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Optimal Implementation of Climate Change Adaptation Measures to Ensure Long-term Sustainability on Large Irrigation Systems

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Abstract

Observed and projected consequences of climate change on streamflow generated in the Pyrenees threatens the long-term sustainability of water resources systems downstream, especially those with high irrigation demands. To tackle this challenge, the participation of stakeholders in defining potential adaptation strategies is crucial to building awareness and capacity for the community, providing agreed solutions, and reducing conflict. However, there is also a need for a top-down approach to incorporate other, large-scale, or innovative adaptation strategies. This article describes a bottom-up-meets-top-down approach to estimate the optimal implementation intensity of adaptation strategies under different climate scenarios on a complex water resources system. Future streamflow projections were used in a water allocation model combined with a Markov Chain Monte Carlo sampling process to obtain optimal combinations of measures to meet different sustainability objectives. The methodology was applied to the Gállego-Cinca River system in NE Spain, which relies on water from the Pyrenees. A stakeholder workshop identified storage development and irrigation modernisation as the preferred adaptation options. However, the modelling results show that more storage in the basin, especially on-farm reservoirs, is not enough to maintain current sustainability levels. This will enable the adoption of demand management measures that optimise water use despite not being among stakeholder preferences.

Keywords Pyrenees · GCM/RCM · Aquatool · On-farm reservoirs · Demand management

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1 Introduction

The importance of mountains for water resources is considerable in arid and semi-arid regions (Viviroli et al. 2003). Being the second-largest basin in the Iberian Peninsula and the Mediterranean Basin, the Ebro River Basin in northeast Spain has up to 70% of its total annual streamflow generated on the mountainous Pyrenean headwater catchments. Several studies assessed global change impacts on the Pyrenees' climate and hydrology, either using observational data (García-Ruiz et al. 2011; Beguería et al. 2003; López-Moreno et al. 2006; Lorenzo-Lacruz et al. 2012; Stahl et al. 2010; Giuntoli and Renard 2010; Le Treut 2013) or modelling (López-Moreno et al. 2014; Quintana-Seguí et al. 2016; Manzano 2009; Candela et al. 2012; Caballero et al. 2007). These studies identified a decreasing trend of mean annual streamflow during the second half of the XX Century. These observed changes could not be attributed only to the evolution of critical climate variables (precipitation and temperature), as land use and land cover changes during this period also affected streamflow generation. Besides, estimates considering future climate change point to further streamflow reduction to c. 35% by the end of this century (López-Moreno et al. 2014; Manzano 2009; Candela et al. 2012; Caballero et al. 2007). Despite this relative abundance of studies, the cascading impacts of these changes on the management of the large water resources systems that depend on streamflow originated on the Pyrenees remains largely unstudied.

Irrigated agriculture represents the largest consumption of water resources generated in the Pyrenees. In the water resources systems downstream of the Central Pyrenees of Spain, agriculture represents up to 98% of all water consumption, which is supplied almost entirely from surface resources (CHE 2016). The transition from rainfed to irrigated agriculture throughout the twentieth century represented a crucial economic advance for the semi-arid regions of the middle Ebro River basin. Despite the favourable effects associated with modernisation (such as higher crop yields, diversification of crops, and a general increase of the family incomes), it also resulted in the intensification of irrigation and a reduction of return flows (Playán and Mateos 2006; Lecina et al. 2010; Gonzalez-Cebollada 2015; López-Moreno et al. 2020). The expected reduction of water resources from the Pyrenees together with further irrigation modernisation intentions can threaten the sustainability of the water resources systems downstream of the Pyrenees and their associated irrigation systems in the long term if no additional measures are implemented.

