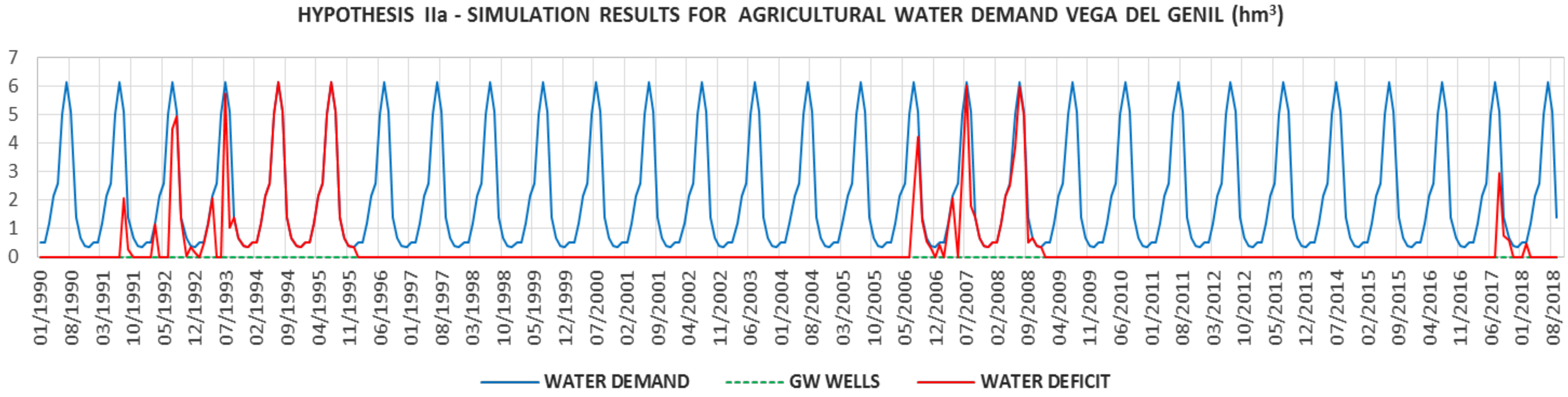

Figure A6. Hypothesis IIa (Reservoirs, no GW wells – USWD priority): Simulation Results for IWD.

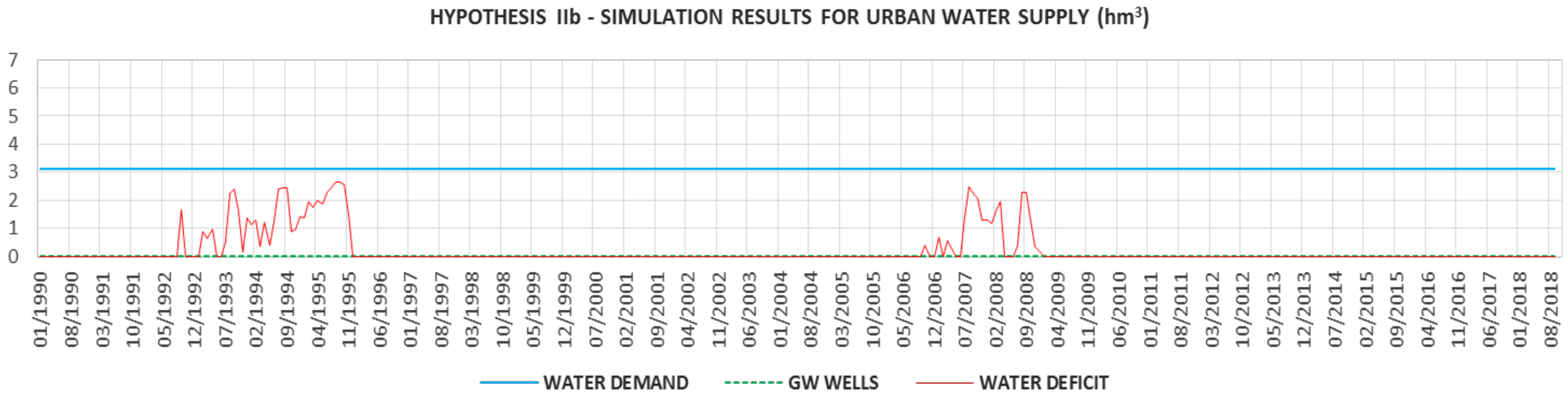

Figure A7. Hypothesis IIb (Reservoirs, no GW wells – Equal priority): Simulation Results for UWSD.

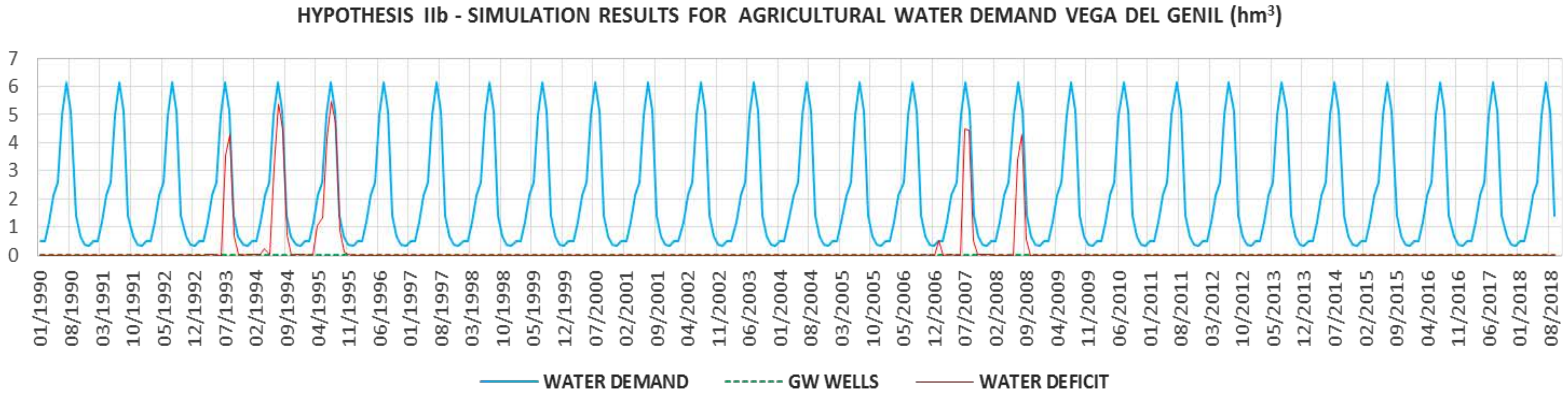

Figure A8. Hypothesis IIb (Reservoirs, no GW wells – Equal priority): Simulation Results for IWD.

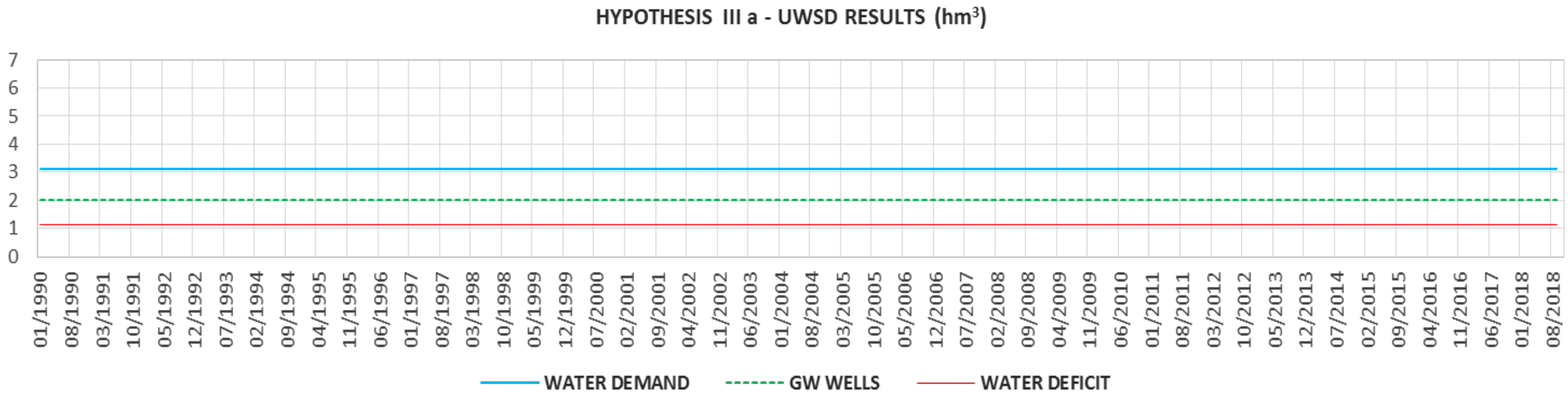

Figure A9. Hypothesis IIIa (No reservoirs, GW wells to serve the USWD)- Simulation Results for UWSD.

