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Irrigation modernization in the Ebro – Aragón region of Spain: Past and future trends

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ABSTRACT

Irrigation modernization has been analyzed in the part of the Aragón region within the Ebro River Basin, in northeastern Spain. A geodatabase was built with 1144 irrigation cartographical units (ICUs) adding up to 476 k ha with access to water and equipped with on-farm irrigation hardware. ICUs were classified in eight categories related to irrigation modernization. The classification revealed that in the past two decades an integral irrigation modernization was achieved in 103 k ha. In a second modernization, 13 k ha were transformed to reduce their dependence on grid energy. A third type of modernization, oriented to the digitalization of irrigation management processes, is only incipient at this time. Public investments in modernization during this period were estimated at 36.8 M€/year. This intense, publicly co-funded, policy-driven process will be far from sufficient to complete the modernization of all irrigated land in the study area in another twenty-year period. In a concurrent process, obsolete, socially unfavored and structurally deficient irrigated areas are being abandoned for irrigation and even for farming. Specific indicators were proposed to approach the abandonment process, revealing that irrigation intensity in temperate climate, riparian ICUs was only 20 %. Irrigation in the study area needs to progress towards sustainable intensification, concentrating agricultural production in areas equipped with the technology and the water management capacities required to face the current agronomical and environmental challenges. The on-going processes of irrigation modernization, new irrigation developments and irrigation abandonment should be coordinated to serve this purpose.

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1. Introduction

Irrigation modernization is a recurrent concern of farmers, water users' associations (WUAs) and agricultural and environmental policy makers. Leading the process, developing a project, securing farmers' support and mobilizing the required private and public funds are complex issues. Modernization has proven very important to improve irrigation efficiency, enhance water traceability, reduce labor requirements and increase crop yield (Ayre and Nettle, 2017; Berbel et al., 2019; Zhang et al., 2023; Ahmed et al., 2024). Projects are introducing new technologies for irrigation, digital water management and renewable energy. Public funds are made available because governments want to improve food security, develop rural employment and make irrigation systems sustainable. Additionally, irrigation modernization has been reported to moderate water use, reduce diffuse agricultural pollution, improve the working conditions of farmers and render these jobs more qualified, efficient and socially attractive (Lecina et al., 2010; Berbel et al., 2019).

Khadra and Sagardoy (2019) analyzed irrigation modernization and rehabilitation in the Mediterranean context. They referred to the definition of irrigation modernization adopted by the FAO (Facon, 1996): "*a process of technical and managerial upgrading (as opposed to mere rehabilitation) of irrigation schemes combined with institutional reforms, with the objective to improve resource utilization (labor, water, economic, environmental) and water delivery service to farms*". While modernization typically changes the irrigation method from surface to pressurized irrigation, it also has important implications in energy use, environmental protection or collective action (Tarjuelo et al.,. 2015; Hoffmann and Villamayor-Tomás, 2023). Modernization – the subject of this research – results in a different and better system, while rehabilitation just results in a better system.

One of the purposes of irrigation modernization is to increase irrigation efficiency. Irrigation hydrology developments in the 20th century shed doubts about the relationship between improving irrigation efficiency and saving water (Willardson et al., 1994). Grafton et al. (2018) recalled that in order to save water (i., e., in order to reduce consumptive water use), improvements in irrigation efficiency must be accompanied by water accounting, a cap on water extractions, strategic analyses and the development of water management capacities among water users. Berbel et al. (2019) signaled "rebound effects" (an increase in water consumption) following irrigation modernization. These authors called for effective policies and water governance to control water allocation.

Successive public plans for irrigation modernization have been in place in Spain since the beginning of the century (Government of Spain, 2002, 2006). Recently, the Spanish plan to apply the Recovery and Resilience Facility of the European Union (EU) also considered investments in irrigation modernization (Government of Spain, 2021). Projects co-funded by this Facility need to enforce the DNSH principle (Do No Significant Harm to the environment) (Government of Spain, 2022). As a consequence, projects are required to "save water or reduce water abstraction or save energy". From the point of view of hydrology, this measure can be achieved by reducing consumptive or non-consumptive water use. Additionally, tools for the monitoring and mitigation of nitrate pollution in return flows are being installed in modernized WUAs.

Berbel et al. (2019) reported macro data for irrigation in the country. Irrigation occupies 20 % of the agricultural area, reaching 75 % of total national water abstraction, leading to 60 % of agricultural production and generating 80 % of food exports. These authors reported irrigation modernization actions of variable intensity in the 21st century, covering 1.8 M ha in the country. The effect of irrigation modernization policies in the landscape of Spain has been very important. According to the ESYRCE annual surveys (Government of Spain, 2024), between 2002 and 2022, surface irrigation has decreased from 42 % to 23 %, sprinkler irrigation has increased from 22 % to 24 % and drip irrigation has increased from 30 % to 54 % (please note that in 2002 4 % of the irrigated area was not classified for the irrigation method). According to this source, in the same period, the irrigated area has increased from 3.4 to 3.8 M ha. The analysis of irrigation modernization in the Guadalquivir river basin concluded that the benefit-to-cost ratio was 4.1, supporting the economic effectiveness of the policy (Borrego-Marín and Berbel, 2019).

The hydrological analysis of irrigation modernization is largely pending in Spain. Playán and Mateos (2006) signaled that consumptive use could increase with modernization due to more intensive cropping patterns and increased evapotranspiration (even with the same crops). This would result from increased irrigation uniformity and the modernization of previously quasi abandoned irrigable land. In the social debate that accompanied the development of national modernization plans at the turn of the century, policy makers and environmentalists did not share these points of view. On the contrary, both groups believed that modernization would save very large volumes of water. Jiménez-Aguirre and Isidoro (2018) analyzed the hydrology of an irrigation modernization process in the Ebro Valley of Spain affecting a 3,9 k ha WUA in transition from surface to sprinkler irrigation. They reported a 36 % reduction in irrigation water use, a 20 % increase in irrigation water consumption and a 70 % decrease in nitrate load in irrigation return flows. More research is required to assess the representativity of these figures.

Water scarcity is increasing in Spain. During the last decades, river flows have been decreasing due to land use changes in the mountain areas (Nadal-Romero et al., 2013). This effect is now amplified by climate change. When facing water scarcity, governments often resort to virtual water (Allan, 1999) as a fast way to increase water supply by importing goods requiring large amounts of water in their production (such as agricultural raw materials and food). Spain has traditionally been a strong net virtual water importer. Vallino et al. (2021) reported that Spain was the 10th *per capita* net importer country in the world. In Europe, only The Netherlands and Belgium imported more virtual water. Spain is a very active exporter of fruits and vegetables, and at the same time the 11th net importer of cereals in the world and the second in Europe (Our World in data, 2024). The agricultural trade balance of Spain is positive in economic terms and also in terms of virtual water.