Water managers, farmers, and policymakers acknowledge the threats of climate change and have fostered adaptation strategies. To date, several projects are working on identifying sustainable practices for the agri-food industry and other economic sectors at the Pyrenees scale and in the regions that depend on them. Some examples are Agroclima (https://www.aragon.es/-/proyecto-agroclima; DGA 2018a, b), OPCC-ADAPYR (https://opcc-ctp.org/en/proyecto/opcc-adapyr), and PIRAGUA (https://opcc-ctp.org/piragua). All these projects include a component of citizen engagement and stakeholder participation. Fostering knowledge exchange and shared learning through the engagement of stakeholders in the design of solutions and the decision-making process can facilitate awareness and capacity building for the local community, contributing to effective action on climate change (Sabatier et al. 2005; Sheppard et al. 2011). Participatory processes are also helpful in informing scientists, such as water resources modellers, thus improving the decision-making processes (Newham et al. 2007; Andreu et al. 2009; Barreteau et al. 2013; Knox et al. 2018). This is referred to as a 'bottom-up' approach in decision-support systems, as the modelling scenarios are built upon a portfolio of community-driven adaptation strategies. However, full-blown bottom-up approaches are often limited by: i) the narrow perspective of the local stakeholders that may downplay relevant long-term, global drivers that are more difficult to recognise; and ii) the limited power and resources of local communities that may hinder more ambitious and disrupting strategies (Scoones 2009; Conway and Mustelin 2014). 'Top-down' planning, on the other hand, implies high-level governance and technical experts with the decision-making process being led by global drivers, i.e., awareness of the bigger picture of a problem. Although top-down approaches are more prone to implement change-driving alternative solutions, they often overlook priorities and issues at the community level (Sherman and Ford 2013). Finally, combined bottom-up and top-down approaches allow combining the strengths of bottom-up and top-down approaches (Barthel et al. 2008; Wilby and Dessai 2010; Ekström et al. 2013; Girard et al. 2015; Butler et al. 2015).

The objective of this research was to develop and apply a methodology to identify the optimal implementation intensity of varying adaptation strategies for irrigated agriculture under climate change scenarios considering the sustainability of catchment-wide water resources management. This approach is developed for the largest irrigated system within the Ebro River basin, so it can be later transferred and applied to other systems within the basin, and wider in other Iberian Peninsula basins. The present article builds upon the work initiated in Haro-Monteagudo et al. (2020), in which a modelling chain was described as a decision-support tool for complex water resources systems under global change. In this article, we further enhance the previous methodological approach by incorporating stakeholders' views, as expressed in a participatory workshop that focused on identifying the preferred climate change adaptation strategies for irrigated agriculture. Another novelty of this article is the application of an iterative optimisation scheme to thoroughly explore the effects of different combinations of adaptation strategies on achieving pre-defined sustainability goals.

2 Case study: the *Comunidad General de Riegos del Alto Aragón* (RAA) Irrigation District

The RAA irrigation district is located between the Gállego and Cinca Rivers, two of the main tributaries of the Ebro River rising in the Pyrenees (Fig. 1). The district includes 48 farmer communities, spanning over 2,500 km^2. In addition to agriculture, 113 urban settlements, ten industrial areas, and 893 livestock operations constitute the region's water demands.

The climate in the RAA district is dry Mediterranean, mainly characterised by scarce and highly variable annual precipitation, averaging 579 mm with two main rainy periods in spring and autumn for the reference period 1970–2015. For that same period, the mean annual temperature was 13.5 Cº. Irrigation supply depends on water resources generated at the Gállego and Cinca Rivers' headwaters. The mean annual precipitation in the headwaters of the system is 1,141 mm, and the estimated maxima can surpass 1,600 mm. Water resources generated in the headwaters area average 1,964 hm^3/year, while the total water resources generated in the whole system, including the lowlands, amount to 2,464 hm^3/year. The headwaters represent only 30% of the entire basin area, which emphasises the importance of the Pyrenees as they produce 80% of the available water resources.

Within the assessed system, circa 135,000 ha are irrigated. The average irrigation water demand is 838 hm^3/year (averaging 6,717 ± 1007 m^3/ha). Irrigation represents

