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Effects of modernization and medium term perspectives on water and energy use in irrigation districts.

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Effects of modernization and medium term perspectives on water and energy use in irrigation districts

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Abstract. Increasing of water use efficiency has been a key strategy for dealing with water scarcity in semiarid countries. In Spain modernization of irrigation schemes has consisted in the substitution of old open channels systems by pressurized networks. However, this improvement has represented a significant increase in water costs, mainly due to the higher energy requirements.

Five irrigation districts of Andalusia, Southern Spain, have been analyzed using performance indicators, before and after the improvement actions. Results indicate an average reduction in water diverted for irrigation of 23 %, but water costs increased in 52 %. Consequently, farmers are migrating to more profitable crops, such as citrus, with higher water requirements. Furthermore, managers' predictions about the cropping patterns for the 2020s suggest that the area devoted to citrus production will increase by 12 %, implying even higher potential maximum irrigation water demand. Hence, farmers will have to adapt to a future scenario by using deficit irrigation and other water saving technologies. Consequently, the vulnerability of the irrigated agriculture to the typical droughts of the Mediterranean climate may increase.

Keywords. Benchmarking, performance indicators, water supply systems, Andalusia

A.1. Introduction

In semiarid countries, crop production must be ensured by irrigation. In Spain, characterized by Mediterranean climate with scarce and irregular rainfall, irrigation agriculture is essential and consumes around 58 % of the water resources (Hardy *et al.* 2012) and more than 80 % in the driest regions. In Spain, the irrigated area is around 3.5 M ha, accounting for almost a third of European Union irrigated land (Lopez-Gunn *et al.* 2012).

Excessive water consumption is the main problem in maintaining a good environmental status in water resources (European Commission 2012). Irrigation water saving technologies have been the main measure used to reduce quantitative water stress in Spain since the Spanish National Plan for Irrigated Areas (MAPA 2001). This plan consisted in the modernization of water distribution infrastructure from old open channel distribution systems to pressurized networks. Annual water savings of 3000 Mm^3 were expected (Lecina *et al.,* 2010a). Most of the analysis of the cost and efficiency of the investment to improve water distribution efficiency (called 'modernization') has been made by ex-ante models. Related to this, Berbel *et al.* (2011) studied the implementation of the Program of Measures according to Water Framework Directive in Guadalquivir river basin (Andalusia, Spain).

The objective of this research was to gain knowledge about the real cost and impacts of modernization in Southern Spain. Preliminary analyses of national data show that:

a) As a result of the modernization process, surface irrigation has decreased from 42 % in 2002 to 30 % in 2011 whereas drip irrigation has increased from 30 % to 47 % over the same period (MAPA 2002, MAGRAMA 2012). Thanks to the continuous efforts to improve the conveyance efficiency, water use for irrigation per unit of irrigated area has been reduced by 21 % from 1950 to 2007 (Corominas 2010).

b) However, the energy consumption has increased by 657 % over the same period involving higher energy costs for farmers (Corominas 2010).

c) Furthermore, farmers must face the amortization, operations and maintenance costs of the new irrigation infrastructures (Rodríguez Díaz *et al.* 2012a).

Several researchers have used performance indicators for the evaluation of the water use in irrigation districts (Alexander *et al,* 2004, Malano *et al.* 2004, Rodríguez Díaz *et al.* 2008). However, in most previous research these indicators have been applied to comparative benchmarking analyses of different irrigation districts within a single year.

Benchmarking is defined as 'a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards' (Malano and Burton 2001). This methodology has been rarely used for the evaluation of modernization processes. Lecina *et al.* (2010a, 2010b) evaluated the effects of the transformation of hydraulic infrastructure on water quantity and quality in the Ebro river basin based on hypothetical scenarios. They concluded that the new pressurized systems lead to more intensive cropping patterns and, therefore, to increments in evapotranspiration.

