The Impact of Climate Change on the Water Sector in Spain

Jose Albiac[*,‡,§], Encarna Esteban[*], Elena Calvo[*], Yolanda Martinez[*], Safa Baccour[†] and Taher Kahil[‡]

[*]Department of Economic Analysis, University of Zaragoza and IA2, Spain

[†]Research Institute of Water Engineering and Environment (IIAMA), Polytechnic University of Valencia, Valencia

[‡]Water Security Research Group, International Institute for Applied Systems Analysis, Austria

[§]maella@unizar.es

[§]Corresponding author

The stress on water resources is very high in the Mediterranean region, with pressures driven by substantial irrigation withdrawals. The impacts of climate change will be severe in the region, which will require a more sustainable water management. In Spain, the strong growth in income and population has doubled water withdrawals and degraded water quality since the 1960s. Although water management in Spain is based on stakeholders' cooperation, the ample range of policy and investment initiatives has been unable to stop water scarcity in basins. The worst scarcity situation pervades the basins of southern Spain, which are almost closed basins with dwindling outflows in the Segura, Jucar and Guadalquivir estuaries. The Spanish plan for adaptation requires integrating climate change in water planning, and the adaptation measures considered are augmenting supply, curbing demand, irrigation modernization, and better control of groundwater. Desalinated seawater and treated urban wastewater are already used in southern basins, and will be expanded in the short term. However, the water unbalance in the long term will require an enormous desalination capacity, or else a strong reduction of irrigation withdrawals, both with high costs to farmers. The evaluation of climate adaptation measures in selected basins indicate the outcomes from alternative policy strategies that impact economic activities and environmental flows.

Keywords: Climate change, water sector in Spain, water scarcity, adaptation measures, policy evaluation.

1. Introduction

Water resources are essential for human water security and for biodiversity. The sharp rise of water withdrawals during the last century is linked to the strong growth in population and income. The consequences are massive pressures on water resources leading to severe environmental degradation and major management challenges in many river basins worldwide (Greve et al. 2018, Vörösmarty et al. 2010). These challenges are expected to become more critical in the coming decades from the impacts of climate change.

The degradation of water resources In the Mediterranean basin is already serious and the main pressure comes from irrigation, which is key for agricultural production in arid and semiarid regions. The development of irrigation in recent decades has been based on the expansion of groundwater extractions, rather than on surface diversions from additional reservoirs. Water reforms for a more sustainable management are needed in the Mediterranean region since the impacts from climate change will be severe.[1]

The drought damages and economic losses in northern Mediterranean countries at present are estimated at € 9 billion per year, mostly affecting Spain (1.5 b.), Italy (1.4 b.) and France (1.2 b.), with damages concentrating in agriculture (50%), energy (35%) and urban supply (13%) sectors. Future damages could increase up to five times for a +3°C scenario (Cammalleri et al., 2020; Feyen et al., 2020).

Several studies have considered the impacts of climate change in large-scale river basins around the world. The approach of these studies is the analysis of future stream flows, without addressing management measures for adaptation. Aich et al. (2014) analyze the stream flows of large African river basins that mostly increase stream flows and would require flood prevention, although the uncertainty of results is high. Vetter et al. (2015 and 2017) also confirm the uncertainty of estimations in large river basins in different continents, and link the uncertainty to RCP scenarios and to general circulation and hydrological modeling. Hattermann et al. (2017) recommend the use of

[1] Reductions in runoff are estimated at between 20 and 40% in 2081-2100 under SSP2-4.5 (IPCC 2021).

regional-scale models rather than global models for the assessments of water management options.

In Spain, the Ministry for Ecological Transition has evaluated the impact of climate change in all Spanish river basins using regional-scale modeling (CEDEX 2017). Other studies analyze the climate impacts on stream flows in Spanish basins without addressing the adaptation measures (Estrela et al. 2012, Majone et al. 2012, Versini et al. 2016, Suarez et al. 2020, Pulido et al. 2021).

The studies analyzing management measures for climate adaptation focus normally on one river basin, although there are also a few studies such as Elliot et al. (2014), Scanlon et al. (2023) or Kahil et al. (2024) that include the majority of river basins around the world. Scanlon et al. indicate that in the last two decades the depletion of water storage is very large in basins and aquifers, whit accumulated depletion above 200 km^3 in Iran basins, Ganges-Brahmaputra, Sao Francisco and Arabia, and above 90 km^3 in North China Plain and Euphrates. Climate change would make untenable the present water mismanagement, and therefore a more sustainable water management is needed for climate resilience in order to protect human economic activities and life support systems.

In Spain, there are few studies analyzing climate adaptation policies at basin scale. Garrido and Garrote (2023) discuss adaptation measures that can be applied in Spanish basins, such as reducing irrigation demand, deficit irrigation, and augmenting water supply with treated urban wastewater and seawater desalination. More detailed analysis of adaptation strategies in specific basins cover mostly the Jucar (Kahil et al. 2015, Escriva et al. 2017, Marcos et al. 2023) and Ebro basins (Baccour et al. 2022, 2024 and 2025), and the adaptation strategies considered are improving irrigation technologies, enlarging dam storage, water markets, seawater desalination, and reuse of treated wastewater.

This study analyzes the impacts of climate change on the water sector in Spain. These impacts will be more intense in the river basins of the southern part of Spain, where the pressure on water resources is already very strong. The contribution with respect to previous literature which dealt only with the Ebro or the Jucar basins in

Spain is that we cover conjointly and in detail the basins in Spain that are more threatened by the impacts of climate change. The case of Spain is an interesting testing ground because of the ample range of management strategies and water technologies that have been displayed in recent decades to address water scarcity and water quality degradation.

Since the main threat from climate change for the water sector in Spain is the worsening of water scarcity, the analytical approach is based on the assessment of the projected balance between water supply and demand in river basins. These projections are obtained using: i) the present and future withdrawals by sector and the potential development of conventional and non-conventional water supply, ii) the official climate predictions of stream flows in river basins (CEDEX 2017), and iii) the measures being already taken by the Spanish government and the basin authorities to address climate risks through climate legislation (BOE 2021, MITECO 2020) and river basin planning for the third (2022/27) and fourth (2028/2033) planning cycles.

The paper is organized as follows: next section describes the institutional organization and policies in the country, and the situation of water resources in river basin districts. Section 3 presents an assessment of climate impacts, the regulation for adaptation, and the policy measures that can be taken in river basins. Section 4 compares the findings with other studies of basins around the world and in Spain. Finally, the conclusions are presented in section 5.

2. The water sector in Spain

Water resources have been always an important issue in Spain since ancient times. Large water projects were undertaken in the nineteenth century for urban supply provision, while the lack of private financing prevented the development of irrigation projects. During the twentieth century, water planning was a key issue for the expansion of irrigation in rural Spain, with successive waterworks plans in the Hydraulic Work Plan of 1933, the Development Plans of the 1960s and 1970s, and the National Hydrological Plans of 1993 and 2001. The growing water scarcity was addressed with the construction of the Tajo-Segura interbasin water transfer in the 1970s, and later with further proposals of interbansin transfers. The Plans of the 1993

Table 1. Water withdrawals in Spain (Mm^3/year)

Year	1960	1990	2020
Irrigation	12,800	23,000	23,700
Urban-Industrial	2,700	5,800	7,900
Total	15,500	28,800	31,600

Source: Eurostat (2022), INE (2024), MIMAM (2000), MOPT (1993). Not including hydropower, refrigeration of thermoelectric power plants, and aquaculture.

and 2001 proposed large interbasin transfers of 4,000 and 1,000 million cubic meters (Mm^3) per year with investments at 5 and 1% of GDP, respectively, that were never implemented.

A substantial degradation on water resources occurred during the period of strong economic development of Spain in the second half of the past century, with large increases in water withdrawals and pollution. Since 1960, the already large irrigation withdrawals have doubled and the industrial and urban withdrawals have tripled (Table 1),[2] while economic activities increased pollution loads by organic matter, nutrients and heavy metals. The enactment of European legislation in 1992 has largely reduced urban and industrial point pollution with substantial investments in wastewater treatment plants. However, agricultural nonpoint pollution is still growing and control is very difficult (Albiac et al. 2023, Baccour et al. 2021).

The distribution of water withdrawals by source and economic sector is presented in Table 2. The share of abstractions (31,600) over renewable resources (110,000) is high, with important losses in outdated delivery networks (20%). Water is used for irrigation (74%) covering 3.7 million ha, industries (17%) and domestic use (9%), although water consumption (utilization minus return flows) is largely spent in agriculture (90%).

2.1 Institutional organization and water policies

The Water Law of 1985 is the basic water legislation in Spain, which was adapted to the European Water Framework Directive approved in 2000. All surface, subsurface, desalinated or regenerated waters are public domain, and water is allocated through temporary licenses. The Law gives an important role to river basin authorities in charge

[2] The expansion of irrigation in Segura, Jucar and Guadiana took place before the 1990s, while in Guadalquivir it took place after the 1990s.

