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Integrating stakeholders' inputs to co-design climate resilience adaptation measures in Mediterranean areas with conflicts between wetland conservation and intensive agriculture

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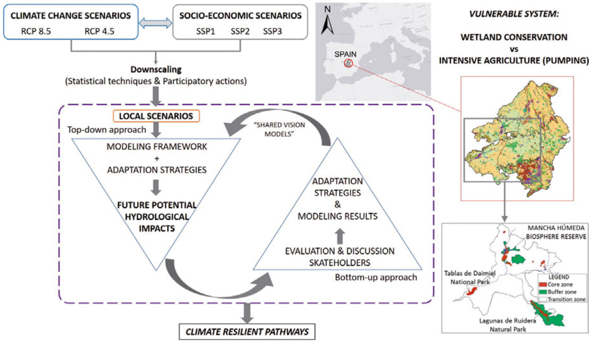
HIGHLIGHTS

- Studying conflicts between wetland conservation and intensive agriculture
- Co-design of adaptation strategies to climate change in water scarcity areas
- The analyses include the climate, hydrological and socio-economic spheres.
- Downscaling procedure to generate potential future local scenarios
- Mixed bottom-up and top-down approaches to identify climate resilient pathways

GRAPHICAL ABSTRACT



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ABSTRACT

Designing sustainable management strategies in groundwater-dependent socio-economic systems in areas with scarce water resources and protected wetlands is a challenging issue. The high **vulnerability** of these systems to droughts will be exacerbated even further under future climate change (CC) and socio-economic scenarios. A novel integrated bottom-up/top-down approach is used to identify "**climate resilient pathways**", from which to co-design adaptation strategies to reduce the impact of potential future CC and socio-economic scenarios. The approach followed two steps (1) the generation of local CC and socio-economic scenarios by **downscaling global/regional climate models** and (2) the **identification and assessment of potential adaptation strategies** through an iterative bottom-up/top-down approach. Top-down assessments of the impact of CC have been undertaken by propagating local scenarios within a chain of mathematical models based on expert criteria/assumptions. This allowed us to analyse of the

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physical vulnerability of the system under different potential CC and socio-economic scenarios by simulating them with a sequential modelling of rainfall–recharge, agriculture, and hydrological processes through a distributed groundwater finite difference model. These model results were discussed with the stakeholders at a first workshop, which aimed to identify potential adaptation strategies. The influence of the adaptation strategies on the future hydrological status was assessed by simulating them through the chain of models. These results were the inputs into the discussions at a second workshop, which aimed to validate and/or improve the results of the first workshop. The methodology was applied in the Upper Guadiana River Basin, where there is a long-standing conflict between wetland conservation and groundwater overexploitation for intensive agriculture. The future horizon 2016–2045 is analysed with the scenarios compatible with the emission scenario RCP4.5. The research has allowed us to conclude that groundwater pumping reduction would be the most robust and effective measure to reduce the impact of CC in the area.

1. Introduction

A big challenge for water management strategies in areas with scarce water resources is how to address droughts and their propagation (Hidalgo-Hidalgo et al., 2022; Barker et al., 2016), which is especially significant in the Mediterranean basin (Cramer et al., 2018; Tramblay et al., 2020). Aquifers play a critical role in providing water supplies in many areas across the world, but are especially important for dry lands where rivers are usually ephemeral (Baena-Ruiz et al., 2021). The combination of global climate change (increasing temperature and changing precipitation regimes), hydrosphere and anthropogenic activities (mostly based on excessive groundwater pumping) threatens the sustainability of groundwater resources (Baena-Ruiz et al., 2018). It also deteriorates freshwater quantity and quality levels which are needed for the good functioning of groundwater-dependent wetlands (important for e.g. biodiversity or flood regulation functions) and often dependent socio-economic activities such as fisheries (Dalin et al., 2017; Alcalá et al., 2018). Therefore, wetland dynamics can be very sensitive to climate conditions and the impact of anthropogenic activities (Anand and Oinam, 2020; Malekmohammadi and Jahanishakib, 2017). This is the case of the UNESCO La Mancha Húmeda Biosphere Reserve (UNESCO website: https://en.unesco.org/biosphere/eu-na/mancha-humeda), which includes the Tablas de Daimiel National Park and the Lagunas de Ruidera Natural Park in the Upper Guadiana River Basin in central continental Spain, where a reduction in water resources has already occurred (Martín Utrillas et al., 2020). The RAMSAR convention lists these wetlands (RAMSAR website: https://www.ramsar.org/es/humedal/spain) as being of key international importance and proposes methodological guidelines for their conservation. In accordance with the RAMSAR convention, the wetlands can be used to improve water quality, store flood water, maintain surface water during dry periods, sustain habitats for biodiversity, and provide recreational, cultural and tourism values to the local community (De la Hera-Portillo et al., 2017, De la Hera et al., 2016).

The simulation of the impact of CC within mathematical models can be used to generate information to support the decision-making process in the planning and management of groundwater-dependent systems (Gómez et al., 2022). For example, these models can provide information about the impact on aquifer recharge and discharge (Pulido-Velazquez et al., 2018a; Pardo-Iguzquiza et al., 2019; Touhami et al., 2014) and groundwater levels (Dubois et al., 2022; Seidenfaden et al., 2022; Moseki, 2018). They can be used as "shared vision models" to assess and discuss feasible measures that take into account the stakeholders' perception as a critical input (Loucks and van Beek, 2017). This assessment typically follows three steps (1) the generation of potential future climate and socio-economic scenarios, (2) the propagation of the impact of local scenarios on the environment and/or the economy, and (3) the identification and simulation of the potential adaptation strategies to assess them.

The generation of potential future climate scenarios is a necessary first step to assess adaptive strategies. These scenarios are not intended to be predictions of future climate scenarios. The latest emission scenarios published by the IPCC (AR5 and AR6) – the RCPs (trajectories of atmospheric concentrations of greenhouse gasses) – have been simulated using climate models to generate global and/or regional climate scenarios, which are available as open access (Herrera et al., 2016). In order to make this information relevant to analyse related adaptation planning and management for specific water resources systems these climate scenarios need to be developed at a regional-local scale (Peker and Sorman, 1982). Potential local future scenarios can be generated by applying statistical correction techniques (statistical downscaling) in accordance with the historical series/fields (Collados-Lara et al., 2018b). There are numerous statistical correction techniques (correction of the first and second moment, regression, quantile mapping, etc.) that can be applied by assuming two different conceptual approaches: bias correction of the RCM (Watanabe et al., 2012; Collados-Lara et al., 2020) or delta correction by disturbing the historical series/fields (Räisänen and Räty, 2013; Collados-Lara et al., 2018a).

The impact of the generated local future scenarios can be propagated by using hydrological models (Pulido-Velazquez et al., 2018a; Renau-Pruñonosa et al., 2016) and/or management models (Escriva-Bou et al., 2017; Pulido-Velazquez et al., 2011). They can provide results at aquifer (Llopis-Albert and Pulido-Velazquez, 2015; Pulido-Velazquez et al., 2006, 2007), catchment (Pérez-Sánchez et al., 2019; Senent-Aparicio et al., 2018; Joorabian Shooshtari et al., 2017), mountain range (Collados-Lara et al., 2019; Pardo-Igúzquiza et al., 2017), country (Pulido-Velazquez et al., 2018b, 2020) or even at a continental (Wood et al., 2003; Trambauer et al., 2013) scale.

Finally, it is also necessary to identify and assess potentially feasible adaptation measures (Iglesias and Garrote, 2015). Top-down ("scenario centred") approaches are commonly applied to identify and assess potential general adaptation strategies (Pulido-Velazquez et al., 2011; Escriva-Bou et al., 2017). The main problem of these top-down approaches is the expanding and growing uncertainty within the modelling chain (Dessai et al., 2013). It often provides results which are too uncertain for decision makers (Girard et al., 2015). These uncertainties can be reduced by integrating scientific and stakeholder knowledge (Ludwig et al., 2011). Bottom-up approaches accept an uncertain future and focus on enhancing adaptive capacities (Ludwig et al., 2011). They have also been increasingly used for this purpose (Zorrilla et al., 2010; Esteve et al., 2018). The engagement of local stakeholders for knowledge co-production is not only increasingly used in CC science and environmental analyses to obtain grounded data inputs to be incorporated within mathematical models (Blöschl et al., 2019). but these techniques are also being used to obtain information in terms of the complexity of adaptation and the need to integrate different types of disciplines and knowledge. As the recent IPCC report states "there are multiple possible pathways by which communities, nations and the world can pursue climate resilient development. Moving towards different pathways involves confronting complex synergies and trade-offs between development pathways and the options, contested values and interests that underpin climate mitigation and adaptation choices" (Pörtner et al., 2022 p. 100).

Bottom-up approaches help to generate validated results that are meaningful for local stakeholders, decision makers and information users (Linnerooth-Bayer et al., 2016; Scolobig and Lilliestam, 2016). Most of them aim to analyse social vulnerability, based on participatory processes developed through workshops where stakeholders from the main social, environmental, economic and productive sectors are able to engage. There are several types of approaches and methods to involve stakeholders in environmental analyses and modelling processes aimed at improving informed decision making. Some examples include methods such as focus groups, scenario analysis, stakeholder workshops, policy exercises, participatory model building, mediated modelling, cooperative modelling, group model building and computer-mediated collaborative decision making (Van Asselt and Rijkens-Klomp, 2002; Tuler et al., 2017). Other less model-focused approaches include training games, policy exercises to explore alternative futures, citizens' juries, consensus conferences, and participatory planning (Van Asselt and Rijkens-Klomp, 2002; Toth and Hizsnyik, 1998).

Examples can be found in the literature of different approaches to integrate top-down and bottom-up techniques that aim to overcome the "drama of uncertainty" that delays adaptation planning at basin or sub-basin scale (Girard et al., 2015: Haro-Monteagudo et al., 2022). To the best of our knowledge, there are no previous climate adaptation studies integrating both approaches focused on the study of vulnerable groundwater dependent systems with high environmental value with a methodological approach adapted to their characteristics.

This paper introduces a novel integrated bottom-up/top-down approach to identify "climate resilience development pathways" (Schipper et al., 2022) in aquifer systems with groundwater dependent wetlands of high environmental value and scarce water resources. It aims to overcome the "drama of uncertainty" by co-designing robust adaptation measures integrating the goals of economic development, social acceptability and environmental sustainability. This approach has been applied to the Upper Guadiana River Basin in central continental Spain, a paradigmatic example where CC can exacerbate the current ongoing conflicts between wetland conservation and groundwater overexploitation for intensive agriculture.