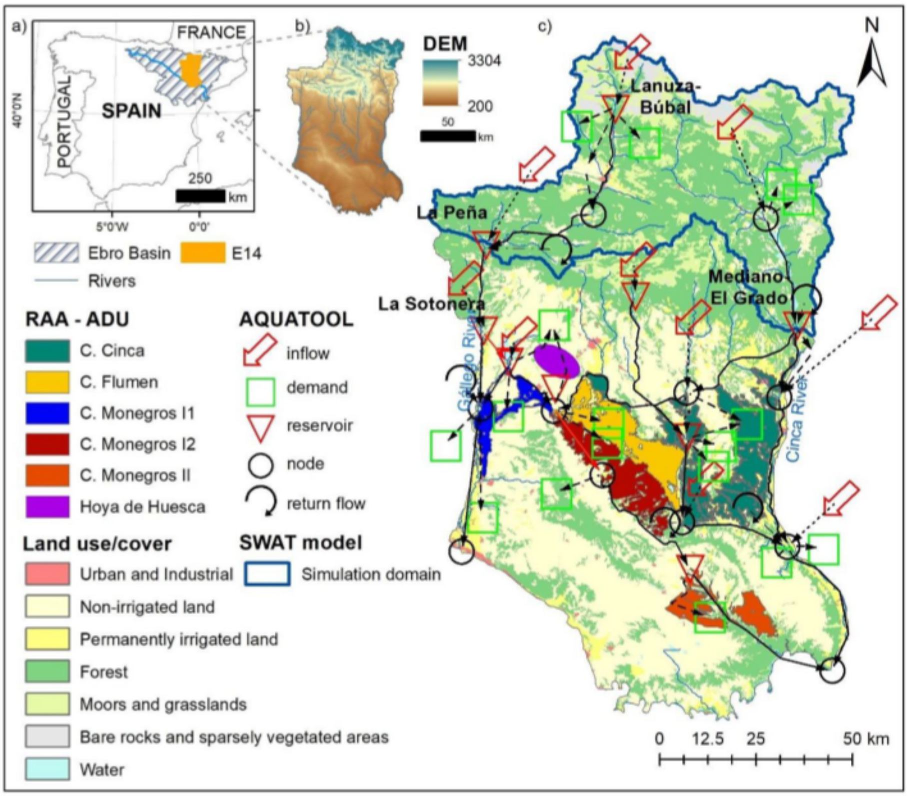

Fig. 1 **a** Location of the E14 System within the Ebro River Basin; **b** digital elevation model (DEM) and river network; **c** land use/cover map, AQUATOOL model configuration, SWAT simulation domain, and location of *Comunidad General de Riegos del Alto Aragón* irrigation district and its agricultural demand units (RAA-ADU)

98% of all water consumption in the system, and the remaining water uses are urban and industrial water supply (CHE 2016). Based on the basin plan for RAA, the water allowance for irrigation amounts to nearly 1,140 hm^3/year. Irrigation supply comes from six main reservoirs, two of which are on the Cinca River (c. 800 hm^3 of maximum storage) and the remaining four on the Gállego River (c. 280 hm^3). The water circulates through a complex network of canals (223 km), secondary conductions (c. 2,000 km), and drainage collectors (c. 3,000 km). There is a planned 40,000 ha extension of the area under irrigation, subject to: (i) the establishment of additional reservoirs; and (ii) the completion of modernisation works in existing irrigated land to improve the efficiency of the irrigation system.

The initial infrastructural development in the RAA evolved since the 1980s in a modernisation process that allowed farmers to switch from winter cereals to more productive summer crops such as corn, lucerne, and rice, which have a higher water demand (Jlassi et al. 2016). In the last 20 years, and due to changes in the European Union's Common Agricultural Policy and irrigation water availability, cropping patterns changed again to crops with lower water requirements, such as winter wheat and barley, often combined with a second summer crop (Sánchez-Choliz and Sarasa 2013).

3 Methodology

This article builds upon the multi-model and multi-scenario methodology described in Haro-Monteagudo et al. (2020). There, we developed a chain of climate–hydrology–water allocation models that allowed us to test the effects of combinations of management and climate change scenarios on the system's sustainability (Fig. 2, left half). A hydrologic model was calibrated and validated using daily climate data (C_{obs}) and observed monthly streamflow series (Q_{obs}). At the same time, a water management simulation model was calibrated and validated with Q_{obs} and observed basin reservoirs storage (Sto_{obs}). Soil and Water Assessment Tool (SWAT, Arnold et al. 2012) and SIMGES (Andreu et al. 2007) were used to develop the hydrologic and water management models respectively, using data from the latest national streamflow monitoring yearbook (CEDEX 2020) for calibration and validation (see Sects. S1 and S2 in the Supplementary Material). A set of climate projections (AEMET 2017) were fed into the hydrologic model to generate an ensemble of future streamflow outputs. The climate change signal was determined using the delta approach by comparing the reference (ref) and future (fut) climate scenarios from the streamflow ensemble (Hay et al. 2000; Räty et al. 2014). The observed flows, Q_{obs}, was modified by the delta change coefficients, and was used to force the water management simulation model under future conditions. The results of this chain of models allowed evaluate the long-term sustainability (Sust) of the system demands supply (S) under four different management scenarios.

In this new research work, we enhanced the previous process by adding a Markov Chain Monte Carlo (MCMC) algorithm to find the optimal combination and intensity of adaptation measures (AM) by maximizing a user-provided objective function (Fig. 2, right half). To build the set of adaptation measures, we followed a bottom-up-meets-top-down approach that combined the results of a participatory approach and expert knowledge.