Table 2. Water withdrawals and utilization by sector in Spain (2020, Mm^3/year)

	Total	Agriculture	Water supply companies	Other sectors
Withdrawals	31,600	23,700	5,300	2,600
Surface	25,300	19,300	3,800	2,200
Groundwater	6,300	4,400	1,500	400
Network losses	7,000	5,500	1,000	500
Utilization				
Agriculture	18,200	18,200		
Domestic	2,300		2,300	
Other sectors	4,100		2,000	2,100

Source: Eurostat (2022), INE (2024). Does not include hydropower, refrigeration of thermoelectric power plants, and aquiculture.

of planning, waterworks, control, and water utilization. Also, water users play a key function, especially the irrigation water users' associations. The institutional organization is set up by the public administrations at national, basin, regional and local levels. The responsibilities are shared and include the water policies, the management of basin authorities, the provision of urban water and treatment of wastewater, and the management of agriculture and protection of the environment. The approach to water management in Spain is based on institutional cooperation, where water stakeholders are inside basin authorities. Also, the management rules give unconditional priority to urban supply during periods of water scarcity.

The water polices in recent decades have addressed the challenges of water scarcity and water quality degradation. The main policies have been the National Irrigation Plan of 2002, the Program AGUA (Activities for Water Management and Utilization) of 2005, and the National Sanitation Plans of 1995, 2007 and 2022. The National Irrigation Plan of 2002 invested 4 billion euros in modernizing 1.5 million hectares, enhancing competitiveness and reducing nutrient pollution. But it failed to reduce water scarcity in basins as intended, but rather aggravated water scarcity because of the fall of return flows, as the literature indicates (Ward and Pulido 2006, Grafton et al. 2018, Perez et al. 2021).[3]

[3] This is the so-called "paradox of irrigation efficiency" which is counterintuitive. The explanation is the following: water efficiency can be 60% in surface irrigation (40% return flows to basin), 75% in sprinkle irrigation (25% returns), and 90% in drip irrigation (10% returns). Modernizing surface irrigation implies less water applied for the same water consumption by plants (evapotranspiration). But farmers maintain water withdrawals, and arrange the remaining water in order to increase the irrigated surface, plant double crops, or for planting more water demanding crops. The consequence is that farmers continue to withdraw the same amount of water than previously, but the return flows to riverbeds fall from 40%

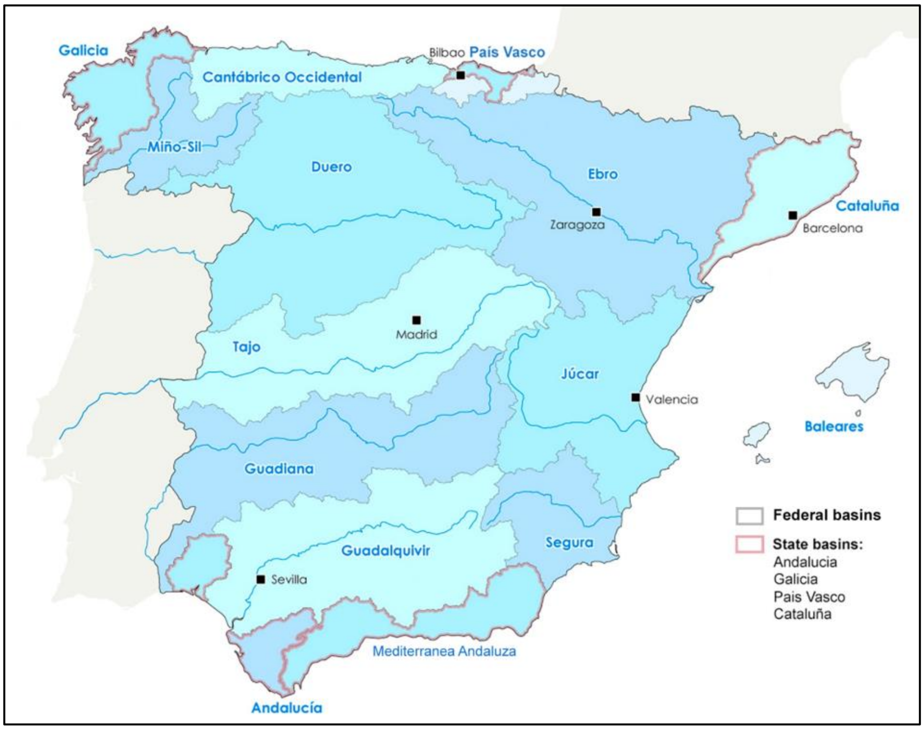

Figure 1. River basin authorities in Spain

The Program AGUA substituted the large Ebro interbasin transfer of the canceled National Hydrological Plan of 2001, with seawater desalination. The investments of 2.4 billion euros in southeastern basins (Jucar, Segura, Mediterranea Andaluza; Figure 1) added 500 Mm^3/year of desalination capacity, bringing the total capacity to 1,300 Mm^3. Production of desalinated water is 600 Mm^3 per year, used mostly in the Segura basin (230) and the Canary Islands (170).

The National Sanitation Plans were established to comply with the European legislation to abate urban pollution. Implementation has been irregular depending on the availability of European funds and the state of the national economy. The investments have been near 15 billion euros, and treated wastewater have reached around 5,000 Mm^3. After the economic crisis of 2008, annual investments fell from 400 to 50 million euros, leading to noncompliance with the European obligations, infraction procedures and fines. The current Sanitation Plan includes 40 billion investments up to 2033 for new treatment plants and renovation. The Plan promotes

with surface irrigation to 10% with drip irrigation. Any policy measure to control this “paradox” of efficiency would have high transaction costs because the regulator has to measure water consumption (evapotranspiration) in each parcel and for each crop, a quite impossible task for large irrigation districts.

the reuse of treated wastewater, which at present is around 500 Mm^3 (10% of treated water), although reuse is above 50% in some Mediterranean regions (MITECO 2021).

Other policies have been flawed, such as the PEAG (Upper Guadiana Plan) of 2008 to address the depletion of the Western La Mancha aquifer, which has caused the drying of 80 kilometers of the Guadiana River and the disappearance of the Tablas de Daimiel wetland reserve. The irrigation acreage over the Western La Mancha aquifer increased from 30,000 ha in the 1970s up to 190,000 ha at present, with accumulated depletion ranging between 2,000 and 4,000 Mm^3.

The Western La Mancha aquifer was declared overdrafted in 1987, and the basin authority took four years to devise a quota system for extractions that was ignored by farmers, who disabled the flowmeters installed with public funds. The overdraft declaration forced farmers to create groundwater user associations, but the users' response was the creation of associations to protect illegal pumping with the support of farmers' unions, city councils and even members of the state government. In the 1990s the so-called "Wetlands Plan" distributed 100 million euros to reduce extractions, but the plan didn´t stop the depletion that augmented to 4,000 Mm^3. After that, the basin authority brought to court the illegal wells of 5,000 farmers in 2005, but the pressure of farmers, social organizations and the state government forced the national (federal) government to withdraw the lawsuits, firing the president and the water commissar of the basin authority.

As an alternative to closing illegal wells, the PEAG called for multi-billion public expenditures to reduce extractions down to aquifer recharge by buying water from farmers, and also to make water related investments in the area. The plan was cancelled in 2012 because almost all water purchases from farmers were fictitious (WWF 2012). In designing this plan, no lessons were learnt from the neighboring Eastern La Mancha aquifer in the upper Jucar, where sustainable extractions were achieved during the 2000s. The PEAG was a flawed policy, because stakeholders' cooperation requires serious commitments to manage and care for the aquifer, and cannot be exclusively bribed for by side payments (Esteban and Albiac 2012). This groundwater sustainable outcome in the Eastern La Mancha aquifer was the result of the collective action of farmers, and not of any payments to farmers or huge investments from the federal government.

Leading world experts on the management of water resources published the Scanlon et al. (2023) article for a resilient water future. They indicate that the critical ingredient for achieving resilient water resources is the adoption of the conjoint management of surface water and groundwater. The Eastern La Mancha case is important for giving background about how to achieve this important recommendation. Without succeeding in the sustainable management of groundwater, conjoint management is useless for resiliency. The task is a wicked problem anywhere, because it requires building the collective action of stakeholders, and to the best of our knowledge it has not been observed in any other large aquifer in arid or semiarid regions across the world.

2.2 The situation of water resources in river basins

The pressure on water resources is much more acute in basins of the southern part of Spain (Segura, Jucar, Guadalquivir and Guadiana) than in the northern part (Duero and Ebro) (Figure 1). The basins of the southern half of Spain are almost hydrologically closed basins, with very small stream flows at their mouth, because of the enormous overdraft of surface and groundwater. Table 3 shows for each basin the renewable resources, withdrawals, outflows at the estuary of rivers, and minimum environmental flows at the mouth regulated by basin plans.

