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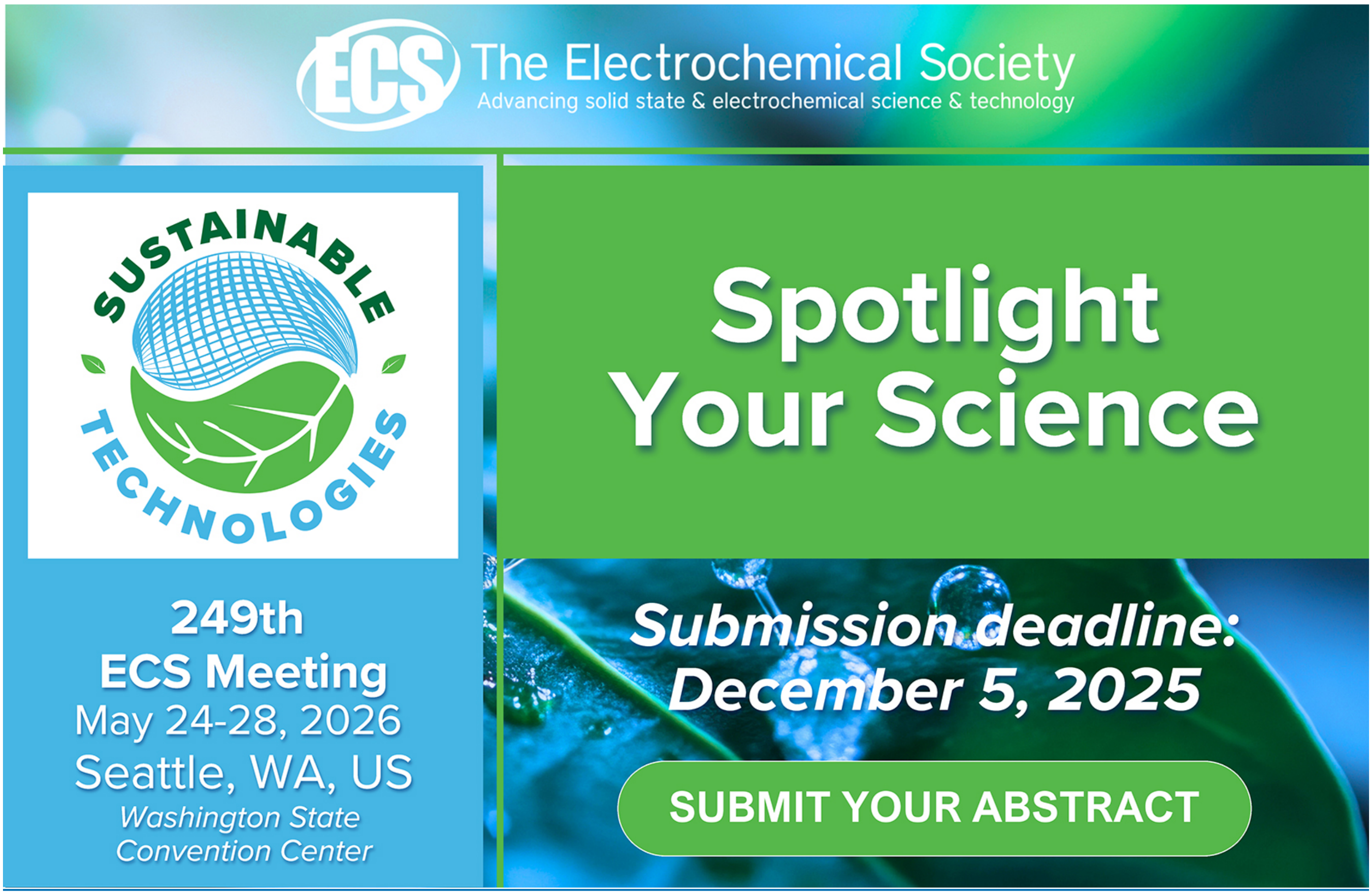

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LETTER

The co-evolution of collective groundwater management: understanding the interdependencies between user-based organizations, remote sensing and state agency support in the La Mancha Oriental Aquifer, Spain

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Abstract

Groundwater governance is a challenge in most arid and semi-arid areas of the world. In many aquifers, groundwater extraction exceeds natural recharge, leading to steady aquifer declines with negative consequences for the social, agricultural and ecological systems that depend on these aquifers. In this article we analyze how in the semi-arid the La Mancha Eastern Aquifer, Spain, organized groundwater users, in close collaboration with knowledge institutes and water authorities, have developed a governance system that ensures aquifer sustainability. Our analysis shows that the use of tempo-spatially explicit data generated through remote sensing technologies co-evolved with the development of a user-based groundwater management institution, and a state agency support framework into an effective co-governance approach for regulating groundwater use in the agricultural sector. This research highlights the importance of socio-technical co-creation for the establishment of effective groundwater governance systems that build on, and are embedded in, user-based organizations that are supported by an enabling institutional environment.

1. Introduction: groundwater co-management and its challenges

Confronted with severe aquifer depletion and to prevent it, around the world, state agencies have developed mechanisms to regulate and control groundwater extractions (Kuper *et al* 2016, Hoogesteger 2018, Molle and Closas 2020a, Wang *et al* 2021). These mechanisms aim to keep or reduce groundwater extraction to levels that ensure the long-term sustainability of aquifer use for human populations and environments. Common mechanisms include closing down illegal wells and establishing drilling bans, pumping quotas, crop prohibitions and penalties for illegal practices (Closas *et al* 2017, Novo *et al* 2015, Molle and Closas 2021). Other mechanisms are based on disincentives such as water and energy pricing (Mukherji 2006, Allen and Smith 2023). These mechanisms are mostly implemented by state agencies.