At the European scale, the EU produces 105 % of the calories required to feed its citizens (Beltrán et al., 2021). By reducing agricultural inputs, the implementation of the European Green Deal (European Commission, 2024) could actually turn the EU into a net food-importing region. There is a risk that sustainable production policies lead to unsustainable food imports. These circumstances require particular analysis of irrigation modernization in Spain and the rest of Mediterranean climate European countries, as related to the sustainability of agricultural production and to food security.

The paragraphs above report on the general effects of irrigation and its modernization on the economy, water quantity, water quality and food security. This paper focuses on the Ebro-Aragón region (Fig. 1). This is the part of Aragón (Spain) belonging to the Ebro River Basin, located in its central part. While the total area of Aragón is 47.7 M m^2, the area of the Ebro-Aragón is 42,1 M m^2, representing 49,2 % of the Ebro River Basin area (Government of Aragón, 2023). This region contains centuries-old irrigation developments in the riparian areas of the Ebro River and its tributaries, and large irrigation projects developed in the interfluvial areas during the 19th, 20th and 21st centuries. The region combines areas of intense irrigation activity with areas where irrigation has been negatively affected by depopulation and ageing structures. Water scarcity has become an issue in parts of the region during the last decades.

The objectives of this research include: 1) to analyze the phases and models of irrigation modernization; 2) to evaluate modernization progress in two decades; and 3) To assess the prospects for future modernization efforts.

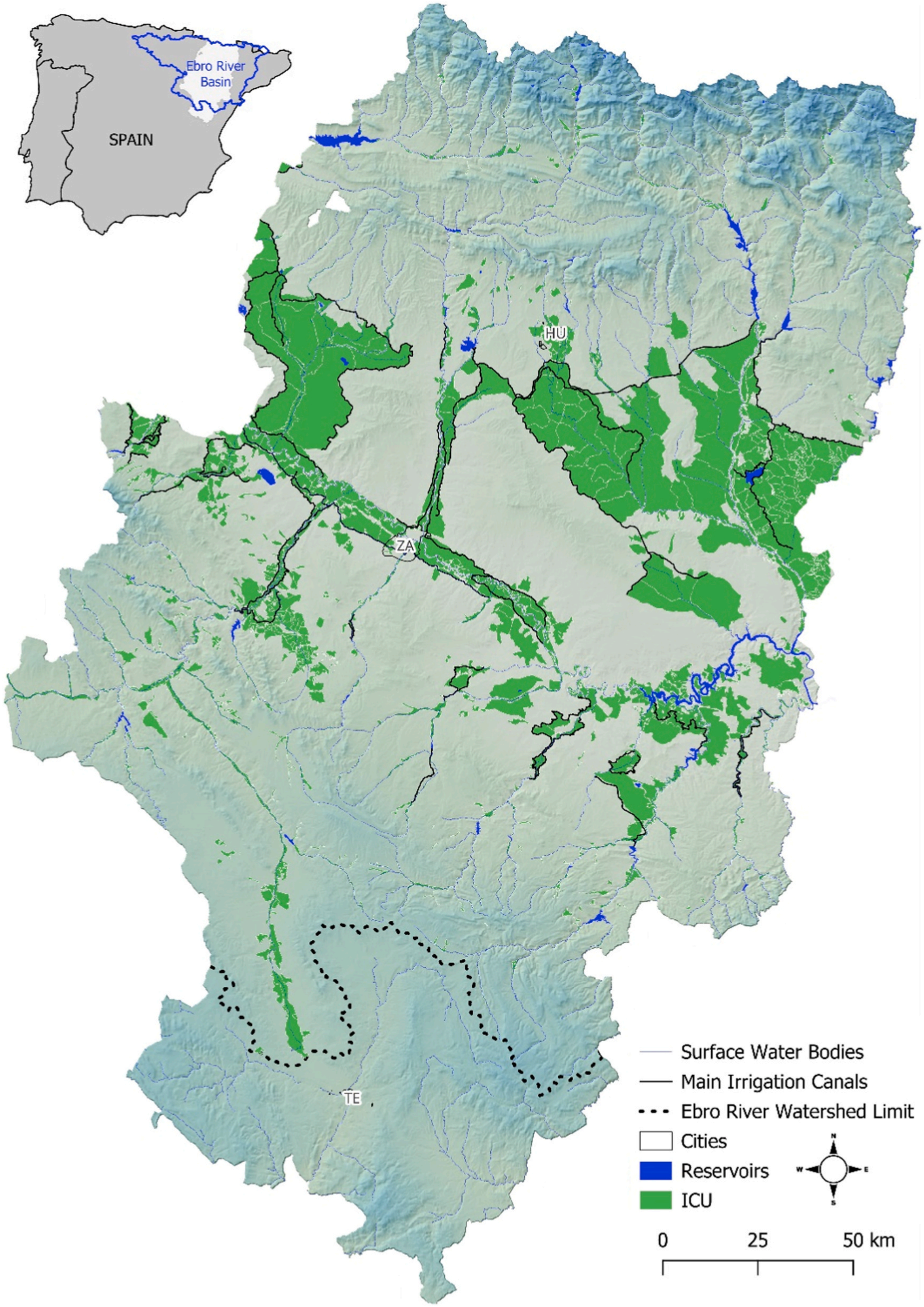

Fig. 1. Location of the Ebro-Aragón region within continental Spain, as an intersection between the Ebro River Basin and the Aragón Region. Irrigated areas within the Ebro-Aragón – obtained from the geodatabase used in this research - are depicted in green. The figure also shows surface water bodies in blue and the location of the three capital cities of Aragón: Zaragoza (ZA), Huesca (HU) and Teruel (TE).

2. Materials and methods

2.1. Policy analysis

Irrigation modernization in the study area has been driven by the policies of the Government of Spain and the regional Government of Aragón. These policies were analyzed to understand the process, to divide it in phases, to determine the physical components of modern irrigation systems and to estimate past public investments in subsidies to collective infrastructure of Water Users Associations (WUAs) and in some cases to private on-farm investments. Most relevant policies were issued by the Government of Spain since the 1990s to date. Legal documents from governments and yearly reports from public companies facilitating irrigation modernization investments were reviewed.

2.2. Classification of the irrigated area for modernization studies

Zapata et al. (2020) presented a classification system for irrigated areas. The system was applied to "Irrigation Cartographic units" (ICUs), polygons containing a number of irrigated plots, homogeneous in terms of administrative, hydrological and farming parameters. It is important to clarify that in the context of this research, an "irrigated" plot is a plot connected to a water source and having sufficient infrastructure to be irrigated. This definition does not imply that the plot is irrigated all along a complete irrigation season or even that is irrigated every year.

ICUs are often coincident with WUAs, but an ICU can also correspond to part of a WUA or even to more than one WUA. The irrigation classification presented by Zapata et al. (2020) was based on a binomial system (genus and species). Internal properties were used to define genera, while external properties were used to define species. Internal properties included the water source, the source of energy for water flow, the irrigation method, and the frequency of scarcity. External properties included land tenure aggregation, crop orientation, environmental protection and socio-economic level. The classification was applied to the Ebro-Aragón region, creating a geodatabase of irrigated areas containing 729 ICUs covering 435,851 ha, and with an average size of 602 ha/ICU.