Overexploitation of groundwater is a serious problem in the southern basins, and despite the declaration of groundwater as public domain in the Spanish Water Law of 1985, aquifer over-abstraction in southern basins is around 1,000 Mm^3 per year. The overexploitation and water quality degradation in aquifers is severely damaging the aquatic ecosystems, including the main ecosystem assets in Spain (Doñana in Guadalquivir, Tablas de Daimiel in Guadiana, Mar Menor in Segura, and L'Albufera in Jucar).

In the last four decades, the irrigation acreage has almost doubled in Guadalquivir, Segura, Jucar and Guadiana. The modernization of irrigation systems during the 2000s has further aggravated the water scarcity problem, with the reduction of irrigation

Table 3. Resources, storage, withdrawals, and environmental flows in basins

Basin authorities	Renewable resources[a] Mm^3/year	Storage capacity Mm^3	Water withdrawals Mm^3/year	Streamflow at river mouth[b] Mm^3/y (m^3/s)	Minimum environmental flow[b] m^3/s
Segura	840	1300	1700	7 (0.2)	0
Jucar	2500	3000	3000	16 (0.5)	0.5
Guadiana	3900	9600	2300	1040 (33.0)	3.5
Guadalquivir	6000	8800	4000	242 (7.7)	7
Tajo	8500	11150	3100	5220 (165.5)	10
Duero	12000	7550	3600	7160 (227.0)	116
Ebro	15500	7600	8800	9025 (286.1)	107

[a] Does not include seawater desalination and reuse of treated wastewater.

[b] Streamflow at the river mouth or at frontier with Portugal for Tajo and Duero.

return flows (paradox of irrigation efficiency). The worst scarcity situation occurs in the Segura basin where withdrawals double the renewable resources, and the gap is covered with the Tajo-Segura interbasin transfer, seawater desalination, reuse of treated wastewater, and groundwater overdraft (CHS 2023).

In Jucar, withdrawals are also above renewable resources with negligible stream flows at the estuary. An interesting development in the Jucar basin since 2000 has been the curtailment of depletion in the Eastern La Mancha aquifer, the largest aquifer in Spain, by reducing extractions to the level of recharge (Esteban and Albiac 2011). The institutional developments leading to collective action started when farmers became aware of the problems from aquifer depletion and responded by creating a water user association aimed to jointly manage the aquifer. This response was driven by the call for control of extractions by the basin authority with the strong support of downstream farmers, the threats of not issuing water rights to pumping farmers, and the increase of pumping costs because of the falling water table. These facts have resulted in a progressive reduction in extractions down to the recharge level (Esteban and Albiac 2012). However, the pressures on the Jucar River are still mounting with the new water transfer south to the Vinalopo River, where the fall in piezometric levels is up to 350 meters (CHJ 2023).

In Guadalquivir, there has been since 1995 a large increase in the irrigated area from 480.000 to 900.00 ha at present. Groundwater pumping has increased from 300 to 900 Mm^3, lowering discharge flows into the basin. This has been coupled with a considerable modernization of irrigation systems with the share of drip irrigation increasing from 20% to 80% (ESYRCE 2022), which has reduced irrigation return flows.

The consequence has been a large fall in average basin stream flows, with a substantial fall in the annual average outflow at the estuary from 3,600 Mm^3 before 1990, down to 240 Mm^3 after 1990.

3. The climate change impacts on the water sector

The main climate change impacts in Spain are the increase in temperatures, the fall in precipitations, and the increase in the frequency and intensity of extreme weather events. These climate hazards will reduce the availability and quality of water resources affecting both human activities and natural ecosystems (CEDEX 2012).

The current average temperature (1991-2020) of 14.2 °C will increase by 1.4 °C in 2040-59 and 2.3 °C in 2080-99 under RCP 4.5, and by 1.9 °C in 2040-59 and 4.7 °C in 2080-99 under RCP 8.5. The current average precipitations (1991-2020) of 647 mm will decrease by 27 mm in 2040-59 and 57 mm in 2080-99 under RCP 4.5, and by 46 mm in 2040-59 and 140 mm in 2080-99 under RCP 8.5 (World Bank 2021). Therefore, in the worst-case scenario at the end of the century, temperatures could increase by 4.7 °C and precipitations could decrease by 140 mm (-22%). Also, the frequency and intensity of droughts and storms will increase.

In the present analysis, only climate averages are addressed given the poor performance of climate models in representing extreme events, even in the last Sixth Coupled Model Intercomparison Project (Scoccimarro et al. 2022, Seneviratne et al. 2021). The available climate averages and stream flows for river basins in Spain have been generated by CEDEX (2017).

Climate induced changes in water resources will have a substantial impact in Spain, damaging the agriculture, energy production and urban supply sectors, but also the ecosystems and the natural environment. The current renewable water resources in Spain of 110,000 Mm^3 per year will decrease by 11% in 2040-70 and 13% in 2070-99 under RCP 4.5, and by 14% in 2040-70 and 24% in 2070-99 under RCP 8.5 (CEDEX 2017).

In northern and central basins (Ebro, Duero, Tajo) the fall in stream flows in 2100 will be in the range 13% (RCP 4.5) to 25% (RCP 8.5). In the southern basins the fall in 2100 will be in the range 18% (RCP 4.5) to 30% (RCP 8.5) for Guadiana and

Guadalquivir, and 20% (RCP 4.5) to 37% (RCP 8.5) for Jucar and Segura. These large declines of stream flows from climate change call for the overhaul of water policies in Spain towards a more sustainable and resilient management of basins, especially in southern basins where the already serious water scarcity can become critical in the coming decades.

3.1 The regulation addressing climate change in Spain

The regulatory and institutional framework is established by the Law of Climate Change (BOE 2021) addressing climate adaptation and decarbonization of the economy, and by the National Climate Change Adaptation Plan (MITECO 2020) which is the instrument that defines the strategic objectives and the policy actions for climate adaptation and resilience. The Law of Climate Change seeks to achieve climate neutrality by 2050 and an efficient and renewable energy system, while the National Climate Change Adaptation Plan integrates the objectives and contributions for every economic sector and the policies and measures required to achieve the objectives.

The current basins' plans of the third planning cycle (2022-2027) assess the adaptation to climate risks, by analyzing hazards, exposure and vulnerability under RCP 4.5 and 8.5 scenarios, and defining adaptation measures in each river basin based on future projections. The major adaptation measures considered are augmenting non-conventional water supply, curbing demand, investments in irrigation technologies, and better control and enforcement of groundwater extractions.

3.2 Policy measures to promote resilience and adaptation

Future economic losses from climate change can be lessened with cross-sectoral water management and enhanced climate resilience planning. Recent contributions in the literature address climate resilience in river basins, and the range of intervention measures found deal mostly with the agricultural sector, because irrigation represents 70% of withdrawals and 90% of water consumption, both internationally and in Spain. Recommendations include reducing demand, increasing supplies, expanding dam storage and water transfers (Scanlon et al. 2017), better management and improved irrigation practices to reduce losses (Hoff et al. 2010), irrigation area expansion in water abundant regions (Elliott et al. 2014), improvements in irrigation efficiency (Kahil et al. 2024), and development and use of non-conventional sources such as treated wastewater and desalinated seawater in the coastal areas. Also, the protection of environmental flows is becoming an important issue to advance sustainable management and climate resilience (Tickner et al. 2020).

The more threatened basins by the impacts of climate change are the Segura, Jucar and Guadalquivir basins, because projections for the 2070-2100 period indicate that they will undergo the largest decline in stream flows, between 20% (RCP 4.5) and close to 40% (RCP 8.5) (CEDEX 2017). Strong adaptation measures are needed because water scarcity in these basins at present is already very high, with negligible outflows at river mouths.

3.2.1 Segura basin district

In the Segura basin, the irrigation acreage expanded from 180,000 ha in 1980, when the Tajo-Segura interbasin transfer became operational, up to 260,000 ha because of the expectations created by the transfer, the profitability of irrigation, and the lack of control by authorities. At present, the unbalance of 240 Mm^3 per year between water withdrawals (1,700) and available resources (1,460) is covered by the depletion of aquifers. Available resources are the sum of renewable resources, water imports through the Tajo-Segura interbasin transfer, seawater desalination, and reutilization of treated urban wastewater. This disproportion between supply and demand has generated an accumulated aquifer depletion above 12,000 Mm^3 with water tables falling by 300 meters in some aquifers, and significant problems of land subsidence in the basin (Esteban el al. 2024). There are also severe water quality problems from agricultural pollution, which has degraded the Mar Menor which is the main ecosystem asset in the basin.