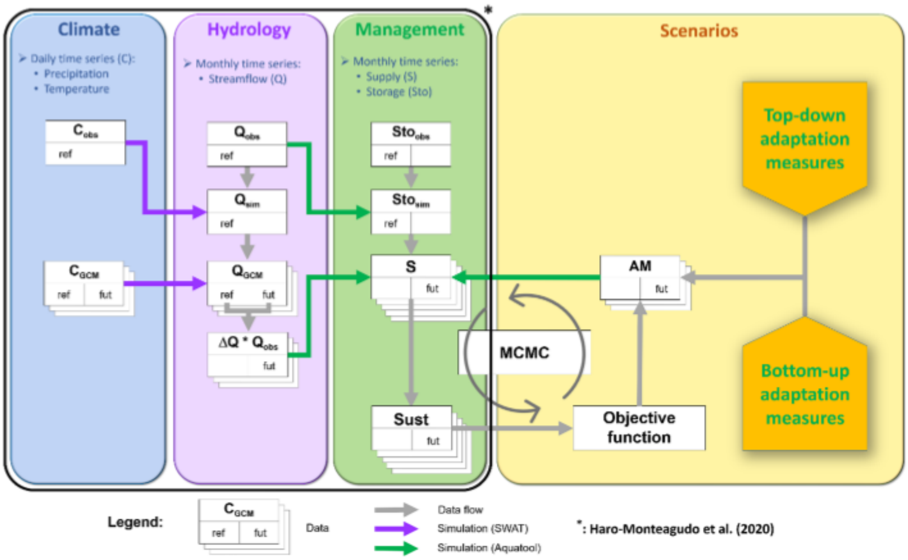

Fig. 2 Combined climate-hydrology-water allocation modelling chain and MCMC process used to find the optimal implementation of bottom-up and top-down supported adaptation measures

3.1 Stakeholder Platform and Participatory Engagement

A stakeholder workshop was organised in March 2019 with the Gállego-Cinca water resources system stakeholders at the RAA headquarters in Huesca (Spain). The participants included the major water users within the RAA system, with representation from the different farmer communities (n = 16), as well as technicians from the CHE (n = 2), the regional government (n = 3), and agricultural research institutions working in the area (n = 4). The establishment of the stakeholder platform and the participant selection process was based on a snowball sampling approach: an open invitation to the workshop was sent to high-level representatives of each institution that was later forwarded to their members and officers. The main objective of the meeting was to discuss and determine the preferred climate adaptation measures. The workshop was designed and facilitated by a professional mediator (ARC Mediación Ambiental) hired ad-hoc to ensure the neutrality of the approach.

Climate projections by the Spanish meteorological agency (AEMET 2017) were presented to the participants and their impact on water resources as assessed by the national hydrographic studies centre (CEDEX 2017). These presentations intended to provide the participants with scientific background regarding climate change in the region and remind them that these are official results being used by water policymakers and managers in Spain to design national climate adaptation and mitigation plans (OECC 2006, 2020). Once a common background regarding climate change was established, the next steps in the participatory process consisted of discussions and ranking of climate change adaptation measures considered suitable for the area (see Sect. S3 in the Supplementary Material).

3.2 Markov Chain Monte Carlo Estimation

To assess the optimal intensity of the proposed measures selected during the participatory stakeholder activity, a Markov-chain random-walk sampling process was defined based on the Metropolis–Hastings algorithm (Hastings 1970).

The Metropolis–Hastings algorithm draws samples from a probability distribution, if there is a function proportional to the density of such distribution. The algorithm uses the Monte Carlo method to generate a sequence of sample values that converges into the desired distribution. The sample values are produced iteratively, with the distribution of the following sample (the candidate) being dependent solely on the current sample value, thus forming a Markov chain. The candidate sample is either accepted (in which case it is used to generate a new candidate in the next iteration) or rejected (in which case it is discarded, and the current value is reused to generate a new candidate in the next iteration). The probability of acceptance is determined by comparing the current and candidate sample values with the desired distribution. Further details on the process are provided in Sect. S4 of the Supplementary Material.

The performance of each combination of measures under each climate scenario was assessed using the sustainability index (Sandoval-Solis et al. 2010), which refers to the combination of the concepts of reliability, resilience and vulnerability (Hashimoto et al. 1982). A synthetic sustainability index was then computed as the geometric average ot the three indicators, as initially proposed by Loucks (1997) and applied by Sandoval-Solis et al. (2010):

$$Sustainability = \sqrt[3]{Reliability \cdot Resilience \cdot (1 - Vulnerability)} \tag{1}$$

where *Reliability* is the probability that the system will fail (demand supply is below a certain threshold) during the simulation period, *Resilience* is the probability that the system recovers after a failure, and *Vulnerability* is the severity of the failures. The system's sustainability index for each combination of measures was compared to a set of sustainability goals used to drive the optimisation process. The adaptation measures considered were those preferred by the stakeholders during the workshop, as described in Sect. 3.1.