The rise of energy consumption is becoming a major issue in the irrigation supply. Rodríguez Díaz *et al.* (2011) evaluated the joint use of water and energy in ten Andalusian irrigation districts with pressurized systems during one irrigation season. They confirmed the increased energy requirements of the pressurized networks (0.4 kWh m^{-3}) and highlighted that energy represents almost 40 % of the water costs. Rodríguez Díaz *et al.* (2012a) reported that in Bembézar Margen Derecha irrigation district (Southern Spain), water diverted for irrigation was reduced by 40 % after modernization due to the migration to more efficient conveyance and application systems. Conversely, water costs per hectare are four times bigger due to higher energy costs.

This research continues with the analysis of cost and impacts of modernized irrigated systems but innovates with a dynamic benchmarking exercise analyzing the effects of the ex-post situation (observed data). Then, a comparison is made with both pre-modernization situation and future scenario. In this paper, the impact of modernization in five irrigation districts of Andalusia (Southern Spain) is evaluated applying water, energy and economic indicators. These indicators have been calculated for the 1996 to 2002 irrigation seasons, before modernization was implemented and for two irrigation seasons (2010-2012), when the new hydraulic infrastructures (pressurized networks) were fully operating. Finally, a future scenario developed according to the perceptions of the irrigation district managers is forecasted for the horizon 2020.

A.2. Methodology

A.2.1. Selection of irrigation districts

The irrigation districts selected for this work were Bembézar Margen Izquierda (BMI), Bembézar Margen Derecha (BMD), Sector BXII (BXII), Genil Margen Derecha (GMD) and Guadalmellato (GU) (Fig. A.1). All of them were modernized in recent years when the collective pressurized networks replaced the old open channels systems, excepting BXII. This irrigation district already had a pressurized system but without water meters at farm level, so volumetric billing was not possible. In all the districts, before the improvement actions, the water pricing system was a fixed rate per irrigated hectare without considering the volume applied. After the modernization processes, users were charged according to a mixed water pricing system. Energy costs for pumping are paid according to a volumetric pricing system, whilst maintenance, operation and management costs are paid at a fixed rate per unit irrigated area.

Before the modernization, users received water without pressure, and more than 70 % of the area used surface irrigation, with only a small percentage using trickle irrigation for fruit trees. These farmers had their own reservoirs and pumping stations. The new infrastructure allows users to irrigate on-demand, so the flexibility has been hugely increased. Drip irrigation is the most widespread system and surface irrigation (predominant before modernization) has virtually disappeared. The total investment was € 123.8 M (€ 3,235 ha^{-1}).

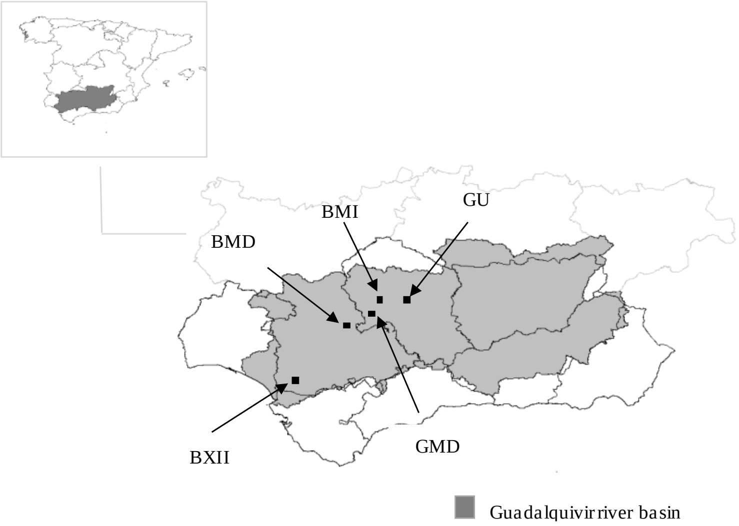

Fig. A.1. Location of the selected irrigation districts

The selected irrigation districts cover a total irrigated area of 38,285 ha, accounting for 11 % of the modernized area in Andalusia (Lopez-Gunn *et al.* 2012). All of them belong to the Guadalquivir river basin, characterized by Mediterranean climate with scarce and irregular rainfall (annual average around 550 mm) and high potential evapotranspiration rates, around 1335 mm as annual average (Rodríguez Díaz *et al.* 2007).

