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The paradox of success: Water resources closure in Axarquia (southern Spain)

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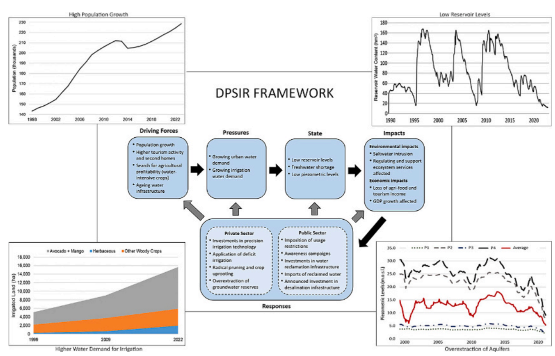
HIGHLIGHTS

- Axarquia is an example of the anthropogenic process of basin closure.
- DPSIR is a useful tool to understand the dynamics of socio-hydrological systems.
- DPSIR detects the causes of basin closure and the public and private responses.
- Supply-side policies cannot solve the water resources structural deficit.

GRAPHICAL ABSTRACT



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ABSTRACT

Axarquia is a semi-arid region in southern Spain that in the past 25 years has experienced significant population growth, along with an economic boom driven by an increasing influx of tourists to Costa del Sol and the expansion of irrigated export-oriented subtropical crops. The combination of these factors has led to a chronic structural scarcity condition that has been intensified by the occurrence of a long and extreme drought. As a result, its only reservoir has reached historically low levels and the piezometric levels in its main aquifer have decreased significantly, suggesting that groundwater reserves are being overexploited. The water crisis is impacting citizens (urban supply), farmers (losses of yields and crops), and the environment (decreasing water reserves). The authorities have responded through supply-side measures such as incorporating reclaimed wastewater in the system and planning the deployment of desalination infrastructure in the region, but demand control and proper governance are required to guarantee sustainability. Consequently, in this case study we apply the European Environment Agency's DPSIR (driving forces, pressures, state, impact, and response model of intervention) framework to understand the basin closure process in Axarquia and assess the main actions that have been undertaken by public and private sector stakeholders to address the challenges faced by the region. Our results provide a valuable reference case to support the analysis of similar closure events, the early identification of potential crisis conditions, and the design of potential solutions in water scarce regions in the European Union, the Mediterranean, and elsewhere.

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1. Introduction

Adequate water management practices are essential for sustainable economic development, especially in rapidly growing semi-arid regions, due to the constant threat of the occurrence of basin closure, a condition that carries major environmental and socioeconomic implications and that results from a complex process driven by a combination of natural and anthropogenic factors (Expósito and Berbel, 2017a; Falkenmark and Molden, 2008; Molle et al., 2010). In these regions, prolonged periods of low precipitation and high evaporation rates can contribute to a gradual decline in water availability within basins while, at the same time, limited rainfall levels may be insufficient to adequately replenish surface water bodies and recharge groundwater aquifers. Human activities can exacerbate the situation as population growth and economic development tend to put increasing demands on water resources, further straining the balance between supply and demand. Furthermore, unsustainable practices such as inefficient water management, including excessive irrigation for agriculture and unregulated groundwater pumping can put additional pressure on the system, while climate change may amplify the challenges by intensifying drought conditions and altering precipitation patterns. The cumulative impact of these factors can thus lead to basin closure, a condition that is marked by diminished water reserves, decreased ecosystem resilience, and heightened vulnerability to the socioeconomic consequences of water scarcity (Keller et al., 1998; Seckler, 1996).

The closure process has been described for various basins and aquifers and can constrain a region's socioeconomic activities (Molle et al., 2010). Declining rivers, reservoirs and aquifers can severely affect economic sectors that rely on water resources, such as agriculture, industry, energy, and tourism. Furthermore, the effects of basin closure can extend to public health and ecosystem services since access to clean and safe drinking water is fundamental for overall health outcomes, and maintaining the quality, quantity, and flow patterns of water is crucial for sustaining ecosystems as well as the many economic and social benefits that they provide (Falkenmark and Molden, 2008).

Addressing basin closure in semi-arid regions therefore requires a comprehensive approach that integrates adequate water management practices, climate adaptation strategies, and the engagement of stakeholders at all levels to ensure the long-term sustainability of these vulnerable systems. Accordingly, in this case study we apply the European Environment Agency's DPSIR (driving forces, pressures, state, impact, and response model of intervention) framework (EEA, 1999; Kristensen, 2004) to understand the past 25 years of the basin closure process in Axarquia, a region in southern Spain facing acute water scarcity challenges. Through this analysis, we aim to demonstrate how the application of the DPSIR framework can support the acquisition of knowledge about the causes, impacts and policy responses to basin closure processes.

Understanding the dynamics of these processes is of growing interest in the European Union and the Mediterranean as water scarcity is increasingly becoming a recurring issue that has significant environmental and economic repercussions. These challenges are expected to intensify due to climate change while projections indicate that more agricultural land, particularly in southern Europe, will require irrigation, further exacerbating the current water stress (EEA, 2018). Against this backdrop, this case study describes a basin closure trajectory in Axarquia that resembles what has been observed in other water scarce regions (Kherbache and Molle, 2023; Molle et al., 2010; Pittock, 2019; Venot et al., 2007), with growing water demand for irrigation being fuelled by the low productivity and profitability of rainfed land, which in the short term is exacerbated by the occurrence of drought events and in the long term by the consequences of climate change. Furthermore, it shows that the supply-side responses that are being implemented by the public sector authorities in Axarquia are similar to those adopted in other parts of the world (e.g., the deployment of reclaimed water in Cyprus and California, and desalinated water in Israel, North Africa and the Middle East) (Jones et al., 2019; Ramm and Smol, 2023; Sheikh et al., 2019). In sum, the insights gained through our research show that Axarquia is an excellent model to understand the dynamics of the basin closure process in water scarce regions in the European Union, the Mediterranean, and elsewhere. In addition, the framework herein described provides a valuable reference case to support the analysis of similar closure events, the early identification of potential crisis conditions, and the design of potential solutions in such regions.

2. Methodology

2.1. Study area

Spanning 1025 km^2 and 31 municipalities, Axarquia is a comarca located in the eastern part of the Andalusian province of Malaga, southern Spain (36°50′25″N 4°06′37″W) (Fig. 1). It lies between a range of mountains at the north and the Mediterranean Sea at the south, which results in a rugged relief with five different types of microclimates and scarce plains. Its average altitude is 391 m, the highest point is La Maroma peak (2069 m) at approximately 17 km from the coastline, and the annual average temperature is about 19 °C in most of the comarca but falls to between 4 and 8 °C at higher altitudes. Likewise, rainfall levels vary significantly from the larger dry areas along the coastline to the smaller humid zones close to the summits. Overall, rainfall is scarce and of a torrential nature, with most of the annual precipitation falling in a few days (Yus Ramos, 2005).

