From local knowledge to decision making in climate change adaptation at basin scale. Application to the Jucar River Basin, Spain

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Abstract

Climate change is challenging the conventional approaches for water systems planning. Two main approaches are commonly implemented in the design of climate change adaptation plans: impact-oriented top-down approaches and vulnerability-oriented bottom-up approaches. In order to overcome the shortcomings of both approaches and take advantage of their strengths, we propose an integrative methodology to define adaptation strategies at basin scale, identifying and combining potential changes in water demand and water supply infrastructure along with climate variability and change. The impact of climate change on future local water availability is assessed applying a top-down approach. Local knowledge is used through a participatory bottom-up approach to foresee future scenarios of evolution of the agricultural sector and agricultural water demand, and to identify locally relevant adaptation strategies. A hydroeconomic model integrates the information from both approaches to identify a socially acceptable and cost-effective program of measures for each climate scenario. This method was applied to the Jucar basin, a highly regulated basin with a tight equilibrium between water resources and demands. The results show an important variability of climate change impacts across the basin, with main inflow reductions in the headwaters. The stakeholders prioritized the adaptation options of change to drip irrigation, use of non-conventional resources, and changes in water governance. The results obtained from the hydroeconomic model show that the portfolio of selected adaptation measures could significantly reduce the system's average annual deficit and cost.

Keywords Water management · Climate change adaptation · Bottom-up approach · Hydroeconomic modeling

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1 Introduction

Climate change adaptation involves the modification and adjustment of certain behaviors in the present, in addition to the development of suitable strategies to tackle the foreseen impacts at different timescales. However, the design of adaptation policies is complex and needs to address multiple challenges. Regarding water resources systems, climate change impacts stand out due to their complexity and unpredictability, as well as the non-linear and chaotic character of some of them (e.g., the appearance of extreme events) and the combination with other stress drivers (e.g., population increase, financial resources rivalry, or conflicts related to water allocation and priority rules) (Vörösmarty et al. 2000; Ray & Brown 2015; Kundzewicz et al. 2018). In this context, adaptation strategies could be beneficial to deal with some of the phenomenon aftermaths, but also unsuitable or even pernicious when it comes to others (Gleick 2011; Refsgaard et al. 2013; Marcos-Garcia & Pulido-Velazquez 2018).

In general terms, there are two main approaches to design adaptation programs at basin scale: the top-down (impact-oriented) approach and the bottom-up (vulnerability-oriented) approach. Top-down approach has several distinctive features: (1) it focuses on the assessment of local impacts for different climate change scenarios (because it is designed to represent the main processes that cause danger and its potential consequences); (2) it is based on a chain of models and; (3) it moves from the global to the local scale. Sometimes, this approach has been named as "predict and then act" (Dessai & Hulme 2004), in allusion to the essential role of climate projections. Furthermore, Wilby and Dessai (2010) defined it as an "uncertainty cascade" because uncertainty propagates and increases from one step to the next in the chain of transformations that links global projections to local impacts. However, there is still an ongoing discussion about the suitability of approaches fully based on climate scenarios to design adaptation strategies. The main reasons are the scarce credibility of projections at the local scale (Koutsoyiannis et al. 2008); the smaller relative importance of climate change for decision making, in comparison with other factors (Stainforth et al. 2007); the optimism of impact studies regarding model credibility, versus the pessimism about climate change effects on society (Blöschl & Montanari; 2010); and its exclusive and paternalistic nature, which only appreciates scientific "expert" knowledge while disregarding local people's insights (Smith 2008).

On the other hand, the bottom-up approach is characterized by (1) being a decision-centered approach (because it is designed to identify thresholds, relevant objectives, and alternative local responses to cope with change-related threats), (2) considering social vulnerability and resilience as a starting point, and (3) moving from the local to the global scale. In this regard, there are several interpretations of the bottom-up approach: while some authors use this term in relation to the exploration of local knowledge through participative methodologies (Harrison et al 2013; Bhave et al. 2014), others refer to scenario-free, robustness-based planning (Brown et al. 2012; Whateley et al. 2014; Shortridge and Zaitchik 2018; Ray et al. 2019). The latter deals with the challenges that model uncertainty poses for future infrastructure planning by integrating the identification of scenarios associated to system failure and their likelihood into robust decision-making frameworks. Current developments of this kind of approach move beyond climate scenarios to include environmental, demographic, and financial ones (Taner et al. 2019). In this regard and unlike top-down approach, it could be said that the bottom-up approach relies more on possibilities than on probabilities (Blöschl et al. 2013). However, the bottom-up approach depends on the

information generated by the top-down approach, when it comes to assign a probability to the potentially risky future climate conditions or to select a certain range for vulnerability assessments (García et al. 2014; Ray and Brown 2015). Regarding participatory bottom-up approaches, other problematic aspects include tokenism, a misconception of "communities" as coherent and cohesive entities and the lack of resources and/or knowledge to implement them successfully (Smith 2008).

In order to overcome the shortcomings of both approaches and take advantage of their complementary strengths, in the last years some authors have advocated the use of mixed methodologies to tackle the challenges of adaptation, bringing together scientists and stakeholders (Mastrandrea et al. 2010; Bhave et al. 2014; Girard 2015; Girard et al. 2015a, 2015b; Mehran et al. 2017). Among the main advantages of this combined approach is its ability to identify key vulnerability thresholds (bottom-up analysis), while assessing the likelihood of exceeding them (top-down one) (Mastrandrea et al. 2010). In any case, there is still a long way ahead regarding the design of adaptation strategies in the water field. Most of the current research in this area is more focused on impacts than on adaptation itself (Prudhomme et al. 2010; Salerno 2017). In addition, although climate risks have three main components (hazards, vulnerability, and exposure), many studies ignore the future dynamics of some of them (Jurgilevich et al. 2017). This aspect is especially relevant because some adaptation strategies could reduce the risk in the short term, but increase vulnerability and exposition in the mid- or long term. Regarding water resources, it is necessary to take into account that globalization and socioeconomic changes play a key role in relation to demand increase and water insecurity and thus adaptation to them deserves more attention (O'Connell 2017). Moreover, the role of participation in the design of adaptation strategies must be highlighted because it could increase not only stakeholders' confidence in the adopted one (Patt 2009) but also the understanding about the perception of local challenges and its implications for water management and governance (Rothman 2008; Berkhout et al. 2002; Pahl-Wostl 2008; Bonzanigo et al. 2015; Iglesias et al. 2015; Ortega-Reig et al. 2018).