2. Materials and methods

2.1. Location and hydro-geological description of the Upper Guadiana Basin system

The Upper Guadiana Basin covers an area of nearly 14,000 km^2 located in central continental Spain (Fig. 1). It includes eight groundwater bodies (Sierra de Altomira, Lillo Quintanar, La Obispalía, Mancha Occidental I, Mancha Occidental II, Campo de Montiel, Consuegra-Villacañas and Rus-Valdelobos). Some of these wetlands present significant vulnerability and have been declared at risk of not complying with the objectives of the EU Water Framework Directive (Baena-Ruiz and Pulido-Velazquez, 2020; Pulido-Velazquez et al., 2020). This area is dominated by high-permeability geological formations (Fig. 1a) which determine a strong natural interaction between surface watercourses and groundwater bodies. This feature gives rise to over one hundred groundwater-dependent wetlands that make up UNESCO's La Mancha Húmeda Biosphere Reserve [UNESCO website: https://en.unesco.org/biosphere/eu-na/mancha-humeda] (Fig. 1c). Under semi-natural conditions this protected area originally covered 25,000 ha, including the Tablas de Daimiel National Park and the Lagunas de Ruidera Natural Park. However, the original wetland area has now been reduced to 7000 ha due to groundwater depletion induced by intensive groundwater pumping. Therefore, the current groundwater management means that a significant number of the remaining wetlands are at risk of disappearing. Although an important and unexpected recovery of the Mancha Occidental aquifer occurred after an intense and out-of-the-ordinary 2009–2011 wet period, the system is still very vulnerable and there are significant uncertainties with regard to ecosystem functionality and its capacity to provide the full range of ecosystem services in the mid and long term (De la Hera et al., 2011).

2.2. Historical climate, agronomical and hydrological data

This pilot is located in the Mediterranean Region. However, in accordance with the EEA maps the climate conditions are typically continental and semi-arid. The summers are hot and dry, and the winters are short and generally mild (Martínez-Santos et al., 2018). The precipitation is irregularly distributed over time (see details in Supplementary material). The annual average value for the period 1904–2014 was 405 mm (Martínez-Santos et al., 2018). The mean annual temperature is 14.7 °C, oscillating between a maximum mean value of 25.5 °C in July and a minimum of 5.4 °C in January. The mean annual potential evapotranspiration was700–800 mm (SURGE, 2018).

The Upper Guadiana Basin has traditionally been one of the most intensively exploited groundwater systems in Spain (Fig. 2). The exploitation

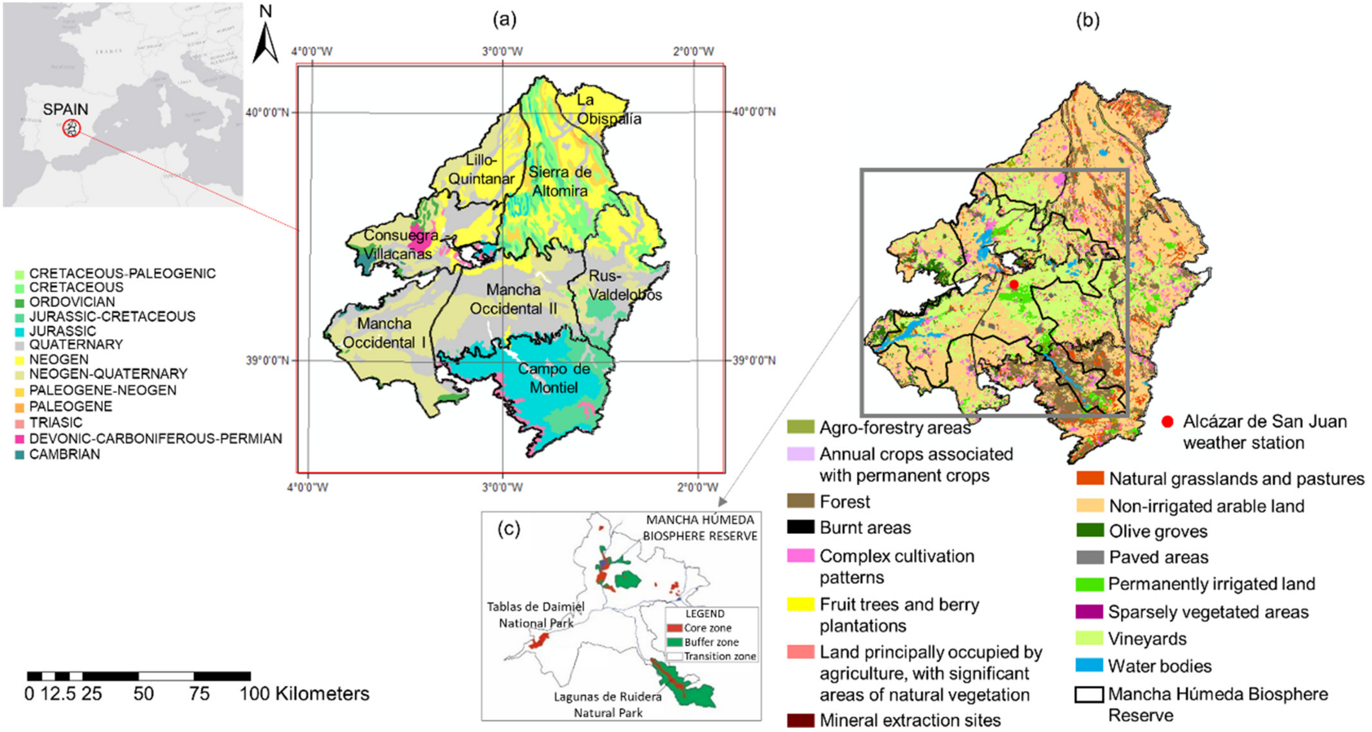

Fig. 1. Location and description of the Upper Guadiana Basin pilot area. (a) Hydro-geological map. (b) Land use map of the year 2012. (c) Mancha Húmeda Biosphere reserve.

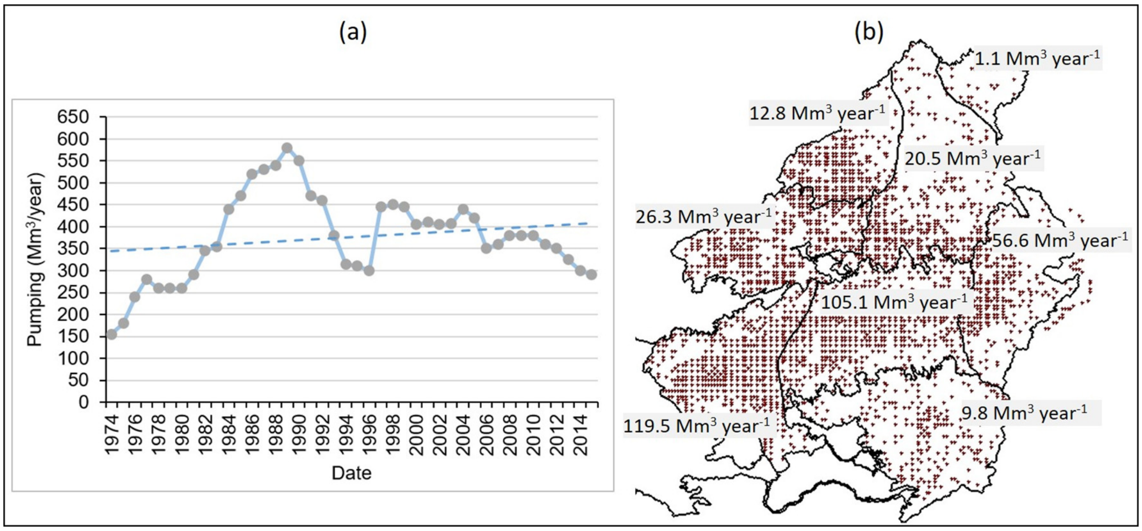

Fig. 2. (a) Evolution of groundwater pumping (Mm^3 year^{-1}) over the period 1974–2015 and (b) spatial distribution of average annual pumping in each of the eight groundwater bodies defined in the system over the period 2006–2015.
Source of data: SURGE (2018).

rate has mostly depended on the combination of a predominantly dry climate, the prevalence of irrigation agriculture, and accessibility to shallow groundwater (Martínez-Santos et al., 2008). From a socio-economic point of view, the Upper Guadiana Basin is an example of inland dry land where transformation of traditional rainfed agriculture into profitable groundwater-dependent irrigation agriculture has been crucial to transforming a poor rural region into a prosperous agro-industry centre (Hernández-Mora, 2002; Llamas, 2005). However, the result of groundwater withdrawals has been aquifer depletion as seen in a drop in the water table of more than 20 m since the mid-1970s. This is reflected in the need to artificially maintain wetlands through the allocation of groundwater pumping in the driest spells since the early 1980s to avoid wetland desiccation (Martínez-Santos et al., 2018). Although non-irrigated agriculture is the most extensive (Fig. 1b), there are important irrigation areas mainly located in the central part of the Upper Guadiana Basin (Fig. 2b). The main irrigated crops in the area are winter cereals, vineyards and olives (Conan et al., 2003). Woody rainfed crops are also irrigated during the summer. Currently, groundwater pumping for irrigated agriculture captures about 90 % of the total water use in the area. These indicators of the current status of the aquifer and the protected wetlands have led to the inclusion of the Upper Guadiana Basin as a hotspot area in the Spanish National Action Plan to Combat Desertification (Martínez-Valderrama et al., 2016; MITECO, 2022).

Precipitation is the main aquifer recharge source in the Upper Guadiana Basin (Martínez-Santos et al., 2018). The predominantly dry climate induces aquifer recharge rates in the range of 40–70 mm·year^{-1} (Conan et al., 2003; Martínez-Santos et al., 2008; Yustres et al., 2013), which are below the groundwater pumping rates (Fig. 2a) used to supply the intensive irrigated agriculture in some groundwater bodies. The two central groundwater bodies, Mancha Occidental I and II, are the most overexploited (Fig. 2b) with pumping representing over 60 % of the total pumping in the basin. In fact the pumping rate in just these two groundwater bodies in some years is above the maximum mean recharge for the entire basin. The consequence is groundwater depletion, which has led to the desiccation of some groundwater-dependent ecosystems in the driest spells, including the RAMSAR-listed Las Tablas de Daimiel National Park. Some previous studies have analysed the change of the wetland extension as a consequence of groundwater overexploitation. Collados-Lara et al. (2021) estimated the monthly dynamics of surface water in the Lagunas de Ruidera wetland from satellite and secondary hydro-climatological data from 1984 to 2015. In that work, the discharge of the aquifer to the wetland was selected as one of the most important secondary variables to estimate water surface. García Fernández et al. (2013) analysed the surface inundation in the Tablas de Daimiel wetland from 1996 to 2006. They applied dynamic water budgets, with hypsometric curves associated with different locations to synthetically characterize the inundation that would be caused by the different water application strategies. The groundwater overexploitation has triggered a series of measures to constrain irrigation in the area. This excessive level of groundwater pumping is partly due to inadequate management and the probable presence of thousands of illegal pumping wells.

2.3. Climate model simulation data. Control and future scenarios

In order to produce a more robust generation of future climate scenarios, results from nine climate model simulations were taken from the website of the CORDEX EU project in accordance with the RCP8.5 (the most pessimistic scenario) and RCP4.5 emission scenarios included in the fifth IPCC report (AR5) (Herrera et al., 2016). These correspond to different RCM simulations, which include control (historical simulations) and future results for the horizon 2015–2045, nested to different Global Climate Models (GCM). These combinations of GCM and RCM simulations are:

- RCM simulation nested to GCM CCLM4-8-17: CNRM-CM5; EC-EARTH; MPI-ESM-LR.
- RCM simulation nested to GCM RCA4: CNRM-CM5; EC-EARTH; MPI-ESM-LR.
- RCM simulation nested to GCM HIRHAM5: EC-EARTH.
- RCM simulation nested to GCM RACMO22E: EC-EARTH.
- RCM simulation nested to GCM WRF331F: IPSL-CM5A-MR.