To complement state regulation, user-based groundwater management, also referred to as self-regulation or local-level governance, has been promoted internationally since at least the early 2000's (Schlager and López-Gunn 2006, Rouillard *et al* 2021, Meinzen-Dick and Bruns 2024). Much in line with the seminal work of (Ostrom 1990, see also Molle and Closas 2020b) we identify the following key aspects that determine the effectiveness of user-based groundwater management arrangements: First, a manageable number of groundwater users (a few hundred and up to a thousand). Second, trust and reciprocity among users, as the basis for developing social and human capital (López-Gunn 2012, Wijnen *et al* 2012, Curtis *et al* 2016). Other important factors are: a credible threat or opportunity that propels users to collaborate (Closas *et al* 2017); 'accountability mechanisms; transparency with regard to the rationale behind the measures; the distribution of costs and benefits; the data/models used to devise the measures; and legal empowerment of the organization' (Hoogesteger 2022, p 3). The legal mandate of user-based organizations and their embedding in, and collaboration with, broader institutional frameworks are crucial. It ensures that groundwater users perceive the advantages and/or needs of being a member of the groundwater-users organization. The latter have to be accountable and transparent to both their constituency (users) as well as vis-à-vis state agencies (see Ostrom 1990).

One of the great challenges that both state agencies as well as groundwater user associations repeatedly face in the implementation of measures to regulate groundwater use is the availability of data about *by whom, where* and *when* groundwater is used. Establishing a groundwater use monitoring system has proven to be, in most aquifers, a big challenge. The latter is related to the dispersed and individualistic character of pumping technologies, the high number of wells active in aquifers, and the 'fragility' of water meters as a reliable tool to measure groundwater extraction and use (Llamas and Martínez-Santos 2005, Curtis *et al* 2016, Rinaudo *et al* 2019). Around the world, water users tamper with meters to show lower water consumption, or meters are skillfully made dysfunctional or bypassed. At the same time, most water agencies lack personnel to control meters regularly and users self-reporting are a rarity (Hoogesteger and Wester 2017). There is, however, a growing consensus that accurate, accessible, and shared information about groundwater use is paramount for establishing aquifer governance mechanisms (Stone 2019, Sharples *et al* 2020, Saidani *et al* 2023, Sanchis-Ibor *et al* 2023).

For monitoring agricultural (ground) water use, remote sensing (RS) data has been utilized for decades (Bastiaanssen *et al* 2000, Bea *et al* 2014). One of the great advantages of RS derived data is that it is spatially and temporally explicit, allowing for the identification of when and where different crops are being grown. Overlaying this data with land ownership data enables us to identify whose crops these are (Hartman *et al* 2022). In arid and semi-arid regions, where some of the cropping seasons are almost entirely dependent on irrigation, crop type and cropping area are a good proxy to estimate groundwater use. This allows for accurate approximations of groundwater use per user in temporally as well as spatially (visually) explicit ways. However, research has also shown that often RS data is initially not understood and accepted as 'objective' and neutral by all users. There is often mistrust in its accuracy (especially when it is translated to water use), especially as it often comes with the threat of external control. Therefore, to be able to use RS data (or any other enhanced information system increasing transparency) for co-management, it is necessary that users get familiarized with, understand and trust the data and its use (López-Gunn *et al* 2024, Shalsi *et al* 2019).

In Spain, groundwater management has generated numerous environmental and socio-political problems and in many cases state action has been insufficient or ineffective (see De Stefano *et al* 2015, Closas *et al* 2017, Green *et al* 2024). One of the few success stories has been that of the La Mancha Oriental Aquifer (MOA), where effective aquifer co-management has been developed with the support of RS data and related monitoring tools. Several works have focused on describing the technological performance of this monitoring system, at its initial stage (Martín de Santa Olalla *et al* 1999, 2003) and more recently (Calera *et al* 2017). In this contribution, we explore how the use of data derived from RS technologies co-evolved and became the cornerstone of a user-based co-management system that has led to aquifer stabilization. As Kallis and Norgaard (2010) point out, in social and natural systems, different elements affect the evolution of each other in both direct and diffuse ways. Though such co-evolution is all pervasive, for analytical purposes it is important to identify 'what is coevolving with what and how in specific conditions or contexts' (idem, p 691). This article focuses on the fruitful co-evolution of the MOA user-based aquifer management association with an RS-based tool to monitor agricultural groundwater use.

This research is based on qualitative research methodologies. Departing from our first contact with staff from the Universidad Castilla–La Mancha, we followed a purposive snowball sampling methodology (Kumar 1999) of key informants engaged in the development and current functioning of the co-management of the aquifer. Between December 2021 and May 2022, and in June 2023, we interviewed farmers, staff members and managers of the groundwater users organization, personnel of the local river basin authority and researchers at the Universidad Castilla–La Mancha (21 interviews). Interviews were audio-recorded and/or interview notes were made and coded; then the information was triangulated to ensure validity and comprehensiveness. We also build on the experience of the co-authors who have been directly involved in the development of the RS tools;