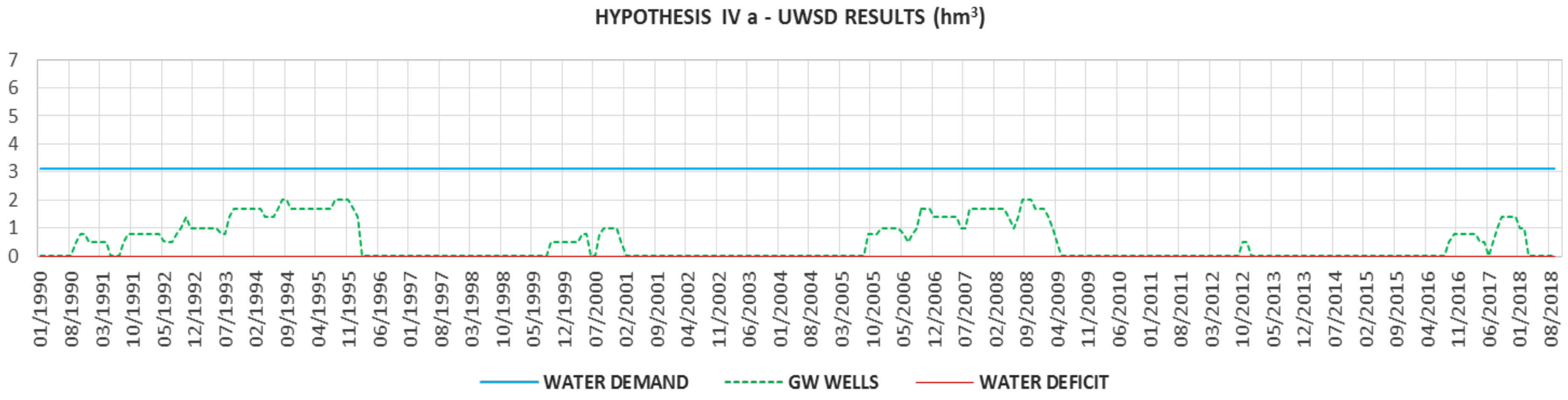

Figure A10. Hypothesis IVa (Reservoirs, GW wells – USWD priority): Simulation Results for UWSD.

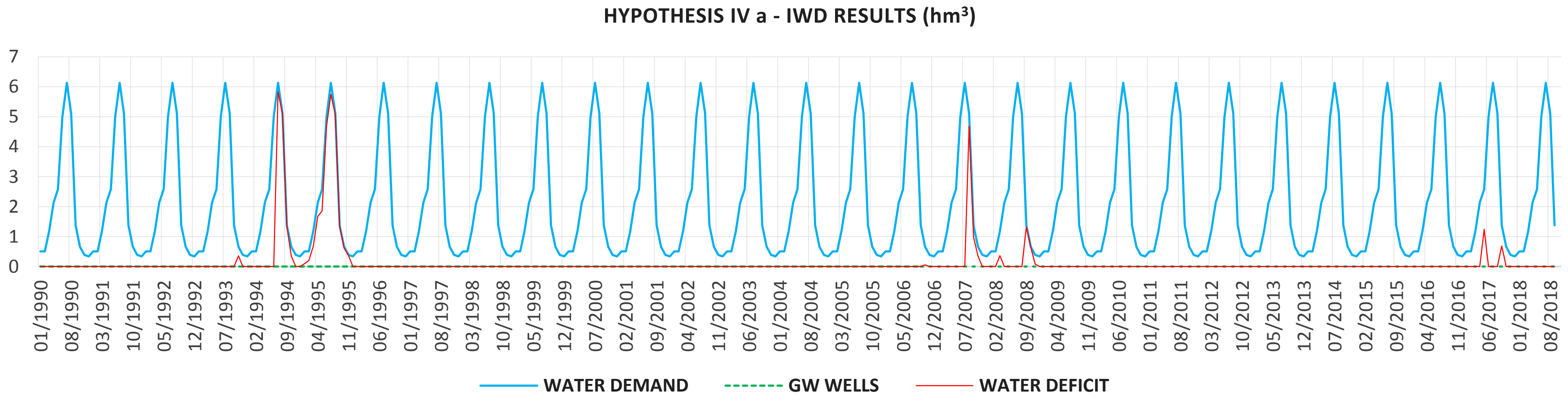

Figure A11. Hypothesis IVa (Reservoirs, GW wells – USWD priority): Simulation Results for IWD.

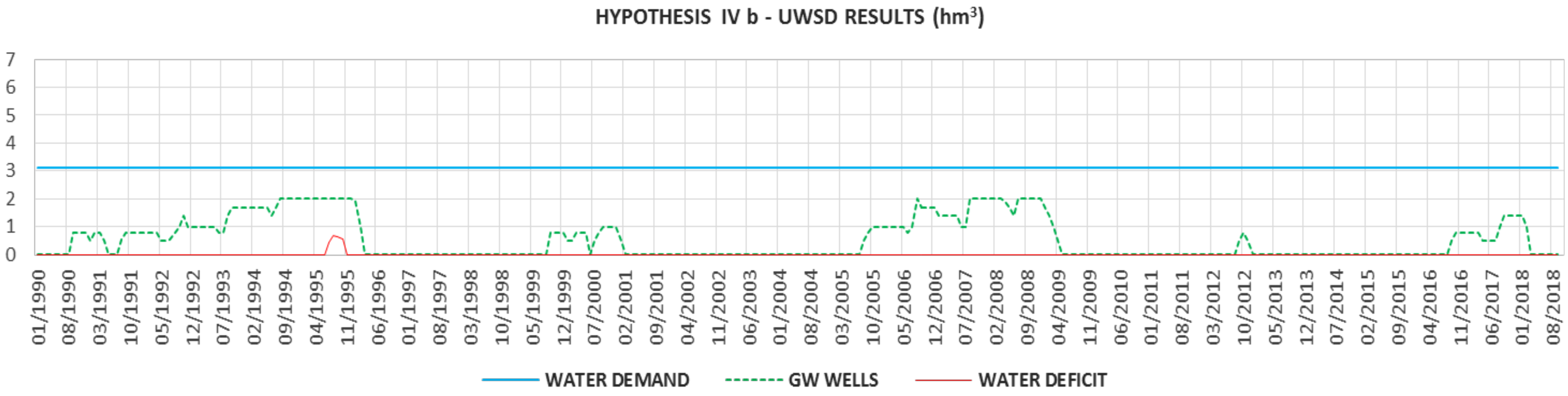

Figure A12. Hypothesis IVb (Reservoirs, GW wells – Equal priority): Simulation Results for UWSD.

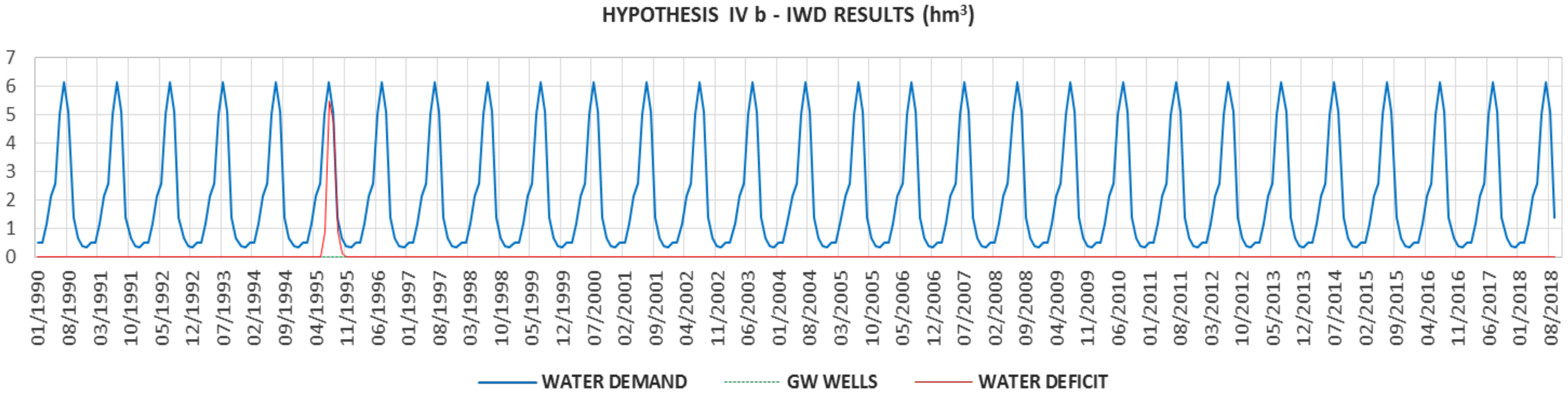

Figure A13. Hypothesis IVb (Reservoirs, GW wells – Equal priority): Simulation Results for IWD.

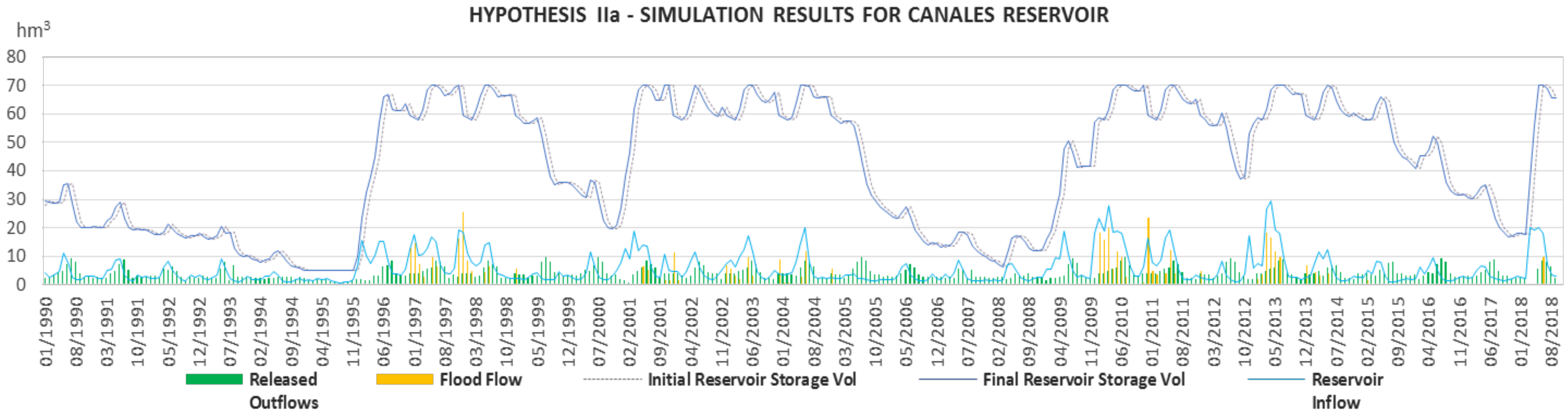

Figure A14. Hypothesis IIa - Simulation Results for Canales reservoir.