The Vélez River, which is fed by many small rivers and streams, is the most important in the Axarquia and its basin covers almost 60 % of the comarca. The remaining is made up of a series of linear basins formed by minor rivers that travel short distances directly to the sea, which is a feature observed also in other parts of the world that are facing similar challenges due to the increasing cultivation of highly profitable subtropical crops (e.g. coastal basins in Italy, Chile, Peru, and California). A key piece of infrastructure in the system is the La Viñuela dam, which was built between 1982 and 1989 across the Guaro River, a tributary of the Vélez River. With a maximum capacity of 165.4 hm^3, it is the sole reservoir of the region, serving a critical role for crop irrigation and as a source of drinking water for the population (Junta de Andalucía, 2024b; Yus Ramos, 2009). Over 90 % of the comarca's territory overlaps with the jurisdiction of subsystem II-1 of the Andalusian Mediterranean Basins Authority (DHCMA), which has an extension of 1026 km^2. The nearly identical extension of the two administration units is explained by the trade-offs between small portions of neighbouring comarcas and basin authorities, and for that reason they are considered as being roughly equivalent throughout this study. According to the estimates of the Regional Government of Andalusia's Hydrological Plan 2022–2027, subsystem II-1 comprises 10 surface water bodies that contribute an average annual discharge of 129.6 hm^3 and 10 groundwater bodies that contain a total of 94.5 hm^3 of water resources (Junta de Andalucía, 2023d).

The Axarquia region's distinctive geography has shaped the three key components of its economy – agriculture, tourism, and construction. Its pleasant climate, natural parks, Mediterranean beaches, and heritage sites have attracted new residents and turned it into a year-round tourist destination, whereas the inland areas provide ideal conditions for agriculture.

2.2. DPSIR framework

DPSIR is a framework developed to help understand the cause-effect relationships between human activities and the environment. It builds on the pressure-state-response (PSR) model first put forth by the Organisation for Economic Co-operation and Development (OECD, 1991) and then expanded upon by the European Environment Agency to include driving forces and impacts (EEA, 1999). It has since been widely adopted by organizations like the United Nations to inform policy formulation and decision-making (WWAP, 2012).

The first element of the framework, "*Driving forces*", refers to the underlying factors that drive human activities, including political, economic, social, and technological trends. The second element, "*Pressures*", corresponds to the actions that exert stress on the environment, such as the extraction of resources, changes in land use, and the production of emissions. "*State*", in turn, represents the combination of the physical, chemical, and biological conditions of the environment that results from the prevailing pressures placed upon it, serving as a baseline for the assessment of changes over time. The fourth element, "*Impacts*", highlights the economic and environmental consequences that these changes can have on ecosystems, human health, and well-being. And, finally, "*Responses*" encompass the measures taken to address and mitigate the identified environmental issues, including policy initiatives, technological innovations, or changes in behaviour that can affect any part of the chain between driving forces and impacts. In sum, the DPSIR framework provides a system map that traces causal links from *Drivers* to *Impacts* and back through multiple feedback loops, shedding light on the relationships between economic and human activities and their interconnections with the environment, and offering a valuable tool for policymakers, researchers, and stakeholders to make informed decisions about sustainable resource management and conservation strategies.

2.3. Data sources

Socioeconomic, agricultural, and hydrological data were obtained from various data sources. Data on population was from Spain's National Statistics Institute (INE, 2024) and the Mediterranean River Basin Districts of Andalusia's Hydrological Plan for 2022–2027 (Junta de Andalucía, 2023d). For the estimation of irrigated cropland area and water demand for irrigation, we used data from Spain's National Statistics Institute (INE, 2022a); Spain's Ministry of Agriculture, Fisheries and Food (MAPA, 2022); Andalusia's Ministry of Agriculture, Fisheries, Water and Rural Development (Junta de Andalucía, 2022a), and Andalusia's Geographic Information System for the Identification of Agricultural Parcels (SIGPAC) (Junta de Andalucía, 2023a). Data on farm costs and incomes was from Spain's Survey on Costs and Income of Agricultural Holdings (MAPA, 2023). For supply and demand of water resources in Axarquia (i.e., sources, extractions, users, and allocations), we used data from subsystems II-1 and II-3 of the Andalusian South Basin Hydrological Plan for 1998 (Junta de Andalucía, 1999) and the Mediterranean River Basin Districts of Andalusia's Hydrological Plans for 2009–2015 and 2015–2021 (Junta de Andalucía, 2012, 2016), and from subsystem II-1 of the Mediterranean River Basin Districts of Andalusia's Hydrological Plan for 2022–2027 (Junta de Andalucía, 2023d). Data about reservoir reserves and agricultural land prices was obtained from the Viewer of Andalusia's Reservoir (Junta de Andalucía, 2024b) and Andalusia's Annual Land Price Survey 2022 (Junta de Andalucía, 2023c), respectively. For piezometric levels, we used data from the Report on the Environment in Andalusia (iMA) (Junta de Andalucía, 2022c). Specific data about per capita water consumption, water reuse and desalination, water network losses, agricultural