2.4. Methodology

The proposed mix of a top-down/bottom-up approach was defined by following the steps described in Fig. 3. It combines desktop CC modelling; hydrological modelling with irrigation planning and management and the co-design of downscaled socio-economic scenarios and climate adaptation strategies through a participatory approach.

The methodology involves an iterative process of modelling (top-down) and participatory workshops with stakeholders (bottom-up) in order to identify "climate resilience development pathways" in the Upper Guadiana

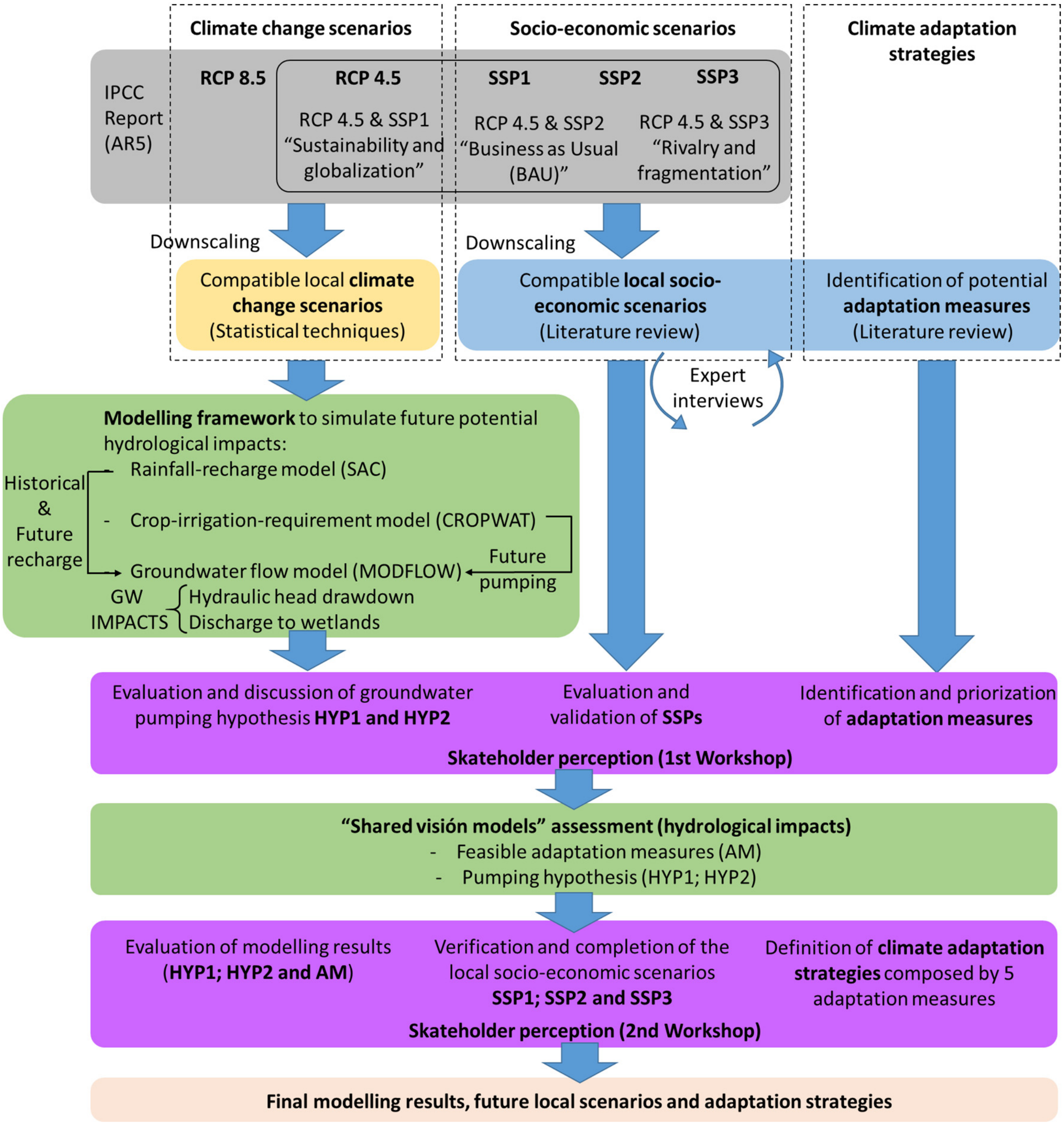

Fig. 3. Flowchart of the implemented bottom-up/top-down approach to co-design scenarios and identify adaptation strategies for the future short-term horizon.

Basin, a groundwater dependent ecosystem of high environmental value with scarce water resources.

2.4.1. Top-down approach

2.4.1.1. Desktop CC modelling. The GROUNDS tool (Collados-Lara et al., 2020) was used to generate multiple precipitation and temperature local series from the available climate model simulations and the historical climate data. This tool applies different statistical downscaling techniques (first moment correction, first and second moment correction, and regression) under two different conceptual approaches (delta change and bias correction). In this research, two downscaling techniques have been used: correction of first and second order moments for both bias correction and delta change approaches. The "bias correction approach" aims to define a perturbation in the control time series to force some of the statistics closer to the historical ones. This approach assumes that the bias between the statistics of the model and the data will remain invariant in the future. The "delta change approach" meanwhile assumes that climate models provide good assessments of the relative changes in the statistics between present and future, but do not thoroughly assess the absolute values. Therefore, the relative difference in the statistics of future and control simulations is used to perform a perturbation of the historical time series in accordance with the estimated changes. In relation to the techniques, in the first-moment correction technique, the transformation function used to correct climate models only aims to provide a good approximation to the mean values. The second-moment correction technique is focused on the approximation of the mean and standard deviation to define the transformation function. These approaches and techniques were applied to nine RCMs. An ensemble of the multiple generated scenarios is defined so that these coalesce and help consolidate the results of individual climate projections, thus generating more robust and representative climate projections than those based on a single model (Spanish Meteorological Agency, AEMET, 2009). Two equi-feasible ensembles were defined according to the approaches used: bias correction or delta change.

2.4.1.2. Modelling framework. Chain of calibrated models. A modelling framework was implemented to approach the historical hydrological impact within the pilot from the climate series and the distribution of crops in accordance with the Land Use and Land Cover (LULC) information (Fig. 2b). It is defined by a chain of auxiliary rainfall-recharge and crop-water-requirement models to generate the input for a distributed groundwater flow model (MODFLOW).

A calibrated distributed MODFLOW groundwater numerical model under operation in the Upper Guadiana Basin has been used. This model was developed by the Guadiana River Basin Authority in 2010 and was updated up to 2015 (SURGE, 2018). The MODFLOW model simulates groundwater flow and stream–aquifer interactions in the eight groundwater bodies defined in the Upper Guadiana Basin. It covers a total area of 14,000 km^2 and the cell size is 1 km × 1 km. The model is discretized into three layers to simulate the different hydraulic properties in some areas of the model. It was calibrated with the hydraulic head data from the River Basin Authority and the Spanish Geological Survey (IGME) for the period 1974–2003. Twenty-three piezometers of the 91 available in the Upper Guadiana Basin were used to calibrate the model by varying the hydro-geological parameters (within reasonable ranges) through a trial-error procedure. The model was validated with data over the period 2004–2015. The root-mean-square error (RMSE) obtained in the calibration and validation periods was 6.8 m and 7.5 m respectively (Fig. S2). In the Supplementary material (Fig. S2) some examples of the calibration and validation results obtained with the MODFLOW model in the Upper Guadiana Basin are shown for groundwater levels. The MODFLOW model uses recharge time series as inputs, which are obtained from the use of a calibrated Sacramento Soil Moisture Accounting (SAC-SMA) model from the US National Weather Service River Forecast System. Five SAC-SMA models were calibrated in the historical period (1974–2003) by a trial-and-error process to fit the simulated flow rates to the observed ones, from five flow gauges in the Upper Guadiana Basin. These flow rates were also validated with the data of the period 2004–2015. The climate series for precipitation and temperature (maximum and minimum) came from the Spain02 project (Herrera et al., 2016). Potential evapotranspiration series were calculated using the Hargreaves formulation (Hargreaves, 1994). CROPWAT models (Smith, 1992) were calibrated to assess the current net irrigation water demand from the crops, based on soil, climate, and crop data. This tool allows the estimation of water requirements for each kind of crop from the precipitation and temperature data. The calibrated CROPWAT models have been used to estimate the future pumping schedule in the area (the historical pumping schedule is shown in Fig. 2a).

This modelling framework was used to simulate the impact of the generated climate scenarios for the horizon 2015–2045 under two different emission scenarios (RCP4.5 and RCP8.5).

2.4.1.3. Desktop selection of relevant reference global scenarios and adaptation measures. The first step to build the socio-economic scenarios consisted of the top-down pre-selection of three global socio-economic narratives that are consistent with the climate change projections used for the modelling exercise, based on the selected Shared Socio-economic Pathways developed by the IPCC (IPCC, 2014). The criteria used to select the global socio-economic narratives were: a) compatibility with the climate projections considered in the models; and b) a substantial difference between scenarios to ensure relevance. As a result, the selected scenarios (SSPs) were SSP1 (sustainability), SSP2 (business as usual) and SSP3 (rivalry and fragmentation) as defined in Riahi et al., 2017. A first desktop downscaling exercise was done to adapt the main assumptions of the selected SSPs to the regional context and to develop preliminary regional narratives. This exercise was supported by a literature review focused on the local socio-economic context.

An inventory of the main typologies of adaptation measures identified in the literature was also prepared in order to both identify and prioritize a sufficiently large number of feasible adaptation strategies with stakeholders (e.g., for infrastructure, social, agriculture, etc.) in the first workshop. Adaptation measures regarding water management were classified mainly based on demand, supply or mixed measures.

2.4.2. Bottom-up approach

The bottom-up participatory process involving regional stakeholders was included to address two main goals: (1) include stakeholder perceptions and priorities in the downscaling of socio-economic scenarios and collaborative scenario building, and (2) to co-design climate adaptation strategies with the stakeholders.

The bottom-up process was supported and informed by the modelling results from the top-down approach for the time horizon of 2015–2045 under different hypotheses on the impact of potential future climate change.

2.4.2.1. Downscaling socio-economic scenarios and collaborative scenario building. The co-development of socio-economic scenarios and narratives for the region was developed by applying a participatory qualitative downscaling and scenario building approach to fit the global socio-economic scenario assumptions to the local context.

The applied methodology was adapted from the usual scenario building approaches, which typically comprise three steps: (1) elicitation of stakeholders' perspectives, (2) gathering of information and inputs to feed the model parameters, and (3) scenario ranking and identification of (in this case adaptation) actions (Gramberger et al., 2015; Kok et al., 2015; Scolobig and Lilliestam, 2016; Wada et al., 2019). A hybrid bottom-up/top-down approach was applied by combining the desktop preselection of relevant reference global scenarios (top-down, see Section 2.4.1.3) and the development of adapted participatory narratives for the case study region (bottom-up). The preliminary preselection of three global socio-economic narratives (SSP1, SSP2 and SSP3) and the first downscaling exercise to adapt these to the regional context was supported by the information gathered from key expert interviews undertaken in a first stage of the stakeholder process.