A.2.2. Water and energy use indicators

Water and energy use indicators selected in this work were mostly suggested by IPTRID (International Programme for Technology and Research in Irrigation and Drainage) (Malano and Burton 2001):

1. Annual irrigation water supply per unit irrigated area, Is (m^3ha^{-1}). This is the ratio of the total annual volume of water diverted or pumped for irrigation and the irrigated area.
2. Theoretical crop water requirements per unit irrigated area, ETc (m^3ha^{-1}). This indicator shows the ratio of the theoretical crop water requirements and the irrigated

area. The crop evapotranspiration is estimated as described in FAO 56 (Allen *et al.* 1998).

3. Theoretical crop irrigation water requirements per unit irrigated area, Ir (m^3ha^{-1}). This is the theoretical volume of irrigation water required by the crops divided by the irrigated area. The value of Ir is obtained by subtracting the effective rainfall (P_{ef}) from crop evapotranspiration.
4. Annual Relative Water Supply, *RWS*. This is the ratio of the total annual volume of water diverted or pumped in the irrigation district, Is (m^3) plus the effective rainfall, P_{ef} (m^3) divided by the theoretical crop water requirements, ETc (m^3).
5. Annual Relative Irrigation Supply, *RIS*. This indicator represents the total annual volume of water diverted or pumped in the irrigation district, Is (m^3) divided by the theoretical crop irrigation water requirements, Ir (m^3).
6. Cost related to the water agency tariff, C_C (€ha^{-1}). This is a fixed cost paid by farmers to the water authorities through the irrigation district for their water allocation withdrawn from reservoirs and delivered to the irrigation district. This cost is computed by hectare (Berbel and Gómez-Limón, 2000).
7. Maintenance cost, C_M (€ha^{-1}), also computed by hectare.
8. Energy cost. This represents the total annual energy cost divided by the total annual irrigation water supply, C_{EW} (€m^{-3}), o per unit of irrigated area C_{EA} (€ha^{-1}).
9. Total water costs per unit of irrigated area, C_{TA} (€ha^{-1}). This is the sum of all costs associated to irrigation (water agency tariff, maintenance and energy cost) per unit of irrigated area.
10. Total water costs per unit of supplied water, C_{TW} (€m^{-3}). This indicator represents the sum of all cost related to irrigation per unit of volume of water delivered to farmers.
11. Ratio of energy to total water costs, C_{EW}/C_{TW}. This is the proportion of total water costs related to the energy cost.
12. Output per unit irrigated area, O_A (€ha^{-1}). This indicator is obtained dividing the gross value of the agricultural production within the irrigation district by the irrigated area.
13. Output per unit irrigation supply, O_S (€m^{-3}). This represents the gross value of the agricultural production divided by the volume of irrigation water delivered to farmers.
14. Output per unit crop water transpiration, O_{ETc} (€m^{-3}). This is the ratio between the gross value of the agricultural production and the total volume of water required by crops, ETc (m^3).

15. Apparent labour productivity, P_L (€ AWU^{-1}). This indicator represents the gross value of the agricultural production divided by labour required in the irrigation district, estimated as annual work units (AWU). One AWU is equivalent to one person working full-time during a year. The labour input according to each crop has been obtained from Berbel and Gutiérrez (2004).

A.2.3. Data collection

In order to evaluate the modernization impacts on water and energy use, two different periods were analyzed for the five irrigation districts:

- 1996 to 2002 (pre-modernization period).
- 2010 to 2012 (post-modernization period).

To ensure consistency in the way the indicators were calculated across all irrigation schemes, IPTRID provides definitions and a methodology for their calculation (Malano and Burton 2001). In this study, all the data were collected in accordance with these guidelines using information routinely collected by the irrigation districts. Data required to calculate the indicators are typically recorded on a daily basis as part of management operations (for example, records on water use, costs and crops grown on each farm). Climate data were obtained from agroclimatic weather stations located in every irrigation district (Fig. A.2).