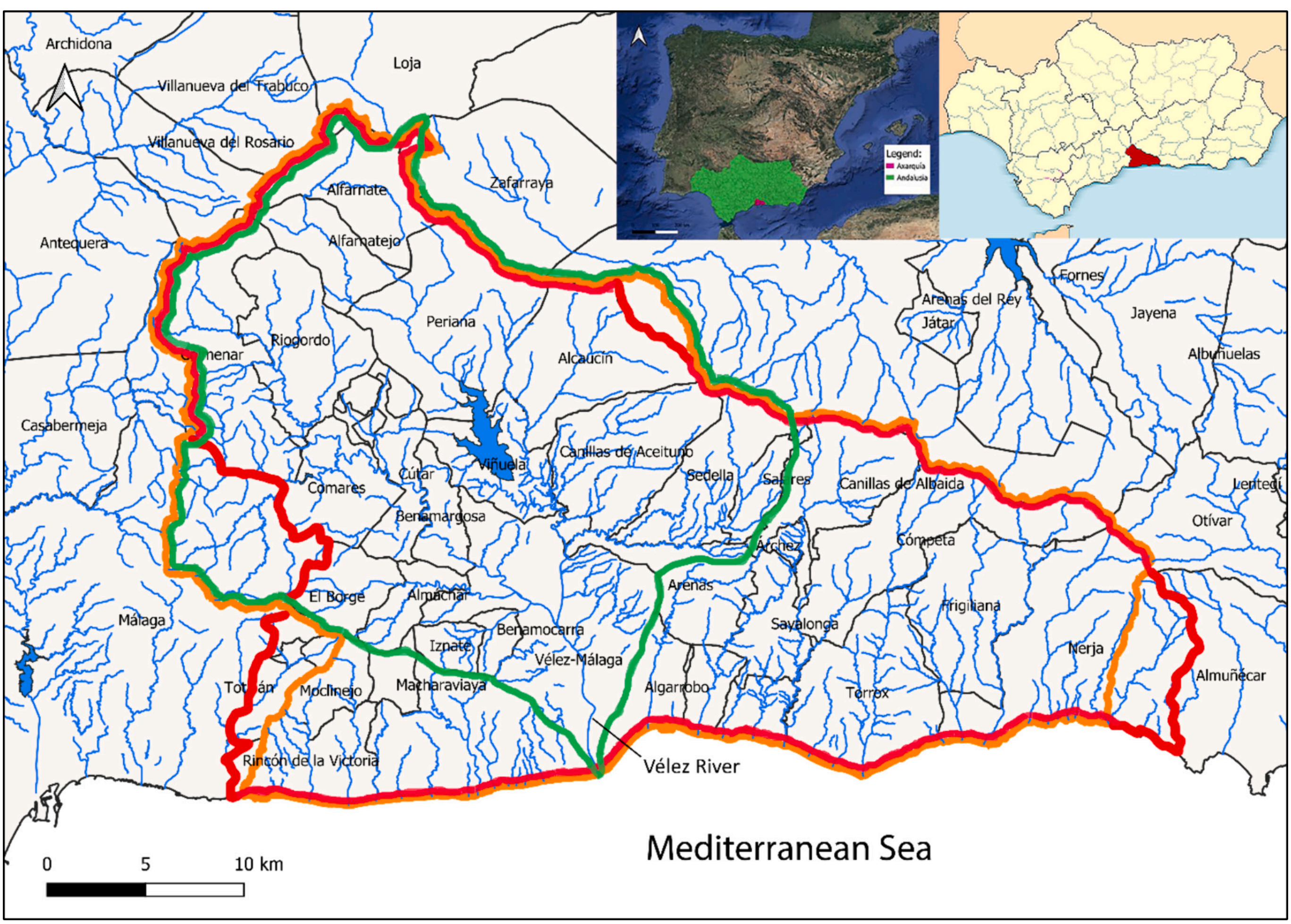

Fig. 1. Hydrological map of subsystem II-1 of the Andalusian Mediterranean Basins Authority (orange), the comarca of Axarquia (red), and the Vélez River basin (green) in Andalusia (Spain), showing the short distance that the region's rivers travel to the Mediterranean Sea. Source: Own elaboration on QGIS 3.34.2 software (QGIS.org, 2023), based on data from REDIAM - the Environmental Information Network of Andalusia (Junta de Andalucía, 2024a).

production losses, and Andalusia's GDP growth losses was gathered from various government bulletins and announcements, press reports and other publications indicated where appropriate throughout this manuscript. Information not available publicly was obtained through consultations with managers from public and private sector organizations.

3. DPSIR analysis of the water resource closure process in Axarquia

3.1. Driving forces: changes in population and agriculture

Three major driving forces explain the substantial increase of water use in Axarquia in the past three decades: population growth, tourism activity, and the search for profitability in the agricultural sector.

The Mediterranean coastal regions of Spain have experienced substantial population growth in the past two decades due to both immigration and internal movements of people from other parts of the country seeking tourism and hospitality jobs, milder climate in retirement, or second homes for vacations. One of the regions impacted by this trend is Axarquia, which has seen its population rise from around 143 thousand people in 1998 to over 228 thousand in 2023, i.e., 2 % annually and 59.5 % overall during this 25-year period. Most of this growth (93.9 %) has occurred along the comarca's five coastal municipalities, which cover approximately one third of the territory and contain the bulk of the population, business activity, and agricultural capacity, whereas the inland municipalities that are furthest away and worst connected to the coast are facing challenges related to population loss (INE, 2024).

Costa del Sol (the Andalusian coastal region where Axarquia is located) has long been a popular destination for tourism and second homes, but its popularity has grown even more in recent decades due to improvements in transportation and infrastructure, including more flights to Malaga's international airport, high-speed rail links, real estate development, and investment in new hotels, conference venues and resorts. In addition, marketing and promotion campaigns showcasing the area's coastline, golf courses, historic sites, and other attractions have made it an appealing destination for all types of visitors. As a result, in 2019 there were 27,245 bed places in tourist accommodation establishments and 59,671 second homes registered in subsystem II-1 of DHCMA, adding an estimated annual average of 63,745 people (i.e. 29.7 % more) to the region's 214,323 residents. During that year, before the COVID-19 pandemic, the influx of seasonal population fluctuated between 30,913 (14.4 % of the resident population) in January and 112,403 (52.4 %) in August, driving the total population to an annual average of 278,067 (Junta de Andalucía, 2023d). The tourism sector is therefore today one of the two key components of the Axarquia's economy and has recently beaten a record with over 770 thousand visitors in the three months between June and August 2023, which is 23 % above the annual average (APTA, 2023).

The third major driving force in Axarquia, and the strongest, is the agricultural sector due to the key role that it has historically played in the region's economy. While there is evidence of Iberian, Phoenician, and Roman settlements in the alluvial plains and near the coast, cultivation on the hillsides likely started to take place during the Nasrid dynasty around the 14th and 15th centuries. Agricultural development and population growth during this period of Muslim rule was accompanied by the production of wine, raisins, figs, almond, and silk from rainfed land as well as to the cultivation of lemon, vegetables, and sugar cane in irrigated lands (Olmedo Lucena, 2007). More recently, in the latter decades of the 20th century, the income generated from traditional rainfed crops that had turned into the most predominant in the region (e.g., olive trees, vines, almond trees, and cereals) started to decline significantly, leading to the abandonment of farmland as well as to increasing investments in irrigation. The increased productivity and profitability of irrigated farmland have in turn pushed their prices upwards across Andalusia, reflecting the expectations of higher returns on investment that farmers and investors place on irrigated agricultural land in comparison to rainfed land. Thus, for example, irrigated land for subtropical crops, citrus crops, and olive groves are currently the most expensive in the province of Malaga, with irrigated land for olive groves being priced 60 % higher than rainfed land for this crop. Most remarkably, irrigated land for subtropical crops is by far the most highly valued in the province, holding a price 2.6 times higher than that of its closest follower (citrus crops) and 23 times higher than grassland (Table 1). The increased land prices, in turn, feed the need to achieve higher productivity yields and profitability, generating a reinforcing feedback loop that drives the development of further pressure on the system.

To summarize, Axarquia's increasing population, rapidly growing tourism industry, and greater demand of water for agriculture, together with the occurrence of a prolonged and extreme drought, have contributed to highlight the existence of important infrastructure gaps in the region, including ageing pipes, outdated distribution networks, and the lack of facilities for the production of unconventional water resources (desalination and wastewater reclamation).

3.2. Pressures: increased water abstraction

In the urban sector, rapid population growth in the region is putting increasing pressure on water resources as more inhabitants lead to heightened demand for drinking, cleaning, landscaping, and municipal uses. Furthermore, the tourism industry exerts additional strain on the system as greater numbers of visitors utilize more water through hotels, secondary residences, and other hospitality venues. Altogether, this results in a daily consumption of 212 L/person in Axarquia (Cabezas, 2023a), which is around 60 % higher than the Spanish average of 133 L/person/day (INE, 2022b). Tourism activity and secondary residences account for an important part of the high municipal use of water resources in the region vis-à-vis national consumption levels, but the substantial losses in the ageing water distribution networks, which are estimated to be above 24 % (Cabezas, 2023b), are also a significant contributor for total water abstractions.