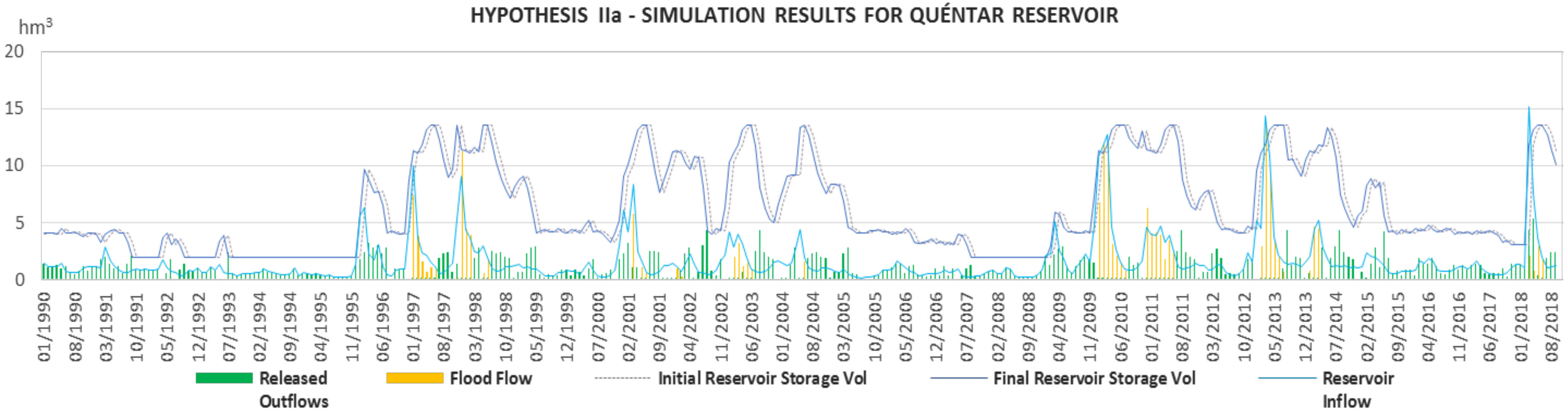

Figure A15. Hypothesis IIa - Simulation Results for Quéntar reservoir.

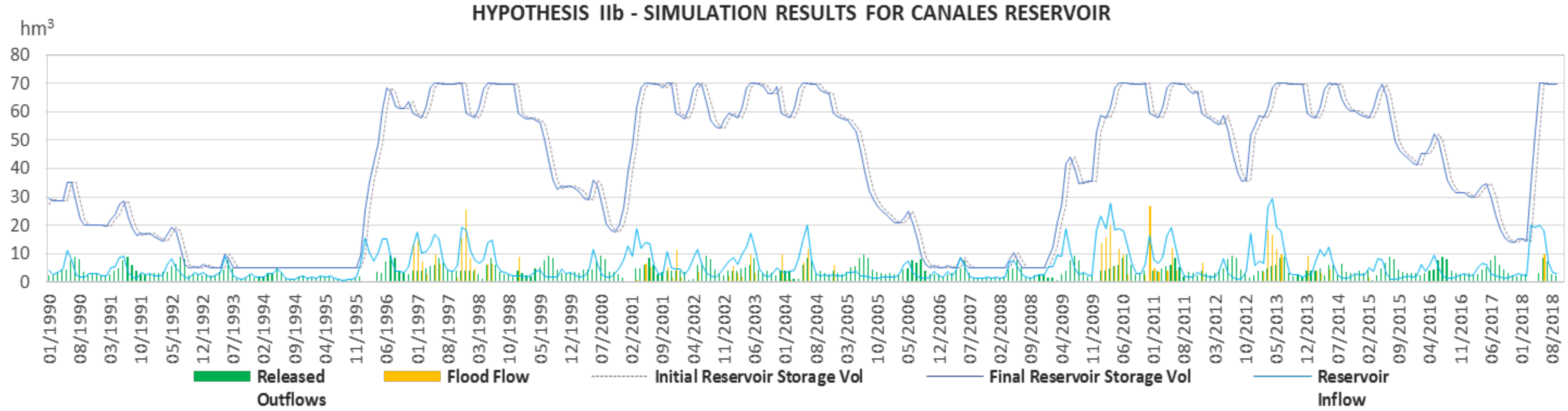

Figure A16. Hypothesis IIb - Simulation Results for Canales reservoir.

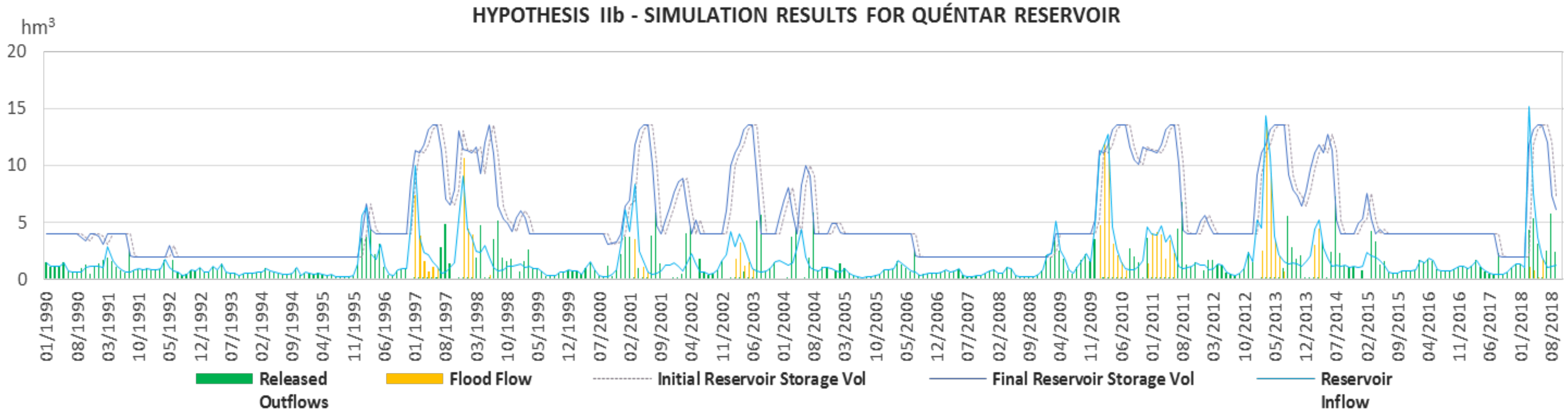

Figure A17. Hypothesis IIb - Simulation Results for Quéntar reservoir.

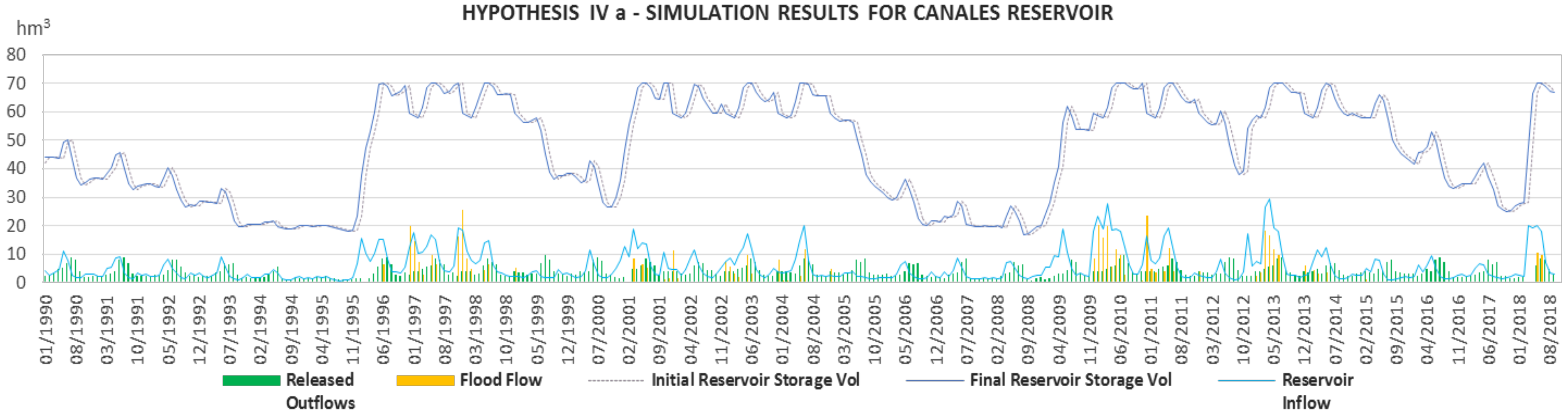

Figure A18. Hypothesis IVa - Simulation Results for Canales reservoir.