In a second step, the resulting narratives were then contrasted, completed and validated with the stakeholders' opinions during the first workshop held in October 2019.

In order to elicit the stakeholder perspectives, breakup groups with a balanced representation of different kinds of stakeholders (water and environmental authorities, local authorities, farmers, researchers, and environmental NGOs) were used to ensure a complete overview of trends from different social and sectoral realities. Each group focused on one of the selected scenarios (SSP1, SSP2 and SSP3) to increase the time available to analyse the proposed narratives and to propose changes to these scenarios.

A third step comprised the validation and scenario ranking, which were carried out in a second round of key expert interviews and during the second stakeholder workshop. The breakup groups were maintained with the same participants working on the same scenarios as in the first workshop, wherein narratives and assumptions were revised and validated to reflect the possible perception changes brought by the COVID19 pandemic and the advances in the implementation of the EU's Common Agricultural Policy reform. Finally, the scenarios were ranked by the pool of participants through a voting exercise to elicit their perception on the most probable scenario.

2.4.2.2. Co-development of climate adaptation strategies. The identification and prioritization of the previously selected adaptation measures was performed as a self-standing activity following the scenario development. The adaptation strategies were defined as feasible combinations of measures to address the water availability and aquifer conservation challenges in view of CC projections under the different socio-economic scenarios. The methodology for co-development of the climate adaptation strategies was inspired by Zorrilla-Miras et al. (2020).

A first co-development step was carried out in the first workshop maintaining the same breakup groups as in the scenario building exercise, with the aim of developing three scenario-specific strategies. A guided brainstorming technique was applied inviting stakeholders to first suggest feasible adaptation measures, which may include structural (grey and green) and non-structural (governance, management, etc.) measures as defined by the UNDRR.[1] In a second round, a list of measures spanning water

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[1] https://www.undrr.org/terminology/structural-and-non-structural-measures.

demand, water supply, and governance measures were shown as an inspiration to support the proposal of any additional relevant measures that may have been left out. The resulting set of measures was then prioritized through a voting exercise in which participants were asked to select the three preferred ones. Based on the results, a ranking was done to finally select the top five measures to develop the strategy. The participants were also asked to place the resulting measures in a timeline from 2020 to 2050 divided into intervals in order to introduce a time dimension for their implementation. These intervals tried to reflect the next river basin planning phases as set out by the European Water Framework Directive (Water Framework Directive, 2000), i.e. the horizons of 2027 and 2033.[2]

The resulting selected measures became the strategies collectively consensualised by the group, which were simulated through the modelling framework (Section 2.4.1.2) to then be revised and validated during the second workshop, keeping the same group composition as in the previous one. The simulations were focused on the emission scenario RCP4.5, which was the most compatible scenario with the selected potential future socio-economic scenarios. A climate change sensitivity analysis was carried out to show the physical vulnerability of the system in terms of impact on aquifer recharge, groundwater pumping schedule or irrigated area, and hydrological status of the aquifer defined by the groundwater balance components and the hydraulic head drawdown.

The modelling framework was used in the bottom-up approach as a “shared vision model” to support further discussions during the workshops based on the quantitative assessment of the potential impact of these measures under climate change scenarios on three key variables; crops in terms of irrigated area, groundwater levels, and groundwater discharge to rivers and wetlands.

A validation step was aimed to reflect any changes in perception on the suitability or the effectiveness of the measures based on the model simulation results, as well as any contextual changes that emerged from the update of the socio-economic scenarios. As a final exercise, the stakeholders were asked to specify the expected effect of the measures on three of the most critical model variables as mentioned earlier, namely crop change (type of crops), irrigated area (ha), and amount of irrigation water abstractions.

3. Results

3.1. Results from the top-down approach

3.1.1. Desktop CC modelling

Fig. 4 summarizes some of the statistics of the equi-feasible ensemble of multiple precipitation and temperature future local series for the horizon 2015–2045 under the emission scenarios RCP8.5 and RCP4.5, which were generated by applying the GROUND tool (Collados-Lara et al., 2020). The mean annual historical precipitation and temperature were 433.2 mm·year^{-1} and 15.4 °C respectively in the period 1974–2015. For the 2015–2045 horizon, the mean annual temperature and precipitation showed respectively for the two future scenarios (RCP8.5 and RCP4.5) a decrease of 10.3 and 19.8 mm·year^{-1} in precipitation and an increase of 2.2 and 0.8 °C in temperature, compared with the average historical values.

3.1.2. Modelling framework. Chain of calibrated models

The two generated ensemble climate scenarios for the future 2015–2045 horizon have been propagated with a calibrated SAC-SMA model to estimate the impact on mean aquifer recharge. The simulations performed show an average reduction of the mean annual recharge of 14 %, in the emission scenario RCP8.5, and 10 %, for the RCP4.5, with the average historical recharge being 46.8 mm·year^{-1}.

The ensemble climate scenarios have also been simulated within the calibrated CROPWAT models to assess future net irrigation water demands and the future potential changes in the pumping schedule (see Fig. 5a). The results have been organized in accordance with the official demand units in the Guadiana Basin.

In the first workshop, two groundwater pumping hypotheses were simulated for both RCP8.5 and RCP4.5 CC scenarios to share the potential impact of CC in the case study area with the stakeholders and to then identify and prioritize a series of adaptation measures based on the options provided. The groundwater pumping hypotheses were:

Hypothesis 1. Maintaining the current (up to 2015) groundwater pumping volume in the future (HYP1). This requires reducing the irrigated areas in accordance with the expected larger future crop water requirements deduced from future temperature increases, the increase of CO_2 concentrations and the decrease in precipitation.

Hypothesis 2. Maintaining the current (up to 2015) crop surface and type of crop in the future (HYP2). This will require increasing the groundwater pumping volume due to the higher future irrigation water requirements obtained from the global warming scenarios.

Fig. 5a shows, for each demand unit, the decreases in the irrigated surface in percentages that must be applied under the demand hypothesis HYP1, which assumes that groundwater pumping volumes are maintained to the same as they were in 2015. It shows a reduction in the irrigated surface between 13 and 15 % for the RCP8.5, and between 3.6 and 4.8 % for the RCP4.5 scenario. The blue bars show the increase in pumping (also in percentage) necessary to maintain the irrigated surface area that existed in 2015 (HYP2). The pumping volume increase would oscillate from 16 to 17 % in the RCP8.5 scenario, to 5–3 % in the RCP4.5 scenario.

The recharge and pumping rates results obtained with the auxiliary models (SAC-SMA model and CROPWAT models) have been used as the input for a groundwater flow model to propagate the impact on the status of the aquifers. For the 2045 horizon, the simulations show that the emission scenario RCP8.5 would produce higher groundwater drawdowns than the RCP4.5 scenario for both the groundwater pumping hypotheses HYP1 and HYP2 (Fig. 5b). Maintenance of the crop irrigation surface (HYP2) produces higher groundwater drawdowns under scenario RCP8.5, with values higher than 16 m, indicating increased aquifer depletion in five of the eight groundwater bodies (Sierra de Altomira, Mancha Occidental I, Mancha Occidental II, Campo de Montiel and Consuegra-Villacañas).

3.1.3. Desktop selection of relevant reference global scenarios and adaptation strategies

The strategies based on a combination of measures identified in the literature review for *Managing Water Demand* included:

- “Changes in land use”, which includes the following measures: transformation of irrigated areas into urbanized areas; relocation of the farm processing industry; introduction of new irrigation areas.
- “Water use efficiency”, which includes the following measures: modernization of irrigation systems; good irrigation practices; improvements in the soil moisture retention capacity.
- “Change in crops and cropping patterns”, which includes the following measures: re-negotiation of allocation agreements (water right concessions); set clear water use priorities; improve crop diversification; increase short life-cycle of (horticultural) crops; promote rainfed woody crops; change to rainfed crops; R + D + I in cropping; develop climate change resilient crops
- “Economic instruments”, which includes the following measures: prices, e.g., set block rate tariff (agricultural demands); subsidies (CAP) to low water requirement crops; water markets; improvements in water charges and trade.
- “Reducing environmental impact”, which includes the following measures: increase water allocation for ecosystems; maintain ecological corridors; create/restore wetlands; improve nitrogen fertilization efficiency; soil carbon management and zero tillage.

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[2] https://ec.europa.eu/environment/water/water-framework/info/timetable_en.htm.

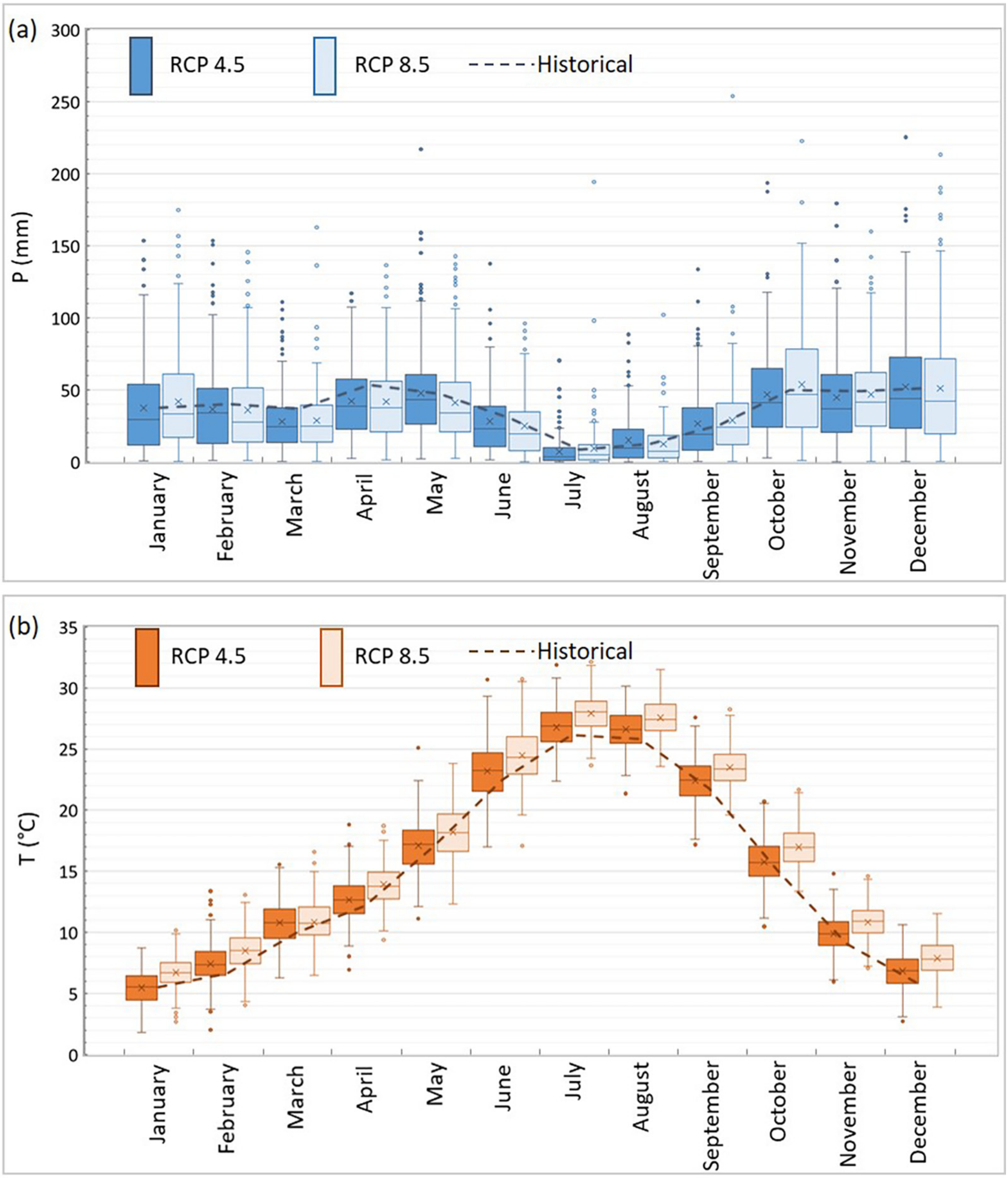


Fig. 4. Box-whiskers of future monthly mean year (a) precipitation and (b) temperature obtained with the equi-feasible ensembles scenarios (ED, EB) under the emission scenarios RCP8.5 and RCP4.5.