On the other hand, in quantitative terms, the most important source of pressure on the system is the transition from rainfed agriculture to irrigation. The low levels of profitability of traditional rainfed crops in the past few decades has pushed many farmers to look for alternatives, leading to a substantial increase of the irrigated area from around 5100 ha in 1999 to over 13,000 ha in 2022. Most of this land is now dedicated to more lucrative water-intensive crops like avocado and mango, which have expanded more than two-fold, from around 4000 ha in 1999 to nearly 9800 ha in 2022 (over 70 % of the total today). Herbaceous crops, and olive and other perennials, in turn, have experienced a decrease since 2014 after a period of significant expansion, while citrus has remained relatively stable during the same period but declined in 2022 (INE, 2022a; MAPA, 2022; Junta de Andalucía, 2022a, 2023a).

According to our estimates, the expansion of irrigated land in Axarquia have led to a significant increase of water demand for irrigation from 37 hm^3/year in 1999 to 90 hm^3/year in 2022 (Table 2), which is lower than the 111 hm^3/year that would result if the FAO irrigation guidelines were applied (Allen et al., 1998; Moldero et al., 2021; Moreno-Ortega et al., 2019). This 19 % difference is explained by the application of deficit irrigation, a practice that is typical in the region

Table 1
Most frequent land prices in the province of Malaga, Spain (EUR/ha) (2022).

Rainfed		Irrigated	
Grassland	5,341	Subtropical crops	122,739
Vines	17,112	Citrus crops	46,402
Olive groves	24,530	Olive groves	39,410
Herbaceous crops	13,452	Herbaceous crops[a]	31,786

[a] Average most frequent price in Andalusia.
Source: Own elaboration based on data from Junta de Andalucía (2023c).

and which consists in supplying crops with less water than their maximum requirement, intentionally creating a controlled water deficit to optimize resource use and enhance water efficiency. Remarkably, our estimated irrigation water demand of 90 hm^3/year exceeds the 79 hm^3/year that the basin authority's hydrological plan allocates for irrigation water rights in 2022–2027 (Junta de Andalucía, 2023d). This difference between the estimated total demand and the official water concession rights (which are in turn equivalent to only 70 % of FAO's recommended irrigation levels) suggests that farmers may be extracting beyond the approved limits to meet their irrigation needs, thus pointing to an unsustainable shortage of water supply for agriculture in Axarquia.

Lastly, diffuse pollution from various non-point sources such as agricultural runoff, urban stormwater, and atmospheric deposition, poses growing pressures on the region's water resources. For example, agricultural runoff containing fertilizers, pesticides, and animal waste enters waterways through surface drainage and leaching into groundwater; stormwater in urban areas washes pollutants into streams and aquifers after rainfall; septic systems leak nutrients and pathogens, impairing nearby surface and groundwater; and atmospheric deposition from, for example, Saharan sand and dust storms ("calimas"), can introduce human-made pollutants into the hydrologic system. Unlike point source pollution that can be more easily identified and addressed, the gradual accumulation of small amounts of contaminants from various individually minor sources is known to be a cause of degradation of water quality and an important threat for essential freshwater resources (Ferrier et al., 2005; Mezzacapo et al., 2020).

3.3. State: falling reserve levels and basin value added

The increasing water demand in Axarquia has produced a structural deficit that has been aggravated by a long drought, leading the region to find itself amid a severe water crisis with consequences at various levels. Thus, one of the main effects of continuing surface water abstractions during the drought has been the significant decline of water levels in La Viñuela reservoir, which in December 2023 had dropped to 7 % of its capacity (Fig. 2A) and in May 2024 had recovered to 19 % after a few weeks of rain (Junta de Andalucía, 2024b). Likewise, a sharp decrease of the piezometric levels has been observed in the region's main aquifer (Fig. 2B), which is usually the result of overextraction of groundwater under these conditions (Pisinaras et al., 2007; Vrba and Lipponen, 2007). These critically low dam capacity and piezometric levels represent an extreme shift compared to the baseline, strongly suggesting that the state of the environment may be severely compromised. Furthermore, as shown in Fig. 2, the structural water scarcity conditions have become more evident during the dry periods (24-month Standardised Precipitation-Evapotranspiration Index below zero) that have affected Axarquia in 1999–2003, 2005–2009, and since the end of 2012 (CSIC, 2024). This indicates that freshwater reserves are struggling to recover, making the region increasingly vulnerable to the altered precipitation patterns that climate change is causing across the world.

Table 2
Evolution of water demand for irrigation of crops in Axarquia (hm^3/year) (1999–2022).

	1999[(1)]	2012[(2)]	2022[(3)]
Avocado and mango	31.4	53.0	73.8
Citrus	2.7	3.1	2.3
Olive and other perennials	0.2	4.5	2.6
Herbaceous	2.8	15.4	11.1
TOTAL	37.2	76.0	89.9

Source: Own estimates based on data from (1) INE (2022a), (2) Junta de Andalucía (2022a), and (3) Junta de Andalucía (2023a).

3.4. Impacts: environmental and socioeconomic consequences of water scarcity

Axarquia has experienced a process of basin closure over the past three decades and has already reached a point where the supply of water is no longer able to fulfil water demand, a situation that has important impacts on both the environment and the economy.

3.4.1. Environmental impacts

Extreme declines in reservoir levels, as it has been experienced by La Viñuela, can have major consequences for the environment and trigger adverse impacts on both regulating and support ecosystem services. For example, changes in water turbidity, quality, and temperature can affect breeding and feeding habitats for fish and other species, and exposed shorelines may result in soil erosion and degradation, which could in turn impact the surrounding vegetation and contribute to the release of sediment into the water and affect the balance of ecological systems. In addition, decreased water availability can extend beyond the reservoir's boundaries, affecting wetlands, riparian zones, and the wildlife that depends on them, leading to a cascading series of ecological disruptions with lasting environmental implications (Dobel et al., 2020; Ploskey, 1982).

Regarding groundwater, low piezometric levels in aquifers near the coastline can also trigger a series of negative effects on the environment. The reduction in piezometric pressure may induce saltwater intrusion, i.e. a process where seawater infiltrates the coastal aquifer, increasing the salinity of fresh groundwater. This phenomenon can adversely impact coastal ecosystems, as many plant and animal species are sensitive to changes in water quality. Likewise, the reduction in freshwater discharge to coastal areas can affect the breeding and feeding grounds of marine species through the disruption of estuarine environments and, as seawater infiltrates the aquifer, land subsidence can be exacerbated and lead to increased vulnerability to floods and other natural events (Pereira et al., 2019; Tully et al., 2019).