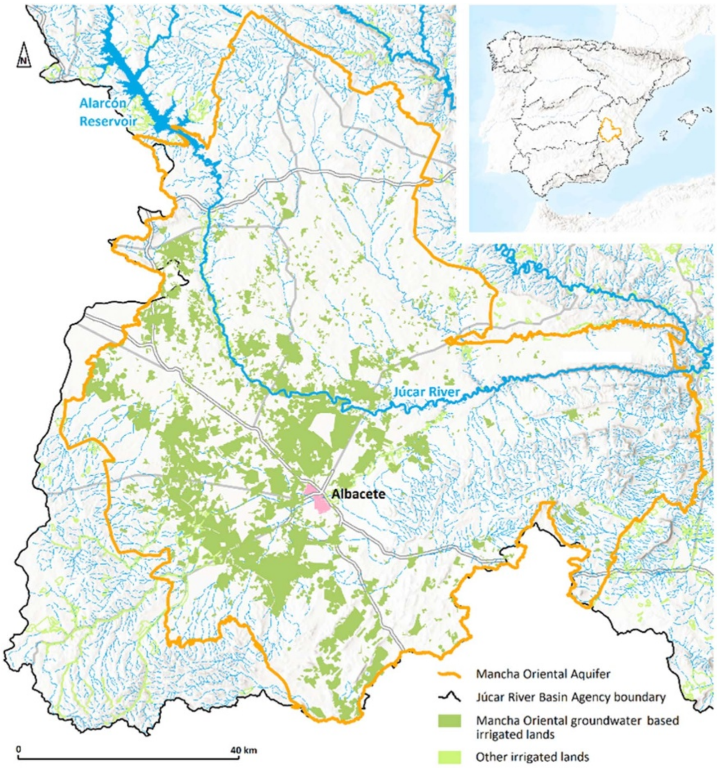

Figure 1. Location of the La Mancha Oriental Aquifer and boundaries of the Jucar River Basin Agency (CHJ) (own elaboration).

and on the data that was shared with us and is freely available from the involved institutions.

2. The rise of the *Junta Central de Regantes de la Mancha Oriental* (JCRMO)

Central East Spain contains one of the biggest aquifers in the country; MOA (Sanz *et al* 2011). It is situated in the upstream part of the Júcar river basin, under the La Mancha plain (figure 1). With a size of approximately 10.000 km^2, it serves up to 125.000 ha of irrigated land, via 10.000 wells (Calera *et al* 2017). The main cultivated crops in MOA are cereals (barley, wheat and corn), fruit and nut trees (almonds, pistachio, and vineyards) and vegetables (onion, garlic, and lettuce) (JCRMO 2024). The droughts of the 1990s, and the reduced base flows from MOA to the Jucar River, led the river basin authority *Confederación Hidrográfica del Júcar* (CHJ) to put pressure on groundwater irrigators to curb down water use. To prevent direct state intervention (sanctions), keep control in their hands and to defend their interests, groundwater users created the JCRMO, in close collaboration with the CHJ, in October 1994 (formally registered in 1995). The main aim of JCRMO was to bring groundwater users together to find ways to collectively manage the aquifer. In 2023, 10 000 farmers belonged to JCRMO, 1,858 as individual members, and the rest of them, represented by 178 water users' associations (constituted as *Sociedades Agrarias de Transformación* or *Comunidades de Regantes*). Public water suppliers and industrial users are also members. JCRMO is structured through a general assembly, the daily board, a technical department, and an irrigation jury. Because the yearly permits (*visados)* to abstract groundwater are only issued by CHJ through JCRMO, every groundwater user in MOA is necessarily a member. This embedding of JCRMO in the state agency's water allocation system, which has been legally warranted since 1998, has been crucial for its development and legitimacy vis-à-vis groundwater users. The Hydrological Plan of the Jucar Basin (CHJ 1997), legally ratified in 1998, established that all groundwater users of MOA had to register through a single organization: the JCRMO. In 2008, regulations also required all surface water users in MOA to become members of JCRMO to access water permits. These provisions also delegated to JCRMO the power to monitor and control (ground) water use, and to sanction its members. For the latter, the irrigation jury was instituted as a user based jury that operates with elected members.

The general assembly (all members are invited) is the highest organ of JCRMO. It has two yearly meetings, one before the end of March and one after the harvest, usually at the end of October. The assembly has the right to vote for new members of the daily board and the irrigation jury, on financial statements, and for the JCRMO annual exploitation plan (AEP).

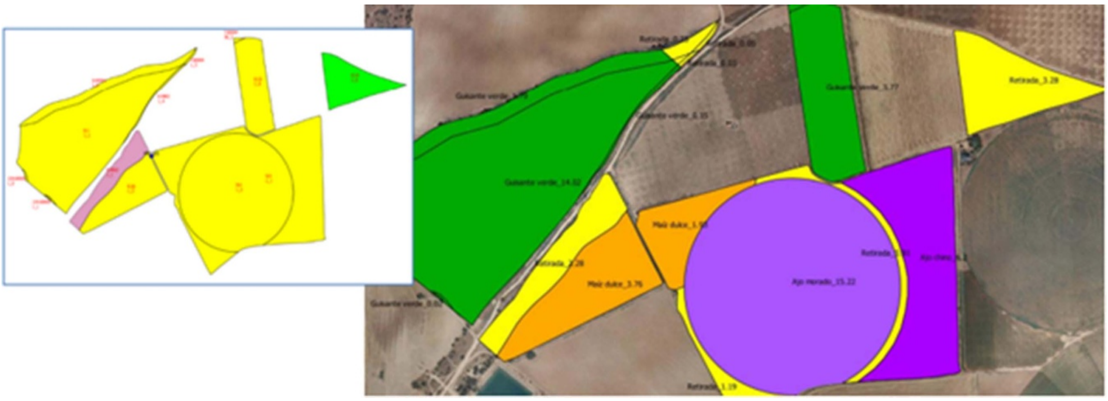

Figure 2. Example of an GIS file of a WMU with and without a cultivation plan in MOA.

AEP includes the total water volume that can be collectively pumped from MOA (established by CHJ based on its aquifer recharge computations and distributed proportionally among agricultural groundwater users with a permit), and the values that will be used that year to determine the theoretical water consumption per crop (established independently by the local Irrigation Advisory Service, ITAP).

3. From AEP to farmers cultivation plans

Based on good relations between JCRMO members, CHJ and the *Universidad de Castilla-La Mancha* (UCLM) started to explore the use geographical information systems (GISs) and RS to map the groundwater irrigated area as well as the crops grown in MOA since 1996. Since 1997, a tool has been developed and implemented by JCRMO to monitor the annual groundwater use per water management unit (WMU). Its development was premised on; a) funding and collaboration through yearly agreements, called the ERMOT agreements, established between JCRMO, CHJ, Universidad Castilla-La Mancha and a private RS company; and b) European Union research funds and collaborative networks. This tool is called the SpiderWebGIS tool. By 2000, the tool was validated by JCRMO and CHJ as an officially recognized tool to compute and monitor annual net theoretical crop irrigation requirements per registered WMU.