In this research, we have produced version 2 of the geodatabase (Lorenzo-González et al., 2024), including additional irrigated areas. The number of ICUs has increased to 1144. The total irrigated area has increased to 476,172 ha (Fig. 1) and the average ICU size has been reduced to 416 ha. This increase in irrigated area (40,321 ha) is partially due to the inclusion of centuries old small ICUs (particularly in areas with low irrigation activity), and partially due to a small increase in the total irrigated area in the last four years.

A specific thematic ICU classification was designed for irrigated areas, focusing on the analysis of irrigation modernization. This led to a drastic reduction in the number of classification categories with respect to Zapata et al. (2020), facilitating the analysis. Additionally, the reduction in ICU size allowed more geographic detail in the current modernization classification than in the original binomial irrigation classification. ICUs were classified in eight categories (Table 1). Six variables were considered in this modernization-oriented classification:

- Geomorphology. The Ebro-Aragón was divided in riparian and interfluvial areas. Riparian irrigation areas are for the most part centuries old, and use earthen canals in derivation of rivers to irrigate strips of land along the river banks. Interfluvial irrigation projects were built in since the late 19thcentury, using more involved engineering and construction.
- Collective network. Distinction was made between networks using open-channel ditches and pressurized pipelines.

- Water allocation. The classification was adapted from Clemmens (1987), using farmers' participation in decision making about flow frequency, rate and duration as the classification criterion. Different models were considered, with growing complexity and flexibility:
  - o Anarchical: Farmers manage water allocation themselves, as the WUA does not provide this service. Farmers decide the frequency and duration; the decisions of different farmers can be in conflict.
  - o Rotation: Farmers have rotational access to irrigation water; they do not have decision capacity.
  - o Negotiated: Farmers negotiate their water allocation with the WUA.
  - o Demand: Farmers can make their own decisions, respecting the maximum rate attributed to each farmer.
  - o Centralized: negotiated demand is used for decision making and the WUA executes the irrigation instead of the farmer. This allocation model requires WUA telemetry and remote control (TM/RC) systems.

- Water management model. Three models, passive, active and mixed were used to describe WUA proactivity in water management. Passive WUAs do not intervene in water allocation: farmers gain access to water trough informal, self-regulated procedures. On the contrary, active WUAs lead the whole water allocation process, receiving some input from farmers.
- Climate. The traditional riparian irrigated areas were classified in semiarid and temperate. An elevation of 450 m amsl was used as threshold separating lower semiarid areas from upper temperate areas, in agreement with the map presented by El-kenawy, Zerouali et al., (2022). These elevated, mountainous areas have narrow riparian irrigated areas characterized by small plots, low dedication to irrigated agriculture and low irrigation profitability.
- Energy for pumping. Interfluvial ICUs with pipelines were qualitatively separated: gravity pressure or moderate energy input *vs.* high energy cost.

Four categories are presented in Table 1 for riparian areas and other four for interfluvial areas. While ditches prevail in riparian areas,

Table 1
Classification of Irrigation Cartographic Units (ICUs) in modernization categories as a function of the geomorphology, type of collective distribution network, water allocation and management model. For each category, the associated ICU genera described by Zapata et al. (2020) are presented.

Geomorphology	Collective Network	Water Allocation	Management Model	ICU Category	Corresponding ICU Genera in Zapata et al. (2020)
Riparian areas	**D**itches	Anarchical	Passive	**RDT**. **T**emperate Riparian Areas	SurGraFloVe
		Rotation	Passive	**RDS**. **S**emiarid riparian areas	SurGraFloVe, SurPumFloVe
		Centralized	Active	**RDC**. Centralized systems	SurGraFloVe
	Pipelines	**D**emand	Mixed	**RPD**. Pressurized systems managed on-demand	SurPumPreVe
Interfluvial areas	**D**itches	**N**egotiated	Mixed	**IDN**. Traditional areas of large irrigation systems	SurGraFloVe, SurGraFloPe, SurPumFloVe, SurVarMetVe
	Pipelines	Demand or negotiated	Mixed	**IPE**. Modern areas with pumping and high Energy cost	SurPumPreVe
		Demand	Mixed	**IPG**. Modern areas with **G**ravity pressure or moderate energy cost (renewable energy)	SurPumPreVe, SurGraPreVe, SurVarMetVe, SurVarPreVe, GroPumPreVe
		Centralized	Active	**IPC**. Centralized systems	SurPumPreVe

pipelines prevail in interfluvial areas. ICUs in interfluvial areas show more WUA intervention in water allocation and are more active in water management. These traits are inherited from the governmental policies used during their construction.

2.3. Sources of information on ICUs

Classification of ICUs relied on the experience of the authors and on the inspection of aerial photographs from different dates. However, field visits and interaction with stakeholders were very important to produce this information. Informal consultations were run with irrigation engineers, WUA managers and the officers of the three largest irrigation projects in the Ebro-Aragón region (Riegos del Alto Aragón, Canal de Bardenas and Canal de Aragón y Cataluña). These three projects have capitalized most modernization activity in the region during the last two decades. These sources of information were complemented with the annual reports of the SEIASA public company for irrigation modernization of the Government of Spain (https://www.seiasa.es) and unpublished irrigation modernization subsidy reports of the Government of Aragón. All these consultations were particularly important to document the changes in the classification since the beginning of modernization processes and to estimate the average annual public investments.

Interviews were also performed in 2020 to the managers of 31 WUAs in the *Riegos del Alto Aragón* project undergoing irrigation modernization processes. These interviews focused on the changes induced by irrigation modernization in water use, land tenure, crops and WUA governance.

Finally, we organized a workshop in July 2023 to gather WUA perspectives about the challenges related to their modernization. The workshop was attended by fifty WUA board members and technicians representing the different classification categories used in this paper (Table 1). Four working groups were established, focusing on riparian WUAs (RDT, RDS and RDC), IDN, IPE and IPG.

2.4. Indicators of farming and irrigation intensity

These indicators were used to estimate farming and irrigation intensity in the modernization classification categories. The ultimate goal was to assess the risk of abandonment. Indicators were derived from anonymized Common Agricultural Policy (CAP) records in geodatabase form obtained from the Government of Aragón for the period 2018–2023. While one of the spatial units of the CAP is the cadastral plot (part of a holding), the spatial unit of the geodatabase for classification of the irrigated area for modernization studies is the ICU. Both polygon layers were intersected in QGIS (QGIS Development Team, 2023), to assign plots to ICUs. Non-agricultural plots were removed before determining the indicators. Plots within each type of ICU classification category were converted to a 5 $\times$5 m raster layer inheriting ICU and CAP properties.

The farming intensity indicator was determined as the percentage of raster cells of agricultural use with at least one CAP application in the six years of records. CAP subsidies are designed to discontinue payments to farms not active in agriculture. Farmers need to declare their crops every year to collect subsidies. Nothing precludes cultivating a farm without CAP subsidies, but this is infrequent. As a consequence, a cadastral plot without CAP applications is indicative of low-intensity farming and high risk of abandonment of farming activities.