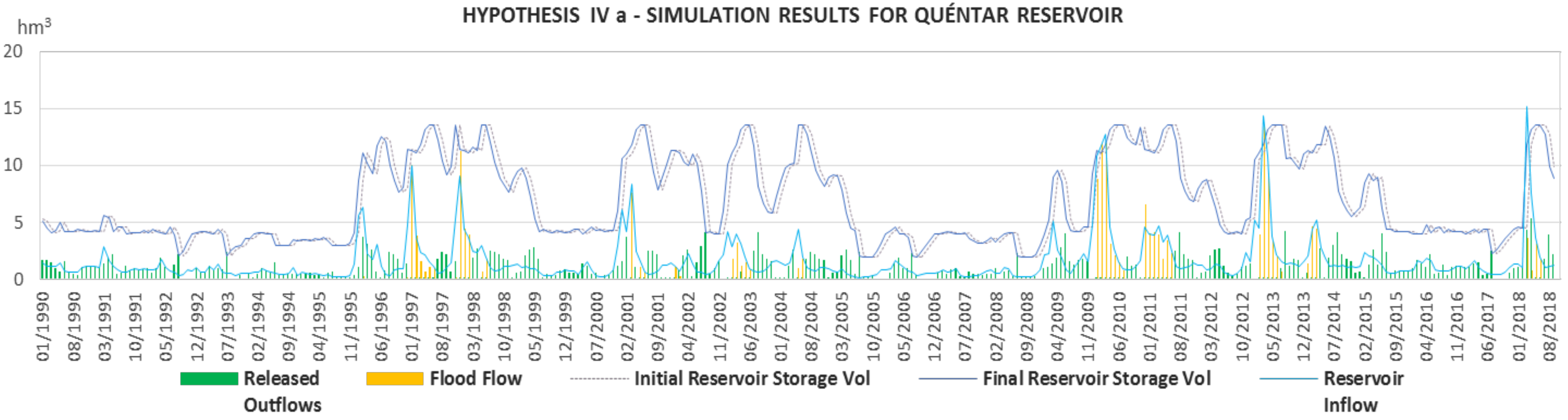

Figure A19. Hypothesis IVa - Simulation Results for Quéntar reservoir.

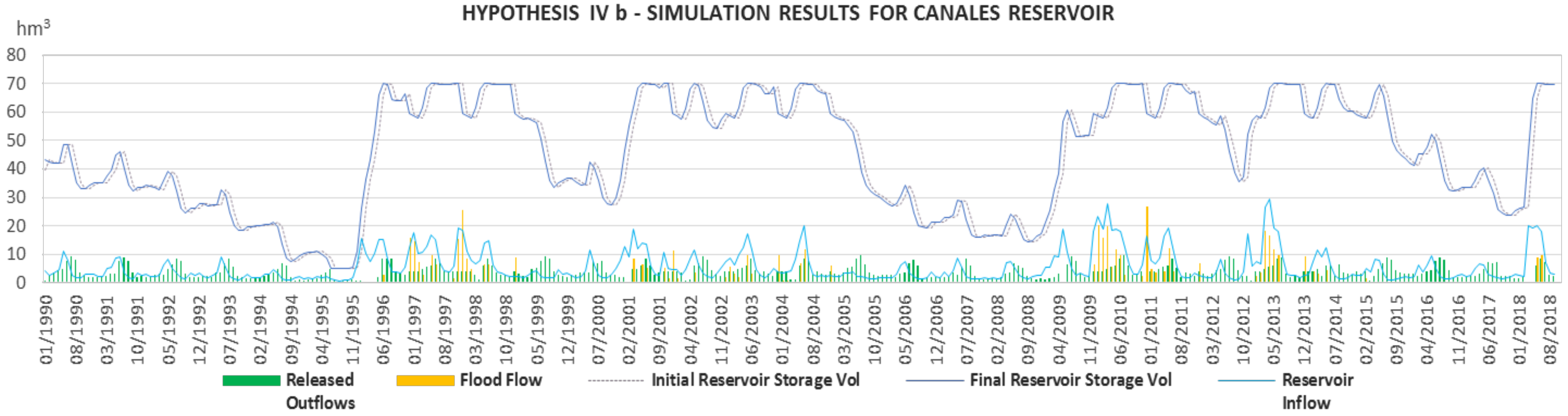

Figure A20. Hypothesis IVb - Simulation Results for Canales reservoir.

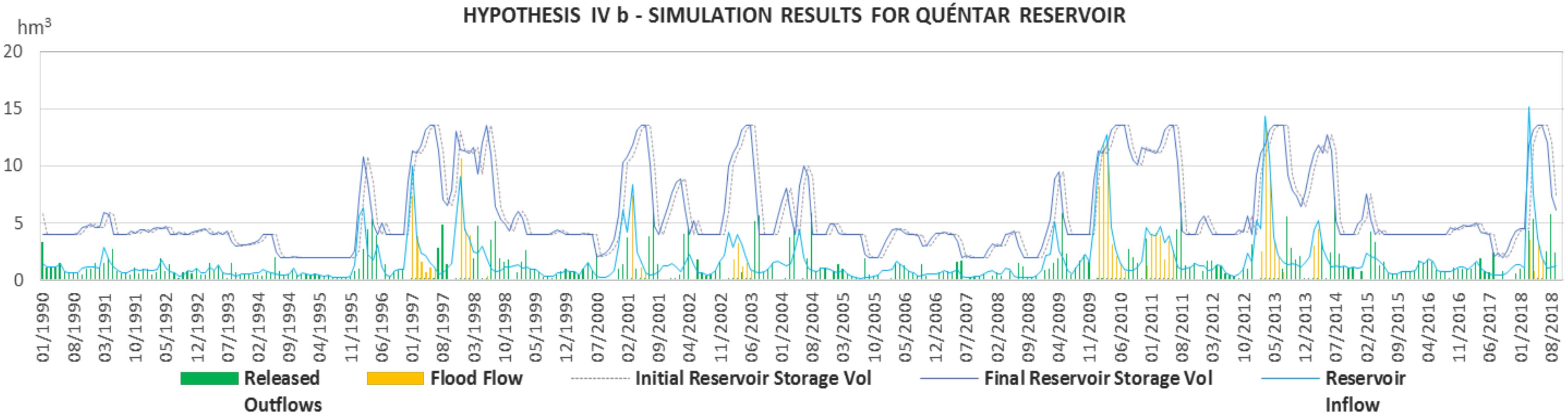

Figure A21. Hypothesis IVb - Simulation Results for Quéntar reservoir.

9. RESULTS AND DISCUSSION

9. RESULTS AND DISCUSSION

This Section presents a summary of the main results obtained from this doctoral thesis as to how they respond to the aim and specific objectives (set out in **Section 2**). Indeed, this Section highlights the contribution made towards improving the existing knowledge and instruments for managing droughts and water scarcity situations, how the results sit within the overall context of the research area and their significance.

The detailed results and discussion were included in Articles I-V (**Sections 4-8**).

9.1 Results and Discussion

The results of this doctoral thesis contribute to building further knowledge and developing new tools in the area of drought management and water cost recovery, so that a more efficient and sustainable use of water can be achieved.

The results can support water authorities, decision-makers, managers and policy-makers to enhance the following areas:

- Drought legislation, policy framework, and governance at European and Spanish level (in response to **Objective 1**);
- Drought management instruments at strategic river basin scale (in response to **Objective 2**);
- Public participation and stakeholder involvement processes: integration of local knowledge and experience in water governance (in response to **Objective 3**);
- Preparedness, planning and management of droughts by using robust forecasting tools (in response to **Objective 4**);
- Transparency in water cost recovery calculations and identification of possible cross-subsidies among water users (in response to **Objective 5**).

A summary of the key outcomes is presented in **Table 18**.

Table 18: Summary of results.

	Objective 1	**Objective 2**	**Objective 3**	**Objective 4**	**Objective 5**
Contribution Area	*Drought legislation, policy framework, and governance at European and Spanish level.*	*Drought management instruments at strategic river basin scale.*	*Public participation and stakeholder involvement: integration of local knowledge and experience in water governance.*	*Preparedness, planning and management of droughts by using robust forecasting tools.*	*Transparency in water cost recovery calculations and identification of possible cross-subsidies among water users.*
Key result	Critical review of the evolution and the current status of European and Spanish water legislation and planning policy framework. It evaluated how drought risk was historically addressed and whether within the current water policy context, an effective drought risk-based management approach might be easily implemented.	Critical assessment of the core technical principles underpinning the proposed methodological and operational framework of the 2018 GRB DMP. To validate this, the practical implications of applying the 2018 GRB DMP were assessed for the Upper Genil River sub-basin (Case of Study).	Critical evaluation of the real influence of the PP process and stakeholder involvement in the 2018 GRB DMP. A set of recommendations for improvement were also provided.	Development of a user-guided, novel, simple, low cost, and robust tool to forecast monthly and annual streamflows within the current hydrological year. The results can support strategic water management decisions and the methodology can be applied to other headwater systems.	Development of a methodology to undertake a hydro-economic evaluation at the sub-basin scale and a tool that objectively calculates the Canon of Regulation for any year of the historical series under different cost distribution assumptions.
Importance, Applicability	The key policy strengths and weaknesses were identified, as well as the main barriers to implement effective drought risk-reduction strategies. A greater integration of drought phenomenon and management of water scarcity episodes from a risk-reduction perspective is required in the EU water legislation. In Spain, the RBAs have made significant strides	The main deficiencies found in the 2018 GRB DMP were: (i) streamflow forecast models were not used; (ii) technical, environmental, and economic assessments were not provided; and (iii) a sound climate change assessment was not included. The results of the comparative assessment showed how the use of robust streamflow forecast models help in achieving the optimal use and management of the existing available water resources of the system during	The major weaknesses were related to the information supply (unclear and insufficient), consultation period (short) and participation approach (late involvement and lack of integration of the local knowledge and experience). Only 8% of the total number of comments received was actually accepted (from which only a minority was related to improvements in the	In average terms, the model performed similarly or even slightly better at providing results for even a longer forecasted period (for up to nine months in advance), using a much simpler methodology than the most recent ARIMA model results (Myronidis et al. [78]). The results can help with the early detection of droughts and water scarcity situations within the current	The methodology developed and results obtained provide transparency in the water cost recovery calculations and help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users. The results from the hydro-economic assessment show that the household user pays an additional average annual cost of approximately € 262,685 (or, €6,863 per