The adaptation measures in the Segura basin plan are the augmentation of water supply with alternative sources (desalination and treated wastewater), efficiency gains in urban networks, and reductions in the demand of low priority uses. In the short and medium term, the basin's plan considers expanding the desalination capacity by 100 Mm^3/year. However, the recent setting of environmental flows in the Tajo basin will reduce by 100 Mm^3 the water imported trough the Tajo-Segura water transfer, and

Table 4. Water available and withdrawals by climate and adaptation scenarios, Segura (Mm^3/y)

Climate scenarios	Baseline	RCP 4.5				RCP 8.5			
Adaptation Policies		**BAU**	**Seawater desalination**	**Reduced irrigation demand**	**Combined**	**BAU**	**Seawater desalination**	**Reduced irrigation demand**	**Combined**
Water available	**1460**	**1270**	**1830**	**1270**	**1750**	**1100**	**1920**	**1100**	**1840**
Renewable	840	670	670	670	670	500	500	500	500
Imported from Tajo	300	0	0	0	0	0	0	0	0
Desalination	230	390	950	390	870	390	1210	390	1130
Treated wastewater	90	210	210	210	210	210	210	210	210
Water withdrawals	**1700**	**1830**	**1830**	**1270**	**1750**	**1920**	**1920**	**1100**	**1840**
Irrigation	1500	1620	1620	1060	1540	1700	1700	880	1620
Urban/industrial	200	210	210	210	210	220	220	220	220
Water available minus withdrawals	**-240**	**-560**	**0**	**0**	**0**	**-820**	**0**	**0**	**0**
Costs of policies to farmers (M€/year)			**170**	**310**	**150**		**250**	**465**	**230**

therefore the planned new desalination capacity will not increase the available water in Segura (Albiac et al. 2023).

The increase in temperature during the century could augment urban and irrigation demand up to 10% and 13% under RCP 8.5, respectively (CEDEX 2012, Bellvert et al. 2024), expanding withdrawals. Since the 840 Mm^3 of renewable resources in the basin could be reduced between 20% (RCP 4.5) and 40% (RCP 8.5) in 2100, the gap between renewable resources and water withdrawals will jump from 860 at present up to 1,160 or 1,420 Mm^3 under RCP 4.5 or 8.5, respectively (Table 4).[4]

This gap between renewable resources and withdrawals is covered at present with water imports from the Tajo (300), desalination (230), treated wastewater (90) and groundwater overdraft (240). In the short term, the reduction of the Tajo water imports will be compensated by the planned expansion of desalination capacity in 100 Mm^3. Another 180 Mm^3 of water can be obtained if the non-conventional water sources are used at full capacity, providing an extra 60 Mm^3 from desalination and 120 Mm^3 from treated wastewater, and this additional supply could be used to reduce the depletion of aquifers (CHS 2023, Albiac et al. 2023, MITECO 2022).

However, the short term available resources will be 1,440 Mm^3, the sum of renewable (840) and non-conventional resources (600), which include desalination (390) and treated wastewater (210), while the Tajo imports will diminish gradually in

[4] At present the gap between withdrawals and renewable resources is 1700–840=860. In 2100 the gap could increase to 1830–670=1160 under RCP 4.5, or to 1920–500=1420 under RCP 8.5.

the coming decades. This is below the current water demand of 1,700 Mm^3, so groundwater depletion will continue.

In the long term, irrigation and urban withdrawals increase and renewable resources decrease as indicated above. The sum of renewable resources in 2100 and the short term non-conventional resources, results in a volume of available resources of 1,270 and 1,100 Mm^3 under RCP 4.5 and 8.5, respectively.[5] Since predicted withdrawals increase to 1,830 and 1,920 Mm^3, the excess demand could reach 560 and 820 Mm^3 for the RCP scenarios.

The only possibility of supply expansion to cover the excess demand at the end of the century would be massive investments in seawater desalination. Any further expansion of water reclamation is limited because almost all urban wastewater will already be treated and reused. There would be no water imports from the Tajo because climate change will worsen water scarcity in this donating basin. Also, the possibilities of new dam storage in Segura are slim, since reservoir storage capacity is already very high in relation to basin stream flows (Table 3).

Augmenting supply with desalination involves significant investments, in the range of 2 to 3 billion euros for an expansion in desalination capacity to cover the predicted excess demand scenarios (560 or 820 Mm^3).[6] The cost of desalinated water is 0.50 €/m^3 which more than doubles the 0.20 €/m^3 costs of surface and groundwater sources. The additional costs to farmers from using 560 or 820 Mm^3 of desalinated water to substitute conventional sources would be 170 or 250 million euros for RCP 4.5 and 8.5, respectively.[7] The control of groundwater pumping will be essential because farmers would be unwilling to buy desalinated water if they can keep using their pumping wells.

Another option for eliminating the excess demand is to curtail the predicted irrigation demand from 1,500 Mm^3 at present down to 1,060 under RCP 4.5 and to 880 under RCP 8.5. The cost of this demand option for farmers is given by the profit losses

[5] This is the sum of renewable and non-conventional resources (670+600 for RCP 4.5, and 500+600 for RCP 8.5).

[6] For large desalination plants (100 Mm^3/year), the average investment cost is around 4 million euros for each million cubic meters of capacity (Zarzo 2020).

[7] (0.50-0.20 €/m^3) multiplied by 560 and 820 Mm^3.

from reducing irrigation acreage. Estimating the direct profit losses under the present crop mix, farmers will lose 310 (RCP 4.5) or 465 (RCP 8.5) million euros per year by reducing the production of the less profitable crops (cereals and fruit trees).[8] However, the costs from abandoning crop production would be higher given the indirect impacts on the food supply chain and the whole economy in the region.

Clearly, farmers will prefer to pay the higher price for desalinated water with additional expenses of 170 (RCP 4.5) or 250 (RCP 8.5) million euros, rather than be deprived of irrigation water and endure the 310 (RCP 4.5) or 465 (RCP 8.5) million euros in direct profit losses.

A combination of both measures, augmenting supply with desalinated water and reducing water demand, can be a good solution. Discontinuing cereal production will free 80 Mm^3 of water with small profit losses of only 10 million euros, and this option will be cheaper than buying 80 Mm^3 of desalinated water. The combination of abandoning cereal production and desalination would be the better option for farmers because the costs of 150 (RCP 4.5) or 230 (8.5) million euros are below the cost of other adaptation policies (Table 4).

3.2.2 Jucar basin district

The Jucar basin district includes the Jucar River and other river basins. The irrigated acreage increased from 280,000 in 1980 ha up to 380,000 ha during the 1990s driven by the expansion of groundwater irrigation over the Eastern La Mancha aquifer. There is an unbalance of 380 Mm^3 per year between water withdrawals (3,000) and available resources (2,620), covered with groundwater overdraft. The worst scarcity problems are located in the Jucar River, where withdrawals are 330 Mm^3 above renewable resources and outflows at the river mouth are below 1 m^3/s.

The adaptation measures planned in the Jucar basin district are the development of alternative water sources (treated wastewater and desalination), efficiency gains in

---

[8] The abandonment of cereals reduces withdrawals by 80 Mm^3, with 10 million euros in profit losses. The reduction in the acreage of fruit trees decreases withdrawals by 480 (4.5) and 740 (8.5) Mm^3, with 300 (4.5) and 455 (8.5) million euros in profit losses (Profits estimated based in Albiac et al. 2008).

Table 5. Water available and withdrawals by climate and adaptation scenarios, Jucar (Mm^3/y)

Climate scenarios	Baseline	RCP 4.5				RCP 8.5			
Adaptation Policies		**BAU**	**Seawater desalination**	**Reduced irrigation demand**	**Combined**	**BAU**	**Seawater desalination**	**Reduced irrigation demand**	**Combined**
Water available	**2620**	**2410**	**3160**	**2410**	**2580**	**2030**	**3240**	**2030**	**2580**
Renewable	2500	1980	1980	1980	1980	1600	1600	1600	1600
Desalination	15	115	865	115	285	115	1325	115	665
Treated wastewater	105	315	315	315	315	315	315	315	315
Water withdrawals	**3000**	**3160**	**3160**	**2410**	**2580**	**3240**	**3240**	**2030**	**2580**
Irrigation	2400	2540	2540	1780	1950	2610	2610	1400	1950
Urban/industrial	600	620	620	620	620	630	630	630	630
Water available minus withdrawals	**-380**	**-750**	**0**	**0**	**0**	**-1210**	**0**	**0**	**0**
Costs of policies to farmers (M€/year)			**225**	**160**	**135**		**370**	**460**	**275**

irrigation and urban networks, and technological advances in drought resistant crop varieties (CHJ 2023).

The climate warming along the century will increase urban (6%) and irrigation (9%) demand under RCP 8.5 (CEDEX 2012, Bellvert et al. 2024), augmenting withdrawals up to 3,240 Mm^3 (3,160 under RCP 4.5). Warming will also reduce the 2,500 Mm^3 of current renewable resources by 21% (RCP 4.5) and 36% (RCP 8.5) in 2100 (CEDEX 2017).