The irrigation intensity indicator was determined as the percentage of raster cells of agricultural use having at least one declaration of a necessarily irrigated crop in the six years of records. A list of 34 necessarily irrigated crops was prepared for this purpose, including summer cereals, grains and vegetables, alfalfa, olive, almond, pistachio, vineyards, fruit trees and poplar. Growing these crops indicates that irrigation was performed, since these crops require water application in the local conditions. Farms growing other crops (like winter cereals) during the six years of record could do it without irrigation. This would be indicative of deteriorated irrigation structures and/or undependable water supply, part of the irrigation abandonment process. Again, it is infrequent that farmers perform their operations without applying for CAP subsidies.

These indicators are subjected to the same errors as CAP applications. Additionally, the CAP records of the Aragonese Government only include beneficiaries with address in the region.

3. Results and discussion

3.1. Phases of irrigation modernization

Irrigation modernization processes in the Ebro-Aragón derive from the policies of the Government of Spain, the main policy source and public financial contributor to this process. By the end of the 20th century, modernization works were performed in a number of irrigated areas in a Pre-modernization phase (M0). A pioneer decree (Government of Spain, 1993) provided funding for the improvement and modernization of traditional irrigation systems. Despite the policy relevance of this decree, its financial support was mild in comparison with the extension of the irrigation systems to be modernized. M0 projects were often formulated as the rehabilitation of deteriorated, surface irrigated WUAs. In other cases, small pressurized irrigation projects were built within large surface-irrigated areas.

In the first years of this century, modernization plans were developed for a national irrigated area of 3.5 M ha, of which 2.3 M ha required urgent modernization (Government of Spain, 2002, 2006). The Plan coordinated investments of 7400 M€ in existing irrigation systems, with the additional participation of Regional Governments (Government of Aragón, 2001) and the European Union (often using European Regional Development Funds, ERDF). Both the Governments of Spain and Aragón created public companies specializing in the promotion of irrigation modernization projects. These works, which are still carried out in many areas, constitute the first modernization phase (M1), often called integral modernization. Projects were developed in WUAs that had not undergone previous modernization, and whose structural condition was generally poor. Typical projects replaced canals and ditches with pressurized collective irrigation networks for sprinkler or drip irrigation, equipped with reservoirs and frequently pumping stations. The need for M1 projects is still important in Ebro-Aragón.

Irrigation modernization did not end with M1. During the second decade of this century, many WUAs found that energy costs were threatening their operation, since the special electricity tariff for irrigation pumping was discontinued in 2008 (Stambouli et al., 2014). In many cases it was necessary to carry out a second modernization phase (M2) to address this issue, which typically required a photovoltaic energy plant. Additional, elevated ponds were also frequently built to decouple daily pumping requirements from hourly fluctuations in electricity cost. M2 is currently very active and will be needed for at least an additional decade. The decrease in the cost of photovoltaic equipment is facilitating the control of energy costs. Some WUAs in Spain may develop their M2 projects without public subsidies, since these projects are particularly cost-effective and urgently needed.

The third modernization phase (M3) focuses on the digitalization of water management. This process started at the beginning of the century, with the promotion of TM/RC systems for M1 projects (Playán et al., 2018). However, technology at that time was not mature and WUAs had a hard time to adopt digital water management procedures. As a consequence, most M1 TM/RC systems are currently obsolete and/or poorly maintained. Digitalization is currently considered an urgent necessity for WUAs, addressing many elements beyond the TM/RC of collective pressurized networks. Thus, for example, the Recovery and Resilience Facility of the EU is being used to boost WUA digitalization (Government of Spain, 2023a). This 200 M€ program is funding WUA digital activities in administration, remote sensing, irrigation and return flow monitoring or pollution control. The first call for proposals received applications amounting to 80 % of the funds, reflecting the difficulties that many WUAs currently find in approaching the digitalization of their operations. This is particularly true for traditional WUAs not previously involved in M1 and M2 modernization activities.

Table 2, based on the experience of the authors, presents the typical components of each modernization phase. M1 and M3 have a wide span of activities. While M1 focuses on infrastructure, M3 focuses on digitalization of irrigation processes and hardware. Both M1 and M3 also fund activities oriented to improve human resources and to advise farmers. As previously discussed, M2 has a narrow focus.

This four-phased modernization process should be seen as a consequence of the specific conditions of local policy and water management. Modernization processes could be designed in just one phase. However, a long time is required to modernize the irrigation infrastructure and – particularly – the managerial capacities. Local experience shows that a decade is a reasonable time frame for a WUA to be able to succeed in exploiting a digitally-intense infrastructure. WUAs do not need to install all components a once: modernization can be done in steps. While M0 did not represent a radical change for most WUAs, M1 has completely transformed local WUAs. Actions in M2 and M3 address specific WUA problems. These problems are very important, but require much smaller budgets than those of M1.

Table 2
Components of irrigation modernization associated to the four phases of Modernization in the Ebro-Aragón: M0 (previous), M1 (first or integral), M2 (second or energy) and M3 (third or digitalization).

Area	Component	M0	M1	M2	M3
Collective open channel network	Electronic flow meter at the inlet		X		X
	Internal reservoir	X	X	X	
	Collective network: ditches, gates and flow meters	X	X		
	Collective network: Telemetry and Remote Control System (TM/RC)		X		X
	Farm turnouts: gates	X	X		
	Farm turnouts: TM/RC		X		X
	Collective drainage and runoff disposal network		X		
Collective pressurized network	Electronic volumetric meter at the inlet		X		X
	Internal reservoir	X	X	X	
	Electric pumping system	X	X	X	
	Pumping system: renewable energy, TM/RC			X	X
	Proportional injection system at the inlet for control of invasive species		X		X
	Collective pipeline network, control elements, pressure sensors		X		X
	Collective pipeline system: TM/RC		X		X
	Hydrants: TM/RC		X		X
	Collective drainage and runoff disposal network		X		
Management, valid for any type of distribution	Continuous training of WUA personnel		X		X
	Continuous improvement of services to farmers		X	X	X
	Web portal for communication with farmers and river basin organization				X
	Software for administration, water allocation, TM/RC, GIS		X	X	X
	Remote control of soil water in WUA plots				X
	Remote control of deep percolation of contaminants				X
	Irrigation advisory service to farmers				X
	Energy generation with renewable sources			X	X
	Services to farmers beyond irrigation		X	X	X

3.2. Modernization as a change of classification category

Irrigation modernization leads to transitions in classification categories (Fig. 2). These transitions depart from the current eight categories and reach only four modernized categories. The M1 phase often converted IDN to IPE. Today, these energy-intensive irrigation systems are no longer produced. As a consequence, modernization is currently producing:

- RDC. Centralized open channel systems for surface irrigation in riparian areas. Only one such system has been created in the Ebro-Aragón, but a few additional projects are currently being discussed in RDS WUAs. Transition from RDT to RDC is possible, but very complex, due to the disaggregated land tenure, the degraded social structure of farming and the lack of market-oriented agricultural production models in those areas.
- RPD. Again, transition from RDT to RPD will be complex, and is bound to happen for specialty crops, such as fruits. These pressurized systems will not be centralized, since WUAs will be too small to develop the required management capacities.
- IPG and IPC. On-demand and centralized pressurized networks with moderate energy input will be very common in interfluvial areas, with IPG being the most common system in the Ebro-Aragón. Only one case of IPC has been built so far.