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
	towards the harmonization of technical procedures across all the basins as well as an effective intergovernmental coordination. Still, an extra effort should be made to ensure that the most updated scientific and technical knowledge (that is relevant, credible, and delivered in a timely manner) can be easily and quickly integrated in the Water Legislation and drought instruments, so that prevention, preparedness and management of droughts can be improved. The learnings could be considered in the revision of the WFD and Spanish Water Legislation, as well as the development of the 3rd cycle RBMPs across EU. This can also contribute towards achieving the 2030 SDG 6 ‘*Ensure availability and sustainable management of water and sanitation for all’ to tackle water scarcity”* Relevant to water authorities, decision-makers and policy-makers.	a drought period providing the greatest guarantee of supply. Indeed, the water deficits of the system were considerably reduced (up to 37%), and the use of strategic resources was minimized (up to 9%). This means that: i) the carbon footprint can be minimized, ii) the compliance with the ecological flow regime can be better guaranteed and managed, and iii) social consequences and economic losses due to the unnecessary measures (water restrictions or activation of strategic resources) can be avoided or, at least, considerably minimised. The lessons learned could be applied in the next revision of the Spanish Strategic DMPs, the elaboration of Operational DMPs (by the water companies) and during the development of the 3rd cycle RBMPs across EU. This can also contribute towards achieving the 2030 SDG 6. Relevant to water authorities, decision-makers, managers, users and policy-makers.	drought management strategy). Recommendations: i) provide all the relevant information; ii) foster proactive involvement from all the water users and key stakeholders at an early stage (when it is still possible to alter the strategy); iii) work towards an effective and genuine communication method based on information transparency and collaborative programs; and, iv) extend the consultation period to a minimum of 6 months. The lessons learned could be applied during the consultation period of the 3rd cycle RBMPs across EU and to improve PP in future processes. Relevant to water authorities, decision-makers, managers, users and policy-makers.	hydrological year. If droughts (and their severity) are anticipated, it is more likely that sensible management strategies can be designed and planned in advance by testing different risk scenarios. This allows the implementation of adaptive or phased approaches as the drought evolves during the year. Consequently, the most optimal and sustainable approaches can be achieved. The risk-based predictions are of great value, especially in Mediterranean countries before the intensive irrigation campaign starts in the middle of the hydrological year (March-April). At this time, the Water Authorities have to ensure that the right decision is made on the best allocation of the available water resources among the different water users and environmental needs of the particular system. Relevant to water authorities, decision-makers, managers, users and policy-makers.	cubic hectometre of water consumed) for having the theoretical priority of water use over the agricultural water user. However, this additional cost paid by the household user is not always translated into a significant increase in guarantee of water supply. In fact, the simulation results showed that if both water users would have the same priority of water use, the current water demands of the system would still be met in practically all months of the entire simulated 30-year period (with only a negligible water deficit in the driest year of the simulated series, i.e. in 1995). The lessons learned could be applied during the 3rd cycle RBMPs across EU and other similar basins to objectively identify the existence of cross-subsidies. Relevant to water authorities, decision-makers, managers, users and policy-makers.

9.1.1 Contribution towards improving the drought legislation, policy framework, and governance at European and Spanish level (in response to Objective 1)

A critical review of the evolution and current status of European and Spanish water legislation, drought management planning policy and recently developed scientific and technical advances was undertaken. It was assessed whether the current water policy provides the appropriate platform to efficiently deal with droughts and water scarcity events along with the implementation of drought risk-based management approaches.

While there have been significant improvements and advances in the last two decades in relation to drought management, there are still some areas that require further work:

At the EU level:

- A greater integration of droughts and management of water scarcity episodes from a risk-reduction perspective is required in the EU water legislation.
- Droughts are only succinctly dealt with within the WFD. These are only mentioned in art. 1(e) in relation to "*mitigating drought effects*" as one of the WFD objectives and art. 4.6 in relation to *prolonged drought* (when a temporary deterioration in the status of water bodies could be allowed). In fact, the elaboration of the DMPs is currently not mandatory.
- Water scarcity is not explicitly dealt with within the WFD. Nevertheless, art. 9 enables Member States to implement incentive and transparent water pricing policies to attain water efficiency and foster improved water allocation strategies. However, it does not establish a clear strategy about how to achieve this in practice.
- After the devastating impacts from the 2003 drought in Europe, droughts and water scarcity were considered as a major challenge afflicting the European territory.
- A key milestone in terms of European drought-risk management was achieved by the 2007 EC Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*". This presented seven policy instruments for tackling water scarcity and drought issues at European, national and regional levels and included options in relation to '*putting the right price tag on water*', '*allocating water more efficiently*', and '*fostering water efficient technologies and practices*'. The proposed water hierarchy considered additional water supply as the last resort option, only to be pursued once water saving, water-efficiency, water pricing policy, and cost-effective alternative solutions had been exhausted. This Communication recommended the development of DMPs (as supplementary documents of the RBMPs in line with art. 13(5) of the WFD), shifting from the traditional crisis/emergency to a risk-reduction management approach.
- The EU has adopted important instruments to identify and monitor droughts and water scarcity such as the European Drought Observatory (EDO) and the water exploitation index plus (WEI+). Additionally, the European database called "*European Drought*

Reference database" (EDR) and the "*European Drought Impact Report Inventory*" (EDII) provide considerable information about historical drought events in Europe. However, there are still key challenges related to the practical integration and application of this information as well as the process of detailing this information and updating these tools with the most recent and relevant information (so that their use can be maximised by all EU members).

At the Spanish level:

- Spain is one of the EU Member States with the longest track record in water legislation and hydrological planning. Proof of this is the fact that the 1985 Water Act already introduced the innovative concept of river basin management approach (which would be incorporated 15 years later in the WFD 2000), all the RBAs were established between 1926 and 1961 [55] and the first RBMPs were finished 1998-1999 (20 years earlier than the first RBMPs in Europe).
- The experience and lessons learnt after the devastating environmental, social, and economic consequences of the 1991–1995 drought in Spain led to a paradigm shift from the traditional crisis/emergency approach (through the adoption of Emergency Drought Orders or Decrees) towards a drought risk-reduction management strategy.
- This need is reflected in art. 27 of Law 10/2001, of July 5, of the National Hydrological Plan that establishes the preparation of Strategic DMPs (Art 27.2) and Operational/Emergency DMPs (Art. 27.3) as mandatory. In response to that, the first Strategic DMPs for the inter-community RBDs were prepared by the RBAs and approved in 2007.
- After a decade since their first publication and 2 RBMPs cycles, all the Strategic DMPs for the inter-community RBDs were revised by the RBAs by the end of 2017 and finally adopted in December 2018. These DMPs established the framework for the drought management approach at the river basin and sub-basin scales, defined droughts and water scarcity indicators and their thresholds, monitoring and early warning systems, and measures to be applied progressively during each drought phase.
- Indeed, important innovative aspects have been integrated in the latest 2018 DMPs such as the clear differentiation of droughts events (natural climatic events) from water scarcity situations (anthropic intervention) by setting out a different diagnosis system and measures to deal with each phenomenon separately.
- A common indicator system was established to be applied in all river basins in Spain in compliance with the Spanish Water Legislation. The great advantage of this common indicator system is that despite the diverse climatic and geographical conditions in each individual sub-basin, diagnosis results are comparable. So if a similar (drought or water scarcity) indicator value is found in two different sub-basins, the (drought or water scarcity) situation is expected to be similar and the measures to be applied are expected to be of the same type.

- This will not only provide support to the RBA decision-making processes (especially when declaring formal drought situations) but it will also be instructive when disseminating drought information to the water users and general public.
- This shows significant strides made by all RBAs in Spain towards the harmonization of technical procedures across all the basins as well as an effective intergovernmental coordination between all the organizations and processes involved at the political, technical, and institutional levels. This demonstrates how a common global indicator system and methodology could be also implemented at the EU level.
- Besides the strengths outlined above, there are some aspects of the latest 2018 DMPs that need further evolution. For example, the methodology to calculate the water scarcity thresholds (onset, duration, severity) remains practically unchanged from that used in 2007. This is based on conservative assumptions that might lead to the activation of more extreme measures than are really required (and their possibly unnecessary environmental, economic and social consequences). Despite the advantages of using reliable and accurate streamflow forecasting models, these still remain underused by many water authorities and water decision-makers.
- Whilst the most important elements of a DMP are included (the identification of the risk, its characterization, and the proposed actions before, during and after the event), the 2018 DMPs lack a methodology to measure the effectiveness of measures, taking into account the possible socio-economic and environmental impacts.
- Even though the DMPs provide the overall protocol of action, it is fundamental that the DMPs establish a clear strategy in terms of water use priorities and the hierarchy of water measures (demand/supply) for each drought/water scarcity phase and each sub-basin (or water exploitation system), as well as specific objectives in terms of water efficiency and water reduction. Generalist approaches could lead to possible misinterpretation among water users and an increase in existing and future water conflicts.
- At the same time, DMPs should be live and flexible documents, so the most updated scientific and technical knowledge that is relevant, credible, and delivered in a timely manner can be easily and quickly integrated to improve drought management (without the need to wait for the next revision) as well as if better solutions are found. This will foster continuous improvement together with the development and implementation of preparedness, adaptive, progressive and proactive management strategies, which can help to deal resourcefully with uncertainty and complexity.
- Strategic DMPs (developed by the RBAs) and Operational DMPs (developed by the water companies) should be fully co-ordinated and integrated in order to ensure that indicators, thresholds and measures are coherent and representative of the local circumstances. For example, they could be developed in parallel, or at least, RBAs should work closely with water companies and other important water consumers (especially, the agriculture sector) of the system when Strategic DMPs are being developed.