3.4.2. Economic impacts

According to our estimates, the increase in irrigated area in the past two decades has had a positive impact on economic activity in Axarquia through the rise of local added value, from around 75 million EUR in 1999 to 200 million EUR in 2022. Nevertheless, since 2023, the prolonged drought, combined with low reservoir levels, is substantially affecting gross margins in the region's farms, and thus having a significant impact on the overall economy which is heavily reliant on agriculture. Thus, while some crops like olive trees adapt better to deficit irrigation (Expósito and Berbel, 2016), the region's farmers estimate that the production of mango and avocado in Axarquia plummeted in 2023 to only 15 % and 40 % of their annual averages, respectively (Rodríguez, 2023), with obvious consequences on farm income and job creation. The effects of the current situation will likely be felt for some time as arid conditions and inadequate irrigation degrades soil health, and stressed crops are more susceptible to pests and diseases (Geng et al., 2015; Zahra et al., 2023).

Additional economic impacts can result from the salinization of aquifers due to seawater intrusion, which may compromise the quality of the groundwater and affect its suitability for urban consumption or agriculture. Although no information is yet available about the state of the quality of the aquifers, it is well known that increased salinity of groundwater can have severe effects on soil health and crop development (Tarolli et al., 2023). Likewise, the overexploitation of aquifers could cause existing wells to run dry, forcing costly drilling of replacement wells.

Furthermore, the historically low levels of La Viñuela reservoir are having a major impact on the economy of local communities that are centred around reservoir recreation and tourism due to the loss of cultural ecosystem services such as recreational fishing, swimming, and other water sports, as well as the loss of aesthetic value of the

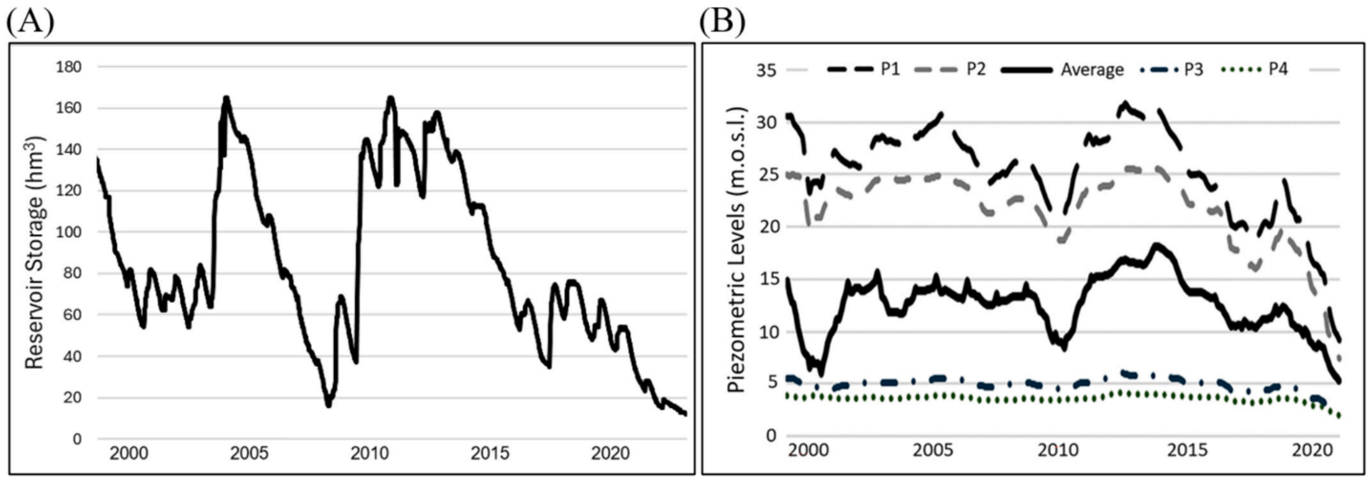

Fig. 2. (A) Storage levels (hm^3) in La Viñuela reservoir (1999-2023) and (B) estimated piezometric levels (12-month moving average, m.o.s.l.) in four points of the Vélez River aquifer of Axarquia (1999-2022). Source: Own elaboration based on data from Junta de Andalucía (2022c, 2024b).

landscapes.

While no estimates are available for Axarquia, a recent report on the effects of the current drought on the overall Andalusian economy has estimated that the combination of water scarcity and infrastructure gaps have so far had an impact of 2.1 % on the GDP, which is due to the weight of the primary sector and related industry and services (around 25 %) (Junta de Andalucía, 2023b).

3.5. Responses

3.5.1. Private sector

The agricultural sector is the largest consumer of water in Axarquia, receiving 79.20 hm^3 (75.1 %) of the 105.48 hm^3 supplied annually to all users of subsystem II-1 of DHCMA during the period 2022–2027, versus 23.04 hm^3 (21.8 %) supplied to municipalities, and 3.24 hm^3 (3.1 %) to industry, golf, and livestock (Junta de Andalucía, 2023d). It has consequently been the most impacted by the water crisis affecting the region and has therefore been forced to employ a range of adaptive response measures beyond merely complying with usage restrictions imposed by the authorities, as it has been the case with the other sectors of the economy.

The extreme water shortage conditions have led the region's farmers to accelerate the implementation of precision irrigation technologies to achieve water savings without sacrificing yields. One such example is a collaborative project carried out by a local IT company and the largest Spanish producer and distributor of subtropical crops, which has led to the development of equipment capable of automatically taking control of irrigation through constant monitoring of tree growth and the farm's microclimate. The application of this technology makes possible the production of Hass avocados with less than 350 L of water per kg of fruit, versus the 600–700 L per kg that are usual in the sector (Cristofol, 2021). Other initiatives in this direction include the operational group “Sustainable Axarquia”, which aims to expand knowledge on the use of reclaimed water for key crops in the region and develop a fertigation management tool to optimize the use of fertilizers, and the “Agua+S” project led by the University of Malaga, which aims to harness renewable energy from photovoltaic plants located in reservoirs to facilitate the production of desalinated water from the sea. Furthermore, private organizations are launching open innovation challenges tailored for high-technology ventures specializing in sustainable water management. These endeavours are collectively seeking to contribute to the advancement of sustainable water management practices and agricultural efficiency in the region.

However, as the situation has worsened, leading in some cases to the loss of their crops, farmers have resorted to the application of more drastic deficit irrigation practices, as well as to radical pruning or uprooting of otherwise highly profitable subtropical crops like mango and avocado. Furthermore, the lack of surface water has driven farmers to resort to trade between entitlement owners as well as to both legal and (possibly) illegal groundwater abstraction, which has in turn contributed to the reduction of piezometric levels in the local aquifers, as described in Section 3.3. A recent investigation launched by the authorities to probe allegations of illegal wells and irregular water concessions estimated that approximately 26 hm^3 of water had been illegally extracted over a period of four years (San Martín, 2023).

3.5.2. Public sector

On the demand side, public sector authorities at all levels of government, have implemented structural and non-structural measures to address the water crisis in Axarquia, which are in line with the catalogue of actions described by Estrela and Vargas (2012) in their analysis of seven drought management plans in Spain. These measures have included: a) awareness campaigns to educate the public on saving water and the need for collective restraint; b) the imposition of limits on non-essential residential, commercial, and municipal water uses with the objective of curbing discretionary consumption, such as shutting down public fountains, turning off showers in the beaches, closing pools, and rationalizing the irrigation of parks and gardens; and c) making golf courses use as much reclaimed water as possible.