The objective is to find the parameter values (the intensity of adaptation measures in this case) that allow reaching a particular sustainability goal under each future climate scenario:

$$f(t) = 100 \cdot \left(Sustainability_0 - Sustainability_t \right)^2 \tag{2}$$

where $Sustainability_0$ represents the objective sustainability index and $Sustainability_t$ represents the sustainability index obtained for a combination of parameters in each step t. The objective sustainability was determined as the sustainability of the system during the reference period. The selection of the above objective function implies that the calibration process would favour parameter combinations that result in sustainability values like those of the reference period instead of optimising the combinations that would improve the sustainability over the observed values, as the latter would not be realistic. Instead, the objective function allows exploring what could happen if the sustainability objectives were relaxed (i.e., accepting lower sustainability levels) or tightened (targeting higher sustainability levels).

4 Results

4.1 Implementation of Preferred Adaptation Measures

Considering the preferences of stakeholders and the discussions on the limitations of different measures (see Sect. S3.1 in Supplementary Material), the development of on-farm reservoirs was the primary supply-side measure implemented in the simulation. This measure was chosen over the most preferred measure of increasing water storage at the system level due to the unlikeliness of its practical implementation, as discussed by stakeholders. The amount of internal storage (on-farm reservoirs) was modelled for each ADU independently and not at the whole system scale, as very different conditions prevail in various sectors of the RAA and because the development of on-farm reservoirs is decided at the local level. The volume of internal storage in each ADU was represented as a percentage of the total annual irrigation demand. It was implemented as a shift from peak demand months in the summer to minimum demand months when water conveyance is not dedicated to irrigation. The reduced peak demand was distributed evenly between December and February to represent the filling time. The maximum possible volume for internal storage was set at 25% of the current annual demand for each ADU; this value also equals the total volume of planned on-river reservoirs (CHE 2016).

The Markov process was run using the hydrology of current and future climate scenarios to test whether the development of on-farm reservoirs in the RAA would improve its current sustainability and identify the necessary internal storage volumes in each ADU to achieve this goal. $Sustainability_0$ was initially set to 1 (the maximum possible value), so the Markov process searched for reservoir volumes that maximised this indicator.

Under current climate conditions, the development of internal storage does not significantly enhance the system's sustainability and it is even slightly lower (Fig. 3). This may be due to the competition for water resources generated in the winter months between storage in the large headwater reservoirs and the on-farm reservoirs. While this may not be a problem in wet years, it can be problematic in dry years when water is delivered to on-farm reservoirs in the winter, and headwater reservoirs do not fill up completely in spring. In general, the internal storage volumes are low, with maximum a priori values well below 10% of the annual demand for the respective ADUs. In physical terms, this would require a total volume of 41.16 hm^3. The estimated values are above the current levels of internal storage capacity within RAA (indicated by X markers in Fig. 3), except for the "C. Cinca" ADU.

Under different climate change scenarios (Fig. 4), the optimum internal storage volume increased slightly above the values obtained for the current climate conditions. On the other hand, sustainability values drop as the XXI century advances. For all scenarios except one (bcc-csm1-1 for RCP4.5 and the 2011–2040 period), the resulting sustainability values are below those of the current period as climate change's effect exceeds the system's capacity despite introducing new storage facilities.

4.2 Implementation of Top-down Proposed Measures to Maintain Current Sustainability

The sole implementation of internal storage was not enough to cope with the expected climate change stress, sustainably maximise the water demand, or even maintain the current sustainability level. Although the bottom-up approach revealed essential insights on stakeholders' preferences, these are driven by personal interests that could limit the system's performance. To reach an equilibrium, top-down measures proposed in national