Therefore, this paper presents a framework for improving the integration between the top-down and the bottom-up approaches for the design of climate change adaptation in water resources systems. The proposed framework combines the characterization of local impacts for climate scenarios along with a participative process that involves the main stakeholders at basin scale. This participative process is applied not only to identify future demand scenarios through scenario-building techniques, but also to characterize an initial portfolio of supply and demand adaptation measures. The selection of adaptation measures is made through a hydroeconomic model, which is able to integrate the spatial distribution of water resources, main infrastructure characteristics, environmental and operational constraints, management rules, and the economic values of the system, in order to identify a socially acceptable and cost-effective portfolio of solutions.

The selected case study, the proposed scenarios (both climatic and socioeconomic), and the cost data regarding potential adaptation measures are described in Section 2. Section 3 explains the overall proposed methodology (Section 3.1), with the integration of the top-down (Section 3.2) and the bottom-up approaches (Section 3.3) through a hydroeconomic model (Section 3.4). Section 4 summarizes the application of the methodology to the selected case study. Finally, Section 5 discusses further research, while Section 6 presents the main conclusions.

2 Material

2.1 Case study description

The case study is the Jucar River Basin, a Mediterranean basin of 22,261 km in Eastern Spain. The system is highly regulated through three main reservoirs: Alarcon (1112 million m^3, Mm^3) and Contreras (872 Mm^3), in parallel in the upper basin, and Tous (314 Mm^3), downstream. The main groundwater body is the karstic aquifer of La Mancha Oriental, one of the most extensive aquifers in Southern Europe (7260 Mm^3), hydraulically connected to the Jucar river (Apperl et al. 2015). A prolonged policy of water demand expansion has resulted in a frail equilibrium between available resources (1713.4 Mm^3 per year) and demands (1648.4 Mm^3 per year, with an agricultural share of about 80%).

The main Agricultural Demand Units (ADUs) are located near the coastal area (in the region known as Ribera del Jucar), except for La Mancha Oriental (Fig. 1). In the Ribera area (Csa Köppen climate classification), mild winters and the absence of frosts are favorable for horticulture (4% of the irrigated area), citrus (53%), rice (20%), and kaki (17%) farming. Generally, mean farm size is small (about 2.5 ha) and irrigation is made through surface water resources (675 Mm^3/year) and, in a lesser amount, through groundwater (130 Mm^3/year). On the contrary, La Mancha Oriental area has a more continental climate (predominantly Bsk Köppen) that conditions the suitable crop types: cereals (40% of the irrigated area), vineyards (15%), and vegetables (18%). Agricultural holdings are larger in this area (over 60 ha), mostly irrigated with groundwater from La Mancha Oriental aquifer. During the last decade, pumping rate has decreased to 280–300 Mm^3/year, but before 2000
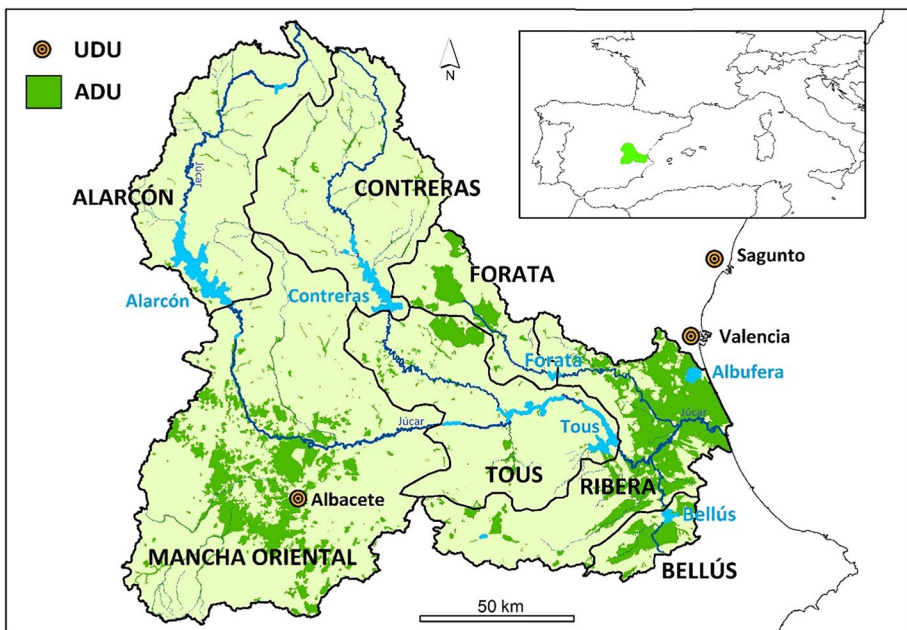

Fig. 1 Jucar basin and sub-basins, along with the main urban demand units (UDU) and agrarian demand units (ADU)

it was higher than 500 Mm³/year and changed the relationship between the river and the aquifer. Consequently, downstream water availability has been significantly reduced (Sanz et al. 2011), triggering noticeable regional strains between the main agricultural areas in the basin (Apperl et al. 2015).

The fragile balance between water demands and resources, as a result of basin closure processes, make this region more prone to droughts, with important socioeconomic and environmental consequences. In this context, climate change could act as an aggravating factor, decreasing water resources (Chirivella Osma et al. 2015; Pulido-Velazquez et al. 2015; Marcos-Garcia & Pulido-Velazquez 2017) and increasing the frequency, magnitude, and intensity of drought events (Marcos-Garcia et al. 2017), due to the combined effect of precipitation decrease and potential evapotranspiration increase. Using a hydroeconomic approach, Escriva-Bou et al. (2017) concluded that the system is highly vulnerable in relation to climate and land use changes (mainly in the mid- and long term). Besides, Carmona et al. (2017) estimated the costs of droughts in the Jucar basin, episodes that are expected to increase under climate change (Marcos-Garcia et al. 2017). Therefore, the implementation of innovative adaptation measures could significantly reduce the economic losses.