The small plot size typical of riparian areas makes it very difficult to develop large M1 projects. This is particularly true for temperate areas. However, modernization from RDS to RPD has happened since the 1980s in the context of fruit production, often affecting individual farms. M2 modernizations can be formulated as transitions from IPE to IPG or from IPE to IPC (there is currently no experience in this second, technically possible transition). Finally, M3 modernizations are depicted in Fig. 2 as horizontal lines, since they do not imply a change in the classification category.

This section addresses the results of modernization in the last two decades, when phases M1 and M2 have been active. M3 has just started, and the first call for proposals was under evaluation at the time of writing this paper. Results are presented in Table 3, summarizing progress in irrigation modernization during the 21st century. Figures are reported in thousands of hectares, although the magnitude of the error could be larger in some classification categories.

Fig. 3 presents sample aerial photographs of four categories in the Ebro-Aragón. RDT areas have smaller plots than RDS areas. This is due to the narrow riparian strips of temperate agriculture in high lands, as compared to the wide riparian strips of the rivers in low lands. IDN plots are large in comparison to riparian areas, but smaller than the plots of modernized IPG areas (land consolidation is often a phase of M1 modernization). Table 3 also presents the average cadastral plot size for each category. A holding is typically composed of one or several adjacent cadastral plots. The plot size can be used as an indicator of the aggregation of land tenure, suitability for mechanized agriculture and cost of M1 modernization (the smaller the plots, the more expensive modernization will be). The smallest plots can be found in RDT (0.24 ha), while the largest plots are in IPC (2.47 ha). Riparian plots are twice as large in semiarid areas than in temperate areas. Land consolidation in RDC also produced comparatively large plots (1.01 ha). Modernized interfluvial plots (IPE, IPG and IPC) are also way larger than the non-modernized ones (IDN), owing to the ease of launching modernization projects in areas with large plots, and to the effect of land consolidation often accompanying modernization.

Table 3 reveals that the irrigated area has increased by 28 k ha in the

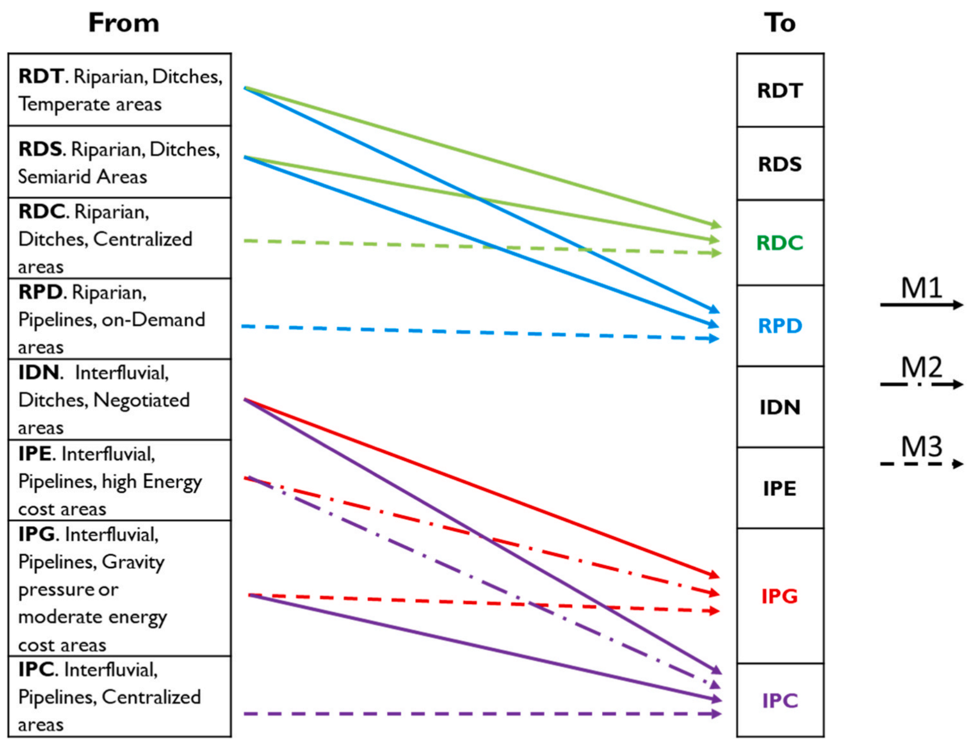

Fig. 2. Typical transitions between Irrigation Cartographic Unit (ICU) categories resulting from irrigation modernization. Arrow colors are associated to the same destination model. Solid lines correspond to modernization phase M1. The point – dash line is the transition from IPE/IPG to IPG, associated to phase M2. Finally, dashed lines are associated to phase M3. Note that complete modernization of the study area would reduce the current eight categories to just four.

Table 3
Average plot size (ha, determined from GIS operations) and area of the eight classification categories in 2003 and 2023 (k ha, determined from aerial photographs, field visits and stakeholder consultations in the Ebro-Aragón).

ICU Classification Category	Average plot size (ha)	Area in 2003 (k ha)	Area in 2023 (k ha)	Change (k ha)
RDT. Riparian, Ditches, Temperate areas	0.24	31	31	0
RDS. Riparian, Ditches, Semiarid areas	0.47	92	86	−5
RDC. Riparian, Ditches, Centralized areas	1.01	0	2	2
RPD. Riparian, Pipelines, on-Demand areas	0.29	9	12	3
IDN. Interfluvial, Ditches, Negotiated areas	0.79	201	102	−98
IPE. Interfluvial, Pipelines, high Energy cost areas	1.55	70	104	34
IPG. Interfluvial, Pipelines, Gravity pressure areas	1.29	46	134	88
IPC. Interfluvial, Pipelines, Centralized areas	2.47	0	4	4
TOTAL	-	**448**	**476**	**28**

20-year period. Most of the new irrigated areas have been developed in the PEBEA project (pumping water from the Ebro River to irrigate fruit trees) (Government of Aragón, 1997), in the progress towards completion of the *Bardenas* and *Riegos del Alto Aragón* projects, and in small, social irrigation developments.

The extent of modernization phase M1 in Ebro-Aragón is estimated in 103 k ha. Modernization reduced the area of IDN by 98 k ha, transferring this area to IPG (67 k ha), IPE (27 k ha) and IPC (4 k ha). Modernization also reduced the area of RDS by 5 k ha, transferring this area to RDC (2 k ha) and RPD (3 k ha). The average M1 intensity in Ebro-Aragón during these two decades has been about 5.2 k ha/year. The area of modernization phase M2 has been 13 k ha, in transition from IPE to IPG. This estimate is particularly complex, since an M2 project often transforms part of a WUA or ICU.