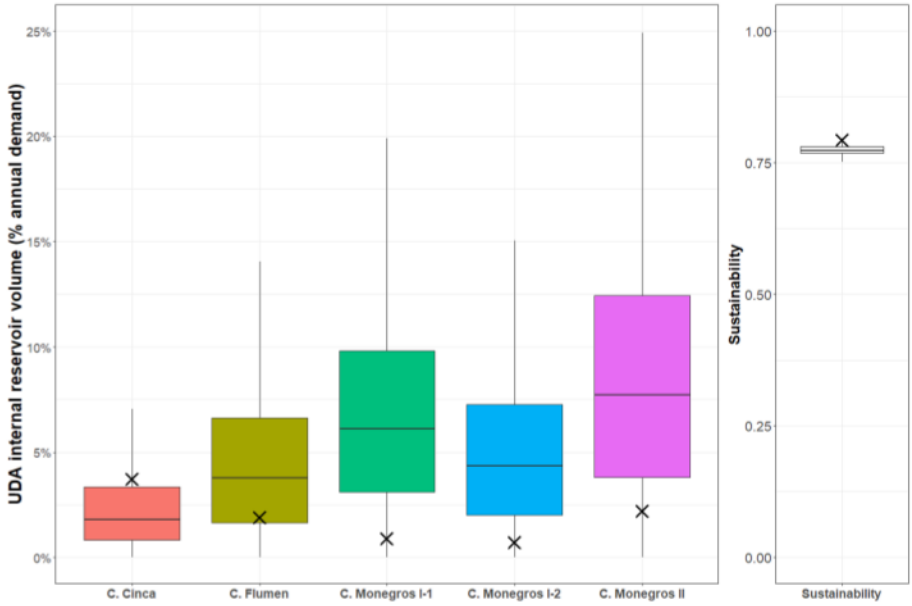

Fig. 3 Boxplots of optimal internal reservoir volume distribution at each ADU and resulting sustainability values obtained under current climate conditions. The volumes are expressed in % of the total annual demand. The X markers represent current volumes of constructed on-farm reservoirs and system-wide sustainability

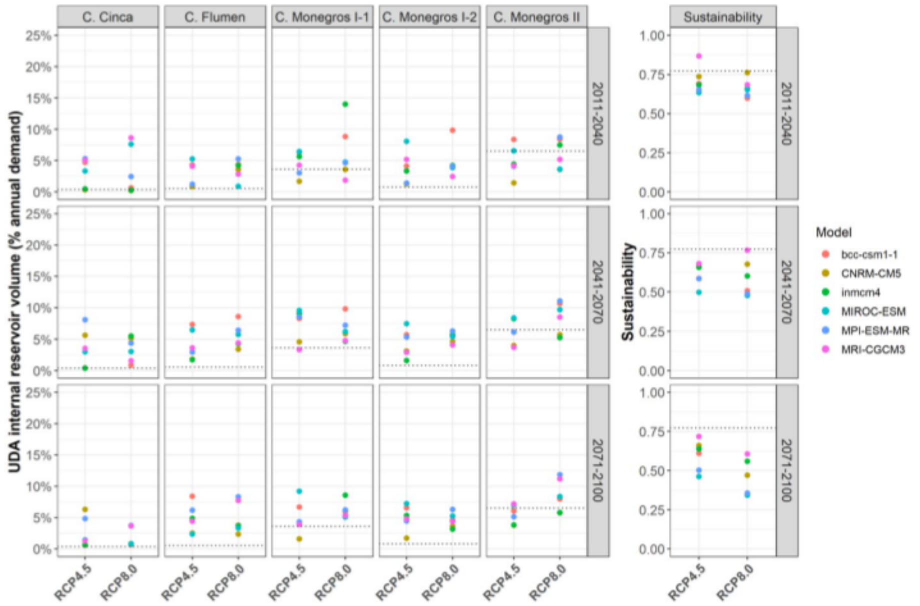

Fig. 4 Distributions under future climate conditions of maximum *a posteriori* values of ADU internal reservoir volume and resulting sustainability values (coloured dots) compared to the same calculated for current climate conditions (dotted lines)

and regional climate adaptation strategies need to be considered. These propositions currently advocate for implementing demand-side water-saving measures, such as increasing irrigation efficiency, adapting irrigation to real-time plot water requirements using technology, and introducing water stress-resistant crops (DGA 2018a, b; MITECO 2020).

The implementation of potential water-saving measures was represented in the water allocation model as a system-wide reduction in annual water allowance to ADUs. This water allowance reduction was limited to a maximum of 50% of the current annual demand.

The Markov process was rerun, including water-saving measures, and setting $Sustainability_0$ at 0.79, which is the current sustainability level for RAA with all the system's reservoirs fully operational. The results in Fig. 5 show that a combination of adaptation measures that include additional internal storage and water-saving actions can maintain and even increase the current sustainability level. The results also reveal that the role of internal storage is less relevant than that of water-saving measures. For all climate scenarios, the optimum values of internal storage reservoirs were found to be similar across the ADUs (c. 12%). At the same time, water-saving measures will need to be applied with increasing intensities towards the end of the XXI Century, depending on how extreme the climate scenario is. Since water-saving measures also reduce the competition for resources during the irrigation season, it is possible to increase water withdrawals from large reservoirs to fill larger internal storage infrastructures during the winter months. Together, the collective volume of all on-farm reservoirs would be circa 140 hm^3.