As a result, the gap between withdrawals and renewable resources will climb from 500 at present up to 1,640 Mm^3 under RCP 8.5 (1,180 under RCP 4.5) (Table 5). The present gap is covered with treated wastewater (105), desalination (15) and groundwater depletion (380). In the short term, non-conventional sources can provide an additional supply of 310 Mm^3 if used at full capacity, increasing available resources to 2,930 Mm^3 and almost covering the depletion of aquifers.

In the long term, irrigation and urban uses will increase while renewable resources will decrease (CHJ 2023). Under RCP 8.5, available resources in 2100 will be reduced to 2,030 Mm^3 while withdrawals will escalate to 3,240 Mm^3, and the resulting excess demand will increase up to 1,210 Mm^3 (840 under RCP 4.5) (Table 5). This excess demand cannot be covered with treated wastewater or new reservoir capacity, because the installation of wastewater treatment plants in urban centers has been completed, and reservoir storage capacity in relation to stream flows is already very high in the basin (Table 3).

The only alternatives to cover the unbalance between supply and demand in coming decades are augmenting supply with desalinated water, or else reducing water demand. The expansion of desalination capacity between 840 or 1210 Mm^3 (for RCP 4,5 or 8,5, respectively) would require large investments in the range 3.4 to 4.8 billion euros. These investments would have to be made progressively until the end of the century, following the example of the mentioned Program AGUA that invested 2.4 billion euros of public funds in desalination plants during the 2000s, where investments are recovered from both urban and irrigation users. Desalination can address the shortfall in conventional water sources, with additional costs to farmers between 225 and 370 million euros, depending on the RCP scenario (Table 5).[9]

The reduction of water demand will consist in cutting back the predicted irrigation use from 2540 to 1780 Mm^3 for RCP 4.5, or from 2,610 to 1,400 Mm^3 for RCP 8.5. The costs to farmers of reducing their water allocations would be the profit losses sustained from decreasing crop cultivation. Based on the current crop mix, farmers will lose 160 (RCP 4.5) or 460 (RCP 8.5) million euros per year in profits from reducing the production of cereals and fruit trees, which are the less profitable crops (Esteban and Albiac 2012, Albiac et al. 2008).[10] The indirect losses of crop abandonment will increase the costs for the region.

Comparing both alternatives, the least cost alternative for farmers change between the RCP 4.5 and 8.5 scenarios. Under RCP 4.5, reducing crop production is less costly at 160 million euros in direct costs than desalination. But under RCP 8.5, expanding desalination is less costly at 370 million euros than curtailing the production not only of cereals but also of a large share of more profitable fruits.

A combination of both measures by abandoning cereal production and expanding desalination is a better solution, since discontinuing the cultivation of cereals will free 670 Mm^3, with moderate direct profit losses and indirect losses. The cost to farmers of

[9] The additional costs of switching to desalinated water is 0.5-0.2 €/m^3 (0.2 being the current costs). The costs to farmers of this alternative are the result of multiplying 0.3 €/m^3 by the water shortfall of 750 or 1210 Mm^3, depending of the RCP scenario.

[10] Abandoning cereal production reduces water withdrawals by 670 Mm^3 and the profit loses to farmers are 110 million €. The remaining reduction in water withdrawals is obtained by reducing fruit production: 80 Mm^3 with profit losses amounting to 50 million € under RCP 4.5, and 540 Mm^3 with profit losses at 350 million € under RCP 8.5.

cereal profit losses will be cheaper than buying 670 Mm^3 of desalinated water with additional costs of 200 million euros over conventional water sources. This combined adaptation policy delivers the lowest cost solution to farmers for both the RCP 4.5 and 8.5 climate scenarios (Table 5).

3.2.3 Guadalquivir basin district

In the Guadalquivir basin the pressure from human activities is lower than in Segura and Jucar, and renewable resources exceed water withdrawals (Table 3). However, the irrigated acreage has increased from 480,000 ha in 1995 up to 900,000 ha at present without any control from the basin authority (Exposito and Berbel 2017). The investments in advanced irrigation systems have expanded drip irrigation from 20 to 88%, augmenting crop evapotranspiration and reducing the return flows to the basin. This counterintuitive fact is known as “the paradox of irrigation efficiency” (see explanation in footnote 3). Also, groundwater extractions have tripled up to 900 Mm^3. The consequence is that during wet years there are enough resources to cover total irrigation, divided between 2,600 Mm^3 of surface water and 900 Mm^3 of groundwater. However, during dry years, aquifer extractions for irrigation reduce considerably the surface water available in river stream flows. The result is that rivers run low and only the urban and industrial demand is fully covered because of the priority rules, while the deep adjustment falls on irrigation supplied with surface water and on environmental flows sustaining ecosystems.

An indicator on the increasing scarcity pressures from the escalating water consumption in irrigation is the large decline of environmental flows at the river mouth, which has decreased from a yearly average of 3,600 Mm^3 before 1990 down to only 240 Mm^3 after 1990 (CEDEX 2024, CHGQ 2023). The dwindling stream flows are degrading the ecosystems across the basin, including the Doñana reserve which is the main wetland in the Iberian Peninsula. Doñana has been seriously threatened in recent decades by the growing overdraft of aquifers in the surrounding irrigation areas (Sanchez et al. 2024).

The planned adaptation measures in the Guadalquivir basin are: i) a strict limitation of irrigation withdrawals by impeding new irrigation areas and by better control of

Table 6. Water available and withdrawals by climate and adaptation scenarios, Guad. (Mm^3/y)

Climate scenarios	Baseline	RCP 4.5	RCP 8.5	
Adaptation Policies		**BAU**	**BAU**	**Reduced irrigation demand**
Water available	**6015**	**4900**	**4120**	**4120**
Renewable	6000	4860	4080	4080
Treated wastewater	15	40	40	40
Water withdrawals	**4000**	**4275**	**4460**	**2030**
Irrigation	3500	3750	3920	3580
Urban/industrial	500	525	540	540
Water available minus withdrawals	**2000**	**625**	**-340**	**0**
Costs of policy to farmers (M€/year)				**50**

withdrawals in irrigation districts; ii) promoting the substitution of low profitable crops with high water requirements (cotton, sugar beet) by high profitable crops with low water requirements (olive and almond trees); and iii) investments in advanced irrigation systems. The available evidence in the basin in recent years indicates that farmers are adjusting to droughts by switching to drip irrigation and cultivating more profitable crops, and by adopting regulated deficit irrigation techniques (CHGQ 2023).

Climate warming along the century will increase urban demand by 8% and irrigation demand by 12% (CEDEX 2012, Bellvert et al. 2024), increasing withdrawals up to 4275 (RCP 4.5) and 4,460 (RCP 8.5) Mm^3. Also, climate impacts will reduce the 6,000 Mm^3 of renewable resources between 19% (RCP 4.5) and 32% (RCP 8.5) in 2100 (CEDEX 2017). Renewable resources are above withdrawals at present, but in 2100 this excess will decrease under RCP 4.5 and become negative under RCP 8.5.[11]

In the short term, renewable resources can be complemented with 40 Mm^3 of reclaimed water if the full capacity of treated wastewater is reused, which at present is mostly used for street cleaning, landscaping, or indirect reuse. Some direct water reuse in irrigation is taking place in the Segura and in the southern Jucar basin districts, but not in the Guadalquivir. The costs of tertiary treated wastewater at plants are around 0.80 €/m^3, and they are covered by urban users (INE 2024). Most of the reuse

[11] At present renewable resources are above withdrawals (6000–4000 = 2000). In 2100 the difference diminishes under RCP 4.5 [4860 (-19%) – 4275 = 585], and becomes negative under RCP 8.5 [4080 (-32%) – 4460 = -380].

in irrigation in Segura and Jucar is indirect use, with treated water discharged in water courses or injected into aquifers.

The development of seawater desalination in Guadalquivir would be limited because nearly all irrigation districts are not close to the coast. Also, there is no room for increasing reservoir capacity because the reservoir storage capacity in relation to stream flows is already quite high (Table 3). Under average stream flows, the basin will not sustain acute water scarcity in the coming decades because average renewable resources will be well above withdrawals. However, climate change will worsen the intensity, frequency and duration of droughts. Here, we only address average stream flows because of the lack of information for Spanish basins.

In the long term, the average balance of supply and demand will depend on the climate change scenario. In 2100, available resources under RCP 4.5 will be close to 5,000 Mm^3 covering the predicted water demand at 4,275 Mm^3, but under RCP 8.5 available resources will be 4,120 Mm^3 with an excess demand at 340 Mm^3 (Table 6). The reduction of water demand would imply cutting irrigation withdrawals. Under the current crop mix, the direct costs to farmers of decreasing irrigation allocations by 340 Mm^3 can be estimated at 50 million euros, which are the profit loses from reducing the production of low profitable cereals and cotton. However, there are also risks in switching to high profitable perennial crops, because future extreme events will increase the agricultural damages to perennials such as olive and citrus trees (CHGQ 2023).