- On the other hand, the Operational DMPs (developed by the water companies) for mixed water systems (where available water resources are shared among different water uses) should be also subject to public consultation (for example, after reaching an “*Agreement in Principle*” with the RBA).

In summary, the key policy strengths as well as the deficiencies in water legislation, water planning policies and instruments that hinder the implementation of drought risk-reduction management strategies were identified. These can be helpful to policy-makers at European and at national level for EU member states, especially when revising water legislation and planning policies.

Indeed, the lessons learned could be considered in the revision of the WFD and Spanish Water Legislation and planning policies, as well as during the development of the 3rd cycle RBMPs across EU. This can also contribute towards achieving the 2030 Agenda Sustainable Development Goals (SDG). Particularly, SDG 6 “*Ensure availability and sustainable management of water and sanitation for all’ to tackle water scarcity*”.

9.1.2 Contribution towards improving the drought management instruments at strategic river basin scale (in response to Objective 2)

A critical technical assessment of the recently approved 2018 GRB DMP was undertaken. The core technical principles underpinning the proposed methodological and operational framework were evaluated. The main strengths and weaknesses, as well as areas of further development and improvement were identified. To validate this, the practical implications of applying the 2018 GRB DMP were assessed for the Upper Genil River sub-basin (Case of Study).

The main deficiencies found in the 2018 GRB DMP were the following: (i) streamflow forecast models (or seasonal climate forecasts) were not used to improve drought management, (ii) specific technical, environmental and economic assessments were not provided to support the proposed drought management measures, (iii) a sound climate change assessment was missing.

A technical analysis of the practical implications of applying the 2018 GRB DMP to a specific sub-basin area (Upper Genil River) was undertaken and based on that, a set of proposals for improvement were provided, which include the following:

- It was recommended to use the long reference period (i.e. the long-term historical precipitation and streamflow series) instead of the short reference period to calculate the Drought Indicator System (Standardized Precipitation Index) and Water Scarcity Indicator System. The 2018 GRB DMP justifies the use of the most recent short reference period because it reflects better the most recent changes in climate in comparison with the long-term data series. However, the historical data sets provide important information for adequate probabilistic treatment, and cannot just be ruled out. An alternative option could be to use a weighting system so that the most recent years are assigned a greater weight compared to previous years.

- It was proposed an alternative methodology to calculate water scarcity thresholds that are more representative of the intrinsic operational reservoir system. These help to objectively identify the potential temporal difficulty in meeting the water demands and recognise different phases of water scarcity in the system, so measures can be proportionate to the real situation and progressively applied to avoid entering in more severe phases.
- It was recommended to use streamflow forecast models to improve drought management during the current hydrological year.

To validate the above, a comparative assessment was carried out to assess how a water scarcity situation had been managed under the following circumstances: (i) complying with the 2018 GRB DMP protocol (indicators, thresholds and measures), and (ii) using a streamflow forecast model in combination with the proposed alternative water scarcity thresholds. The results showed that for the Case of Study:

- The optimal use and management of the existing available water resources of the system during a drought period that provided the greatest guarantee of supply was achieved through the use of streamflow forecast tools.
- The water deficits of the system were considerably reduced (up to 37%), and the use of strategic water resources was minimized (up to 9%) thanks to the use of streamflow forecast tools.
- So, the carbon footprint could be minimized, the compliance with the ecological flow regime could be better managed, and social consequences and economic losses due to the unnecessary water restrictions could be avoided or, considerably minimised.

The lessons learned could be considered in the next revision of the Spanish Strategic DMPs, the elaboration of Operational DMPs as well as during the development of the 3rd cycle RBMPs across EU (to further integrate the management of droughts and water scarcity).

9.1.3 Contribution towards improving public participation and stakeholder involvement processes: integration of local knowledge and experience in water governance (in response to Objective 3)

A critical review of Public Participation (PP) and Stakeholder Involvement Process associated to the recently adopted 2018 GRB DMP was carried out. This evaluated whether and to what extent the contribution provided by the different stakeholders and interested parties actually meant a significant change and a real influence on the approved drought management strategy established in the 2018 GRB DMP.

The outcomes from the review showed that the major weaknesses were related to the information supply (unclear and insufficient), consultation period (short) and participation approach (late involvement and lack of integration of the local knowledge and experience provided by the participants).

The most frequently repeated concerns among the participants were related to the proposed actions and measures to be applied during the occurrence of a drought event (i.e. the core of the drought management strategy).

The results from the analysis showed that only 8% of the total number of comments received (157) were actually accepted. From this small proportion, the majority corresponded to typo, conceptual or calculation errors, while only a minority of the accepted comments were related to improvements in the drought management strategy.

Bearing in mind those results, it could be concluded that PP was a mere box-ticking exercise to comply with the EU WFD legal requirements rather than a real mechanism to improve the drought management strategy taking into consideration the contribution made by water users.

For future PP processes, it was recommended to:

- Involve all interested parties at an early stage (when the options are still under consideration and there are still opportunities to adjust the strategy) and extend the consultation period to a minimum of 6 months (in line with Art. 14 of the WFD).

- Work towards an effective and genuine communication method based on information transparency and collaborative programs among water users. This could help towards integrating site-specific knowledge and achieving consensus among water users in controversial topics (which come to light or are being exacerbated precisely during drought periods).

These recommendations may contribute to achieving consistent, transparent and responsible drought management solutions during the entire life-cycle of a DMP (development, implementation, monitoring, control and recovery/lessons learnt). Other important benefits could be brought in, such as taking more ownership and responsibility from water users while stimulating innovation, increasing acceptance of solutions, building constructive relationships and reducing potential future water conflicts.

Therefore, learnings could be applied to improve PP in water governance issues and efficient implementation in water management tools, decisions, practices and policies. For example, these could be applied during the current consultation and development of the 3rd cycle RBMPs across EU, as well as the development of other water management planning policies or instruments at National or Regional Scale.

9.1.4 Contribution towards improving the preparedness, planning and management of droughts by using robust forecasting tools (in response to Objective 4)

Nowadays, water authorities and decision-makers are facing considerable challenges in achieving a resource and cost-efficient water allocation strategy, especially in water-stressed basins. The main reasons are the increasing water demands and environmental requirements, the climatic variability and uncertainty, as well as the lack of using reliable forecasting and simulation tools to support their decisions.

In Mediterranean countries (for example, Spain), where agriculture plays an important socio-economic role, the critical decision point is in the middle of the hydrological year just before intensive irrigation campaigns commence (usually in April [89]). At this time, water authorities must make responsible management decisions on the optimum allocation of available water volume from a wide range of possible water sources (reservoirs, non-regulated rivers, groundwater resources, water re-use schemes, desalination plants, etc.) among the demands of, usually, multi-sectoral water users (urban, agriculture, industry, tourism, energy, etc.) and taking into account the environmental needs.

One of the key deficiencies found in the most recent 2018 GRB DMPs was the absence of using streamflow forecasting models to improve drought risk-reduction management.

Given the extensive archive of available local hydrological information (including previous droughts events) for the Upper Genil River sub-basin, the historical relationship between rainfall and streamflow was investigated.

A practical and robust streamflow forecasting tool was developed. The procedure innovatively combines the use of well-known regression analysis techniques, the two-parameter Gamma continuous cumulative probability distribution function and the Monte Carlo method. The model outputs are the probabilistic mean annual and monthly streamflows within the current hydrological year along with the 10th and 90th percentiles (which can be easily modified by the user, if needed). The model also has the ability to incorporate seasonal climate predictions and climate change effects.

The model results were compared with the most recent ARIMA model results (shown in Myronidis et al. [78] and similar works cited by the same author). It was found relevant that in average terms, the model performed similarly or even slightly better at providing results for even a longer forecasted period (for up to nine months in advance), using a much simpler methodology.

The methodology was successfully applied to two headwater reservoirs (Canales and Quéntar) within the GRB in southern Spain, achieving good levels of accuracy (especially in March/April).

The key advantages of this procedure are:

a. The use of relatively simple algorithms and well-known techniques, which can be easily implemented in an excel spreadsheet;
b. the use of a minimum number of hydrological variables (streamflow and precipitation);
c. the model saves substantial computational time in comparison with any other data-driven models (the model takes just a few seconds to run the simulations);
d. the model does not depend on other software to achieve the results;
e. the model offers an intuitive user interface, which can be easily used by

non-technical experts such as water authorities, water managers or water users. Therefore, it overcomes one of the major traditional limitations associated to the use of this kind of models;

f. the model integrates easily and quickly new observed hydrological information;

g. the results achieved are robust, In fact, they are similar or slightly better than those achieved with other more complex models.