Riparian temperate areas (RDT) have not changed in extent during these two decades. A large fraction of these areas is progressing towards abandonment. In this sense, it is important to recall that the classification in Table 3 indicates the possibility to irrigate, not the actual irrigation. Riparian semiarid areas (RDS) have suffered small changes to RPD and RDC, which are interesting for the planning of future modernization activities. In the Ebro-Aragón there are still 117 k ha of irrigated riparian areas facing an often difficult and expensive modernization process (M1).

In interfluvial areas, the surface irrigated area (IDN) has been reduced by half in these two decades, however, it still covers 102 k ha. Progress is needed in the integral modernization of these areas (M1). In the Ebro-Aragón, surface irrigation in currently used in 222 k ha, representing 47 % of the irrigated area. This figure is similar to the 45 % attributed by the ESYRCE survey of irrigation methods for the whole Aragón region (Government of Spain, 2024). The same survey attributes 38 % to sprinkler irrigation and 17 % to drip irrigation.

Pressurized irrigation areas with high energy requirements (IPE) have increased from 70 to 104 k ha, although at the same time some WUAs have implemented M2 projects to reduce grid energy demand (13 k ha). Pressurized irrigation areas with low or no grid energy requirements (IPG) have multiplied by three, reaching 134 k ha.

The two centralized WUAs in ditches (*Pina de Ebro* in RDC) and pipes (*Almudévar* in IPC) are important examples of the deployment of new technologies in WUA management. These WUAs use the TM/RC system controlling specific parts of irrigated farms (individual level-basins in *Pina de Ebro* and sectors in *Almudévar*) to apply irrigation with minor intervention by farmers. Additional WUAs in riparian areas, particularly in RDS by the Ebro River, could follow the example of *Pina de Ebro*. Projects are currently being discussed to reproduce this model, taking advantage of the high potential uniformity and application efficiency of level-basins. RDS areas can accommodate large level-basins and can use

Fig. 3. Aerial photographs obtained from Google Earth, characteristic of different Irrigation Cartographic Units (ICU) classification categories in the Ebro-Aragón. All photographs are displayed in the same scale. The photographs represent: a) an RDT ICU near Villalengua (Zaragoza) in 2018; b) an RDS ICU near Villafranca de Ebro (Zaragoza) in 2023; c) an IDN ICU near Santa Anastasia (Zaragoza) in 2022; and an IPG ICU near Castejón del Puente (Huesca) in 2023.

very high discharges, making irrigation fast and rendering its automation cost-effective. In the case of pressurized irrigation, *Almudévar* is also a successful, digitalized model to explore in future M1 IDN modernizations and in future M3 IPE and IPG modernizations.

3.3. Changes induced by modernization in WUAs: water use, land tenure, crops and governance

According to *Riegos del Alto Aragón* WUA managers, modernization lasted between 3 and 9 years, with the interval 3–5 years being the most common. The government of Spain funded 56 % of the interviewed WUAs, while the Government of Aragon funded 28 %. Integral modernization (M1) was performed in 60 % of the WUAs, while the remaining 40 % built reservoirs or part of the collective pressurized distribution network, as a phase of M1. In general, WUAs increased their effective irrigated area during modernization, because irrigation was previously impossible in part of the area due to structural problems. Transition from surface to sprinkler irrigation was very frequent in the area. Drip irrigation was used in many farms, but it was not the most important method in any interviewed WUA. Modernization brought an increase in farm size due to farm trading and land consolidation. The most common farm size before and after modernization was 10–30 ha, but the second most common was “less than 10 ha” before modernization and 30–60 ha after modernization.

The growing water scarcity in the Ebro-Aragón region increased the frequency of WUAs suffering occasional water restrictions from 71 % to 82 %. However, modernization reduced the most common average water use from the class 7.500 – 10.000 m^3/ha to the class 5.000–7.500 m^3/ha. The cost of water increased with modernization: before, the most common class was “less than 10 €/1000 m^3”; afterwards, this class was still common, but water costs between 10 and 50 €/1000 m^3 became the most common. This bimodal character seems to be related to the prevalence of the IPG and IPE categories.

Modernization increased the number of farmers’ representatives at the WUA boards (typically, more than ten), as well as the number of young representatives (below 35 years), which typically grew by one to three persons. However, the number of women in the board was low and became even lower after modernization. The WUAs without female representatives increased from 82 % to 93 %. Following modernization, WUAs increased the technical staff. The frequency of WUAs without technical personnel decreased from 68 % to 23 %. Most modernized WUAs hired one or two persons. The number of women in the WUA staff also increased with modernization. WUAs with one woman in the staff increased from 28 % to 44 %. The staff of modernized WUAs had received formal education. The frequency of WUAs without professional technicians decreased from 61 % to 42 %, while the frequency of WUAs without University graduates decreased from 68 % to 47 %.

Modernization required WUAs to provide new services to farmers. Among them, use of specific software tools for water management and for the distribution of modernization costs (Playán et al., 2007), chemical treatment against invasive species (Morales-Hernandez et al., 2018), and cleaning of plastic-lined reservoirs. As previously discussed, on-demand irrigation has become more frequent in the area, but the intra-day variation of grid electricity cost for pumping has maintained negotiated systems. Both allocation models were equally frequent in the interviewed WUAs. After modernization, 53 % of WUAs had reservoirs and 22 % had operational TM/RC systems.

3.4. Future modernization processes in Ebro-Aragón: beyond 2023

Given the current situation of the Ebro-Aragón, pending M1 modernization still requires a very large effort: 102 k ha of IDN areas, 86 k ha of RDS areas and 31 k ha of RDT areas. This results in a total area of 219 k ha. However, irrigation modernization is not likely to reach all this area, given the current process of abandonment of marginal irrigated areas. In addition, the current IPE area (104 k ha) should undergo M2 modernization to become IPG. Finally, despite a few digitalization success stories (such as in RDC and IPC), virtually all irrigated area (476 k ha) is susceptible of M3 projects. However, it seems like only WUAs having completed M1 will be ready for M3.

In order to estimate the future progress of irrigation modernization, it is important to consider the availability of funds (the supply side) and the WUA interest in modernization projects (the demand side).

3.4.1. The modernization supply side: public funding

The supply side was analyzed through the investment records of the Governments of Spain and Aragón (Table 4), both of them partially using EU Funds. The Government of Spain invested 21.8 M€/year

Table 4
Analysis of public funding for irrigation modernization in the Ebro-Aragón. The analysis was applied to funds received from the Governments of Spain and Aragón, both partially using European funds.