Any future reduction of water allocations among farmers will require a better control of both surface withdrawals and groundwater extractions by the basin authority, which has not been able to control and monitor them in recent decades, especially for groundwater.

3.2.4 Other basin districts

The impacts of climate change in the main central and northern basin districts will have more moderate impacts on the water available for economic sectors and for environmental flows, although drought events will increase in frequency, duration and intensity. The predictions of stream flows and withdrawals under both RCP 4.5 and 8.5

indicate that average renewable resources will be well above water demands. The main problems to be addressed in these basins are groundwater depletion in some aquifers, and point and nonpoint pollution degrading water quality (CEDEX 2017).

In the Guadiana basin, groundwater overdraft has resulted in the disappearance of important wetlands and 80 kilometers of the upper Guadiana River (CHGD 2023). In the Tajo basin, there are problems of low environmental flows in the middle basin, and point pollution from urban centers needing wastewater treatment (CHT 2023). In the Duero basin, there is a large groundwater overdraft in the middle basin, and serious problems of urban point pollution and agricultural nonpoint pollution (CHD 2023). In the Ebro basin, the main management issues are agricultural nonpoint pollution and the low reservoir storage in relation to stream flows (CHE 2023).

4. Discussion

The results obtained on climate adaptation can be compared with the findings in studies of basins around the world and basins in Spain. Two studies on adaptation are selected which cover river basins around the world, and seven other studies are selected covering the Jucar and Ebro basins in Spain.

Scanlon et al. (2023) analyze the situation of world water resources and review the strategies for a water resilient future. The adaptation strategies are: i) increase alternative water supplies by expanding current levels of wastewater reuse (41 km^3/year) and seawater desalination (35 km^3/year); ii) reduce demand by relocating crops, planting less water demanding crops, and more efficient irrigation systems; iii) nature-based solutions for pollution abatement; iv) water storage by expanding current reservoir capacity (8,000 km^3) and conjoint management of reservoirs and aquifers; and v) expanding water transfers from current levels (200 km^3/year) up to existing planning proposals (1,900 km^3/year), although water transfers are very expansive and entail negative economic and environmental effects in donor basins. The policy recommendation is to provide water managers with a sufficient body of knowledge in order to implement water management portfolios adapted to basin conditions, giving priority to the conjunctive management of groundwater and surface water. However, even if water managers have all the operational and scientific information on adequate management portfolios, policy measures would fail in the absence of full cooperation by stakeholders.

Kahil et al. (2024) develop a global hydroeconomic model (ECHO-Global) for the assessment of the economic and environmental performance of management strategies in almost 300 basins worldwide. The analysis deals with the allocation of multiple sources (surface water, groundwater, desalination, treated wastewater) across sectors (irrigation, domestic, industrial), and includes the choice of management options, the selection of crops and irrigation practices, the planning of water infrastructures, and the response to policy instruments such as water quotas, water pricing and infrastructure subsidies. Four adaptation strategies are considered: environmental sustainability by minimizing groundwater depletion, demand management by maximizing irrigation efficiency, non-conventional sources with unlimited seawater desalination and full wastewater capacity, and increased reservoir storage capacity. Results indicate that a business as usual scenario will increase water withdrawals up to 5,000 km^3/year by 2050, while adaptation strategies can reduce these withdrawals between 12 and 27 percent. The highest withdrawal reduction is obtained by improving irrigation efficiency, although all adaptation strategies reduce irrigation withdrawals. The main policy finding is that gains in irrigation efficiency are critical for water conservation, efficient sector allocation, environmental protection, and climate adaptation.

Four studies analyze adaptation strategies in the Jucar basin in Spain. Escriva et al. (2017) propose the improvement of irrigation efficiency and the reduction of Common Agricultural Policy subsidies in order to abandon low profitable cereals and alfalfa. Marcos et al. (2023) recommend wastewater reuse and improvements in irrigation efficiency, and indicate that water markets and interbasin water transfers are rejected by the society in Spain. Kahil et al. (2015 and 2016) find that the current institutional cooperation[12] and water markets are efficient policies to address climate impacts, while water pricing is the worst policy option.[13]

In the Ebro basin, Baccour et al. (2022, 2024 and 2025) analyze climate adaptation strategies. Water and its numerous services are spatially and temporally allocated between different sectors (agriculture, urban, hydropower, and ecosystems), under a range of policy options and climate water scenarios. The policies considered are the current institutional cooperation, irrigation modernization, enlarging dam storage, and water markets. All adaptation policies increase social welfare, and each policy option results in a different mixture of sector benefits: irrigation modernization promotes agricultural benefits, enlarging dam storage procures the highest river stream flows and energy production, and water markets secures the largest urban benefits.

The findings from the two studies covering the basins around the world indicate that the main adaptation recommendations are conjoint management of surface water and groundwater in the case of Scanlon et al. (2023) and improvement of irrigation efficiency in the case of Kahil et al. (2024). The studies in the Jucar and Ebro basins recommend improving irrigation efficiency, using nonconventional supply sources, expanding reservoir storage, and water markets.

The conjoint management of surface water and groundwater seems a good option but it involves overcoming substantial barriers, because sustainable groundwater management is a wicked challenge requiring the collective action of stakeholders. The large and increasing groundwater overdraft in past decades in Segura, Guadalquivir and Jucar basins show the difficulties of implementing conjoint management in coming decades. The achievement of sustainable management in the Eastern La Mancha aquifer mentioned in section 2.1 demonstrates its feasibility, although it is the only documented case for large aquifer systems in arid or semiarid regions. Efforts to curtail groundwater depletion have been taken also in the USA. The regulatory and incentive schemes implemented in Arizona, Nebraska, Kansas and California have reduced the

[12] Institutional cooperation is the current management approach in basin authorities. The basin authorities reduce irrigation withdrawals in proportion to the water shortfall during periods of scarcity, with the support of the irrigation districts.
[13] Water pricing is the worst option, since during droughts farmers will lose 75% of their profits compared with 25% losses under institutional or water markets policies.

pace of depletion (e.g. Arizona, Nebraska, Kansas) but without achieving sustainable management.

The improvement of irrigation technologies is not an effective adaptation strategy in southern Spanish basins because of the already high share of drip irrigation systems in Segura (88%), Guadalquivir (84%) and Jucar (74%) (MAPA 2024). The strategy of expanding water storage in dams is not feasible in these basins because reservoir storage capacity is already very high in relation to basin stream flows (Table 3).

The adaptation strategies examined for the Segura, Jucar and Guadalquivir seek to balance water supply and demand. In Segura and Jucar the options considered are boosting non-conventional supply sources, seawater desalination and reuse of wastewater, and reducing water allocations to less profitable crops. In Guadalquivir the strategy considered is reducing the allocation of irrigation water, since the augmentation of non-conventional sources is limited. However, the adoption of management portfolios for climate adaptation depends on social priorities in basins and the political clout of the groups of interest.

An aspect not considered in the analysis is the evolution of agricultural markets in the coming decades, and the competition from foreign producers especially from countries that may benefit from climate change. There would be also social concerns related to the future livelihoods of farmers abandoning agricultural activities, although the share of agriculture in the GDP of the regions is small, and training programs could be devised to reallocate workers in other sectors.

The policy outcomes in Spain can be compared with the policy experiences undertaken in other regions. This is the case of California, where policy efforts include the control of groundwater depletion, the augmentation of non-conventional water supply with treated wastewater and seawater desalination, and the promotion of economic instruments such as water markets and water banks. Some problems facing water management in California are the difficulties in organizing the collective action of stakeholders at river basin scale, and the lack of regulation on environmental flows which can be addressed only through the Endangered Species Act. Another problem is the poor design of the Sustainable Groundwater Management Act with an excessive number of control entities: the groundwater area is organized as 95 sub-basins with about 200 management agencies in control, while the equivalent area in Arizona is organized into three separate basins each with a single management agency.

In Spain, despite the fact that both stakeholders' cooperation in river basins and environmental flow regulation are implemented, water policies have been unable to dampen down the unrelenting increase of water withdrawals that are aggravating water scarcity in basins. The issue needs to be solved in Spain in order to confront climate related risks and achieve a climate resilient water sector.

5. Conclusions

Water resources deterioration in the Mediterranean region has become a serious problem in recent decades. A more sustainable management is needed in Mediterranean basins, since the impacts from climate change will be severe in the region.

In Spain, the water sector underwent a strong growth in the second half of the twentieth century driven by the expanding water demand from the urban, industrial and irrigation sectors. The consequence has been the mounting pressures on water systems in basins, in terms of both water scarcity and water quality degradation. Despite the policy and management efforts in recent decades and the existing stakeholders' cooperation inside basin authorities, water withdrawals have continued to increase aggravating water scarcity in major basins. The present situation is especially acute in the basins of southern Spain, where the outflows at the estuary of rivers are dwindling.