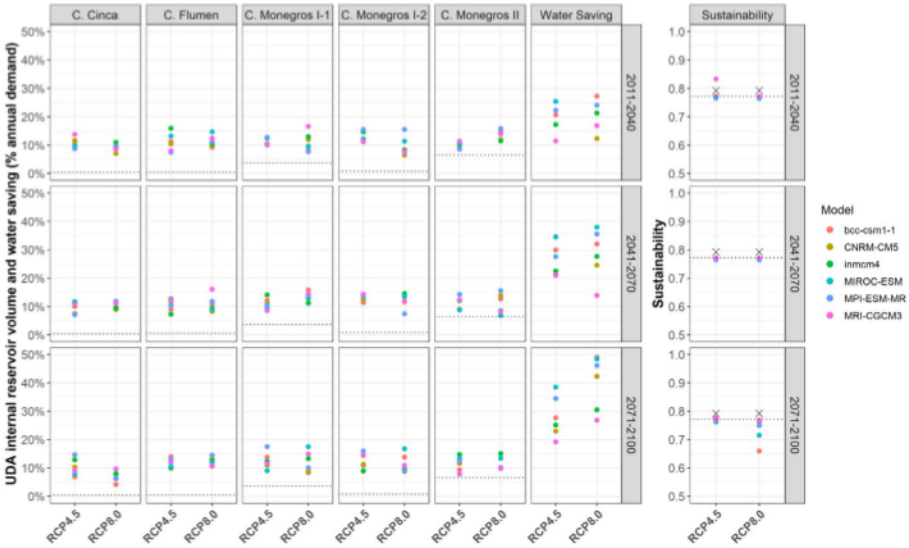

Fig. 5 Distributions under future climate conditions of maximum *a posteriori* values of ADU internal reservoir volume and water-saving measures and resulting sustainability values (coloured dots) compared to the same calculated for current climate conditions (dotted lines). The X markers in the sustainability plot represent the median sustainability calculated for the situation without water-saving measures under current climate conditions

5 Discussion

The development of on-farm reservoirs has been used in the RAA, notably since 2000, to improve the storage capacity and facilitate pressurised irrigation (Jlassi et al. 2016). Our results indicate that there is room for enlarging on-farm reservoir storage in RAA under current climate conditions up to approximately 41 hm^3. According to the latest RAA's annual report (Riegos del Alto Aragón 2020), there are 100 on-farm reservoirs within the region with a total volume of 27.1 hm^3, which leaves room for the development of additional on-farm reservoir storage. However, any new storage would only be possible in ADUs that have recently received substantial economic investments for irrigation modernisation (Monegros I, 1 and 2, and Monegros II). This means that farmers within these ADUs would have to undergo additional efforts to pay for the new infrastructure. The extra financial burden was discussed extensively during the stakeholders' workshop.

At the same time, the study results show that on-farm reservoirs are not sufficient to maintain current sustainability levels under climate change due to the competition generated by reduced inflows to reservoirs during the filling period. On-farm reservoirs could still be helpful to buffer insufficient short-term supply, but they will not have a relevant role in the long-term sustainability of the system. The long-term decrease of available water resources in the system means that there will be years in which the storage capacity will exceed resources availability. Also, although the availability of on-farm reservoirs could help farmers saving energy costs as they provide water head for pressurised irrigation on some occasions, these savings could be compensated or even surpassed by the energy cost of other operation tasks such as filling up the reservoirs. This is in line with previous work from Habets et al. (2014) that showed that small farm reservoirs have impacts on the sustainability of the very demands they are intended to serve. Also, Haro-Monteagudo et al. (2020) showed that annual streamflow in both the Gállego and Cinca rivers would decrease under all climate scenarios. However, this reduction will not be uniform, but there would be seasonal differences, with winter months experiencing an increase while decreasing in spring and summer. This explains the increase in the optimum size of internal storage as they are filled during winter months, for which the climate change scenarios are projecting higher water resource availability. Similarly, reducing water resources in the months before the irrigation campaign will prevent filling up the large headwater reservoirs in the system, leading to potential failures during the summer. These results indicate the necessity of considering measures that affect water demand despite these being generally less favoured by farmers due to not being aligned with their business strategy.