2.2 Climatic and hydrologic data

Observed daily precipitation and temperature for the control period (1971–2000) were obtained from the SPAIN 02 project (Herrera et al. 2010), which provides high-spatial resolution datasets (0.11°). Regarding the hydrological data, we used the monthly discharge time series from the Jucar River Basin Agency (CHJ 2014), previously naturalized.

Climate projections are derived from the IPCC's Fifth Assessment Report (AR5) (IPCC 2014), which describes potential trajectories for the greenhouse gas emissions during the twenty-first century and the radiative forcing in 2100 by means of the representative concentration pathways (RCPs). We selected the RCP 4.5 and RCP 8.5 scenarios in order to include a medium and a high emission scenario. We obtained these scenarios from the output of the CORDEX project, which aims to evaluate and improve regional climate downscaling models and techniques (Christensen et al. 2014). The gross climatic projections were extracted for three periods: control period (1971–2000), short-term period (2011–2040), and mid-term period (2041–2070), considering a spatial resolution of 0.44° (≈50 km), and a monthly time resolution.

2.3 Socioeconomic scenarios

The RCPs are not associated with fixed hypothesis about the socioeconomic or technological development. Therefore, a wide variety of different socioeconomic futures could entail the same level of radiative forcing (van Vuuren et al. 2011). The main objective of the Shared Socioeconomic Pathways (SSPs) is the description of these potential socioeconomic futures, considering the implementation of mitigation policies or their absence (Riahi et al. 2017). There are five SSPs which address different challenges in relation to both mitigation and adaptation policies (O'Neill et al., 2014; 2017): SSP1 (low challenges regarding adaptation and mitigation); SSP2 (medium challenges for both policies); SSP3 (high challenges for both policies); SSP4 (low challenges for mitigation and high challenges for adaptation); SSP5 (high challenges for mitigation and low challenges for adaptation). Van Vuuren et al. (2014) related the climate (RCPs) and the socioeconomic scenarios (SSPs). In this regard, we selected the two scenario combinations that pose the biggest

future challenges for both adaptation and mitigation, SSP3 and SSP5 (Kok et al. 2015). Table 1 presents the main characteristics of these scenario combinations.

2.4 Costs of the adaptation measures

The costs of the considered adaptation measures (Table 1 in Supplementary material) were obtained from Marcos-Garcia (2019), based on available information about ongoing projects, cost predictions of similar measures included in the river basin plan, etc.

3 Method

3.1 General framework

Figure 2 shows the general framework applied to the case study (Marcos-Garcia 2019). The graph presents a traditional top-down approach (left) where the results from several Global Climate Model (GCM)/Regional Climate Model (RCM) combinations are used as inputs for a previously calibrated hydrological model, in order to simulate the future inflows. On the right, a participatory bottom-up approach is depicted: global socioeconomic narratives are adapted to the local context through interviews with local experts and potential adaptation measures are identified by means of workshops with the main stakeholders of the basin. Finally, the outputs from both approaches are integrated into a hydroeconomic model (center) that, through an optimization algorithm, is able to select the most cost-efficient combination of adaption measures under the future scenarios.

3.2 Top-down approach

3.2.1 Climate change scenarios

In order to select the most suitable combinations of GCMs-RCMs for the case study, we compared the observed time series of mean annual precipitation and temperature with the ones

Table 1 Main features of the climate/socioeconomic scenario combinations

| SSP3 (×RCP 8.5)	SSP5 (×RCP 8.5)
Protectionist policies	Globalization increase
Economic deceleration	Economic growth
Few social and educational advances	Strong educational development
Environmental decline	Environmental focus on local scale, little concern with global issues
Weakening of the supranational institutions	Decrease of social inequalities
Technological progress	Strong technological progress
Intensive use of fossil fuels	Low compliance level of international agreements on climate change

Source: adapted from Kok et al. (2015)
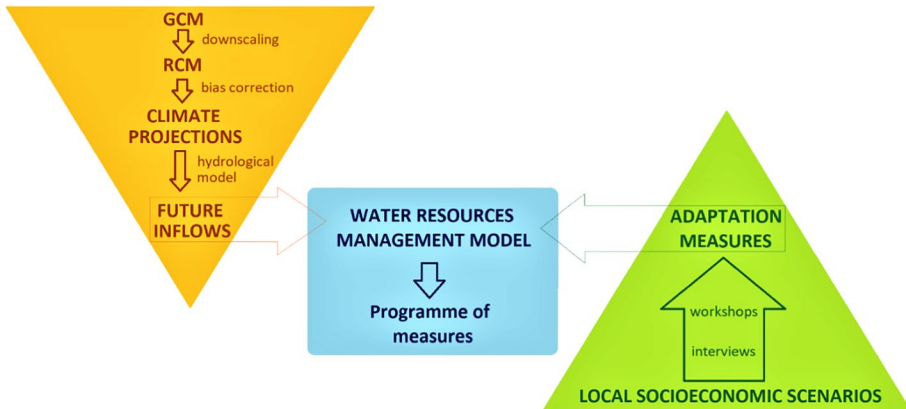
Fig. 2 Conceptual top-down meets bottom-up approach

from the models' control period (1971–2000). Concretely, we obtained the mean relative error for both climatic variables (precipitation and temperature) regarding the monthly mean and the standard deviation of the control period (Marcos-Garcia & Pulido-Velazquez 2017).

After selecting the climate models, the next step involved the bias correction of the climate variables, in order to obtain reliable estimations of the local conditions. We used the statistical correction method known as quantile mapping (Li et al. 2010), implemented in the R "qmap" package (Gudmunsson et al. 2012). This procedure considers the difference between the cumulative distribution functions (CDFs) of the climate model output and the observed data for the control (baseline period), in order to correct the bias of the climatic projections.