The development of JCRMO as the groundwater use control and monitoring entity went hand in hand (co-evolved) with the development and institutionalization of the SpiderWebGis tool. The latter enabled the former through the generation of reliable and transparent groundwater use data. Its use legitimized JCRMO, the procedures it had established for monitoring, and its sanctioning mechanisms through the irrigation jury. This recognition and legitimacy was further strengthened in 2012 by the Spanish Supreme Court ruling that established that RS data could be used as evidence in court.

The tool functions as follows. At JCRMO, all the production units (farmers) and their operations have been registered as WMUs. Each WMU is verified and checked based on official land tenure documents, maps of land registry, water use concessions from CHJ, well registries, interviews with farmers, and field visits. This data is stored and updated in a GIS managed by JCRMO technicians, enabling them to couple data obtained from RS to WMU's yearly cultivation plans and water use rights (see figure 2).

Based on AEP, every year, before March 31st, individual farmers submit their yearly cultivation plans per WMU to JCRMO. These plans specify which crops will be planted where, when, and covering which area. These have to comply with the guidelines established in the yearly AEP, and theoretical net water use cannot exceed WMU's water allocation for that specific year. There is also the possibility of handing in a cultivation plan for two or three years, which creates an opportunity for the farm to use more water in one year than their annual allowance. Farmers who do this have to hand in their WMU cultivation plan before December 31st of the next growing season. It is not allowed during this two- or three-year period to make changes that lead to increased water use. Once these plans are made and submitted to JCRMO, the latter checks whether these fit within the guidelines of AEP and the resulting theoretical water use of the plan. This is calculated based on planned crop(s) type, area(s) cropped and the reference water use per crop as established by ITAP and ratified in the AEP that was approved at the JCRMO General Assembly of the previous October. If these comply, they are approved. If not, they are discussed with the farmers who have to adapt them. Once cultivation plans for each WMU are approved, these are also monitored as explained below.

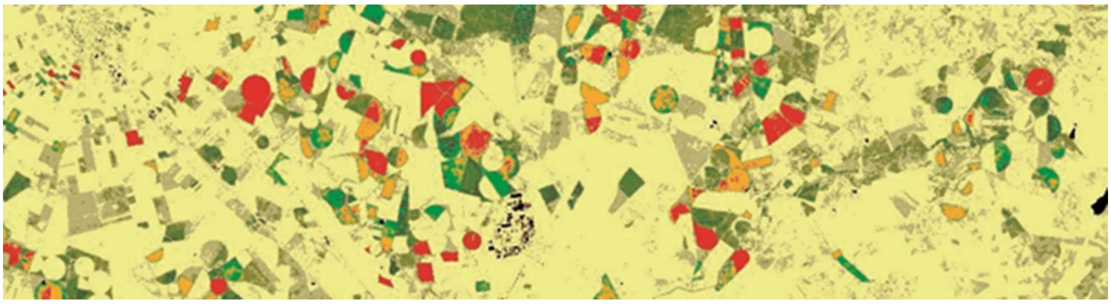

Figure 3. RS map with NDVI layer by the SpiderWebGIS tool. The greener the color, the higher the NDVI value at a specific date.

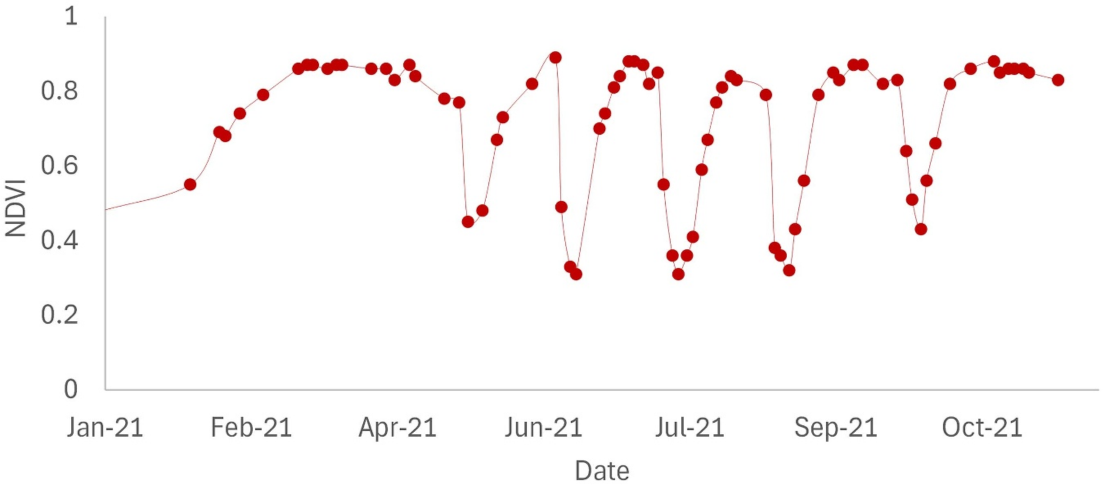

Figure 4. Graph of NDVI values over the period January—November 2021 for one point in one plot.

4. Monitoring AEP with the use of RS data

JCRMO technical staff monitor the implementation of the yearly cultivation plans of each WMU with SpiderWebGIS. SpiderWebGIS uses a multitemporal and multispectral approach by using satellite imagery data from the Landsat 8 and Sentinel 2A&B orbits, which both have a spatial resolution of 10 by 10 meters (100 m^2). The Landsat orbit uses the operational land imager (OLI) and the thermal infrared sensor (TIRS) instruments, the sentinels use multispectral instruments (MSI) which are used to determine the normalized difference vegetation index (NDVI). SpiderWebGIS uses NDVI to distinguish what crops are produced, with what vegetation density, how healthy these plants are, where and when (Meneses-Tovar 2011). Figure 3 shows a map with a NDVI layer of irrigated plots in MOA.