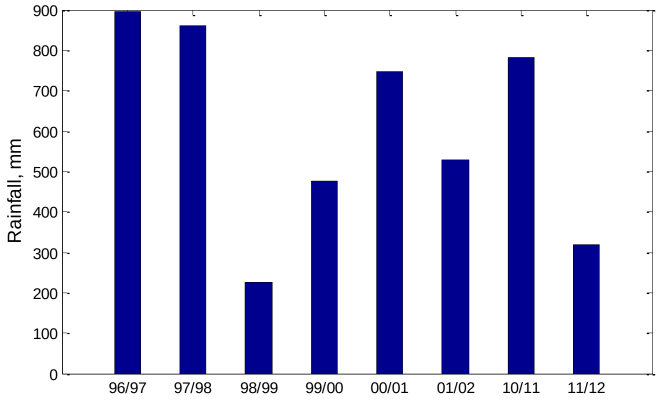

Fig. A.2. Annual average rainfall in the selected irrigation districts

A.2.4. Future scenarios

To provide medium-term trends for water demand, an estimation of the areas that may be devoted to each crop in 2020 was carried out. For this purpose, a survey was conducted among managers of irrigation districts asking about their predictions of growth / decrease of the area devoted to every crop in the next ten years. Then the crop water requirements for the 2020 scenario were estimated using the CROPWAT computer model (Clarke 1998). Afterwards, both the past and present water demand were compared with the 2020 synthetic trending scenario.

A.3. Results and discussion

The performance indicators were calculated for 1996 to 2002 irrigation seasons, related to pre-modernization period and for 2010 to 2012 irrigation seasons, corresponding to post-modernization period. Most of the data corresponding to the pre-modernization period were previously collected by Rodríguez Díaz *et al.* (2008). The obtained results are presented below.

A.3.1. Water use

The water allocations for the irrigation districts in the studied seasons are shown in Fig A.3. The average value obtained in pre-modernization period was 7164 m^3ha^{-1} whereas the average value in post-modernization period was 5508 m^3ha^{-1}.

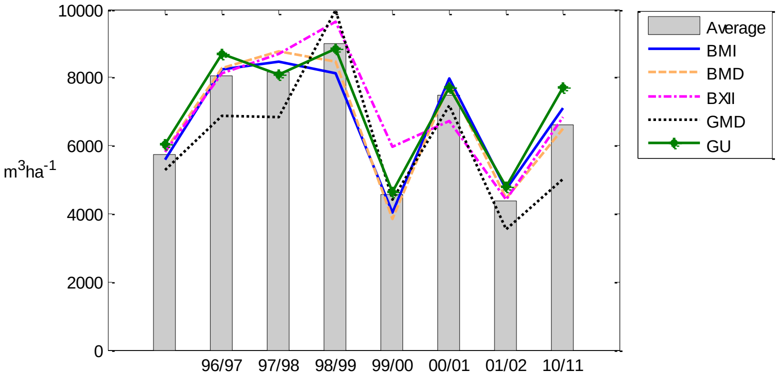

Fig. A.3. Water allocation for the irrigation districts.

Thus, the average allocations were reduced in 23 %. Concerning to annual irrigation water supply (Fig. A.4.a), a significant reduction of this indicator was obtained after the modernization process in all irrigation districts. The reductions in water use (water diverted for irrigation) were 2823 m^3ha^{-1} (37 %) in BMI, 1705 m^3ha^{-1} (22 %) in BMD, 1465 m^3ha^{-1} (20 %) in BXII, 2094 m^3ha^{-1} (33 %) in GMD and 1242 m^3ha^{-1} (16 %) in GU. On average, annual irrigation water supply was reduced by 1693 m^3ha^{-1} (23 %), similar figure to the reduction of average allocations. The transformation of the hydraulic infrastructures to pressurized networks is the main cause of the reduction of the irrigation supply. Furthermore, the new irrigation systems allow the use of trickle or sprinkler systems that enhance the water use efficiency at field scale (Carrillo Cobo *et al.* 2011).