The strategies identified for *Managing Water Supply* were related to:

- “Complementary resources”, which includes the following measures: water reuse; water transfers; desalination plants; increase in groundwater pumping.
- “Increase in regulation and control”, which includes the following measures: small-scale water reservoirs on farmland; improvements in reservoir capacity; improvements in drainage systems; farmers acting as ‘custodians’ of the flood plains; hard infrastructure defenses; enhancement of flood plain management; protection against soil erosion; insurance for floods or droughts; conjunctive water use management, including managed aquifer recharge (MAR); new technologies in aquifer control; increase in rainwater harvesting capacity.

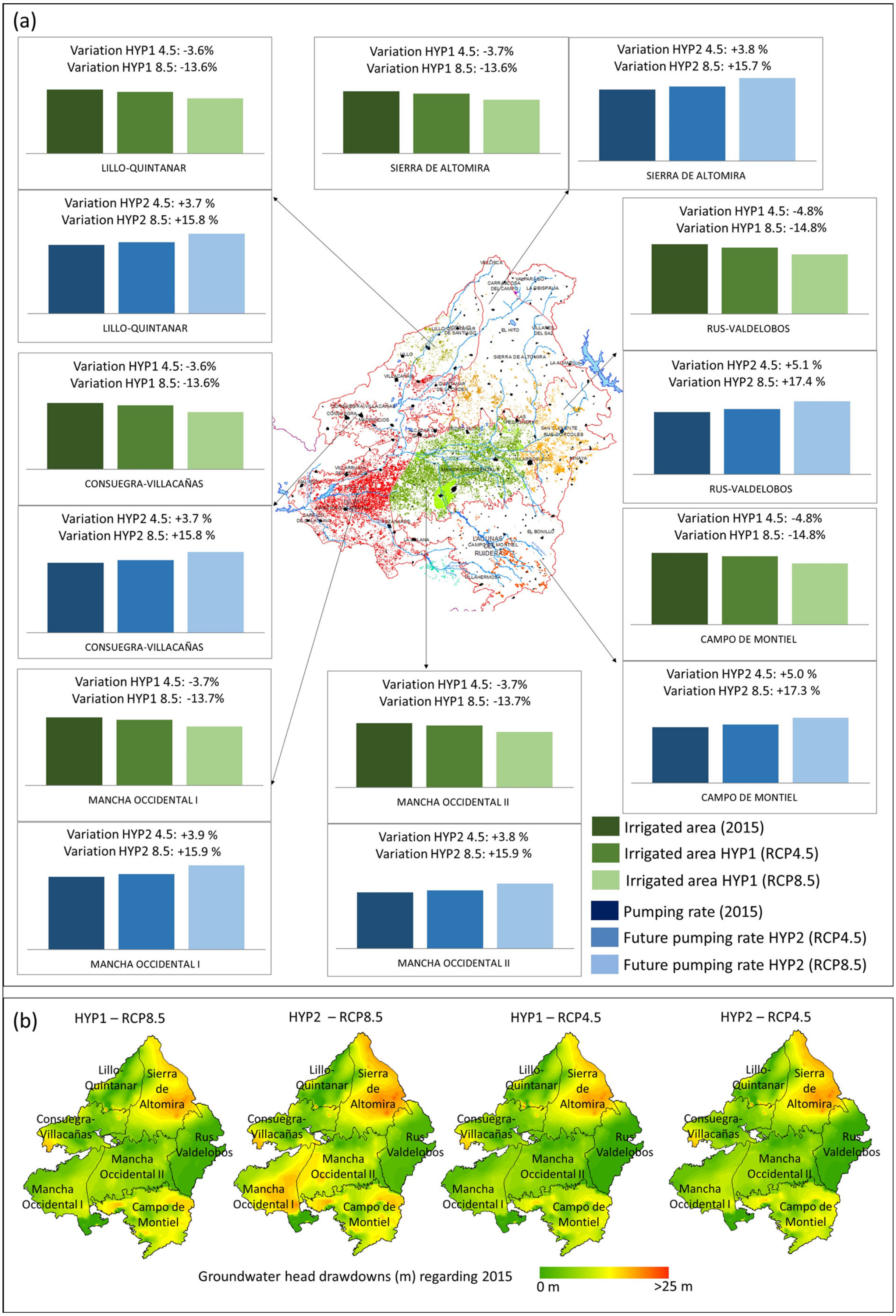
The *mixed strategies*, which would improve resilience and adaptation capacity, are: improve water and land use planning, control and resource allocations; more participative and transparent management; implement regional adaptation plans; improved monitoring and early warning systems; innovation and technology; integrate water demands in conjunctive systems.

3.2. Results from the bottom-up approach

3.2.1. Downscaling socio-economic scenarios and collaborative scenario building

The qualitative downscaling of global socio-economic scenarios for the Upper Guadiana Basin has resulted in an in-depth identification of trends in the social, economic, political and technological arenas, as presented in the

Fig. 5. (a) Distribution of estimated mean reduction of the irrigated area (HYP1) and groundwater pumping increase (HYP2) for the most pessimistic emission scenarios RCP8.5 and RCP4.5; (b) distribution of groundwater drawdowns under the groundwater pumping hypotheses HYP1 and HYP2 for the most pessimistic emission scenarios RCP8.5 and RCP4.5.


(a)
Variation HYP1 4.5: -3.6%
Variation HYP1 8.5: -13.6%
LILLO-QUINTANAR
Variation HYP1 4.5: -3.7%
Variation HYP1 8.5: -13.6%
SIERRA DE ALTOMIRA
Variation HYP2 4.5: +3.8 %
Variation HYP2 8.5: +15.7 %
SIERRA DE ALTOMIRA
Variation HYP2 4.5: +3.7 %
Variation HYP2 8.5: +15.8 %
LILLO-QUINTANAR
Variation HYP1 4.5: -4.8%
Variation HYP1 8.5: -14.8%
RUS-VALDELOBOS
Variation HYP2 4.5: +5.1 %
Variation HYP2 8.5: +17.4 %
RUS-VALDELOBOS
Variation HYP1 4.5: -3.6%
Variation HYP1 8.5: -13.6%
CONSUEGRA-VILLACAÑAS
Variation HYP2 4.5: +3.7 %
Variation HYP2 8.5: +15.8 %
CONSUEGRA-VILLACAÑAS
Variation HYP1 4.5: -4.8%
Variation HYP1 8.5: -14.8%
CAMPO DE MONTIEL
Variation HYP2 4.5: +5.0 %
Variation HYP2 8.5: +17.3 %
CAMPO DE MONTIEL
Variation HYP1 4.5: -3.7%
Variation HYP1 8.5: -13.7%
MANCHA OCCIDENTAL I
Variation HYP1 4.5: -3.7%
Variation HYP1 8.5: -13.7%
MANCHA OCCIDENTAL II
Variation HYP2 4.5: +3.9 %
Variation HYP2 8.5: +15.9 %
MANCHA OCCIDENTAL I
Variation HYP2 4.5: +3.8 %
Variation HYP2 8.5: +15.9 %
MANCHA OCCIDENTAL II
Irrigated area (2015)
Irrigated area HYP1 (RCP4.5)
Irrigated area HYP1 (RCP8.5)
Pumping rate (2015)
Future pumping rate HYP2 (RCP4.5)
Future pumping rate HYP2 (RCP8.5)
(b)
HYP1 – RCP8.5
HYP2 – RCP8.5
HYP1 – RCP4.5
HYP2 – RCP4.5
Lillo-Quintanar
Sierra de Altomira
Consuegra-Villacañas
Rus Valdelobos
Mancha Occidental II
Mancha Occidental I
Campo de Montiel
Groundwater head drawdowns (m) regarding 2015
0 m
>25 m

narrative for each scenario (see detailed description in Table S1 of the Supplementary material). These narratives have allowed us to contextualize the assumptions for the modelling component, as well as the development of socially and economically relevant climate adaptation strategies. Some transversal trends mentioned across the three scenarios highlight key drivers that need to be considered in the modelling assumptions.

The first of these common trends is social demographic trends, since rural depopulation is a recurring trend to a greater or lesser extent, albeit in a slower and smoother way in scenario 1 (*Sustainability*). This reflects an endemic problem in the region and for the whole of the country, under which - even in the most innovative scenarios – it would be difficult to reverse these depopulation trends completely.

The second common trend (scenario 2, BAU), regardless of the potential emergence of alternative activities, is that agriculture is an important economic sector for these rural areas. As a result, water withdrawals are likely to continue to be high in future decades. Scenarios 1 (*Sustainability*) and 2 (*BAU*) however, also foresee a shift towards woody crops (i.e., vines, olives, etc.), which could reduce the overall aggregate water demand and thus the water consumption in the area. Meanwhile, scenario 3 (rivalry and fragmentation) favours horticultural and staple crops due to the reduction in exports and the increase in local demand. The increase, however, of horticultural and staple crops would imply an increase in water consumption. Nevertheless, crop diversification at farm level is a common trend across the three scenarios as an essential mechanism to ensure the livelihoods of the farmers and profitability of the farms, as well as to reduce overall risks. This is in line with the recent IPCC report, which has identified "Improved cultivars and agronomic practices" as one of the top four globally adopted adaptation responses in terms of recorded observed adaptation and adaptation outcomes. However, although these adaptation measures these are seen as incremental in terms of income and crop production, they probably fall short in terms of transformative outcomes and climate risk reductions (Caretta et al., 2022).

Another driver is the technification and digitalization of agriculture (including smart agriculture) leading to higher productivity and better working conditions for farmers, but also to a reduction in labour force needs and thus in agricultural jobs, which feeds back into the first trend of rural depopulation.

In terms of perception of probability, scenario 2 (BAU) was considered the most probable with 60 % of the votes, followed by scenario 1 (sustainability) with 33 %, and scenario 3 (fragmentation) with 7 %.

3.2.2. Co-development of climate adaptation strategies

During the workshops, the participants designed three different climate adaptation strategies, one for each of the socio-economic scenarios presented in Section 3.2.1. The adaptation strategies try to provide a response to the conditions of each future scenario. Each strategy is composed of a combination of five adaptation measures.