Investor	Variable	Value
Government of Spain through public company SEIASA, partially using European Funds	Initial year	2005
	Final year	2022
	Total investment, constant M€	302.0
	Average investment, constant M€/year	17.8
	Average investment, current 2023 M€/year	**21.8**
	Average investment, current 2003 k€/ha	**5.65**
Government of Aragón, partially using European Funds	Initial year	2016
	Final year	2021
	Total investment, constant M€	67.7
	Average yearly investment, constant M€/year	13.5
	Average yearly investment, current 2023 M€/year	**15.0**
Total	**Average yearly investment, 2023 M€/year**	**36.8**

(current € of 2023) in M1 projects, equivalent to 5.65 k€/ha. The government of Aragón invested 15.0 M€/year (Current € of 2023). The total public investment was 36.8 M€/year. Public funds were used to subsidize about 60 % of the collective WUA infrastructure. As a consequence, private investments in an M1 WUA modernization would amount to about 3.39 k€/ha. Additionally, farmers would need to invest some 4–5 k€/ha for the on-farm irrigation systems. Only a few professional, young farmers could qualify for subsidies from the Government of Aragón applied to the on-farm equipment.

Considering public funds as the limiting factor on the supply side and the land available for M1 modernization, the time required to complete the process in IDN, RDS and RDT areas would be 16, 13 and 5 years, respectively. This estimation was made considering the same cost per hectare in all these areas. However, the cost is expected to grow from IDN to RDS and to RDT. A period of 34 years would be required for the complete M1 modernization of the Ebro-Aragón.

As for M2 and M3, the costs are more uncertain. In the case of M2, three important factors come together. On the one hand, the rapid decline in the costs of renewable energies, and the current volatility in the price of electrical energy. On the other hand, the fact that M2 is associated with a rapid decrease in operating costs. Finally, as previously discussed, M2 is addressed by WUAs having executed M1 modernization, which are used to invest in their infrastructure, and could eventually invest without public support. In the case of M3, it is not possible at this moment to analyze the results of the first call for proposals.

We assumed that the current levels of public modernization funding could continue in the future, as there are at this time no conflicting policies. Even if funding was to continue at the current levels, time oscillations could be expected, as has been the case in the past two decades, which were strongly affected by the global financial crisis and the COVID-19 pandemic.

3.4.2. The modernization demand side: WUA push vs. abandonment of farming and irrigation

The WUA push for modernization has been constant since the onset of the modernization policy. Interest for modernization continues now a days, and Governments continue to face a strong demand for M1 and M2 projects, almost exclusively from IDN areas. In parallel to this strong demand, there has long been a trend to abandon irrigation in specific areas of the region. This trend is motivated by poor irrigation infrastructure, small holdings, migrations and industrialization. The depopulation of rural areas in Spain was a very intense process in the second half of the 20th century, particularly in mountain areas with temperate climate. The process intensified towards the end of the century (Douglas et al., 1994), affecting both irrigation and farming. During the field research at the *Almudévar* WUA before modernization, when it was classified as IDN (Playán et al., 2000), all persons in charge of irrigation had passed the age of retirement. Surface irrigation was seen as a time-consuming, low-productivity task. In this particular case, the situation was reverted with modernization, but for other WUAs, it may already be too late. In fact, farmers perceive that modernization transforms their dedication to irrigation from manual, time-consuming unskilled labor to automated, technology-rich supervision.

Characterizing the different aspects of abandonment is a complex task, not in the scope of this research. This is why we devised indicators of related processes: the intensity irrigation and farming. Table 5 presents the results of this analysis. Indicators are presented for all five modernized categories on one side and for each of the three non-modernized categories (IDN, RDS and RDT) on the other. Indicators are more relevant in their relative values (establishing comparisons) than in their absolute values.

Despite the possible sources of error, the indicators reflect intense activity in modernized areas, and low-activity farming and particularly irrigation in non-modernized areas. Modernized areas have intensity indicators of farming and irrigation of 85 % and 70 %, respectively. These indicators are lower in non-modernized areas in all cases. RDS is the most similar category to modernized areas, with 2 % less intensity of farming and 9 % less intensity of irrigation. The agricultural and irrigation value of these semiarid areas seems to be still high. The indicators for IDN are worse: farming shows low intensity, but the irrigation intensity indicator is 33 %, revealing that only one-third of the area is cultivated with irrigation-dependent crops. Barley is a common crop in these areas, benefitting from between zero and one surface irrigation events. It is clear that M1 modernization already transformed the most agriculturally active interfluvial areas. Finally, RDT is the category showing the worst indicators of farming and particularly irrigation intensity. Only 20 % of the RDT land is used to grow irrigation-dependent crops. It seems like this category will be unable to develop many modernization projects in the future. The area of intense irrigation in the Ebro-Aragón would amount to 272 k ha, a figure much smaller than the 476 k ha reported in Table 3. This indicator suggests that abandonment is at this point particularly intense in IDN and RDT. In the case of IDN, the indicator may be partially influenced by the areas currently under M1 modernization, in which irrigation practice is hindered by construction. Modernization will increase the value of this indicator, but modernization will be difficult in RDS and very difficult in RDT.

Interest in modernization decreases from IDN to RDS and to RDT due to a mix of social and structural reasons. The context of agricultural production, the limited availability of irrigation water and the intensification of diffuse pollution will be additional determining factors on this demand. It is reasonable to think that WUAs with high interest in

Table 5
Intensity indicators of farming and irrigation in the classification categories, as obtained from the database of CAP applications in Ebro-Aragón in the period 2018–2023. Modernized systems were combined using their respective areas in 2023. Low-intensity farming and irrigation indicate a high risk of abandonment.

M1 Modernized System	ICU Classification Category	Intensity Indicator	
		Farming (%)	Irrigation (%)
Yes	RDC, RPD, IPE, IPG and IPC	85	70
No	IDN	77	33
	RDS	83	61
	RDT	65	20

modernization and low technical complexity have already completed their M1. The demand for modernization will decrease as time goes by. Although the non-modernized surface irrigated area in Ebro-Aragón currently amounts to 219 k ha, it seems unlikely that M1 modernization will exceed another 103 k ha in the coming two decades. On the other hand, the area of RDT, IDN and RDS not being modernized will probably continue to progress towards irrigation abandonment and then, probably, farming abandonment. This would eliminate not only agricultural production, but also the important ecosystem services currently provided by traditional irrigation areas (Vila, 2018).

3.5. Challenges of irrigation modernization

At the stakeholders' workshop, all WUA representatives identified a number of common technological and structural challenges. Among them, the importance of land consolidation before M1, the need to optimize renewable energies for pumping, the importance of reusing water at the WUA level, the need to control diffuse pollution – interiorizing its costs – and the adoption of new, digital technologies in water management. Regarding WUA organization, stakeholders signaled that modernization requires providing more services to farmers, more cooperation with public water administration, strengthening governance, addressing bureaucracy, increasing transparency and gathering societal complicity as food providers. Workshop attendants identified relevant challenges in two processes currently following modernization with public funds. The first one is farm buy-out operations by farming companies. These companies, often owned by investment funds, are developing large farming operations associated to specific crops like almond. Their relation to irrigated land is very different from the family farming model which has been widespread in the region. The second one is the development of photovoltaic plants with rental agreements well exceeding the net margin of irrigated agriculture.