For the monitoring of AEP regulations, NDVI values are controlled over time with an interval of at least once every five days for every plot. Based on this an NDVI fingerprint is made for each plot. This fingerprint allows technical staff to identify which crop is being produced (each crop has a distinct fingerprint), in which plot, and in which time period (figure 4). Harvesting moments are also identified. The date range is adjustable, and it is possible to extract an Excel-file with specific NDVI values per date.

Figure 5 shows how SpiderWebGIS is used to identify different crop categories based on their NDVI fingerprints. The next step in the monitoring of JCRMO regulations, is to get an overview of every crop and the number of hectares per crop within a WMU. After that, the total actual theoretical water consumption demand per WMU is determined and compared to the plan submitted in March.

Before using the RS methods to keep track of groundwater use in MOA, *in-situ* flow meters were used for monitoring. This is still an option for farmers but it is rarely used because, as interviewed farmers indicate, ITAP reference values coupled to RS monitoring gives them more flexibility in water use as it is based on theoretical water use values per crop. This is

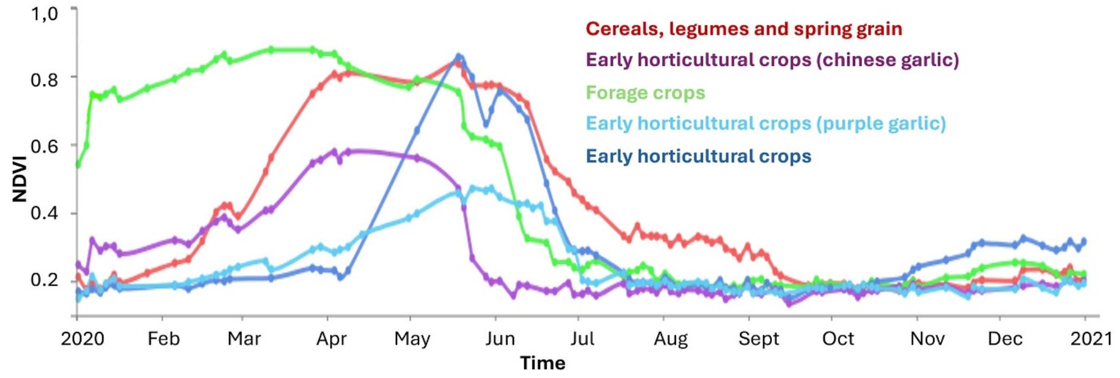

Figure 5. Standard NDVI graphs/fingerprints for the most cultivated annual crops in MOA (Calera and González-Piqueras 2022).

especially important for farmers in very dry and hot years. Another reason that most of the farmers are not in favor of this method is because they have to hand in their cultivation plan before December 31st if they want to make use of this option.

5. Sanctioning WMUs that exceed their yearly water allocation

When technical staff identify, with SpiderWebGIS, that a WMU exceeds its yearly water rights, the case is passed to the irrigation jury of JCRMO. The jury is composed of elected water users who are supported by technical staff. If a farm does not hand in their WMU cultivation plan on time, or it seems that there is information missing in the plan, JCRMO contacts the farmer by telephone and/or email and asks for this information. If this information is not provided the technical department informs the irrigation jury which can decide to sanction the farmer, based on how much information is missing and how long it takes for the farm to deliver the requested information.

If a WMU's actual crop cultivation differs from the handed in cultivation plan, which leads to higher groundwater use, JCRMO technical staff invite the farmer to give an explanation. This explanation can be given by telephone, at the JCRMO office and/or with a field visit of JCRMO staff, depending on the situation. If the actual cultivated crops differ from the cultivation plan, but the total WMU's water rights are not exceeded, these are adjusted in the JCRMO databases, but no sanction is given. If the water rights are exceeded, the farm responsible is asked to come to the JCRMO irrigation jury. Here, the JCRMO's technical staff present the evidence showing that the WMU uses more water than allowed. The evidence is in most cases a combination of the outcomes of the SpiderWebGIS tool with NDVI graphs of the farm's plots, QGis files of the farms plots boundaries, photos from field visits where you can see the cultivated crops, and information on the irrigation water requirements per crop for that year. Farmers can defend themselves by providing information showing that they did not exceed their water rights. However, the use of NDVI data coupled to crop fingerprints and the SpiderWebGIS has proven to be a very reliable technology to monitor groundwater use; and therefore one that is seldomly challenged by water users.

When the jury concludes that the water rights, as established in AEP are exceeded, it gives a double sanction consisting of: (a) a monetary fine, and (b) a reduction in water rights for next year. The monetary fines range from 600 Euros for mild exceedances, 6.000 Euros for severe exceedances, and up to 80.000 Euros for very severe exceedances (see figure 6 for sanctions imposed). Reduction of water rights for the next season are established by calculating a percentage equal to that with which they exceeded their water rights, plus an additional 10% of this percentage (e.g. a WMU has 100.000 m^3 of water rights, they exceed with 10.000 m^3 in 2022, then in 2023 they will only have (100.000–11.000 =) 89.000 m^3 of water rights).

When groundwater users do not accept JCRMO's sanctions, the CHJ *Comisaría de Aguas* (CdA) takes the case over with much harsher sanctions (from up to 10.000 Euros for mild exceedances, between 10.000–500.000 Euros for severe exceedances, and 500.000 and 1.000.000 Euros for very severe exceedances (JCRMO 2021, p 35)). CHJ can also charge 0,12 euros per m^3 of excess, to account for damages to the public water domain (JCRMO 2021, p 35). CHJ can if necessary take the users to court, but so far this has not happened. CHJ receives very few cases.