3.2.2 Hydrological model

In order to assess the climate change impacts on the system's future inflows, the bias-corrected climate variables (precipitation and temperature) were used as inputs for a set of Temez hydrological models (Témez Peláez 1977), one for each of the seven sub-basins in which the case study was divided (Fig. 1). The model is able to represent the essential processes of water transfer in the different phases of the hydrological cycle, using balance equations and specific laws of distribution and considering monthly time steps. Here, we used the modified version of the Temez model described in Marcos-Garcia and Pulido-Velazquez (2017), which introduced two independent aquifer storages (each acting as a linear reservoir) in order to improve the representation of stream–aquifer interaction. The model was calibrated for the historical naturalized discharge time series for 1971–2000, while the validation period was 2001–2007.

3.3 Bottom-up approach

As agriculture is by far the main water user in the Jucar basin, the characterization of future land and water use scenarios for this sector is crucial for water management. Currently, there are two main approaches to tackle the problem: (1) modeling land use change (LUC) and (2) using participatory approaches to develop plausible alternative futures. While the first approach usually involves the identification of the change drivers and the application

of dynamic, statistical, or machine-learning models to spatially explicit historical data (Aburas et al. 2019; Pulido-Velazquez et al. 2015), the second takes advantage of the local actors' knowledge through scenario-building workshops (e.g., Hatzilacou et al. 2007; Rinaudo et al. 2013; Faysse et al. 2014).

In this regard, participatory approaches could be used to develop both qualitative and quantitative scenarios. Qualitative scenarios allow to incorporate multiple viewpoints in order to generate ideas and strategies, bridging gaps among experts, decision-makers, and stakeholders. In contrast, quantitative scenarios use numerical descriptions and spatial allocations of land use associated with a potential pathway (Mallampalli et al. 2016). Here, we aim to identify the future trends of the agricultural sector through qualitative scenarios, which could be subsequently transformed into quantitative assessments of land use change.

3.3.1 Expert interviews and "scenario building" workshops for adaptation in irrigated agriculture

Although the SSP scenarios were formulated at the global scale, the adaptation strategies should be designed at the local scale. In order to bridge this gap, it is necessary to nuance the main elements of the SSPs by taking into account the particular features of the case study. For this purpose, we applied the following three-stage methodology proposed by Ortega-Reig et al. (2018) for the study of adaption of agriculture in the Jucar river basin:

1. Expert interviews: a first round of interviews was carried out to identify the main drivers and trends of change in the agricultural sector at basin scale, as well as the associated uncertainty. Eighteen semi-structured interviews of 90 min each were undertaken, selecting experts in related fields (agriculture economics, irrigation technologies, environmental aspects, etc.) and ensuring a balanced representation of the main agricultural zones.

2. Storytelling design: we used the information obtained through the previous interviews to adapt the main elements of the selected SSPs to the local context. We proposed four storylines (one for each scenario combination described in Section 2.3 in two different local contexts, La Mancha and La Ribera). These storylines were included as fictional news in well-known local newspapers (dated in year 2030, see Fig. 1 in Supplementary material) to make them more approachable to the workshop participants (as in Rinaudo 2008; and Rinaudo et al. 2013).

3. Participative workshops involving local farmers: the main objective was to develop a local vision for each storytelling. We held two separate workshops in La Mancha and La Ribera, selecting 10 representative participants from the local agricultural sector and then dividing them in two parallel working groups (one for each SSP). The first part involved the following tasks: (1) to discuss the plausibility of the storylines at the local scale; (2) to debate their potential consequences for the local agriculture and water management (focusing on crop pattern changes, water uses, and policies); (3) to draw a cause-effect map between the identified key aspects. Once the first part of the workshop was completed, both work groups shared their results.

For the second part of these workshops, we reorganized the work groups to allow the interaction between participants that had been in different work groups during the first part. This part focused on the proposal of adaptation measures for the agricultural sector, considering the socioeconomic and climate context set up in the storylines. Participants discussed these potential measures at different spatial scales

(from the plot scale to the basin scale), without considering economic or policy restrictions. They classified the measures as priority, interesting, or undesirable. At the end of this part, we included some additional measures in the discussion, which had not been previously identified by the participants. Finally, both work groups summarized and shared their results.

3.3.2 Confronting adaptation options at basin scale

In order to discuss the suitability of the adaptation measures proposed by the farmers at the basin scale, we designed a third workshop that involved 14 representatives of the main stakeholders in the Jucar basin (policy makers, users from the agricultural, urban and hydropower sectors, environmental action groups, etc.).

In first place, we introduced each of these adaptation measures in brief. Next, the participants discussed their feasibility and potential implementation barriers. Finally, the participants graded each measure (both quantitatively and qualitatively) using an interactive participatory presentation platform (Mentimeter, https://mentimeter.com) through their mobile phones.

3.4 Hydroeconomic model

Here, we used a simulation water management model at the monthly scale implemented for the Jucar River Basin (reported in Marcos-Garcia et al. 2020), which considers the current environmental restrictions, allocation rules (in accordance with the Spanish and river basin regulations), and existing agreements. The network of the water resource system was implemented using the Hydra Modeller software (built on the Hydra Platform open-source software; Meier et al. 2014) and exported to a format compatible with the General Algebraic Modeling System software (GAMS; GAMS Development Corporation 2013). The equations that govern the model are similar to the ones described in Macian-Sorribes et al. (2017). The model was calibrated for the period 2003–2012 with regards to storage in the main reservoirs (Alarcon, Contreras, and Tous) and Tous reservoir releases (Fig. 2 in Supplementary material) in order to meet the downstream water demands stated by the water agency (CHJ 2014).