In *strategy 1*, designed for Scenario 1 (SSP1, sustainability), the following adaptation measures were included:

- Increased control of groundwater abstraction by the Guadiana River Basin Authority and better planning.
- Improved aquifer knowledge through hydro-geological research.
- Capacity building and training of farmers on best agricultural practices for climate adaptation.
- Incentives to alternative economic activities in rural areas to generate new income, e.g., tourism, residential, agro-food industry, renewable energy, …
- Water transfers from other basins as an alternative surface water source for implementing managed aquifer recharge.

In *strategy 2*, designed for Scenario 2 (SSP2, business as usual (BAU)), the following adaptation measures were included:

- Increased control of groundwater abstraction by the Guadiana River Basin Authority and better planning.
- Improved aquifer knowledge through hydro-geological research.
- Improved groundwater resource management and planning by the Guadiana River Basin Authority and WUAS (Water Users Associations).
- Technological innovation in agriculture, including modernization of the irrigation systems.
- New water sources through water transfer, treated urban wastewater reuse, desalination, etc.

In *strategy 3*, designed for Scenario 3 (SSP3, rivalry and fragmentation), the following adaptation measures were included:

- Increased control of groundwater abstraction by the Guadiana River Basin Authority and better planning.
- Improved aquifer knowledge through hydro-geological research and crop innovation research.
- River restoration to reduce floods and soil erosion.
- Prioritization of irrigation water use for high-value crops (vegetables, tree crops and legumes) whilst reducing wheat, maize and lucerne crops.
- Cost recovery by introducing a tax on natural water resource use and subsidies for using non-conventional water, such as treated urban wastewater reuse.

After the first workshop, the defined modelling framework was used to assess these strategies that could then be shown in the second workshop as "shared vision models", i.e., the potential future hydrological impact for scenario RCP4.5 that would be compatible with the considered socio-economic scenarios in the first workshop, and under the different identified pumping hypothesis and adaptation measures.

The identified measures that were modelled (to be validated subsequently in the second workshop) were:

- Water Supply Measures:
  - o *A water transfer* between river basins, which will be used for managed aquifer recharge in Mancha Occidental I, Mancha Occidental II and Rus-Valdelobos groundwater bodies (see Fig. 1). Two starting dates, 2016 and 2033, were considered, with a sensitivity analysis regarding the water transferred (25 $\mathrm{Mm^3\ year^{-1}}$ and 65 $\mathrm{Mm^3\ year^{-1}}$).
- Water Demand Measures:
  - o *Increase groundwater pumping control:* this measure results in reducing pumping. A sensitivity analysis was performed considering a pumping decrease of 20 % and 30 % over the whole future period regarding the pumping volume calculated under HYP2.
  - o *Modernization of irrigation systems:* this hypothesis considers that irrigation efficiency will increase by 10 %, decreasing the required pumping volumes and also accordingly the irrigation returns.
  - o *Change to woody crops* considering the following hypothesis:
    - ▪ Oilseeds, citrus and irrigated other fruit trees are replaced by almond and pistachio rainfed trees with a ratio of 2:1;
    - ▪ Vineyards and grain cereal are partly replaced by almond and pistachio trees so that the maximum extension in each agricultural demand unit is 40 % and 30 %, respectively;
    - ▪ The total irrigation area does not change;

To sum up, the following groundwater pumping hypotheses (HYP1 and HYP2) and adaptation measures (AM) were simulated for the second workshop:

- Pumping Hypothesis 1: Maintaining the current (up to 2015) pumping schedule in the future (HYP1 or "2015"); pumping Hypothesis 2: Maintaining the current (up to 2015) crop distribution in the future increasing crop pumping requirements (HYP2);

- Water transfer 25 Mm^3 $year^{-1}$ since 2016 (AM1); Water transfer 65 Mm^3 year–1 since 2016 (AM2); Water transfer 25 Mm^3 year–1 since 2033 (AM3); Water transfer 65 Mm^3 year–1 since 2033 (AM4);
- Pumping reduction (20 %) due to increased groundwater pumping control (AM5); Pumping reduction (30 %) due to increased groundwater pumping control (AM6);
- Modernization of irrigation systems (+10 % efficiency) (AM7);
- Crop change (AM8).

Fig. 6 shows the impact of the future scenarios on groundwater pumping volumes when different adaptation measures are applied for the different demand units. A lumped analysis shows that HYP2 will produce a future increase in the Upper Guadiana Basin pumping volumes of 16 % and 4 % under scenarios RCP8.5 and RCP4.5, respectively. The adaptation measure AM7 is the only option of the listed ones that would require an increase in pumping volume. It is only obtained for the emission scenario RCP8.5, but not for RCP4.5.

Fig. 7a shows that all the simulated future alternatives for the RCP4.5 scenarios would produce a reduction of the mean total discharges to rivers and wetlands (Mm^3 $year^{-1}$). The maintenance of crop irrigation areas not applying any adaptation measures (HYP2), and water transfer measures of 25 Mm^3 $year^{-1}$ since 2033 (AM3) are the alternatives where higher reductions in mean groundwater discharge to rivers and wetlands would occur. The greatest groundwater discharge would be obtained for the alternative involving a 30 % reduction of groundwater pumping. Nevertheless, it will also be lower than the mean historical discharge to rivers and wetlands and slightly higher than that obtained for 2015.

All future scenarios under the described alternatives will produce hydraulic head drawdown in almost the entire Upper Guadiana Basin (Fig. 7b) (i.e. a drop in the aquifer water level). The maximum drawdown varies between more than 25 m in the management alternative HYP2 (not applying any adaptation measures) and 20 m in the alternative AM6 (groundwater pumping reduction of 30 %), which would be achieved in an area smaller than 1 % of the Upper Guadiana Basin. 75 % of the areas defined by the aquifer systems would experience drawdowns below 11 m and 9.5 m for the management alternatives HYP2 and AM6, respectively. Those drawdowns decrease up to 8 m and 4 m in 50 % of the Upper Guadiana Basin for these alternatives.

The perception of stakeholders on the potential impact of these measures based on the modelled variables is summarized in Table 1. These perceptions were gathered during the first stakeholder workshop and used as an input for the modelling exercises in terms of a) "sense checking" the results and calibrations, and b) validating or on the contrary, challenging the modelling outputs. Any inconsistencies were raised with the check consistency of the stakeholders during the second workshop to seek consensus and identify potential causes or drivers for these changes.

Crop change and crop water allocation rights would be the most important water-consumption actions from the point of view of the impact perceived by stakeholders. Five out of the eight measures (control of groundwater abstraction, better management and planning, technological innovation in agriculture, water transfer, and capacity building on best practices) are expected to have a positive effect on (and thus facilitate) crop changes. Four of the measures (aquifer knowledge, better management and planning, technological innovation in agriculture, and capacity building on best practices) are expected to drive a reduction in the water allocation for crops. Meanwhile, only two measures (control of groundwater abstraction and river restoration) are perceived to have some impact on the irrigated surface, although the extent and the way it influences could be either null or positive/negative depending on other external factors.

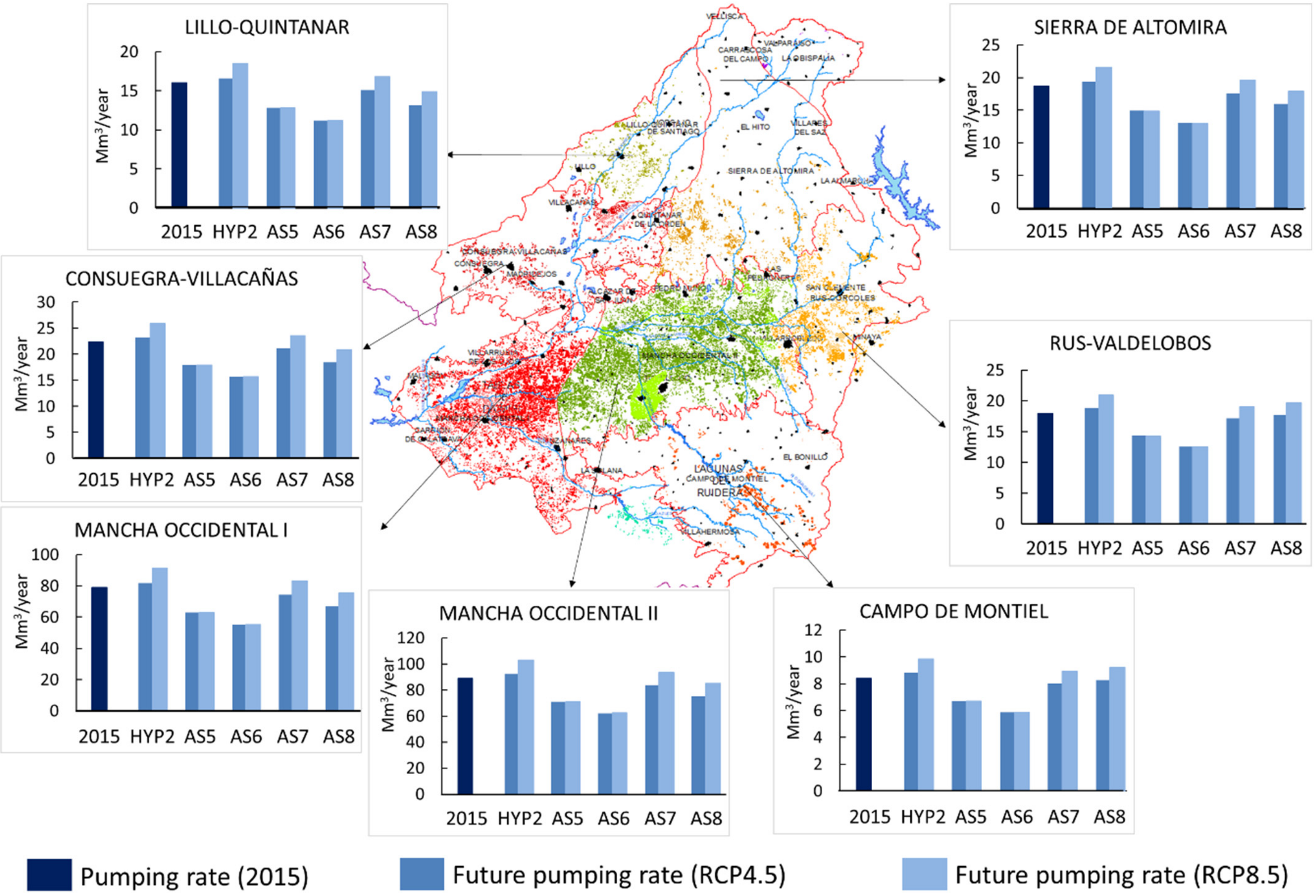


Fig. 6. Estimated mean groundwater pumping rates for the emission scenarios RCP8.5 (a) and RCP4.5 (b) under different potential adaptation measures (AM).