Another recent measure on the demand side is the Regional Government of Andalusia's pledge to provide support to the municipalities that make an effort to improve water distribution efficiency and impose penalties to those that have unacceptable water distribution losses (Junta de Andalucía, 2023h). In addition, the price of water from La Viñuela reservoir for irrigation purposes was recently increased from 8.85 EUR/hm^3 to 9.066 EUR/hm^3, but the price for urban supply was at the same time lowered from 29.85 EUR/hm^3 to 26.28 EUR/hm^3 (Junta de Andalucía, 2024c).

On the supply side, the main measures undertaken by the authorities have been the construction of tertiary treatment infrastructure in local and neighbouring wastewater treatment plants (WWTP), which is necessary for wastewater reuse, and the transportation of reclaimed wastewater from the city of Malaga (outside the catchment limits of Axarquia). As a result, approximately 80 % of the urban wastewater generated in the comarca is treated and reused today, and about 13.5 hm^3/year of reclaimed water have been introduced in the system to date. An additional 9.0 hm^3/year are imported from Malaga, increasing the total to 22.5 hm^3/year, which accounts for approximately 20 % of all water supply in the region, virtually all of it destined to agriculture (Junta de Andalucía, 2023f). Furthermore, planning for the construction of a desalination plant in Axarquia is currently under way, and a projected 25 hm^3/year of desalinated water are expected to be added to the system when this infrastructure is operational (Junta de Andalucía, 2022b, 2023g).

Lastly, and probably a fundamental measure, has been the initial agreement to create a "Community of Groundwater Users" (*Comunidad de Usuarios de Aguas Subterráneas*) that will bring together representatives from the three main groups of groundwater users in the basin: the two "second order associations" that represent the irrigators from the right and left banks of the Guaro River (i.e., the main irrigator communities in the region), and Axaragua (the confederation of local public supply operators and municipalities). The Regional Government of Andalusia has stated that this initial agreement needs to be fully developed before desalinated water can come into operation.

4. Discussion

4.1. Insights from the application of the DPSIR framework to the case study

As described in the previous sections, the process of water closure in Axarquia shows a typical trajectory where increased supply (the coming into operation of La Viñuela reservoir at the end of the 1990s) has not been able to meet the growing demand caused by the confluence of high population growth, greater influx of tourists and seasonal residents, and a more than two-fold increase of the area cultivated with water-intensive subtropical crops. These factors, combined with a water infrastructure maintenance deficit and a long drought, have led to a severe shortage of freshwater and extremely low levels in the only reservoir of the region.

Responses to this state of resources have come from both the private and public sector. The private sector is implementing measures that include further investments in precision irrigation technology as well as the application of deficit irrigation, radical pruning, and crop uprooting practices. The public sector authorities, on the other hand, are implementing measures to address the water scarcity crisis, most notably through a significant increase of non-conventional water supply (currently through reclaimed wastewater, and desalination infrastructure planned to be deployed soon), but it is unclear if these measures will succeed unless further expansion of demand is controlled (Fig. 3).

The case of Axarquia is not an isolated one as several instances exist of basins that have experienced significant pressures related to water management, including basin closure to varying degrees. In these cases, factors such as extensive agricultural irrigation, high industrial water usage, and increasing urbanization have contributed to substantial flow reduction or even the complete cessation of flow in certain sections of the rivers, particularly during dry seasons. Some of these examples include the Murray-Darling Basin in Australia, the Macta River basin in Algeria, the Krishna River in India, the Yellow River in China, the Indus River in South Asia, and the Colorado River in the United States (Kherbache and Molle, 2023; Molle et al., 2010; Pittock, 2019; Venot et al., 2007).

Several studies anticipate that the pressure on basins will continue to grow as global water consumption by the agricultural sector is expected to undergo a substantial rise in the coming decades. For instance, in a scenario where there are no enhancements in land and water productivity or significant shifts in production patterns, the volume of water utilized by crops is projected to grow by 70–90 % in the next four decades, from 71,300 hm^3 consumed in 2007 to 120,500–135,000 hm^3 in 2050, contingent upon actual population and income growth, as well as assumptions concerning the water requirements of livestock and fisheries (de Fraiture et al., 2007).

The substantial implications that basin closure has for water management, allocation, and the environment makes it imperative to scrutinize the underlying reasons behind the excessive development of catchments. Catchment closure is fundamentally a consequence of human activity, whereby the overdevelopment of river basins extends beyond the prioritization of water supply strategies, overlooking