The evolution of the disciplinary procedures of JCRMO over the last 23 years shows a learning process. Over time both JCRMO staff as well as the

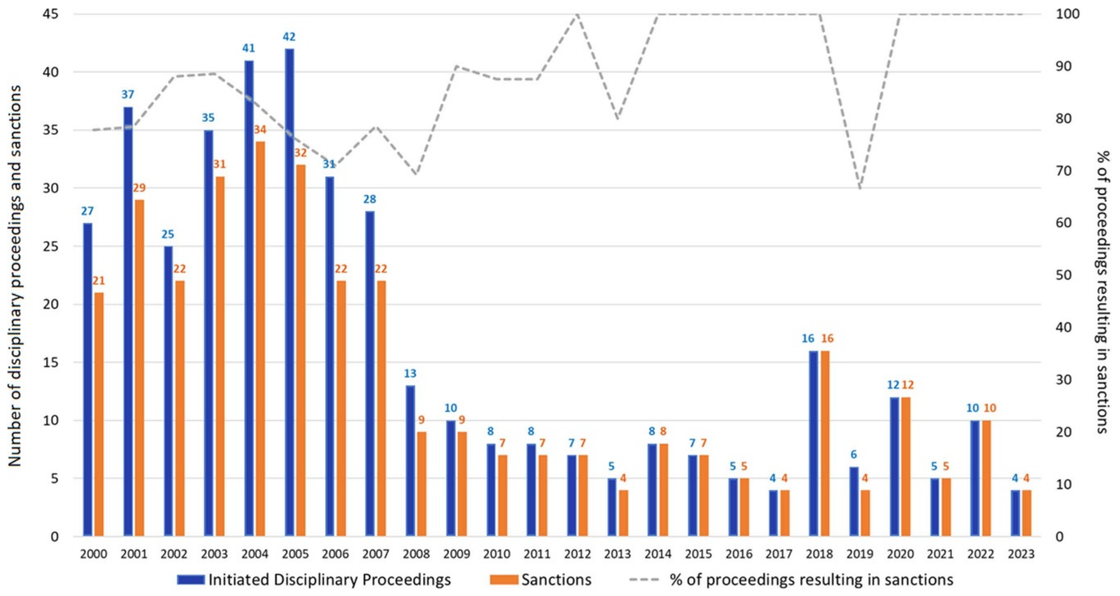

Figure 6. Disciplinary proceedings and sanctions imposed by JCRMO (own elaboration based on JCRMO annual reports).

users have come to trust the data used and generated by SpiderWebGIS to monitor cropping calendars and its translation to water use volumes. An important aspect that technical staff indicated is that over time users learned, sometimes by challenging the decisions of JCRMO, that SpiderWebGIS is very accurate and transparent. Field visits and on-the-ground other visual material that staff collect and corroborate with users when in doubt, has played an important role in the development of trust, not only in the data and tool, but also importantly, in JCRMO staff, the irrigation jury, and the JCRMO institutionally. Its credibility and legitimacy has led users to try to avoid breaching the rules (figure 6). As put by a technician: 'they have learned that they cannot fool the system'. Most interviewees also stressed the importance of irrigators being judged by fellow (elected) irrigators in the irrigation jury, based on a normative system that the users themselves have established in the general assembly. At the same time, most interviewees also showed great pride and confidence in the co-governance system which they have collectively developed and institutionalized over the years. This shows the high levels of acceptance, legitimacy and trust that has grown over the years in the system and its different components, something that is also reflected in a lower level of infractions.

The volume of water affected by sanctions peaked at 7.03 hm^3 in 2002, but it has remained below 0.6 hm^3 since 2008. This proves the effectiveness of 'credible threats' and of proportionate sanction mechanisms as key elements to induce responsible groundwater use through collective management. This has been a mutual learning process, as over time not only the number of infringements have reduced, but also the proportion of cases that end in sanctions.

6. Achievements and challenges

The self-monitoring and related management system developed in MOA has controlled groundwater extractions. Figure 7 shows a clear decrease in agricultural groundwater use with a very sharp drop from 2007 onwards. The average water use for the period 2000–2006 was 380 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$, while between 2007 and 2023, it was 296 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$. The implementation of this RS control system has been key, as shown by the parallelism between the decrease in groundwater use and penalties (figures 6 and 7). However, there have been other factors that have facilitated the decline in groundwater abstractions: (1) the incorporation, since 2001, of surface water from the Jucar River (supplemented with water from the Tajo-Segura transfer system) to replace groundwater use (up to 35 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$) (figure 7); and, (2) the use of economic incentives to reduce groundwater use by not cultivating crops in 2007 and 2008 (see Sanz *et al* 2019). These actions (Public Offers of Acquisition of Rights, Spanish acronym OPAD), regulated by the Water Law, made it possible to purchase from farmers 27.3 hm^3 of groundwater rights in 2007 (at 0.19 € m^{-3}), and 50.6 hm^3 in 2008, (at 0.25 € m^{-3}) (Ferrer and Garijo 2013, Palomo-Hierro and Gómez-Limón 2016).