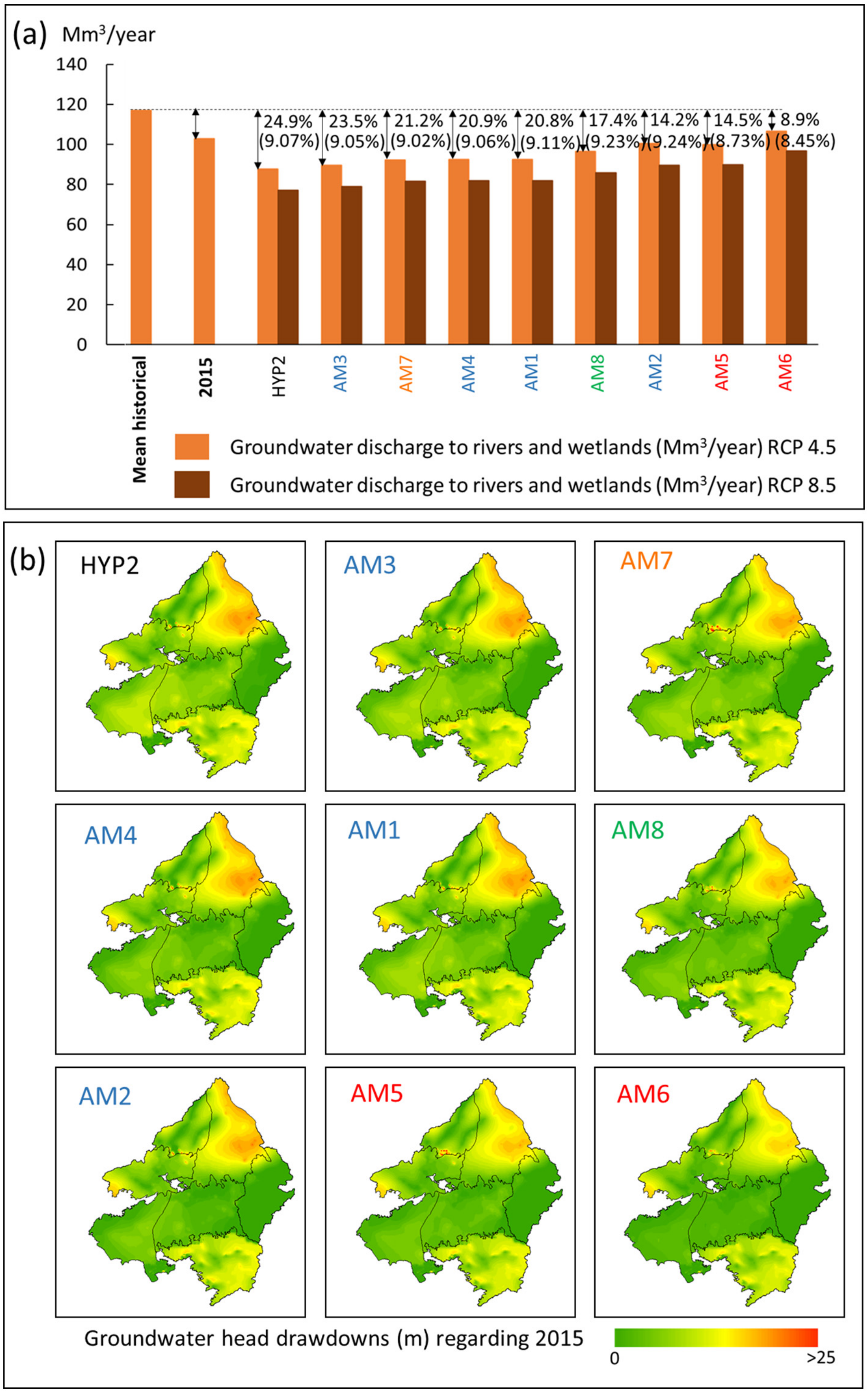


Fig. 7. (a) The impact of groundwater discharge to rivers and wetlands (Mm^3 year^{-1}) for different adaptation measures (AM) and the two emission scenarios RCP8.5 and RCP4.5 for the horizon 2016–2045; (b) distribution of groundwater head drawdown under the different pumping hypothesis (HYP1 and HYP2) and adaptation measures (AM) for the emission scenario RCP4.5.

4. Discussion

4.1. Problem and methodological approaches. Uncertainties and lessons learned

This research focuses on the analyses of climate change adaptation strategies on vulnerable groundwater dependent systems. Although most of the effort in CC research was initially oriented to the mitigation and the study of potential impact, nowadays it is clear that there is a necessity to advance in the identification and assessment of adaptation strategies. The interest in adaptation measures for CC grows rapidly, given that "the cost of repairing damages is estimated to be 6 times greater than adaptation costs" (H2020WATER-2014/2015). On the other hand, despite the uncertainties in the evaluation of potential impact (Ekström et al., 2013), given that water resources systems such as the one presented in this case study can be very vulnerable, indicates the interest in more effective adaptation. Considering uncertainties, adaptation must be flexible, and adopt a comprehensive approach, taking into account not only CC but also other potential socio-economic changes (UNECE, 2009), as well as mitigation synergies.

Table 1
Perception of the proposed adaptation measures by stakeholders. The signs indicate whether the measures that according to stakeholders would have a positive (+), negative (−) or no (=) effect on the three selected variables. These variables were chosen by the study authors as the best to monitor key drivers of change in the evolution of aquifer water quantity.

Solution	Irrigated surface	Crop change	Irrigation amount	Factors for implementation
Control of groundwater abstraction	+/=	+/−	+/=	Limited availability of economic and human resources
Aquifer knowledge	=	No	−/=	Increase of measurement points (citizen science)
Better management and planning	No	+	−	Need for better planning at the Water User Associations WUAS and Guadiana River basin Water Authority level
Technological innovation in agriculture	=	+	−	Need for additional capacity building for farmers for optimal use
Water transfer	=	+	+	Lack of consensus on its viability and appropriateness
Capacity building on best practices	No	+	−	Need for human resources
River restoration	=/−	No	No	Need to align with local norms and economic development
Cost recovery	No	No	No	

In this study a mixed top-down and bottom-up approach has been applied to co-design adaptation strategies. Top-down approaches (expert dominated and scenario centred) are commonly focused on the analyses of physical impact. This study reflects the necessity of using models for a quantitative analyses of management alternatives in complex water resource systems that include many components (particularly including stakeholders' local knowledge and perceptions) and the interaction between these and even more so when multiple aspects have to be taken into account in the decision-making process. Quantitative analyses are crucial to improve our knowledge of system behaviour, testing if the adopted hypothesis fit with the data and the conceptual model (i.e. the hypothesis assumed about how the system works), or if these need to be redefined (Zheng and Bennett, 1995). Nevertheless, in many cases their use in decision making processes has been limited for different reasons (Harken et al., 2019). For example, there is a necessity to maintain the models "alive", by updating data, results and parameters and even the conceptual models, which is very resource intensive. On the other hand, in order to make these quantitative management models useful, the results need to be explained and summarized properly to share them and, if possible, validate them with the stakeholders. A key issue to be studied is how to communicate these results (Leal Filho, 2009), which has often been a sort of adapted storytelling to local stakeholders and practitioners (Phillips, 2012). Nevertheless, the main inconvenience in the analyses of potential future scenarios is the propagation and growth of uncertainties within the modelling chain, the "drama of uncertainties" (Mearns, 2010), which sometimes make results simply too uncertain to really help within the decision-making process. This study also shows a significant uncertainty in the definition of local future climate scenarios in our pilot (see Fig. 4), which has been identified as the main source of uncertainty in the top-down analyses of CC impact in other Mediterranean basins (Pulido-Velazquez et al., 2021).

Bottom–up approaches (decision-centred approaches) aim to identify and assess adaptation decisions based on the study of social vulnerability and adaptive capacity to climate variations by integrating local knowledge. They overcome the problem of the "drama of uncertainty", but they have other significant issues (Haro-Monteagudo et al., 2022): i) the local perspective of the stakeholders may reduce the ability to recognize relevant global drivers; and ii) the limited resources of local communities may hinder more ambitious and disrupting strategies (Conway and Mustelin, 2014). From a methodological point of view, the participatory approach applied in this study has allowed us to correctly address some of the recommendations provided by the literature to implement participatory climate adaptation research (Cvitanovic et al., 2019). The participants were chosen in advance based on their involvement in the basin activities and including all of the different interests. The objectives of the workshops were clearly stated at the beginning of the workshop, and the methodology was designed to minimize conflict. This is because the downscaling of the scenarios followed a discursive narrative that allowed the inclusion of all the proposed important points in a coherent way. As well the selection of the adaptation measures, three steps were followed: brainstorming, voting and final considerations and discussions. The selection of the adaptation measures was based on voting, which decreased the conflict between participants. The final discussion exercise also allowed the participants to highlight their concerns over a specific proposed measure. The balance of power was also taken into account, e.g. by including technicians from different areas of knowledge and also a similar number of farmers, as well as different types of farmers (size of farms, type of crops, etc.) (Hügel and Davies, 2020). More resources could have allowed us to implement a longer process in time, that would have allowed a greater learning from all participants; and the involvement of a higher number of participants, thus increasing the different voices heard. One weakness of the participatory process was the small number of female participants, even after a special effort from the research team to invite them. The invitation was mainly done to institutions and those institutions selected the participants who were usually technicians or directors. The identification of female farmers was also difficult. Therefore, future participatory activities will need to make a significant effort in the identification, selection and invitation of participants, if a proper equal gender representation is to be achieved.

Both approaches were combined by integrating scientific and stakeholder knowledge. Many authors have already discussed the benefits of mixed approaches in the analyses of adaption strategies (e.g. Ekström et al., 2013), although only a few studies have combined them in practice (Haro-Monteagudo et al., 2022; Girard et al., 2015). This paper shows an example of how to overcome the "drama of uncertainty" to help in the decision-making process by co-designing robust adaptation measures integrating the goals of economic development, social acceptability and environmental sustainability. A novel integrated bottom-up/top-down approach to identify "climate resilience development pathways" (Schipper et al., 2022) in aquifers systems with groundwater dependent wetlands of high environmental values and scarce water resources. Each of the applied approaches in this study and the participatory and the groundwater modelling exercises provide information/feedback that might help to improve the assessment performed if they were used alone. For example, the discussion on the model results with the stakeholders during the first workshop allowed us to identify some weak points in the initial model regarding the groundwater head drawdown in a small area with scarce official monitoring data, so these were already improved in the second workshop. In addition, despite the cited issue of the propagation and the growth uncertainties, the results of the models, used as "shared vision models" (Loucks and van Beek, 2017) in the workshops, have helped to raise stakeholders' awareness on the potential impact of CC on their systems. This has also helped to obtain more robust and sensitive results regarding the impact of CC thanks to this participatory approach. The combination of the participatory activities with the modelling exercises has also allowed the incorporation of independent reviews of the different stages of the research.

4.2. Hypotheses, shortcomings and uncertainties

In this study a range of different hypotheses and a series of simplifications have been assumed. An attempt was made to demonstrate the utility of the proposed combined bottom-up/top-down approach to identify and assess robust **climate resilient development** for the Upper Guadiana basin to define the effectiveness of different stakeholder validated adaptation strategies. In this section, some assumptions from these hypotheses and limitations to identify potential future research lines are highlighted.