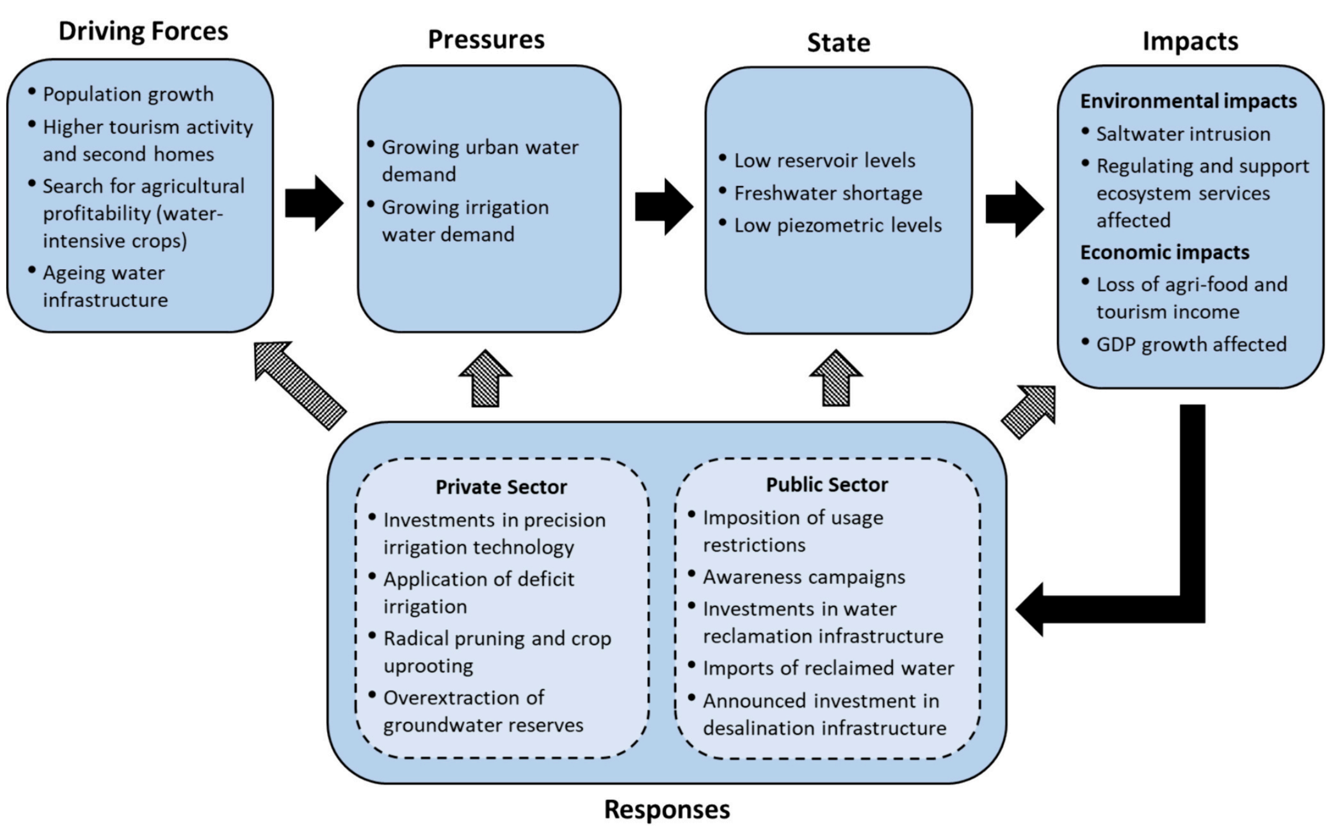

Fig. 3. DPSIR framework for the closure of water resources in Axarquia (1998–2023).

demand management approaches and environmental concerns, which often entails the construction of infrastructure that surpasses available water resources and the resilience of ecosystems (Molle et al., 2010).

In Axarquia, one of the key factors acting as a barrier for the solution of the water closure state is the chronic structural imbalance that exists between water supply and demand in the region, which is due mainly to the important role that highly profitable water-intensive crops have acquired in the local economy and is compounded by the growing demand from increasing tourist activity and a larger population. As shown in Table 3, this condition can be traced back to at least 1998, when the first hydrological plan for the region was developed. Back then, total water demand was 83 hm^3 but the available resources were 12 hm^3 shorter, which was made up by a combination of 9 hm^3 of undersupply for irrigation, and 3 hm^3 of overexploitation of the Vélez River aquifer (Junta de Andalucía, 1999). Furthermore, although it was finished in 1989, La Viñuela reservoir was not fully operational until after 1998 due to the lack of the canals and pipelines required to connect it to the system. Until then, water demand in subsystem II-1 of DHCMA was met through a combination of extractions from aquifers (67.6 %) and stream flows (32.4 %) (Table 3). The connection of the reservoir to the system was also seen by the authorities as being pivotal to eliminate barriers for tourism development in the coastal zones of the DHCMA (Junta de Andalucía, 1999).

The coming into operation of La Viñuela reservoir in the late 1990s brought about some relief to the region's aquifers as (planned) groundwater extractions fell 33 %, from 48 hm^3 in 1998 to under 32 hm^3 in 2009 and 2015. However, the estimated deficit between supply and the growing demand for urban and agricultural use still reached 9.74 hm^3 (15.3 %) in 2009 and 14.38 hm^3 (20.3 %) in 2015 (Table 3). Since water supply for urban needs takes precedence over other uses, these deficits have been absorbed by the region's farmers, either through the over-abstraction of aquifers or deficit irrigated crops.

Table 3 also shows the Regional Government of Andalusia's attempts to balance demand and supply through the DHCMA's Hydrological Plan 2015–2021 and 2022–2027 (Junta de Andalucía, 2016, 2023d). For the period 2022–2027, the authorities have planned to reduce aquifer extractions from 55.95 hm^3 in 2021 to 33.27 hm^3 by 2027 through the introduction of reclaimed wastewater and desalinated water (Junta de Andalucía, 2023d). However, the combination of structurally high demand with the prolonged drought is making this goal virtually impossible to achieve as the region's only reservoir has remained below 50 % of its capacity since February 2016 and ended 2023 sitting at only 12 hm^3 (7.4 %) (Junta de Andalucía, 2024b). Furthermore, the importance of the reservoir to meet urban needs and the overall supply-demand balance cannot be understated. In 2021, 47.6 % (11.38 hm^3) of the 23.89 hm^3 destined to urban use was withdrawn from La Viñuela and 48 % (11.47 hm^3) from aquifers, with the remaining 4.4 % (1.05 hm^3) made up by surface water from stream flows (Junta de Andalucía, 2023d).

Table 3
Water balance in subsystem II-1 of DHCMA (1998–2027).

	1998(1)	2009(1)	2015(1)	2021(2)	2027(2)
Resources (hm^3)					
Surface water					
Reservoir	0.00	37.40	37.29	32.18	34.46
Stream flows	23.00	9.24	9.23	15.07	11.40
Groundwater	48.00	31.13	31.56	55.95	33.27
Regenerated	0.00	0.17	0.17	0.28	14.07
Desalinated	0.00	0.00	0.00	0.00	12.28
Transfers	0.00	−0.01	−0.01	0.00	0.00
TOTAL	71.00	77.93	78.24	103.48	105.48
Demand (hm^3)					
Urban	19.00	23.03	23.35	23.89	23.04
Irrigation	64.00	63.64	68.28	78.40	79.20
Industry	0.00	0.00	0.00	0.20	0.20
Golf	0.00	0.82	0.82	0.82	2.87
Livestock	0.00	0.17	0.18	0.17	0.17
TOTAL	83.00	87.67	92.62	103.48	105.48

(1) Estimated and (2) target in the Hydrological Plans (1st, 2nd and 3rd cycle). Source: Own elaboration based on data from Junta de Andalucía (1999, 2012, 2016, 2023d).

According to the Regional Government of Andalusia, up to 22.5 hm^3/year of reclaimed water are expected to be part of the system in 2024 (Junta de Andalucía, 2023f), thus exceeding the 14.07 hm^3/year originally planned for 2022–2027 (Table 3). In addition, if the current extreme drought continues, the deployment of a mobile desalination plant that would provide between 4 and 5 hm^3/year by 2025 is foreseen as an emergency solution (Junta de Andalucía, 2023e). Under the current basin closure conditions, the increasing supply of unconventional water is certainly bringing some relief to the system, but it is unlikely to provide a lasting structural solution for the problem when the drought is over.

Water demand for irrigation of subtropical crops is the highest source of pressure in the system due to the significant expansion that the cultivation of avocado and mango experienced in the past two decades, which has led these crops to account today for about 76 % of all water resources required for irrigation (Table 2). Furthermore, based on the data shown in Section 3.2 and Table 3, the annual water shortage for irrigation is estimated to be between 17 and 32 hm^3, a condition that is severely affecting crop productivity and overall profitability in the region's agricultural sector, and consequently forcing the economic development authorities to look for solutions.

The increasing supply of unconventional resources will therefore help address some of the issues faced by Axarquia in the short term, but the mounting pressures are expected to continue hampering the solution of the structural water scarcity problem. Firstly, the variability in reclaimed water quality introduces uncertainties in its usability for agriculture due to the potential presence of residual contaminants, such as salts, nutrients, heavy metals, or trace chemicals, which can adversely affect soil health and crop productivity over time. Managing and monitoring the quality of reclaimed wastewater requires stringent regulatory frameworks, analytical and technical expertise in WWTPs and farms, and continuous investments in water treatment and monitoring technologies to ensure that the quality of water is always adequate. Secondly, the infrastructure required for the distribution and delivery of reclaimed water to agricultural areas also poses an important barrier. Retrofitting existing irrigation systems or establishing new transportation and storage networks demands investments in infrastructure development. Lastly, and perhaps most importantly, the high profitability of subtropical crops makes the higher costs of water reclamation and desalination unlikely to deter the growing demand for irrigation. This contrasts with the case of traditional crops, where higher water-related costs significantly affect their economic viability.