These risk-based forecasts outputs can help with the early detection of droughts and water scarcity situations. If droughts (and their severity) are anticipated, it is more likely that sensible management strategies are designed by testing different risk scenarios, and consequently, optimal actions can be implemented (following, for example, a phased approach as the drought evolves in time and engaging the key Stakeholders in the process). Therefore, these can support strategic water management decisions when deciding on optimum water allocation to achieve resource and cost-efficient strategies.

These risk-based forecasts outputs can be also helpful to all water users and stakeholders involved in the planning, management, and decision-making processes.

9.1.5 Contribution towards improving transparency in water cost recovery calculations and identification of possible cross-subsidies among water users (in response to Objective 5)

The current lack of transparency in the water cost recovery calculations is one of the most important obstacles for attaining a rational water pricing policy consistent with the requirements of the WFD. This was highlighted by the forth European Commission report on the implementation of the WFD RBMPs in 2015. A consequence of this is, in many cases, the existence of cross subsidies between water users of the same water system.

It was assessed whether there was a cross-subside among the main competing water users of the Upper Genil River (i.e. households and agriculture). This is, if some water users pay part of the cost attributable to other water users, justifying it as a theoretical greater guarantee of water supply during drought events and water scarcity periods (without being accompanied by a transparent cost-benefit analysis).

It was found necessary to shed light on this by developing a hydro-economic evaluation at the sub-basin scale. A tool was developed that objectively calculates the Canon of Regulation (or, fee paid by the beneficiaries of the surface water or groundwater regulation infrastructures to contribute towards the financial costs supported by the State) for any year of the historical series under different cost distribution assumptions.

This allowed the development of a quantitative assessment of the impact of the 3 to 1 increase in the contribution costs applied to the SW volume consumed by the priority water user of the Upper Genil River (i.e. the household water user).

After calculating the economic contribution to the recovery of the raw water service cost from each water user of the system, it was found that the household user pays an additional average annual cost of approximately €262,685 (or, €6,863 per cubic hectometre of water consumed) for having the theoretical priority of water use over the agricultural water user.

However, this additional cost paid by the household user is not always translated into a significant increase in guarantee of water supply. In fact, the simulation results showed that if both water users would have the same priority of water use, the current water demands of the system would be met in practically all months of the entire simulated 30-year period (with only a negligible water deficit in the driest year of the simulated series, i.e. in 1995).

This means that despite the extra annual cost paid by the household water user, in practice, the priority of water use would only be patent in very extreme drought events (approximately 200-year return period) and when all the water resources of the system have been completely exhausted.

However, that theoretical priority of water use is not always applied in practice during historical drought events. After the 1991-1995 drought and only for the Upper Genil River sub-basin of the GRB, the urban water supply user was requested to economically compensate the agricultural sector for the loss of harvests (since all the available SW from the two existing reservoirs was made available to the urban water supply user).

It was therefore concluded that in Spain, a greater emphasis should be placed on the critical role played by the water pricing policies as an effective and direct tool to communicate the real water service cost to the water user.

The methodology developed and results obtained provide transparency in the water cost recovery calculations and help in identifying the economic efficiency in the allocation of water resources as well as potential cross-subsidies among water users. Therefore, it can be applied to other similar basins to quantitatively identify the existence of cross-subsidies. The learnings could be applied during the current consultation and development of the 3rd cycle RBMPs across EU to improve transparency in the economic assessments.

10. CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH LINES

10. CONCLUSIONS, RECOMMENDATIONS AND FUTURE RESEARCH LINES

This Section draws the overall conclusions and recommendations from this doctoral thesis as well as the proposed lines of future research. The detailed conclusions and recommendations were included in **Sections 4-8**.

10.1 Conclusions

Droughts are natural phenomena that affect countries throughout the planet, albeit unevenly. The characteristics of droughts (duration, magnitude and frequency) are specific to each climate region and determine the impact on water resources (soil moisture, river flows, groundwater levels, snow storage, reservoirs storage water levels, etc.) and ultimately, the impact on the rest of water-dependent sectors (environment, society and economy).

The severity of the drought impact on the environment, society and economy will depend on (apart from the inherent characteristics of the drought hazard) diverse site-specific circumstances like: i) the level of resilience and efficiency of the existing water infrastructures; ii) the water resources management protocol in place; iii) the existing socio-economic factors such as the population and water use patterns, urbanization, economic development and agricultural practices, etc.; and iv) the environmental water constraints (e-flows). So, the same drought event might have different impacts on different communities.

Droughts cannot be avoided since they form part of the climate variability of a region. However, these natural phenomena are being altered by the impacts of global warming. According to climate change projections, it is expected that they will become more frequent and intense as the 21st century progresses and therefore, adding pressure to those already water stressed regions.

Efforts should thus be focused on learning how to live with these complex phenomena by improving preparedness, risk-reduction management strategies and progressive adaptation in order to enhance resilience and reduce vulnerability, and with all that, avoid (where possible) or minimise the potential negative impacts.

Precisely for this reason, it is fundamental to manage droughts from an integrated perspective, so that optimal balance can be found among technically feasible, environmentally sensible, economically efficient, and socially acceptable measures to deal with droughts and water scarcity.

In this context, DMPs represent key strategic tools to support rational water resources management and build resilience to drought extremes. DMPs should define relevant drought and water scarcity indicators and their thresholds, provide robust early warning systems, and establish a clear hierarchy of measures and priorities among water users, together with a clear action roadmap to be followed during each drought phase. In order to be effective tools and provide reliable support to water decision-makers, DMPs should promote simple, practical, and scientifically sound approaches. These should be based on technical evidence, the latest engineering and scientific knowledge, as well as lessons learned from managing historical droughts.

Although the organizational and institutional framework of each country is different, three drought management levels can be pointed out: Strategic, Operational, and Contingency (or Emergency). For example, in Spain each RBA is the competent authority responsible for not only preparing the Strategic DMP at the river basin scale, but also its implementation, management, monitoring, control, and follow-up. Additionally, water companies should elaborate Operational and Contingency DMPs for urban water supply systems serving more than 20,000 people (to be approved by the RBA) in order to ensure water services under drought situations in accordance with the directions provided in the Strategic DMP. It is however crucial that Strategic Plans are fully co-ordinated with Operational and Contingency DMPs, so that, the key water-related issues are addressed.

The most significant challenge that surfaces, when a new drought event strikes, is the difficulty in predicting its duration (which can vary from months to years), the severity (or degree of affection to water resources), and the potential environmental, economic, and social impacts. Hence, there is an importance of integrating reliable forecasting and modelling tools in the development of modern DMPs, so the potential risk can be assessed under a range of possible drought scenarios and preventive drought-risk management strategies can be developed. This will ensure that the proposed measures and actions of the DMP are sufficiently robust and proportionate to the drought and water scarcity situation.

This doctoral thesis assessed and proposed different tools for improving drought management by providing: (1) a critical review of the strengths and weaknesses of European and Spanish water legislation and planning policies; (2) a critical analysis of the limitations and practical implications of applying the most recent 2018 Guadalquivir River Basin (GRB) Drought Management Plan (DMP), with a special focus on the methodological approach and operational framework; (3) a critical assessment of the real influence of the public participation and consultation process in shaping the 2018 GRB DMP, providing recommendations for improvement; (4) a practical streamflow forecasting tool to support strategic water decisions; and (5) a hydro-economic methodology to provide transparency in the water cost recovery calculations and identify potential cross-subsidies among water users of a particular water system.

At the European level, one of the objectives of the WFD (2000/60 / EC) is to "*mitigate the effects of floods and droughts*" (Art.1 (e)). However, droughts are only succinctly dealt with in the WFD and the elaboration of DMPs is not compulsory. The 2007 EC Communication "*Addressing the Challenge of Water Scarcity and Droughts in the European Union*" recommended the development of DMPs (as supplementary documents of the RBMPs in line with art. 13(5) of the WFD). On the other hand, even though the EU drought management tools (EDR, EDII, EDO, WEI+, etc.) are instructive and informative, the key challenges are related to the practical application of this information and updating these tools with the most recent data (so their use can be maximised in practice by EU members). The results of the critical review showed that there are still certain deficiencies in water legislation, water planning policies and instruments that hinder the implementation of drought risk-reduction management strategies.

In Spain, the preparation of DMPs is mandatory and is regulated in article 27 of Law 10/2001, of July 5, of the National Hydrological Plan. In fact, the first DMPs for all inter-community basins were approved in 2007. Since then, important innovations have been integrated in the latest 2018 DMPs such as the clear differentiation of droughts events (natural climatic events) from water scarcity situations (due to anthropic interaction with water resources) by setting out a different diagnosis system (indicators, thresholds and phases) and measures to deal with each phenomenon separately. The great advantage of this common methodology (applied in all inter-community basins) is that diagnosis results are comparable across all river sub-basins, and therefore, measures to be applied should be of a similar type. This highlights not only the significant strides made by all River Basin Authorities (RBAs) in Spain towards the harmonization of technical procedures but also an effective intergovernmental coordination between all the organizations and processes involved at the political, technical, and institutional levels. This demonstrates how a common global indicator system and methodology could be also implemented at the EU level.

Nevertheless, there are important technical aspects (such as the methodology applied to calculate water scarcity thresholds) that remain practically unchanged and which hardly differ from those used over a decade ago in the previous 2007 DMPs. Despite the considerable advances in streamflow forecasting models, these still remain under-used by many water decision-makers and have not been integrated in the latest drought management instruments.