The following types of nodes were considered: 8 inflow nodes (in accordance with the 7 sub-basins of Fig. 1, although the inflow of Molinar sub-basin was split up in two nodes); 5 reservoir nodes (Alarcon, Contreras, Tous, Forata and Bellus); 5 aquifer nodes (La Mancha Oriental, Cabriel, and three nodes corresponding to La Plana de Valencia aquifer); 18 simple nodes (where input equals output, without storage capacity); 4 urban demand nodes (in accordance with the urban demand units (UDUs) of Albacete, La Mancha Oriental, Valencia, and Sagunto); 13 agricultural demand nodes (corresponding to the Agricultural Demand Units (ADUs), one of them in La Mancha Oriental, and 8 in La Ribera (Magro, Canal Jucar-Turia, traditional irrigation areas downstream Tous reservoir (flowing), Acequia Real del Jucar, Cuatro Pueblos, Cullera, Escalona, and Sueca). Concretely, Acequia Real del Jucar, Cuatro Pueblos, Cullera, and Sueca ADUs were represented by two nodes each, in order to consider the main crop types: citrus fruits and rice.

The implementation of the main adaptation measures entailed the inclusion of additional nodes (Fig. 3) and satisfied the following conditions (Marcos-Garcia 2019):

– Desalination: Sagunto desalination plant is represented by the "Desal_Sagunto" node, linked to the UDU nodes of "Sagunto" and "Valencia." The annual desali-
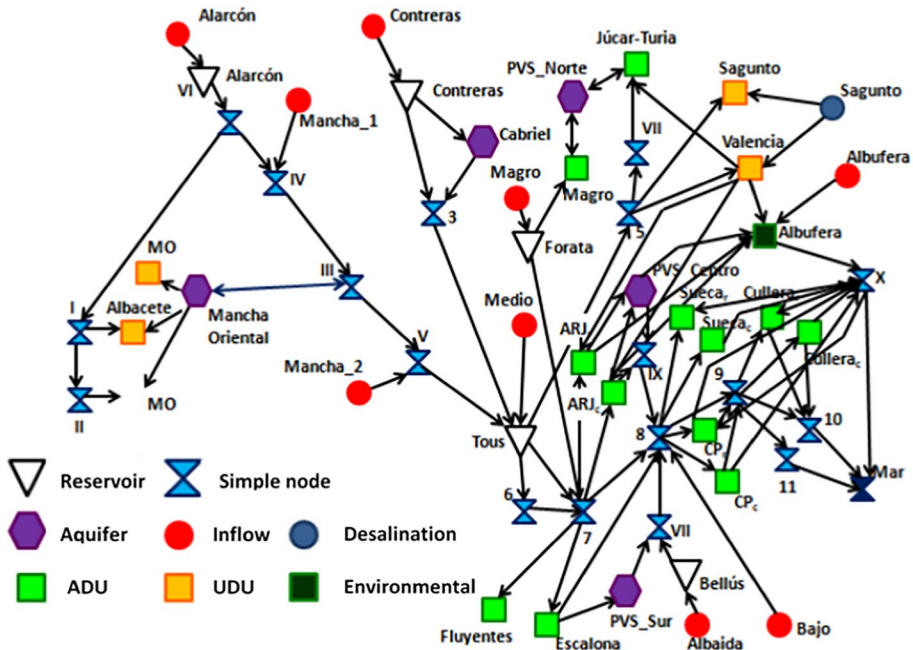
Fig. 3 Water management model with adaptation measures

nated volume should be equal or lower than the maximum capacity of the plant (8.36 Mm^3/year).

– Water reuse: to take into account the potential reuse from Pinedo II wastewater treatment plant, located in the Valencia urban area, the UDU node of "Valencia" was linked to the ADU nodes of "Canal Jucar-Turia" and "Acequia Real del Jucar," as well as to the "Albufera" environmental demand node. The water reused volume should be equal or lower than the maximum capacity of the tertiary line of the plant. We established a maximum annual water reused volume of 71.2 Mm^3/year for agricultural uses, considering the estimates of the competent authorities with regard to the amount of reused water which could be directly used to irrigate the rice fields (ACUAMED 2006).

– Change to drip irrigation: for each suitable ADU node, we defined two different monthly demands (according to CHJ 2015): gravity irrigation demand and drip irrigation demand. Once that the drip irrigation link is activated, the gravity irrigation link goes inactive for the rest of the optimization period.

– Water re-pumping for rice irrigation: the maximum annual volume which could be re-pumped from Node X to the ADU nodes of Sueca, Cullera, and Cuatro Pueblos should be equal or less than the maximum annual volume allowed in the drought emergency scenario (CHJ 2017). Respectively, these amounts were 13, 6, and 2 Mm^3/year.

– Surface water resources for La Mancha Oriental irrigation area: according to CHJ (2015), up to 80 Mm^3/year could be transferred from Alarcon reservoir to La Mancha Oriental irrigation area ("Mancha Oriental_agriculture").

By means of the GAMS software, we developed an optimization model at the monthly scale using nonlinear programming (NLP). The model is able to automatically select the

combination of adaptation measures that simultaneously minimize a weighted combination of the maximum deficit and the cost for each climatic scenario. The selected algorithm in order to maximize the objective function was CONOPT (originally developed by Drud 1985). The objective function could be represented in a simple way by Eq. (1):

$$Obj = \sum_{i=1}^{n} Prior(D_i) x S(D_i) - \sum_{j=1}^{m} Penal(M_j) x V(M_j) - \sum_{k=1}^{l} Penal(R_k) x Def(R_k) \quad (1)$$

where:

- Obj: value of the objective function (Mm.^{3})
- $Prior(D_i)$: priority of demand "i" (dimensionless)
- $S(D_i)$: water delivered to demand "i" (Mm.^{3})
- $Penal(M_j)$: penalty assigned to measure "j" (dimensionless)
- $V(M_j)$: increase in water availability associated with measure "j" (Mm.^{3})
- $Penal(R_k)$: penalty assigned to restriction "k" (dimensionless)
- $Def(R_k)$: deficit in relation to the accomplishment of restriction "k" (Mm.^{3})

The final value of the objective function would be the aggregated value of all the years and months of the optimization period (from 2011 to 2070). The demands' priority coefficients were assigned by taking into account that urban demands have priority over agricultural demands (MMA 2001) and, within agricultural demands, the traditional irrigation districts have priority over the more recent La Mancha irrigation area (due to the Alarcon agreement). Regarding the measures' penalty coefficients, we set them as proportional to their cost. Finally, in relation to the system's restrictions (environmental flows and minimum reservoir volumes), we assigned them large penalty coefficients, in order to ensure compliance as long as possible.