This has resulted in a stabilization of the aquifer. While between 1995 and 2010 there was a generalized decrease in piezometric levels, between 2010

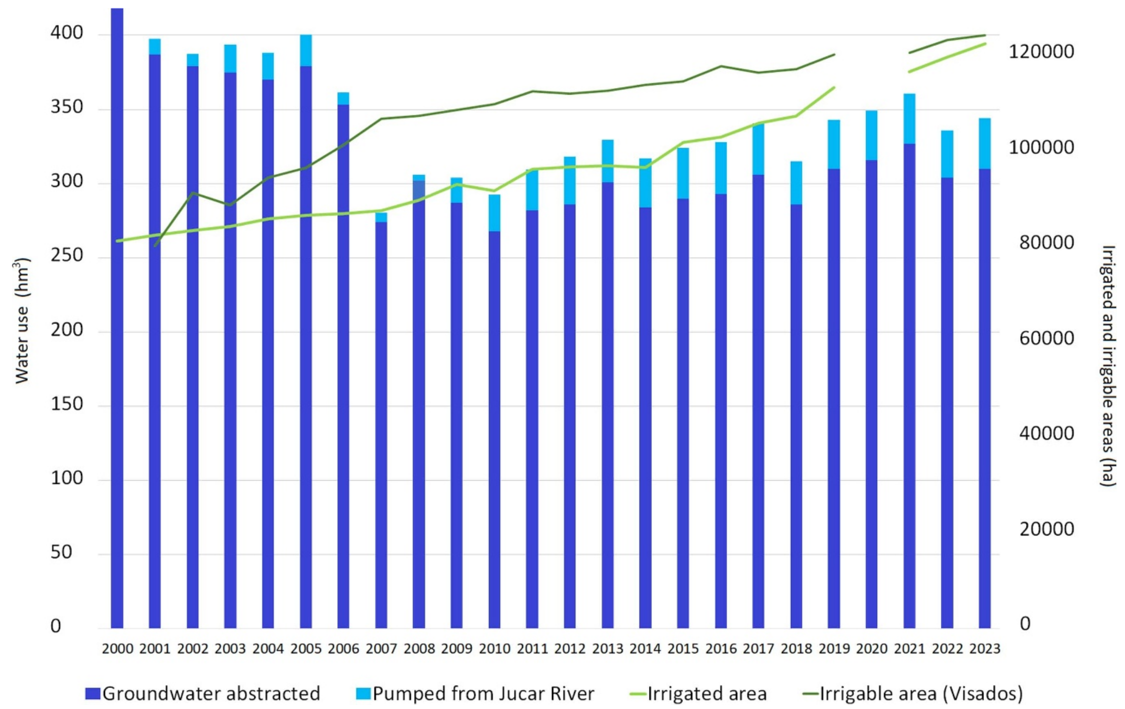

Figure 7. Groundwater abstractions and substitutive resources pumped from Jucar River compared to the irrigable and irrigated area (own elaboration based on JCRMO annual reports).

and 2023 the behavior is stable (Gómez-Hernández *et al* 2023, JCRMO 2024). Renewable resources have been estimated at 320 $hm^3\ yr^{-1}$, and CHJ set a target of extractions of 300 hm^3 for 2021. It has established a target of 275 hm^3 for 2027. This target is conditional on an increase in pumping from the Júcar river, which could replace extractions up to a maximum of 80 $hm^3\ yr^{-1}$. Almost 35 $hm^3\ yr^{-1}$ of surface water has been in use since 2001 to replace groundwater. In November 2023, the construction of the second phase of this groundwater replacement scheme started. This will allow for the replacement of an additional 35 $hm^3\ yr^{-1}$. The aim is to go beyond stabilization and progressively recover the levels that the aquifer had before the 1990s (CHJ 2023; p 102).

Achieving these recovery objectives is not an easy task. In the last 5 years there has been a slight upturn in withdrawals, which have averaged 312 hm^3. This is attributed to two factors: (a) climate change induced thermal rise which increases crop evapotranspiration and increases crop water demands, and (b) the expansion of woody crops (mainly grapes, almond and pistachio trees), which occupied only 1000 ha of MOA in 2000 and in 2023 cover 41 000 ha. Users estimate that the expansion of woody crops could bring the total irrigated area in MOA to 150 000 ha in 2030 (Ortega-Reig *et al* 2019). Irrigation of these crops is controlled through meters, as irrigation determination by RS is much more complex in permanent woody crops than in annual arable crops. Generated data for permanent wordy crops is not accurate enough to allow for sanction procedures with full legal guarantees. This makes the control of extractions much less reliable and requires a greater inspection effort. However, it is possible that the advance of RS tools will enable JCRMO to control these crops in the future, mainly due to the progress in the use of machine-learning techniques (Sadeghi *et al* 2017, Dari *et al* 2021, López-Pérez *et al* 2024), something UCLM is working on together with ITAP.

7. Conclusions: towards co-evolving socio-technical governance arrangements

Since 1995, JCRMO has co-evolved with the use of the SpiderWebGIS tool, and a strong facilitating institutional embeddedness. Table 1 presents a summarized timeline of this co-evolution which has rendered a co-management system that sustainably manages MOA. The development of the organizational and institutional framework of JCRMO co-evolved with the use of RS data. The SpiderWebGis tool enabled users organized under the umbrella of JCRMO to implement a system of groundwater use monitoring (based on reliable and by now widely accepted RS derived data) and control that is transparent, legible and understandable by all users. Without it, JCRMO would not have been able to develop its current institutional and organizational framework and capacity. On the other hand, if there had not been a user-based organization that is institutionally supported by the state water agency (CHJ), the SpiderWebGis tool would not have become the

Table 1. Timeline of most important events that marked the co-evolution of JCRMO.