At the GRB management level, significant deficiencies have been found in the 2018 DMP, including the following: (i) streamflow forecast models (or seasonal climate forecasts) are not used to improve drought management; (ii) specific technical, environmental, and economic assessments are not provided to support the proposed drought and water scarcity management measures; and (iii) a sound climate change assessment is not included. An alternative methodology to calculate the water scarcity thresholds has been proposed, and the benefits of using those in combination with streamflow forecasting tools have been demonstrated.

Whilst establishing water scarcity thresholds may be an approach to identify the water scarcity situation and the sort of measures to be applied, the results showed that the use of these trigger curves alone is not sufficient to ensure an accurate diagnosis of the water resources position or the best moment to apply the most optimal and proportionate measures. Those should be looked at in combination with streamflow forecasting tools, especially, during the current hydrological year (when the most recent and relevant hydrological information is available). The outcomes from the critical comparative assessment (applied to the Upper Genil River during the 2004-2008 drought period) demonstrated that thanks to the better use of streamflow forecasts tool, the water deficits could be considerably reduced, especially, during long droughts events (up to 37% in total) and the use of strategic groundwater water resources minimized (up to 9%). So, the carbon footprint and socio-economic impacts could be avoided or, at least, considerably reduced.

Additionally, it was found that the public participation (PP) and stakeholder involvement process had, in reality, a negligible influence in shaping the 2018 GRB DMP. Only 8% of the total number of comments received was actually accepted. From this small proportion, the majority corresponded to typo, conceptual or calculation errors, while only a minority of the accepted comments were related to improvements in the drought management strategy. This means that there was a very limited incorporation of the local knowledge and experience of participants, which highlights the absence of a truly inclusive participation strategy. Nonetheless, PP should proactively involve all interested parties at an early stage when it is still possible to alter the strategy. This could bring significant benefits, given that water users would thus assume more ownership and responsibility.

To address one of the previously mentioned key DMP weaknesses, a practical and robust streamflow forecasting tool was developed. The main aspects of this model are: (i) the procedure innovatively combines the use of well-known regression analysis techniques, the two-parameter Gamma continuous cumulative probability distribution function and the Monte Carlo method; (ii) the use of a minimum number of hydrological variables (streamflow and precipitation); (iii) substantial computational time savings (the model takes just a few seconds to run the simulations); (iv) the model does not depend on other software to achieve the results; (v) intuitive user interface, which can be easily used by non-technical experts (authorities, decision-makers, managers or even water users) and therefore, it overcomes one of the major limitations associated with the use of this type of models (vi) the results achieved are similar or slightly better than those achieved with other more complex models.

Another significant obstacle to achieving an efficient and sustainable use of water resources in Spain was the lack of transparency in water-cost recovery calculations (as highlighted in the fourth European Commission report in 2015). A methodology has been developed to increase transparency in the water cost recovery calculations and identify potential cross-subsidies among water users. A tool was developed that calculates the Canon of Regulation (or, fee paid by the beneficiaries of the surface water or groundwater regulation infrastructures to contribute towards the financial costs supported by the State) for any year of the historical series under different assumptions. This also allows a quantitative assessment of the impact of the 3 to 1 increase in the contribution costs which are applied to the surface water volume of water consumed by the household user (priority water user) of the Upper Genil River (GRB). The results revealed that the household user pays an additional average annual cost of approximately €6,863 per cubic hectometre of water consumed for having the theoretical priority of water use over the agricultural water user. However, this additional cost does not translate into a significant increase in the guarantee of water supply.

The results obtained in this PhD thesis could be used by water authorities, decision-makers, managers, policy-makers and water users. These could be considered during the revision of the WFD and Spanish Water Legislation, as well as in the development of the 3rd cycle RBMPs across the EU. They can also be applied to other similar drought-prone and water-scarce basins to improve the following: i) planning and preparedness for droughts; ii) implementation of risk-reduction management strategies; and iii) stakeholder participation in water governance issues.

10.2 Recommendations

The following overall recommendations are drawn from this doctoral thesis, which might be helpful to water authorities, decision-makers, policy-makers, managers and water users:

a) The European water legislation needs to be reviewed and updated to further integrate the drought phenomenon and management of water scarcity episodes. This should be considered during the review of the Water Framework Directive and the development of the 3rd planning cycle RBMPs 2021-2027. The preparation of Strategic DMPs should be compulsory, and the link between DMPs and RBMPs clearly established (in terms of the Programme of Measures and the investment requirements to deal with droughts in the short and long term). Additionally, the basic principles for a common methodology to tackle prolonged drought and water scarcity in Europe (indicator system, thresholds, hierarchy of measures, etc.) should be set out in order to move towards a preventive and risk-reduction strategy. On the other hand, it is fundamental that further technical guidance is provided in relation to the practical implementation of the ‘User pays’ principle and application of economic instruments to safeguard water resources. The EU Member States should optimise the use of the monitoring instruments developed by the EU and latest research advances.

b) In Spain, at the moment, the Strategic and Operational DMPs are not developed in parallel either sufficiently coordinated. This sometimes leads to the mismatch between the overarching principles set out in the Strategic DMPs at the river basin scale and the detailed assessments carried out at the sub-basin level for the Operational DMPs. It is paramount that these Plans are fully aligned and coordinated (at least, on the main drought management issues) and take into account all the environmental and socio-economic aspects. To achieve that, it is fundamental that they are prepared together, or at least, with a consistent level of interaction, collaboration and liaison with the key stakeholders and interested parties. For example, the Operational DMPs (prepared by water companies) should include preliminary discussions with the relevant Stakeholders, achieve an “Approval in Principle” by the RBA and then, be subject to a public consultation period (same as the Strategic DMPs). Information transparency from the RBAs on key aspects such as the real water allocation among water users and priority of water use is fundamental to achieve effective management strategies.

c) Additionally, DMPs should not be considered in isolation but as an integral part of the wider water resources management strategy and other sectorial polices. This is, they must be integrated with the urban and land-use development plans, agricultural management practices, economic and environmental assessments, etc.

d) The RBMPs and Strategic DMPs are prepared based on a six-year time horizon, and only based on historical recorded extremes. They should also considered the possibility of facing drought events which are worse (longer or more intense) than historic or recorded.

e) Long-term water resources management plans should be developed to deal with long-term infrastructure plans, climate change and sustainable goals. These are fundamental in an ever-growing environment of uncertainty, complex interactions and climate extremes. The main principles of long-term plans can be integrated in the RBMPs to improve resilience and reduce vulnerability working with preparedness and risk-reduction strategies.

   For example, in the UK the private water supply companies are required to develop Water Resources Management Plans (i.e. “strategic plan setting out the planned investments required over a 25 year planning horizon to demonstrate their ability to ensure sufficient supply to meet anticipated demand”) while DMPs “describes the company’s tactical and operational responses during a drought event”.

f) Reliable risk-based forecasting tools should be used to support strategic water management decisions. Still today, there are many important river basins where strategic water decisions are based on the professional judgement of technical experts and the assumption that a severe drought (100 year return period) will occur. This approach leads to the undertaking of many actions and measures which later, with the benefit of hindsight, result to be completely unnecessary or disproportionate. These erroneous decisions could have considerable negative economic, environmental and societal consequences, for which water authorities would seldom take responsibility.

   The integration of reliable risk-based forecasting tools within the decision-making process could significantly minimise those situations. These can help with the optimization of resources to meet the water demands, while minimising the potential negative economic and environment consequences.

g) DMPs should provide sufficient flexibility and the required legal mechanisms to implement alternative solutions (to those established in the original protocol of action) if better solutions can be clearly justified.

h) Drought responses and measures established in DMPs should be supported by economic, environmental and societal impact assessments. Based on this, priority to risk-reduction measures should be clearly provided. Currently, DMPs seem to be focused on the technical aspects without paying sufficient attention to economic, environmental and social aspects.

i) Effective participatory processes in issues regarding Water Governance should be implemented by water authorities. The public information and participation process should consider the public concerns, so that the most beneficial outcomes from the process can be achieved. This will work towards the achievement of a consistent, transparent and responsible drought and water scarcity management framework. This is relevant during the whole life-cycle of a DMP (elaboration, implementation, monitoring, control and lessons learnt).

It is paramount that all the relevant Stakeholders and interested parties (including water authorities, water managers, policy-makers and water users) have the opportunity to take an active part in the issues regarding Water Governance. The information (at least, on the key issues) must be clear, easily accessible and understandable to all.

j) Education and awareness among the population must be promoted. It is important that people understand the real value of water and accept droughts as natural phenomena. They should also know the measures that they can take to prevent and reduce droughts impacts. Water companies play a key role in disseminating this information.

10.3 Lines of Future Research

To optimise the use of the knowledge gained and tools created as a result of this doctoral thesis, the main future research line would be focused on the development of a novel incentive-based methodology to estimate the environmental and resource costs in line with the WFD requirements. It will be aimed at promoting a competitive water-saving, water-efficient and environmentally-friendly culture among the water users of a particular water system, while encouraging them to reduce costs.

Apart from the above, throughout the development of this doctoral thesis the following areas have been identified as needing further research and development:

- long-term drought forecasting methods, and associated long-term planning and management plans;
- impact of global climate patterns on the Deficit-Duration-Frequency drought curves for the different river sub-basins during the 21st century;
- integration of the potential economic, environmental and social impacts in the decision-making tools, in order to ensure that the optimal decision is made on how to best allocate the available water volume between the different water users and environmental needs of a particular water system.

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