The main hypotheses adopted in the modelling approach oriented to perform a quantitative top-down analysis are:

- The validity of the information about potential future socio-economic and emission scenarios from the last IPCC assessment report is assumed, and about global/regional climate projections (e.g., the CORDEX project). Another assumption is that local scenarios can be generated from global/regional projections by using statistical downscaling approaches in accordance with the historical information (Gudmundsson et al., 2012).
- Both bias and delta change correction methods, have been used based on the assumption of bias stationarity of climate model outputs. However, other approaches could be explored to consider the non-stationarity bias of RCM simulations (e.g., Hui et al., 2020).
- Univariate bias and delta correction methods have been used. These do not consider the dependence between precipitation and temperature. However, these could be explored in future assessments. Meyer et al. (2019) found that incorporating or ignoring inter-variable relationships between temperature and precipitation could have an impact on the conclusions drawn in hydrological climate change impact studies in alpine catchments.
- The propagation of the uncertainties in the study of the impact of potential future climate change has not been analysed. The study of uncertainties was limited to the generated local future climate scenarios defined by considering multiple climate models (see Fig. 4), which have been identified as the main source of uncertainty in the top-down analyses of the impact CC of in other Mediterranean basins (Pulido-Velazquez et al., 2021). From those scenarios, a single ensemble scenario has been defined to coalesce and consolidate the results of individual climate projections, thus allowing a far more robust and representative climate projection than those based on a single model (Spanish Meteorological Agency, AEMET, 2009).
- Improving the uncertainty analyses would require addressing the challenges of a more complex probabilistic multi-model ensemble forecast (Knutti et al., 2010) or, addressing the propagation through all the steps involved in climate downscaling and mathematical modelling (Ekström et al., 2013).
- Future crop water requirements were assessed to estimate future groundwater pumping for agricultural demands. This assessment only considers changes in temperature and precipitation. The effects of CO_2 and other possible factors were not considered. However, the rising CO_2 concentrations will have a nutrient effect leading to decreased crop yield losses (Long et al., 2006). In addition, the foreseen rising temperatures will have dramatic effects on the ecological functionality of crops, starting with increasing water needs and subsequent evapotranspiration rates and ending up with soil salinization and land abandonment or the changing of crops.
- The definition of the chain of models to propagate climate change scenarios also required us to adopt hypotheses. The historical information about system status and operation is sometimes completed under different assumptions (e.g., linearity for a regression approach to assess missing pumping data). Finally, the parameters (which represent the behaviour of the system) of the models are considered to remain invariant in time, and the impact of CC can be assessed by simulating local CC scenarios within the models (Collados-Lara et al., 2022). Note that one of the limitations of these distributed numerical approaches is that they require long enough data series to calibrate and validate the chain of models in order to have confidence in the assessment of potential impact under different scenarios. When the spatial density of data is low, lumped conceptual approaches might be applied.

The main hypotheses adopted in the bottom-up approaches are:

- Firstly, a representative sample of the main water users was proposed through stakeholder mapping. However, in view of the results and the dominant use of irrigated agriculture it would also be good to have sectorial, more detailed workshops in the future. In addition, the gender bias has been identified as an issue to be given further consideration.
- Secondly, in the organization of the workshops, it was mainly considered discussions on the most effective measures for climate resilient development addressing the current and even more probable conflict between irrigated agriculture and groundwater dependent ecosystems. However, with hindsight not enough attention was paid to the just transition elements of the implementation of these measures of the haves (and have-nots) e.g., in terms of current resource allocation and also to procedural aspects to open up the space to other uses such as public water supply, or cultural and recreational uses.
- Thirdly and probably even more importantly, the discussions centred mainly on an incremental adaptation model. In retrospect and particularly in the context of having these workshops in the midst of a global pandemic, there was an opportunity to discuss more transformative scenarios (and development pathways). For example, there was discussion on the potential for renewable energy to substitute some of the irrigated agricultural areas, combined models such as agrivoltaic, etc., or even more disruptive world visions that imagine local innovation centres around local expert knowledge on local crops such as vines or horticultural high-quality produce. With hindsight, it might have been more relevant to attempt to explore these other climate development pathways and their resilience to the impact of climate change.

4.3. Discussion of selected strategies

From this co-design process the two most robust strategies that spanned and topped in terms of prioritization of all the scenarios were “increased control of groundwater abstraction by the Guadiana River basin Authority and better planning”, and “improved aquifer knowledge through hydrogeological research”. These are the strategies to prioritize, because they can both contribute to increasing the resilience in the Upper Guadiana Basin to CC, as these would be beneficial in any of the possible socio-economic future scenarios (Oteros-Rozas et al., 2013).

These solutions involve a relatively low adoption cost, effort or change for farmers and other players. However, there are subtle differences, for example improving scientific knowledge through increased research does not inherently cause a conflict between competing uses, and therefore it does not have any direct conflicting viewpoints. Meanwhile, increased control on groundwater abstractions by the river basin authority puts – at face value- all the responsibility for action on public administration. The increase in control could involve a number of things that would need much more detailed exploration (as discussed below) with the different players, for example the decrease in illegal irrigation could potentially increase available future water resources for legal irrigators. Alternatively, it could also involve a shared reduction for all irrigators, and therefore allow a more secure future for those that currently do not have formal water rights. Thus, in fact the lack of a detailed characterization in this measure and strategy of how it would be implemented could be in fact one of the reasons for consensus. The reason could also be that many of the participants in the workshop were not farmers, and thus the stakeholders (where farmers were a minority even if they represent 80 to 90 % of the water use) voted for control of water use because this is seen as the most effective way to decrease water abstractions. Therefore, water abstraction control could be seen as a consensus action or as a no-regret action.

The modelling exercise showed that a “pumping reduction (30%) due to increased groundwater pumping control” would in fact be the most effective climate change adaptation measure. The performed simulations show that this reduction in groundwater pumping volume would help deliver higher groundwater discharge to rivers and wetlands. Nevertheless, the implementation of this measure is not easy, due to limited capacity in the river basin agency in terms of number of river police and the budget available, which makes it difficult to perform an exhaustive pumping control. However, with the increased potential for the use of satellite information as an indirect estimate of the pumped groundwater volume opens up new opportunities to control pumping (Molinero et al., 2011).

It is worth mentioning the low level of consensus observed in the workshops regarding the effects of the irrigation abstraction control measure. The participants considered that the effect could be positive, null, or negative depending on the administrative responses to that control. For instance, if the control of illegal abstractions led to more resource availability for legal concessions, the legally irrigated surface could increase whilst crop change would decrease. Meanwhile, if the control of abstractions entailed a generalized reduction in per/hectare irrigation provisions, the result would trigger crop changes towards less water demanding crops that would therefore allow maintaining the irrigated surface and water amounts for stable irrigation.

This is an important result since the participatory exercise (bottom up) and the modelling exercise (top down) came to the same conclusion: i.e., for climate resilient development in the Upper Guadiana Basin, increased pumping control would make the area better prepared for a range of climate change scenarios and their impact from a physical and socio-economic point of view, highlighted by local stakeholder knowledge and perceptions. Although further research is needed to identify who bears the burden of this increased pumping control in terms of reallocation of water (i.e., how to ensure a just transition) it remains clear that this would be the best strategy to adopt for climate resilient local regional development to reduce current and future conflict between the socio-economic development needs of the region and the impact on groundwater dependent wetlands.

Another adaptation measure that was also considered by the stakeholders (and simulated in the modelling chain) was the modernization of irrigation systems. However, previous experience in other case studies has shown the high uncertainty about the real impact of this measure, due to the rebound effect (Berbel et al., 2015; Dumont et al., 2013), and have even proved to end up with a higher water use in agriculture than before (Lopez-Gunn et al., 2012; Grafton et al., 2018; González Cebollada, 2017; Perry et al., 2017). In addition, this measure could provoke an increasing soil salinization, as observed in other irrigated drylands. This risk associated when irrigation optimization led in the past to the inclusion of the Upper Guadiana Basin as the groundwater-related hotspot of the National Plan to Combat Desertification in Spain (Martínez-Valderrama et al., 2016). In fact, both better control of water abstractions and irrigation modernization have just been included in the National Plan on Desertification approved in June 2022 (MITECO, 2022).

Finally, another important adaptation measure was changing the type of crops farmed in the case study area. This measure completely supports the recent evidence in the last IPCC report that indicates this is one of the most frequent adaptation measures with proven adaptation outcomes in relation to water in general, and to water and agriculture in particular (Caretta et al., 2022). Our case study area shows that it has the second highest impact in the modelling exercise. Therefore, it is a measure worth considering by both by the water and agriculture public authorities in the Guadiana basin for the region of La Mancha. The combination of crop change and increased abstraction control has not been modelled, however at face value they would appear in principle to be compatible measures that when combined could deliver the best results in terms of a climate resilient development strategy. The change in crops to more valuable and less water-intensive ones has also been proposed as a way to improve the groundwater bodies and to maintain the social and economic benefits from irrigation (Zorrilla Miras, 2009).

5. Conclusions

This paper introduces a novel integrated bottom-up/top-down approach to identify "climate resilient development pathways" in a vulnerable aquifer systems that include groundwater dependent wetlands of high environmental value and where water resources are already scarce. To the best of our knowledge, there are no previous similar adaptation studies focused on this system typology. It has been applied in the Upper Guadiana River Basin, where CC will exacerbate the current ongoing conflicts between wetland conservation and groundwater overexploitation from intensive agriculture.

In this research, the study of uncertainties was limited to the generation of local future climate scenarios defined by considering multiple climate models, which have been identified as the main source of uncertainty of the future potential impact of CC in other Mediterranean basins. From these scenarios, a robust single ensemble scenario has been defined, which has been propagated to assess the impact on aquifer status and groundwater discharges. It has not included the assessment of other variables of interest, such as the surface water dynamic in wetlands.

Our study shows that the "drama of uncertainty" can be overcome in groundwater dependent (eco)systems by co-designing robust adaptation measures integrating the goals of economic development, social acceptability and environmental sustainability. The combination of bottom-up and top-down approaches has helped us to understand how the preferred stakeholder strategies really do (or do not) make the overall system more resilient under different climate change scenarios. This is even more pertinent for adaptation strategies in areas where the starting point is already vulnerability, likely to be further exacerbated under the impact of climate change (as is our case), making existing conflicts even more difficult to be addressed.

The research allowed us to conclude that reducing groundwater pumping would be the most robust and effective measure to reduce the impact of CC in the area. These adaptation measures involve a relatively low adoption cost, effort or change for farmers and other stakeholders, but it does put all the responsibility for action on the public administration.

In the future, the top-down approach could be extended to assess potential future impact on other key variables, such as the surface water dynamic in wetlands, to study environmental impact under different scenarios and adaptation strategies. The uncertainty analyses could be also extended to the study of hydrological impact by developing complex probabilistic multi-model ensemble forecasts or, addressing the propagation through all the steps involved in climate downscaling and mathematical modelling. In addition (and not explored in this paper) the engagement of local stakeholders will help to build the necessary adaptive capacity and "will to act" in the face of climate change, by helping to integrate scientific knowledge with locally knowledge with the players who are best positioned to take action based on this knowledge. So far, the adaptation measures and strategies analysed in this paper would fall under the umbrella of incremental adaptation. Nevertheless, the process itself, created with the combination of top-down and bottom-up approaches, provides the ideal framework to explore the more transformative adaptation options which emerged in the workshops.

CRediT authorship contribution statement

David Pulido-Velazquez: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Leticia Baena-Ruiz:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **Beatriz Mayor:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Pedro Zorrilla-Miras:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Elena López-Gunn:** Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Juan de Dios Gómez-Gómez:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing – review & editing. **África de la Hera-Portillo:** Conceptualization, Formal analysis, Methodology, Supervision, Validation,

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the research reported in this paper.

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Appendix A. Supplementary data

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