The main climate change impacts in Spain under the worst-case scenario (RCP 8.5) at the end of the century could be an increase in temperatures of 4.7 °C and a decrease in precipitations of 140 mm (-22%), coupled with more frequent and intense extreme events. This would result in substantial declines of stream flows in the range of 30 to 40% in the Guadalquivir, Jucar and Segura basins. The adaptation measures considered in water planning are augmenting supply, curbing demand, irrigation modernization, and groundwater protection.

The Segura and Jucar basins are the more threatened basins because renewable resources are well below water withdrawals at present. Even accounting with the full capacity of alternative resources (urban treated wastewater and current desalination), the future excess demand per year at the end of the century could grow up to between 560 and 820 Mm^3 in Segura, and between 750 and 1,210 Mm^3 in Jucar, with the range defined by the impacts of RCP 4.5 and 8.5 scenarios. One option is to cover the excess demand with seawater desalination, with additional costs to farmers from substituting conventional sources in the range of 170-250 million euros in Segura and 225-370 million euros in Jucar, depending of the RCP climate scenario. Another option is eliminating the excess demand by cutting back the allocation of irrigation water and reducing crop production, with direct losses to farmers in the range 310-465 million euros in Segura and 160-460 million euros in Jucar, depending on the climate scenario.

Farmers will prefer to pay the higher price of desalinated water rather than being forced to reduce crop production in all cases except in Jucar under RCP 4.5. The reason is that the high profitability of crops cover the cost of desalination, although in the case of Jucar under RCP 4.5 the better choice is discontinuing the low profitable cereals. The burden of adaptation on farmers will be lower by combining both options, seawater desalination for high profitable crops, and reduced production for low profitable crops. This policy combination achieves the lower costs to farmers in Segura and Jucar for both climate scenarios.

In the Guadalquivir basin, an excess demand of 340 Mm^3 appears under RCP 8.5 and the only option is cutting irrigation withdrawals. The reduction in crop production results in 50 million euros of direct losses to farmers. In other river basins in Spain, renewable resources will be above water withdrawals at the end of the century, and the challenges include the abatement of point and nonpoint pollution, solving groundwater overdraft in some locations, and addressing extreme climate events.

Studies by leading experts covering the river basins around the world recommend conjoint management of surface water and groundwater, and irrigation efficiency gains as critical climate adaptation measures. In Spain, the available studies for adaptation in the Jucar and Ebro basins recommend irrigation efficiency gains, use of nonconventional sources, more reservoir storage, and water markets.

In this study, the policies recommended in southern Spanish basins are expanding seawater desalination, and curbing irrigation demand by abandoning less profitable crops. In southern basins, gains in irrigation efficiency are limited because the share of drip irrigation is already high, close or above 80%. The option of conjoint management of surface water and groundwater is appealing, although quite difficult to implement as shows the pervasive mismanagement of aquifer systems in arid and semiarid regions worldwide and in Spain. In this regard, the success of collective action in the Eastern La Mancha aquifer in the Jucar basin deserves full consideration by managers and policy makers.

Anyway, the selection of policies for advancing sustainable water management in the coming decades depends on the priorities of societies living in river basins, which should determine the specific management strategies combining command and control, economic and cooperation instruments that are able to ensure the uptake by basin stakeholders. The case of Spain is interesting because it shows the successes and failures of an ample set of technological and organizational efforts to address water quantity and water quality challenges. These experiences could be valuable learning lessons for dealing with future climate risks in basins across the Mediterranean.

Acknowledgments

This research has been supported by financing from the Government of Aragon, FEDEA, and the PID2020-115495RA-I00 project of the Spanish Ministry for Science and Innovation, partly financed by European ERDF funds.

ORCID

Jose Albiac https://orcid.org/0000-0002-9074-2942
Encarna Esteban https://orcid.org/0000-0002-4485-3158
Elena Calvo https://orcid.org/0000-0002-7793-7892
Yolanda Martinez https://orcid.org/0000-0003-3552-1810
Safa Baccour https://orcid.org/0000-0002-8098-7129
Taher Kahil https://orcid.org/0000-0002-7812-5271

References

Aich, V, S Liersch, T Vetter, S Huang, J Tecklenburg, P Hoffmann, H Koch, S Fournet, V Krysanova, E Müller and F Hattermann (2014). Comparing impacts of climate change on streamflow in four large African river basins. *Hydrology and Earth System Sciences*, 18, 1305–1321.

Albiac, J, J Tapia, A Meyer, M Hanemann, M Mema, J Calatrava, J Uche and E Calvo (2008). Los problemas económicos de la planificación hidrológica. *Revista de Economía Aplicada*, 47, 25-50.

Albiac, J, E Esteban and S Baccour (2023). La Situación y Perspectivas de los Recursos Hídricos en España. Working document 2023/29, Estudios sobre la Economía Española. Madrid: FEDEA.

Baccour, S, J Albiac, T Kahil, E Esteban, D Crespo and A Dinar (2021). Hydroeconomic modeling for assessing water scarcity and agricultural pollution abatement policies in the Ebro River Basin, Spain. *Journal of Cleaner Production*, 327, 129459.

Baccour, S, F Ward and J Albiac (2022). Climate adaptation guidance: New roles for hydroeconomic analysis. *Science of The Total Environment*, 835, 155518.

Baccour, S, J Albiac, F Ward, T Kahil, E Esteban, J Uche, E Calvo and D Crespo (2024). Managing climate risks: New evidence from integrated analysis at the basin scale. *International Journal of Water Resources Development*, 40(6), 915–939.

Baccour, S, A Tilmant, J Albiac, V Espanmanesh and T Kahil (2025). Probabilistic trade-offs analysis for sustainable and equitable management of climate-induced water risks. *Water Resources Research*, 61, e2024WR038514.

Bellvert, J., M Pamies-Sans, P. Quintana-Seguí and J. Casadesús (2024). Analysis and forecast of crop water demand in irrigation districts across the eastern part of the Ebro river basin (Catalonia, Spain): estimation of evapotranspiration through copernicus-based inputs. *Irrigation Science*. https://doi.org/10.1007/s00271-024-00971-1

BOE (2021). Ley de Cambio Climático y Transición Energética. Boletín Oficial del Estado 121. Madrid: Agencia Estatal Boletín Oficial del Estado.

Cammalleri, C, G Naumann, L Mentaschi, G Formetta, G Forzieri, S Gosling, B Bisselink, A De Roo and L Feyen (2020). Global warming and drought impacts in the EU : JRC PESETA IV project : Task 7. Joint Research Center EUR 29956 EN. Luxembourg: Publications Office of the European Union.

CEDEX (2012). Estudio de los Impactos del Cambio Climático en los Recursos Hídricos y las Masas de Agua. Efecto del cambio climático en el estado ecológico de las masas de agua. Informe final. Centro de Estudios Hidrográficos. Centro de Estudios y Experimentación de Obras Públicas. Madrid: MIMAM.

CEDEX (2017). Evaluación del Impacto del Cambio Climático en los Recursos Hídricos y Sequías en España. Informe Final. Centro de Estudios Hidrográficos. Centro de Estudios y Experimentación de Obras Públicas. Madrid: MAPAMA.

CEDEX (2024). Anuario de Aforos. Centro de Estudios Hidrográficos. Centro de Estudios y Experimentación de Obras Públicas. Madrid: MITECO.

CHD (2023). Plan Hidrológico de la Demarcación Hidrográfica del Duero 2022-2027. Confederación Hidrográfica del Duero. Valladolid: MITECO.

CHE (2023). Plan Hidrológico de la Demarcación Hidrográfica del Ebro 2022-2027. Confederación Hidrográfica del Ebro. Zaragoza: MITECO.

CHGD (2023). Plan Hidrológico de la Demarcación Hidrográfica del Guadiana 2022-2027. Confederación Hidrográfica del Guadiana. Badajoz: MITECO.

CHGQ (2023). Plan Hidrológico de la Demarcación Hidrográfica del Guadalquivir 2022-2027. Confederación Hidrográfica del Guadalquivir. Sevilla: MITECO.

CHJ (2023). Plan Hidrológico de la Demarcación Hidrográfica del Júcar 2022-2027. Confederación Hidrográfica del Júcar. Valencia: MITECO.

CHS (2023). Plan Hidrológico de la Demarcación Hidrográfica del Segura 2022-2027. Confederación Hidrográfica del Segura. Murcia: MITECO.

CHT (2023). Plan Hidrológico de la Demarcación Hidrográfica del Tajo 2022-2027. Confederación Hidrográfica del Tajo. Madrid: MITECO.

Elliott, J, D Deryng, C Müller, K Frieler, M Konzmann, D Gerten, M Glotter, M Flörke et al. (2014) Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, 111(9), 3239-3244.