Year(s)	Important development in relation to functioning of JCRMO
1980's	Start intensive groundwater use for agriculture in the La Mancha Oriental Aquifer.
Early-1990's	Droughts increase pressure on water resources in the Jucar Basin, CHJ (River Basin Authority) threatens to intervene in MOA to reduce groundwater use in agriculture.
1994–1995	JCRMO is created by group of groundwater irrigators to defend the interests of the users and to search for solutions for groundwater overdraft in MOA, institutionally embedded and with good relations with CHJ.
1996	JCRMO and Universidad Castilla–La Mancha start to explore possibilities of remote sensing (RS) for groundwater use monitoring in the irrigation sector.
1997	First agreement (ERMOT) to monitor irrigated area with RS. Agreement signed between CHJ, JCRMO, Universidad Castilla–La Mancha, Ministry of Agriculture and private consultancy. Through it, RS based tools are developed and officially recognized as valid to monitor groundwater use.
1998	CHJ only emits yearly groundwater use permits (*visados*) to Water Management Units through JCRMO. This forced all groundwater users of MOA to become JCRMO members (further ratified in 1999).
2000	Start use of RS generated data to monitor and control groundwater use and implement sanctions through the irrigation jury of JCRMO.
2001	Finalization of the infrastructure (first phase) to replace groundwater with surface water for irrigation from the Jucar Basin and the Tajo Segura inter-basin transfer with a capacity of up to 35 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$ (of allocated 80 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$).
2000–2006	Gradual decrease of yearly groundwater abstractions from MOA, from more than 400 hm^3 to just above 350 hm^3 with an average over this period of 380 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$.
2005–2008	Drought period in the Basin leading to reductions in groundwater use permits to below 300 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$ in 2006 and keeping and average of below 300 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$ until 2019 and slightly above since then (2007–2023 average of 296 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$).
2007–2008	Public Offer for the Acquisition of Water Rights (OPAD) as drought management strategy offering groundwater users in certain regions of MOA financial compensations for not producing crops (groundwater rights bought: 27.3 hm^3 in 2007 (at 0.19 € m^{-3}), and 50.6 hm^3 in 2008 (at 0.25 € m^{-3}).
2008	CHJ regulations require surface water users within MOA to become members of JCRMO to acquire their water use permits.
2012	Spanish Supreme Court recognizes remote sensing data as evidence in court.
2016	Agreement between JCRMO, Regional Authority and CHJ to exchange hydrological and piezometric data.
2014–2017	Start of a spiked increase in cultivation of Almonds and Pistachios, on top of the gradual increase of grapes and to a lesser degree olives since 2000 (most of these woody crops are produced with supplementary groundwater irrigation. Estimated woody crops in 2000 at around 1000 ha, in 2023 around 41 000 ha).
2017-running	Research for improving the accuracy of RS in monitoring woody crops and estimating corresponding water consumption (collaboration ITAP, JCRMO, Universidad Castilla–La Mancha).
Nov 2023	Start of the construction of infrastructure (second phase) to replace groundwater with surface water with an additional capacity of up to 35 $\mathrm{hm}^3\ \mathrm{yr}^{-1}$.

groundwater management instrument it is now. Its current functioning hinges on the trust and cooperation of the users, not only in the data and the technical system behind the data, but also in the organization and institutions in which it is embedded and functioning. This shows that, as in other cases, the institutionalization of new technologies requires a process of co-evolution with social institutions and practices (Sanchis-Ibor *et al* 2024).

Key factors that contributed to this successful co-evolution are summarized in table 2.

This co-management structure has proven its effectiveness over the last two decades and has become a reference in the country. This structure was not 'fixed' since the beginning, but has been co-evolving and adapting to new challenges and external demands. It has for instance incorporated new advances in RS, is now searching for ways to monitor and control irrigation of woody crops, has co-implemented groundwater substitution programs, and more. It is probably also a good example of the positive influence of awareness, within JCRMO

Table 2. Key factors in the co-evolution of the co-management of MOA.

Factor	Description
Existing human and institutional capital	Existing good relations and trust between users (later JCRMO), CHJ and UCLM, which enabled the establishment of initial collaborations that sparked the co-evolution of the co-management system of MOA, facilitating a continued channel for dialogue and negotiation.
Credible external threat	The threat that CHJ would declare the aquifer as overdrafted to start strict control over the users after the droughts of the mid 1990's. Hard sanctions by the CdA of CHJ.
Strong institutional embedding	JCRMO as single MOA-users organization in Hydrological Plans of the Jucar Basin. Yearly water permits (*visados*) extended by CHJ *through* JCRMO. Recognized (by CHJ and law) user based irrigation jury. SpriderWebGis recognized by CHJ as valid monitoring mechanism for agricultural groundwater use, and RS legally recognized as evidence in court since 2012. Strong political commitment by CHJ to support aquifer stabilization mechanisms.
Strong support to sustain agricultural production	Programs to compensate groundwater users for not irrigating in the dry period 2007–2008. Groundwater substitution programs with surface water from the Jucar River and the Tajo-Segura water transfer since 2001 (potential 35 $\mathrm{hm^3\ yr^{-1}}$), and start of construction of second phase in November 2023 with potential for an additional 35 $\mathrm{hm^3\ yr^{-1}}$.
Clear monitoring and control mechanism based on RS data	SpiderWebGis has proven to provide reliable data for monitoring agricultural groundwater use per WMU. Users have come to understand and accept the spatio-temporal data generated by SpiderWebGis as a trustworthy proxy to calculate groundwater use per WMU.
Clear normative and organizational users-based framework	JCRMO has been recognized by users as 'the and their' organization that functions with transparency, democratically and fairly. JCRMO has established a widely accepted and institutionalized normative framework (rules and regulations) for monitoring agricultural groundwater use among users based on RS data. The irrigation jury of JCRMO is recognized as a transparent user based institution that 'judges and sanctions' those that do not comply with the normative framework in a fair, transparent and peer-to-peer manner.

and its members, of the need and related pride of taking care of a common resource (Calvo-Mendieta *et al* 2017, Zwarteveen *et al* 2024).

Although the principles identified above combined with advances in RS technologies might refine and enhance the possibilities of monitoring groundwater use to support the creation of control systems that use this technology, some reflections are prudent. In many aquifers, there is a lack of starting human and institutional capital, upon which a system can co-evolve. In many aquifers overexploitation has reached levels that are irreversible in the short term, and in which reaching a balance between recharge and use would have severe social and political consequences. There are important future challenges associated with the uncertainties brought about by climate change and higher temperatures, which makes identifying sustainable aquifer levels and related management systems much harder. It is also good to realize that aquifer stabilization has been achieved without dismantling the intensive agricultural model, something that, as Petit *et al* (2021) point out, is common in cases of groundwater management success; and which often leans on groundwater substitution programs and large financial investments in the sector.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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