4 Results

4.1 Climate and socioeconomic scenarios

4.1.1 Climate change scenarios

The selected GCM/RCM combinations (Table 4 in Supplementary material) were the same as in Marcos-Garcia and Pulido-Velazquez (2017). Besides, we used the Temez hydrological model previously calibrated by Marcos-Garcia et al. (2017), whose goodness of fit (GOF) is presented in Table 5 in Supplementary material. The changes in precipitation and temperature in the midterm RCP 8.5 scenario (regarding the control period) and in the future inflows for the same scenario (regarding the 1940–2009 inflow time series) are summarized in Table 2.

4.1.2 Socioeconomic scenarios

For the scenario combinations of Section 2.3, Table 3 and Table 7 in Supplementary material summarize the potential trends foreseen by the local farmers for each combination of

Table 2 Climate scenario RCP 8.5 midterm summary

	Precipitation			Temperature	Inflow
	Spring	Autumn	Winter	Max. increase	Median
Upper	−35%	−24%	+8%	+3.75 °C (Sep)	−44%
Middle	−40%	−16%	+13%	+3.50 °C (Jun)	−31%
Lower	−27%	−7%	−25%	+3.50 °C (Aug)	−13%

climate and socioeconomic scenarios. Differences in the results for both agricultural areas could be largely explained by their distinct features (Mediterranean vs. continental climate, surface water vs. groundwater as main water source, small vs. large plot size, cereal crops and vineyards vs. citrus fruits, kakis, and rice as main crops, etc.) and therefore cannot be extrapolated to other agricultural regions.

4.2 Potential adaptation measures

Table 4 summarizes the main adaptation measures identified by the workshop participants.

4.3 Assessment of adaptation measures at basin scale

Figure 4 shows the quantitative assessment of the adaptation measures performed by the stakeholders at the basin scale (considering grades from 0 to 10, most preferred). Generally, the participants of the third workshop agreed with the farmers in relation to supporting the improvement of irrigation efficiency (through the change to drip irrigation), of water governance (through the review of water rights), and the increase of non-conventional water resources use (water reuse and desalination). Moreover, they showed low interest with regard to water markets and water transfers. However, the introduction of water price policies was considered positively, although participants highlighted its potential for triggering political conflicts and the lack of social support as two of the main barriers for its implementation. This perception is supported by the results of the previous workshops, where most of the farmers characterized water price policies as "undesirable."

Regarding the potential barriers in order to implement these measures, the stakeholders highlighted the lack of public financing (change to drip irrigation), high operational costs (water reuse and desalination), and high potential for conflict (water transfers, economic instruments, and water governance) (Figs. 3 to 8 in Supplementary material).

4.4 Cost-effectiveness assessment of adaptation measures

Figure 5 represents the mean annual deficit in the water system obtained through the hydroeconomic model for the different climatic scenarios, considering two configurations: without the implementation of any adaptation measure (red) and with the potential ability to select some of the measures already identified by the stakeholders (green). According to the median of the models, in the short term (ST) the implementation of adaptation measures could reduce the mean annual deficit in 62 Mm^3/year for the RCP 4.5 scenario (from 171 Mm^3/year to 109) and in 58 Mm^3/year for the RCP 8.5 (from 185 Mm^3/year to 127). In the midterm (MT), for the RCP 4.5 scenario the mean annual deficit decrease is low (22 Mm^3/year in relation to the same scenario without measures) regarding the median,

Table 3 Summary of the farmers' vision regarding the SSP3×RCP 8.5 scenario

	SSP3×RCP 8.5 (protectionism)	
	La Ribera	La Mancha
Plausibility	No, protectionism contradicts the current tendency of the sector towards internationalization	Yes, although the influence of protectionism in local production would be scarce
Crop patterns	*General trends*: diversification and introduction of less water-consuming varieties. *Expected decrease*: citrus fruits. *Expected increase*: kaki, almond tree, avocado, pomegranate, and other tropical crops	*General trends*: promotion of seasonal and local products, introduction of new varieties (due to biotechnology). *Expected decrease*: extensive crops (cereals, corn). *Expected increase*: green vegetables, agro-industrial and woody crops (of high-added value)
Technological development	Change to drip irrigation 2.0: oriented to correct the negative impacts associated to drip irrigation and maximize its potential	Improvement of water efficiency due to new technologies: smart agriculture, humidity control, remote sensing combined with the study of leaf phenology
Consequences	Increase of water conflicts. Changes in the sector structure, due to the population increase and the decrease of water resources availability	Increase of water conflicts. Cost rises and land property concentration

Table 4 Summary of the main adaptation measures identified in the farmers' workshops

	Measure	Observations
Supply side	Desalination	Only considered in La Ribera (coastal area). Participants did not reach an agreement, a few considered it as "priority" while some of them thought it as "undesirable" (due its high associated cost)
	Water reuse	Positively assessed in both regions. According to the participants, its success would depend on the implementation of quality control mechanisms (to avoid soil or crop damages) and the preservation of current surface water rights (to avoid social conflicts)
	Water transfers	Negatively assessed in both regions due to its high potential to trigger social conflicts (e.g., Ebro water transfer)
Demand side	Drip irrigation	Unanimously supported in La Mancha, but intensively discussed in La Ribera (some stood up for its utility, while others criticized the way in which it has been implemented). Need of a second generation of drip irrigation (consideration of territorial features, avoidance of the "rebound effect," training to the farmers, etc.) and public financing to support it
	Economic instruments	Water markets were negatively assessed in both regions (appearance of large water dealers, need for new infrastructures, etc.). Most of the participants considered water prices as "undesirable"
Others	Governance	Transparent and participative water management, effective mechanisms for water allocation control and water rights review