Riparian WUAs identified specific challenges in allocating water on demand, measuring irrigation water and return flows, optimizing flooding events to minimize their impacts, identifying the optimum technological level for their specific conditions, developing proportional water billing capacities, making agricultural irrigation and societal leisure compatible (particularly in periurban areas, where public interest on modernization should be explicit). IDN WUAs were aware that they will most likely be the next ones undergoing M1 modernization. As a consequence, they requested higher subsidies and plans for structural modernization and maintenance. IPE WUAs showed concern for energy costs, and focused on the need to share energy problems and solutions. Despite their low energy input, IPG WUAs also expressed concern for energy issues: they saw challenges in the adaptation to renewable energies, and expressed the need for progress towards energy communities.

3.6. Recommendations for future irrigation modernizations

Future modernization projects should combine M1, M2 and part of M3. The time required for integral modernization projects is shorter than the time required to acquire digital skills. However, digitalization should be considered from the beginning of the project. This will require strengthening the WUA capacities with properly trained personnel, as has already been observed in the modernized WUAs. Minimizing grid energy requirements is already a target for irrigation engineers. New projects should not result in relevant energy bills to WUAs. A variety of solutions from photovoltaic plants to turbines capturing excess energy in irrigation water are widely available. Environmental liability is a growing concern for project funders. The implementation of the DNSH principle in the projects funded by the Recovery and Resilience Facility of the EU needs to be assessed to retain its best performing traits. The control of diffuse pollution is a much-needed objective to ensure sustainability. Most imminent modernization projects will be performed in IDN WUAs, where commitments have already been made by public administrations. The modernization of selected RDS WUAs is also expected to accelerate, particularly by the Ebro River, where plots are large and projects will be more cost-effective. Finally, pilot RDT projects could be formulated, particularly if linked to specific crops with a well-developed market. The difficulties in the modernization of RDS and RDT could lead to increased public subsidies. Resilience against flooding in RDS and the fight against depopulation in RDT could justify this additional public effort.

IPE WUAs need urgent M2 reforms to evolve to IPG. As previously discussed, in some cases these reforms may be performed before public funds can be allocated. In any case, transforming 104 k ha of IPE will require relevant private and public investments. Finally, it is not possible at this time to estimate the funds required for M3 in the coming decades. M2 and M3 continue to be strategic investments, critical for the sustainability of irrigation.

3.7. A contribution to the discussion on modernization and consumptive water use

This scientific discussion has focused on the comparison between consumptive use before and after modernization in a given irrigated plot or WUA (Playán and Mateos, 2006; Grafton et al., 2018; Jiménez-Aguirre and Isidoro, 2018; Berbel et al., 2019). However, this point of view does not seem sufficient to understand the process in the Ebro-Aragón and elsewhere. In fact, two problems arise when applying the analysis to the Ebro-Aragón.

The first problem is in the status of the land prior to modernization. As time goes by, in the Ebro-Aragón region, WUAs entering modernization processes will have more degraded infrastructure and more abandonment traits. As a consequence, modernization will be more likely to increase consumptive use respect to the situation immediately before. A WUA where most of the land is devoted to crops with low irrigation requirements will experiment a strong increment in consumptive use following modernization, when intensively irrigated crops are grown. The question is how to establish a fair before-after comparison in terms of consumptive water use. When assessing the change in irrigation hydrology following a change in technology, scenarios before and after should be assessed at the same farming intensity. This would permit to assess the effect of the change in technology. Otherwise, a number of concurrent aspects would be assessed at the same time (like technology, ease of cultivation, need to pay the investment back and revitalization of societal structures).

The second problem is related to the scale of the study. Basin-wide analyses are required to assess the time evolution of consumptive water use as affected by all concurrent processes, particularly modernization, abandonment and the expansion of irrigation. The current Ebro River Basin Hydrologic Plan 2022–2027 (Government of Spain, 2023b) contemplates 38 k ha of new irrigated land in the Ebro-Aragón region, of which 26 k ha are a carry-over from the previous Plan. Our analysis has estimated an increase in irrigated area of 1.4 k ha/year (Table 3), much smaller than the planned 7.6 k ha/year. The current level of *de facto* abandonment of irrigation could be more important than the planned irrigation developments. On the other hand, modernization has not yet reached WUAs with high risk of abandonment. Our results suggest that the area effectively irrigated in the Ebro-Aragón region is significantly lower than the area presented in Table 3. The net effect of these processes on the consumptive water use of irrigated agriculture is to be determined.

The basin is also the key level to control consumptive use in real time, particularly in the case of water shortages. When the river basin organization restricts access to water by farmers, modernized WUAs are in a much better situation than the rest. First, modernization almost always increases the water storage capacity of the WUA. Additionally, modern technologies permit to attain high irrigation efficiencies and facilitate implementation of regulated deficit irrigation (Fereres and Soriano, 2007). The need to adapt to variable water allocations from year to year has facilitated the expansion of crops like almond, which in the local conditions can maintain a positive economic margin even with relevant water restrictions (Girona et al., 2005; Goldhamer et al., 2006).

Irrigation modernization can bring many positive effects to farming and food security (Berbel et al., 2019), but it needs to maintain or increase the environmental outcomes of irrigated areas in order to contribute to the sustainable intensification of agriculture (Pretty et al., 2018). A critical issue is to maintain consumptive water use within the limits established by river basin organizations. Since these limits change every year to accommodate water availability, adaptive irrigated farming is required for success. Sustainable intensification requires additional environmental checks, such as diffuse pollution, for which irrigation modernization has shown limited but promising results in the Ebro-Aragón region (Jiménez-Aguirre and Isidoro, 2018).

4. Conclusions

The classification of irrigated land for modernization purposes has permitted to assess the effect of public policies in the Ebro-Aragón during the last two decades. Progress has been observed in three phases of irrigation modernization, and the change between categories of irrigated land has been quantified. The integral modernization of 103 k ha has revitalized the irrigated agriculture sector and many rural areas in the Ebro-Aragón. Modernization efforts will be required to continue reforms in the remaining 102 k ha of IDN, the 86 k ha of RDS and the 31 k ha of RDT. Maintaining the public investments of the last two decades would sustain the current integral modernization rate of 5.2 k ha/year. However, public funds are also required for energy rationalization in the 104 k ha of IPE and for digitalization, particularly in WUAs having already gained access to modern infrastructure. Progress in modernization in the coming two decades will be far from completing the process in the Ebro-Aragón.

Modernization processes are happening in the Ebro-Aragón while some new land is set to irrigation and the intensity of irrigation is low in traditional WUAs: RDT (20 %), IDN (33 %) and RDS (61 %). As a consequence, the effectively irrigated area seems to be way lower than the reported 476 k ha. Modernized irrigated agriculture will continue efforts towards sustainable intensification, with less land facing the challenge of sustaining agricultural production while reducing environmental harm. These complex changes need to be assessed from the point of view of basin-wide consumptive use of irrigated agriculture.

CRediT authorship contribution statement

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Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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