The introduction of water-saving measures could allow for a larger volume of on-farm reservoirs within the system, as reducing water use would allow filling the reservoirs more often. However, the required water savings amount circa 20% of the total annual irrigation demand in RAA for the most optimistic climate scenarios for the mid and end XXI century periods and reach up to 50% in the worst-case scenario. These values translate into savings in the range of 225–562 hm^3/year for the RAA. The catalogue of good agricultural practices elaborated by the regional government of Aragón (DGA 2018b) assumes savings of up to 70% from introducing more efficient irrigation techniques such as spray and drip irrigation. However, some studies argue that these improvements depend very much on local conditions and are case-specific (van der Kooij et al. 2013). Besides, this measure would have a limited application in RAA as approximately 75% of the irrigated area use modernised infrastructures as of 2014 (http://riegosaltoaragon.es/lineas-de-trabajo/modernizacion-de-regadios/situacion-actual/). Moreover, like the construction of on-farm reservoirs, irrigation modernisation requires substantial economic investments by farmers.

Other adaptation measures identified and quantified in the catalogue are related to optimising plot irrigation using moisture sensors and tensiometers (more than 10% savings) and digital water management tools (between 5 and 35%). Like modernisation, RAA was one of the first farming communities to implement management tools, adopting the ADOR software for daily management (Playan et al. 2007; Lecina et al. 2010). Other measures whose saving are not quantified include implementing a better water metering to identify excessive water uses and detect leaks; adapting irrigation to real-time weather conditions; stimulating rainwater harvesting; and using alternative water resources such as recycled water. The latter option is currently under study by RAA concerning the reuse of irrigation return flows for fertigation purposes. However, reused water is limited (RAA, personal communication) and cannot grow substantially as return flows are reduced due to modernisation. Finally, the catalogue also considers the possibility of selecting crop varieties with lower irrigation requirements or more resistance to water stress. However, these tend to result in reduced revenues as they require more labour to achieve objective yields, or they have lower market demand.

In summary, the water-saving measures under consideration by the agricultural community in the region can help accomplish optimal water reductions, at least for the most favourable climate scenarios. Although water-saving measures are preferable, especially those that enhance the system's efficiency, these will only work if water users understand that saved water is not to be put for other uses such as increasing the irrigated area or promoting higher water-demanding crops or double cropping. However, when faced with water shortages, irrigation systems are often subject to the 'tragedy of the commons': there are few incentives for farmers to reduce their use of the resource as they cannot restrict others from over-using it. There is a strong need for cooperation to diminish the collective water demand to cope with climate change. Irrigation systems are common pool resources that depend on robust governance systems and solid internal collaboration between water users. Scholars have extensively discussed institutional solutions to improve drought management in irrigation systems. For instance, Villamayor-Tomas (2014) studied the adaptation performance of irrigation associations within the RAA system during a severe drought and explored the use of transferable quotas as a measure to improve the system's resilience. However, the tools for implementing long-term adaptation measures remain comparatively understudied.

6 Conclusions

We followed a multi-scenario approach to assess the suitability of combinations of offer-increasing and water-saving adaptation options to cope with future water scarcity in systems with large irrigation agriculture demands. The methodology was applied to the largest irrigated system in the EU (i.e., RAA), using stakeholders' preferred adaptation measures in a top-down meets bottom-up approach. The results show that the stakeholder choice for adaptation, that is increasing on-farm storage capacity, will not be enough to secure the future sustainability of water resources in the region. This result raises some concerns over ongoing bottom-up stakeholder-led climate adaptation initiatives, as some of the preferred options can be seen as positive but do not really have a significant effect in the long term. This is in line with existing regional top-down initiatives to tackle climate change in agriculture, e.g. the project Agroclima (DGA 2018a, b), where water-saving options appear to be the most promising to maintaining current sustainability levels in the RAA irrigation system. The results can be extrapolated to other irrigation districts where similar initiatives are taking place. These applications might benefit from including a larger representation of stakeholders like traditional upstream irrigation or downstream dependent areas. In future works, the proposed methodology can be adjusted and applied to the whole Ebro River Basin, as well as to other water resources systems to assess the potential implementation of different adaptation strategies.

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Availability of Data and Materials The data supporting the conclusions of this work can be found in the following sources: AEMET climate projections are available at http://www.aemet.es/es/serviciosclimaticos/cambio_climat/datos_diarios. Modelling results are available at https://github.com/dharomonteagudo/Haro_et_al_Adaptation. SWAT and AQUATOOL models are available upon request to the corresponding author.

Declarations

Ethical Approval N/A.

Consent to Participate N/A.

Consent to Publish N/A.

Competing Interests The authors declare that there are no financial or non-financial competing interests related to this article.

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