On the other hand, urban water demand pressures are also unlikely to abate. Officials in water-scarce tourist regions like Axarquia face a delicate balance between sustaining the economic benefits of tourism and second homes and implementing necessary conservation measures. Predictably, they may hesitate to impose stringent water restrictions, fearing potential backlash from resident voters who might resist such measures when it directly affects potential income opportunities as well as their own daily lives. Nevertheless, a study recently conducted by Malaga's provincial government detected very high levels of water distribution network losses in small municipalities (30 % in average, with some municipalities reaching around 50 %), which indicates that substantial investments are required in the upgrading of urban networks. Thus, a political challenge arises from the delicate task of reconciling short-term benefits with the long-term imperative of water conservation.

4.2. DPSIR framework to support water governance

Originally developed for the identification of environmental indicators and to assist in the formulation and implementation of environmental policy, the DPSIR framework has also become a useful interdisciplinary tool for communication between researchers, policy makers, and stakeholders (Svarstad et al., 2008; Tscherning et al., 2012). In the water sector, it has been widely used to evaluate and support the implementation of the European Union's Water Framework Directive in Greece (Apostolaki et al., 2019), Spain (Berbel et al., 2013; Borja et al., 2006; Expósito and Berbel, 2017b), England and Wales (Henriques et al., 2015), and France (Lalande et al., 2014), among many others, and its application has extended to other parts of the world (Gari et al., 2018; Kosamu et al., 2022; Sun et al., 2016; Zhang et al., 2023). Furthermore, some extensions have been proposed beyond the traditional framework. For example, Vannevel (2018) proposed its integration with a broader conceptual model governance (Governance by Actor-Subject Impact Assessment), Zhang et al. (2023) have integrated it with water resources carrying capacity (WRCC) modelling to enhance the special applicability of the framework, Malmir et al. (2021) show an interesting application of DPSIR in conjunction with the MODFLOW model to determine the effectiveness of aquifer restoration responses, and Tsitsis et al. (2023) have combined it with artificial neural network to evaluate a Mediterranean lake.

In this study, we have demonstrated that the DPSIR framework is a useful tool to understand the dynamics of socio-hydrological systems and to support the design of public and private responses that avoid perverse effects that could eliminate in the long term the gains obtained in the short term. In this regard, it has been pointed out that the DPSIR framework has some limitations, perhaps most importantly that its simplicity suggests that the dynamics of complex systems don't change over time, and that causal chains are linear and unidirectional (Carr et al., 2009). However, a thorough review conducted by Gari et al. (2015) on the merits and limitations of the framework concluded that it is a valuable instrument that has succeeded in its task, but its use for the design and implementation of policies requires the application of complementary approaches to gain a thorough knowledge of the system. Likewise, Tscherning et al. (2012) concluded that the DPSIR framework is an effective approach for the structuration of data and suggested that the participatory integration of stakeholders would be required for the incorporation of knowledge from various sources into conceptual models reflecting multiple cause-effect relationships. Accordingly, further to the work presented in this case study, our team has designed system maps through participatory modelling, and is developing hydro-economic models, building a database, and conducting analyses of wastewater reclamation costs with the objective of contributing to the design of policies for the improvement of long-term sustainability and governance in the region.

Preliminary results from our ongoing analysis suggest that pressures on Axarquia's basins are unlikely to abate. Instead, water scarcity is expected to worsen due to increasing demand from various sectors, climate change, and poor governance and monitoring. This could reduce water security, harm agricultural yields, negatively affect economic sectors like tourism, and impact the well-being of local populations. Ecosystems relying on these basins could also suffer, affecting biodiversity and disrupting food webs.

Paradoxically, supply increases promoted by government might induce new demand through the emergence of new irrigated areas and other economic uses of water, which could only be avoided through the enforcement of governance mechanisms designed to monitor and prevent a rebound effect. This is the approach being (currently) pursued by the Andalusian authorities through the establishment of a common governance structure that integrates all unconventional resources prior to the construction of a water desalination plant in the region. In addition to this new governance framework, it will be crucial to implement demand-side measures like raising social awareness on water-related issues, increasing water efficiency in urban and irrigation sectors, and imposing strict penalties for illegal groundwater extraction. Furthermore, economic tools such as water trading, insurance, and full cost recovery could incentivize efficient water use and encourage private sector investment in water-saving technologies. In sum, an effective regulatory and governance framework, community engagement, and technological innovation will be essential to address the challenges of declining water availability in these basins.

5. Conclusions

In this paper, we apply the DPSIR framework to analyse the enormous challenges that Axarquia faces to maintain the well-being of its population, with surface water scarcity and groundwater overexploitation (and potential degradation) posing major threats to sustainability in the region.

The process of water closure in Axarquia shows a typical trajectory where increased supply (the coming into operation of La Viñuela reservoir in the 1990s) has not been able to meet growing demand. This scenario is due mainly to a combination of population growth, higher tourism activity, and a more than two-fold increase of the area cultivated with water-intensive subtropical crops. The chronic structural water scarcity condition that affects the region has been compounded by the occurrence of a long and severe drought event that has driven its only reservoir to historically low levels as well as to low piezometric values in its main aquifer.

Axarquia's economic reliance on agriculture and tourism makes it especially vulnerable to water scarcity impacts across sectors. Declining water allotments for farmers are affecting incomes and threatening the viability of the region's vital irrigated crop exports. Groundwater reserves are also under stress from overexploitation to supplement scarce surface water, leading to an increase of the risk of salinization of coastal aquifers that would in turn inflict further damage to the agricultural sector. Furthermore, water shortages could threaten tourism activity if they start to degrade the natural landscapes and amenities that visitors expect, or if the authorities are forced to impose major limitations on usage.

The authorities' response to date has relied mainly on increasing unconventional water supply (currently through reclaimed wastewater, and desalination infrastructure planned to come soon). However, our findings indicate that a supply-side approach alone, neglecting demand control and effective governance mechanisms, is insufficient to solve the underlying structural imbalance between limited resources and unsustainable consumption. Likewise, strong governance measures that address issues such as water pricing, allocation, and monitoring are necessary to optimize the utilization of resources, prevent overexploitation, and ensure long-term sustainability (OECD, 2015). Future responses to the current water resources imbalance should consider not only past hydrological data and socioeconomic trends. They should adopt a comprehensive approach that includes a variety of climate projections and scenarios to enhance river basin management planning, incorporating these insights into water demand projections, water reuse plans, and the effects of climate change on various industries.

CRediT authorship contribution statement

Antonio R. Hurtado: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Esther Díaz-Cano:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julio Berbel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no competing interests.

Data availability

Data will be made available on request.

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