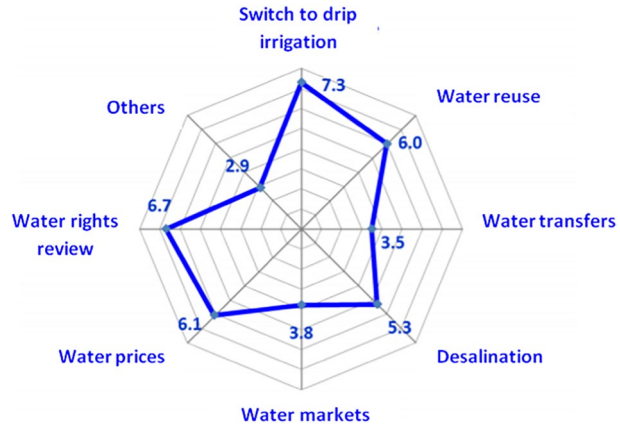**Fig. 4** Quantitative assessment of adaptation measures
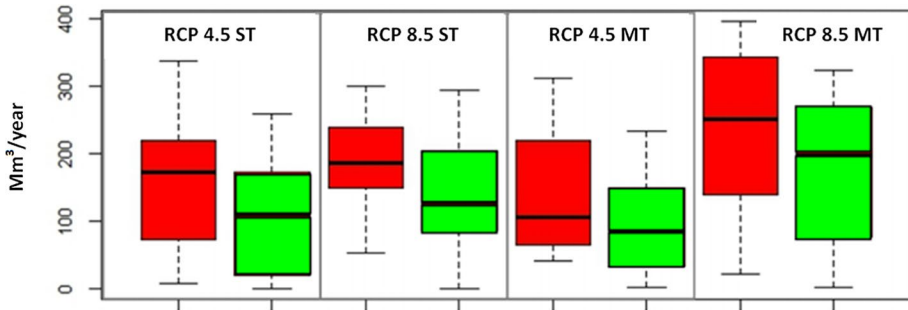
Fig. 5 Mean annual deficit regarding the scenario without (red) and with measures (green)

but the maximum deficit could be reduced in 78 Mm^3/year. Finally, the RCP 8.5 scenario in the midterm presents more variability than the other ones. Regarding the median of the models, the mean annual deficit could be reduced to 53 Mm^3/year once the measures are implemented.

Figure 6 shows the mean additional volume available per year (for the RCP 8.5 scenario in the midterm), due to the implementation of some of the stakeholders' best valued adaptation measures (Fig. 4): supply-side measures (desalination, water reuse, and re-pumping to rice areas) or due to demand-side measures (change to drip irrigation).

The cost of each program of measures was estimated according to the data of Section 2.4. Figure 7 shows the avoided deficit for scenario RCP 8.5 in the midterm and the cost of the implemented program of measures, regarding the same scenario without measures. The outcomes for the rest of the considered scenarios are depicted in Figs. 9 to 11 in Supplementary material.

Regarding the programs of measures that showed the best ratio with regards to the avoided deficit, we could highlight the one implemented for CSIRO_RCA4 model combination in the short-term RCP 4.5 scenario. However, this program of measures avoided a relatively small deficit in the midterm for this scenario (around 30 Mm^3/year). The program of measures that presented the best ratio for RCP 4.5 in the short and in the midterm was the one implemented for MIROC_RCA4 model combination (which presented larger challenges for the system than CSIRO_RCA4). For the RCP 8.5 scenario, the program of
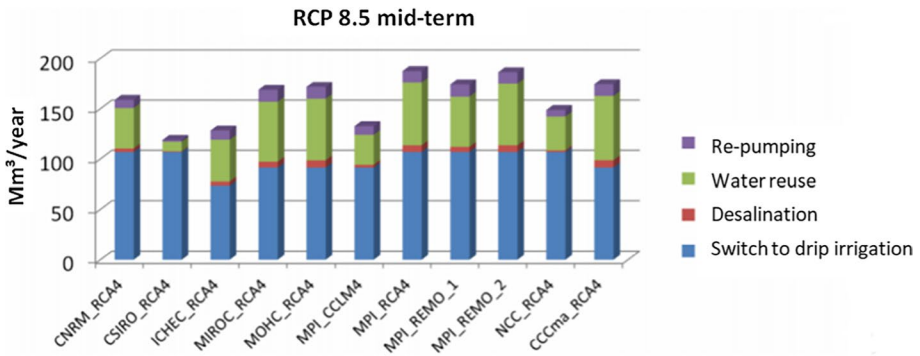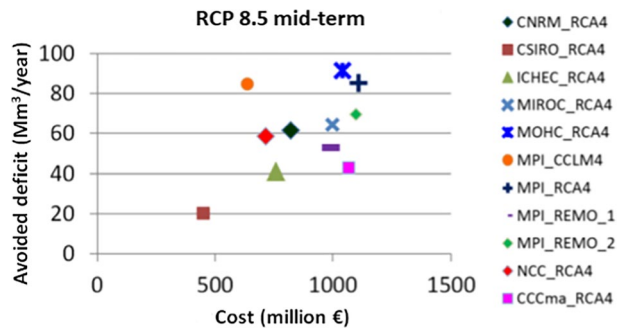
Fig. 6 Mean additional volume available per year (RCP 8.5 in the midterm) due to the implementation of measures

Fig. 7 RCP 8.5 scenario in the midterm. Avoided deficit and cost. *Acronyms correspond to the combinations of GCM/RCM models of Table 4 in Supplementary material

measures implemented for CSIRO_RCA4 model presented the best ratio (although the avoided deficit in the midterm was small, its cost was relatively low because the mean annual inflows were large in relation to the rest of model combinations) (Table 6 in Supplementary material).

5 Discussion

Regarding the results of the top-down approach, the inflows under the climate change scenarios show a great variability across GCM/RCM model combinations. Therefore, there is a great uncertainty in relation to future water resources availability. This uncertainty arises not only from the future climate scenarios, but also from the potential failure of the conceptual hydrological model to predict discharge changes under climate conditions which are very different from those of the calibration period (Duethmann et al. 2020). This fact is consistent with the current literature in the Mediterranean area (Koutroulis et al. 2013; Pascual et al. 2015; Marcos-Garcia et al. 2017). For the Jucar basin, Chirivella Osma et al. (2015) quantified these impacts as between − 13.45% and 18%, with a mean value of − 2.13%.