Escriva, A, M Pulido and D. Pulido (2017). Economic Value of Climate Change Adaptation Strategies for Water Management in Spain's Jucar Basin. Journal of Water Resources Planning and Management, 143(5), 04017005.

Esteban, E and J Albiac (2011). Groundwater and ecosystems damages: Questioning the Gisser–Sánchez effect. *Ecological Economics*, 70 (11), 2062-2069.

Esteban, E and J Albiac (2012). The problem of sustainable groundwater management: The case of La Mancha aquifers, Spain. *Hydrogeology Journal*, 20, 851–863.

Esteban, E, A Dinar, E Calvo, J Albiac, J Calatrava, G Herrera, P Teatini, R Tomás et al. (2024). Modeling the optimal management of land subsidence due to aquifers overexploitation. *Journal of Environmental Management*, 349, 119333.

Estrela, T, M Pérez-Martin and E Vargas (2012). Impacts of climate change on water resources in Spain. *Hydrological Sciences Journal*, 57(6), 1154-1167.

ESYRCE (2022). Encuesta sobre Superficies y Rendimientos de Cultivos. Análisis de los Regadíos en España. Subdirección General de Análisis, Coordinación y Estadística. Madrid: MAPA.

Eurostat (2022). Water statistics. Statistical Office of the European Union. Luxembourg: European Commission.

Exposito, A. and J Berbel (2017). Evolución de la productividad del agua en el proceso de cierre de la cuenca del Guadalquivir. In *Efectos de la modernización de regadíos en España*. J Berbel and C Gutierrez (eds.). Almeria: Cajamar.

Feyen, L, S Gosling, J Ciscar, D Ibarreta and A Soria (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. Joint Research Center EUR 30180 EN. Luxembourg: Publications Office of the European Union.

Garrido, A and L Garrote (2023). La adaptación al cambio climático: los recursos hídricos en España. Un reto social, económico y territorial ante un escenario acelerado de cambio. In *Informe España 2023*. A Blanco, S Mora and J Lopez (eds.). Madrid: Universidad Pontificia Comillas.

Grafton, R, J Williams, C Perry, F Molle, C Ringler, P Steduto, B Udall, S Wheeler et al. (2018). The paradox of irrigation efficiency. *Science*, 361 (6404), 748–750.

Greve, P, T Kahil, J Mochizuki, T Schinko, Y Satoh, P Burek, G. Fischer, S Tramberend et al. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, 1(9), 486-494.

Hattermann, F, V Krysanova, S Gosling et al. (2017). Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins. *Climatic Change*, 141, 561–576.

Hoff, H, M Falkenmark, D Gerten, L Gordon, L Karlberg and J Rockström (2010) Greening the global water system. *Journal of Hydrology*, 384(3-4), 177-186.

INE (2024). Estadística sobre el Suministro y Saneamiento del Agua. Año 2022. Madrid: Instituto Nacional de Estadística.

IPCC (2021). Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. V Masson, P Zhai, A Pirani et al. (eds.). Cambridge: Cambridge University Press.

Kahil, T, A Dinar and J Albiac (2015). Modeling water scarcity and droughts for policy adaptation to climate change in arid and semiarid regions. *Journal of Hydrology*, 522, 95-109.

Kahil, T, J Albiac, A Dinar, E Calvo, E Esteban, L Avella and M García-Molla (2016). Improving the Performance of Water Policies: Evidence from Drought in Spain. *Water*, 8 (34).

Kahil, T, S Baccour, J Joseph, R Sahu, P Burek, J Ng, S Asad, D Fridman, J Albiac, F Ward and Y Wada (2024). Development of the global hydro-economic model (ECHO-Global version 1.0) for assessing the performance of water management options. *Geoscientific Model Development*, Preprint for discussion.

Majone, B, C Bovolo, A Bellin, S Blenkinsop and H. Fowler (2012). Modeling the impacts of future climate change on water resources for the Gállego river basin (Spain). *Water Resources Research*, 48, W01512.

Marcos, P, M Pulido, C Sanchis, M García, M Ortega, A Garcia and C Girard (2023). From local knowledge to decision making in climate change adaptation at basin scale. Application to the Jucar River Basin, Spain. *Climatic Change*, 176, 38.

MAPA (2024). Encuesta sobre superficies y rendimientos de cultivos. Análisis de los regadíos en España. Subdirección General de Análisis, Coordinación y Estadística. Madrid: Ministerio de Agricultura.

MIMAM (2000). Libro blanco del agua en España. Dirección General de Obras Hidráulicas. Secretaría de Estado de Aguas y Costas. Madrid: Ministerio de Medio Ambiente.

MITECO (2020). Plan Nacional de Adaptación al Cambio Climático 2021-2030. Madrid: Ministerio para la Transición Ecológica.

MITECO (2021). Plan Nacional de Depuración y Saneamiento. Dirección General del Agua. Madrid: Ministerio para la Transición Ecológica.

MITECO (2022). Informe de Seguimiento de los Planes Hidrológicos de Cuenca y de los Recursos Hídricos en España. Año 2021. Madrid: Ministerio para la Transición Ecológica.

MOPT (1993). Plan Hidrológico Nacional. Memoria y Anteproyecto de Ley. Madrid: Ministerio de Obras Públicas y Transportes.

Perez, C, A Loch, F Ward, C Perry and D Adamson (2021). Agricultural water saving through technologies: a zombie idea. *Environmental Research Letters*, 16(11), 114032.

Pulido, D, A Collados, J. Perez, F. Segura and J. Senent (2021). Climate change impacts on the streamflow in Spanish basins monitored under near-natural conditions. *Journal of Hydrology: Regional Studies*, 38, 100937.

Sanchez, G, I Martínez, C Díaz, H Martínez, J Arntzen and I Gomez (2024). Pond area and availability safeguard amphibian genetic diversity across Iberia's largest protected wetland. *Freshwater Biology*, 69, 917–931.

Scanlon, B, B Ruddell, P Reed, I Ruth, C Zheng, V Tidwell and S Siebert (2017). The food-energy-water nexus: Transforming science for society. *Water Resources Research*, 53(5), 3550-3556.

Scanlon, B, S Fakhreddine, A Rateb, I de Graaf, J Famiglietti, T Gleeson, R Grafton et al. (2023), Global water resources and the role of groundwater in a resilient water future. *Nature Reviews Earth & Environment*, 4, 87–101.

Scoccimarro, E, D Peano, S Gualdi, A Bellucci, T Lovato, P Fogli, and A Navarra (2022). Extreme events representation in CMCC-CM2 standard and high-resolution general circulation models. *Geoscientific Model Development*, 15, 1841–1854.

Seneviratne, S, X Zhang, M Adnan, W Badi, C Dereczynski, A Di Luca, S Ghosh, I Iskandar et al. (2021). Weather and Climate Extreme Events in a Changing Climate. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate*

Change. V Masson, P Zhai, A Pirani et al. (eds.). Cambridge: Cambridge University Press.

Suarez, S, A. Solera, J. Madrigal, J. Andreu and J. Paredes (2020). Risk assessment in water resources planning under climate change at the Júcar River basin. Hydrology and Earth System Sciences, 24(11), 5297–5315.

Tickner, D, J Opperman, R Abell, M Acreman, A Arthington et al. (2020). Bending the curve of global freshwater biodiversity loss: An emergency recovery plan. *Bioscience*, 70, 330–342.

Versini, P, L Pouget, S McEnnis, E Custodio and I. Escaler, I. (2016). Climate change impact on water resources availability: case study of the Llobregat River basin (Spain). Hydrological Sciences Journal, 61(14), 2496–2508.

Vetter T, S Huang, V Aich, T Yang, X Wang, V Krysanova and F Hattermann (2015) Multi-model climate impact assessment and intercomparison for three large-scale river basins on three continents. *Earth System Dynamics*, 6, 17–43.

Vetter T, J Reinhardt, M Flörke, A van Griensven, F Hattermann, S Huang, H Koch, I Pechlivanidis et al. (2017) Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins. Climatic Change 141, 419–433.

Vörösmarty, C, P McIntyre, M Gessner, D Dudgeon, A Prusevich, P Green, S Glidden, S Bunn et al. (2010). Global threats to human water security and river biodiversity. *Nature*, 467, 555–561.

Ward, F and M Pulido-Velazquez (2008). Water conservation in irrigation can increase water use. *Proceedings of the National Academy of Sciences*, 105 (47), 18215-18220.

World Bank (2021). Climate Change Knowledge Portal. Country: Spain. Washington: World Bank.

WWF (2012). El fiasco del agua en el Alto Guadiana. Informe 2012. Programa de Aguas Continentales. Madrid: World Wildlife Fund España.

Zarzo, D (2020). La Desalación del Agua en España. Working document 2020/22, Estudios sobre la Economía. Madrid: FEDEA.