The "scenario foresight" approach seems to be a useful approach for a bottom-up exploration of local alternative futures under climate and global change, and for the identification

of adaptation options. Experts and farmers have helped to analyze the consequences of various global climate and socio-economic change scenarios in a structured way, concretely with regard to the future of agriculture in a local context, and then to discuss and identify potential adaptation measures. In this way, scenario workshops can usefully supplement modeling methods in assessing long-term climate and global change scenarios design and test adaptation options. Economic instruments such as water markets or water transfers were clearly rejected by farmers, whereas technical solutions such as reuse or drip irrigation were favored. The proposed methodology allowed us to contrast these first conclusions with the stakeholder's view at the river basin scale, what mainly confirmed farmer's view, except for water pricing. This two-step stakeholder consultation process reinforces the consistency of the results and is able to provide better policy recommendations than a conventional top-down modeling approach.

The utility of hydroeconomic models to explore climate change adaptation options at different scales has already been demonstrated by multiple authors. For example, Esteve et al. (2015) combined an optimization economic model at the plot scale with the WEAP hydrological model to analyze climate change impacts and identify potential adaptation measures in the Guadiana basin (Spain). At the basin scale, Girard et al. (2015a) implemented an optimization model for the Orb basin (France) in order to minimize the cost of climate change adaptation measures along with the maximization of water supply. Moreover, Herman et al. (2018) used an optimization hydroeconomic model to estimate the annual supply for each demand without knowing the future availability, as well as assessing future inflow projections that represented a wide range of climate conditions.

Thus, the approach presented in this work sums up to these examples by showing that, for the majority of the climate change scenarios, the selected adaptation measures could substantially reduce the mean annual deficit of the system. This can contribute to narrow the existing wide range of uncertainty about the impact of climate change on water resources management in the Mediterranean region. However, it is necessary to take into account that deterministic optimization assumes a perfect knowledge of the future. Therefore, it could "choose" to implement measures that are apparently unnecessary in the short term, because it already "knows" that they are going to be needed in the midterm. Nevertheless, in the real world this kind of decisions could have a high potential for conflict (mostly if they entail strong investments and they are not necessary in the end). A good example regarding our case study could be the desalination plant of Sagunto, which was built during a prosperous economic period to address future urban development (that never took place) and currently it is not operating. Besides, adopting a multiobjective optimization instead of a single one could allow the exploration of the full trade-offs among the different water uses, thus providing a clearer feedback to the stakeholders involved in the participatory process.

Another key aspect could be the estimation of future demands. Here, we considered them as constant although the selected methodology provides the inputs for their integration in the hydroeconomic model (through the farmers' insights about the potential evolution of the irrigation area and crop patterns). Therefore, it would be necessary to "translate" the qualitative data derived from the workshops into quantitative irrigation demand projections and assess their associated uncertainty. Moreover, the population evolution and the trends of industrial and urban water demands (including those of non-permanent population, e.g., tourism) should also be considered, as non-agricultural demands account for a non-negligible 20% of the total demand.

Another issue is that our hydroeconomic model considered the current allocation rules, which are based on the existing priorities between users. Nevertheless, in a context of

great reduction of the available resources, it could be necessary to contemplate new allocation rules (in order to avoid that some users could be disproportionately affected, along with ensuring that environmental restrictions are satisfied), as Gómez-Limón et al. (2020) have recently suggested. In our case study, the Alarcon agreement assigns less priority to La Mancha Oriental irrigation area with respect to La Ribera one. Therefore, the model tended to "penalize" more La Mancha area than La Ribera one. Moreover, a minimum environmental flow should be respected in the Jucar river reach connected to La Mancha Oriental aquifer (so pumping could be restricted during some periods). Girard et al. (2016) addressed this aspect in the Orb basin through two different approaches: game theory and social justice. In this regard, it would have been interesting to take the results (including the costs) back to the workshop participants, to identify whether their acceptance of some of the adaptations changed as a result of the outcomes on water availability and the costs.

6 Conclusions

The main contribution of this work is the development of an integrated method to identify climate change adaptation options at basin scale, through the combination of a top-down assessment of climate change impact at local scale with a participatory bottom-up approach to assess vulnerability, future demand scenarios, and locally relevant adaptation options.

In relation to climate change impacts on water resources, we need to highlight the importance of spatial variability. In our case study, the upper basin (where the main reservoirs are located) seemed to be more prone to precipitation decrease and temperature rise than the coastal area. This fact could have key implications for future water management in the basin.

Regarding the vulnerability assessment and the identification of adaptation options, the use of participative methodologies has proved itself as a valuable tool for the structured analysis and design of global change adaptation strategies. Concretely, its main strengths are the integration of the valuable local knowledge and the assessment of local adaptation priorities, which are crucial aspects for the successful implementation of adaptation measures (as the implication of local actors is a necessary condition). Furthermore, participatory scenario foresight methodologies make possible the effective communication of the projections' uncertainty (which could be a key aspect for the success of the adaptation strategy).

Finally, in relation to the hydroeconomic model, we found that the implementation of adaptation measures could substantially reduce the mean annual deficit of the system across the considered climate change scenarios. However, the allocation of the remaining deficit was not equitable between the different users. Therefore, it would be necessary to explore potential ways to tackle this issue, in order to avoid the intensification of the existing water conflicts when facing a future context of increasing scarcity.

Data availability Climate change datasets used in the current study are available in the Zenodo repository (http://doi.org/10.5281/zenodo.4642827).

Declarations

Ethical approval There is no ethical conflict or ethical issues in the paper, and the research is done in compliance with the ethical standards of the journal.

Consent to participate All the authors are informed about the submission and consent on participating.

Consent to publish All the authors consent on the publication of the paper once accepted.

Conflict of interest The authors declare no competing interests.

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