Table A.1. Irrigated areas (ha), irrigation systems (%) and key crops (%) in the studied irrigation districts in pre-modernization and post-modernization periods

	BMI		BMD		BXII		GMD		GU	
Area, ha	3,900		11,912		14,643		2,235		5,500	
%	pre	post	pre	post	pre	post	pre	post	pre	post
gravity	80	1	75	25	*	30	90	10	90	*
drip	20	90	25	75	*	70	10	75	5	*
citrus	9	47	15	50			34	64		
maize	47	26	33	28		9	24	15	34	33
cotton	13		24	8	41	49	25	5	9	12
sunflower	10	3	8	3	5	4	9	6	10	13
wheat									17	18
sugar beet					44	20				
tomato					4	11				
olive tree		10								

*Not available

Fig. A.4.b shows the evolution of the total crop water requirements (*ETc*) before and after modernization. *ETc* decreased in BMI (from 8653 m^{3}ha^{-1} to 7076 m^{3}ha^{-1}) and GMD (from 8781 m^{3}ha^{-1} to 7546 m^{3}ha^{-1}), it was more or less constant in BMD (8385 m^{3}ha^{-1} in the pre-modernization period and 8410 m^{3}ha^{-1} in post-modernization) and it was increased in BXII (from 8310 m^{3}ha^{-1} to 9267 m^{3}ha^{-1}) and GU (from 7979 m^{3}ha^{-1} to 8430 m^{3}ha^{-1}). Differences on the *ETc* evolution are caused by the changes in the cropping patterns after the modernization (Table A.1). In BMI and GMD, maize and cotton, high water demanding crops, have been replaced by young citrus trees that are currently the main crops (47 % and 64 % of cultivated area respectively). Therefore, crop water requirements have diminished temporally in the post-modernization period. In BMD, citrus (which most of them are young trees and therefore demanding less water) are now the main crops. However, the presence of cotton, which is the third most important crop, has meant that *ETc* has remained practically constant. Either way, in BMI, GMD and BMD, an increase of *ETc* over the coming years is expected because citrus trees that are currently young will be in full production and, therefore, will require more water. In BXII, the replacement of sugar beet by cotton has led to an increase of *ETc*. Although this irrigation district already had a pressurized network, after the installation of water meters (facilitated with the modernization), farmers pay according to the volume of water applied and hence, they try to maximize their benefits by growing most profitable crops. In GU, the rise of cotton area has increased crop water requirements.

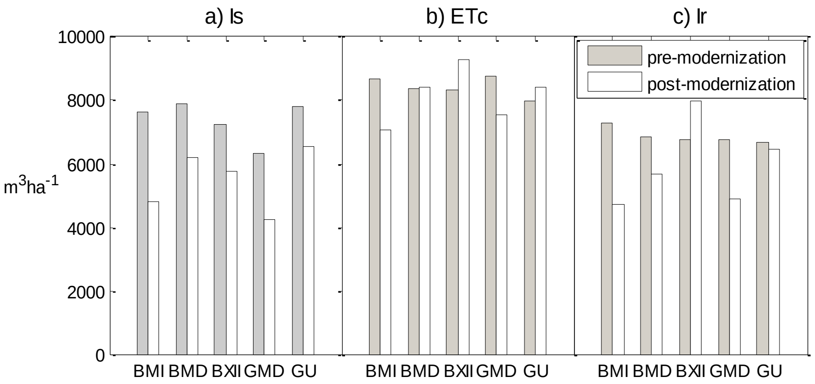

Fig. A.4.a Annual irrigation water supply (Is), **b** crop water requirements (ETc) and **c** crop irrigation requirements (Ir) in pre and post-modernization periods.

Crop irrigation water requirements (Fig. A.4.c) have decreased in most of the irrigation districts where spring-summer crops were replaced by annual crops, such as citrus. This change entails a greater rainfall use. In contrast, in BXII, the replacement of sugar beet (that uses an important fraction of the rainfall due to its cropping period) by cotton, has led to a raise of maximum irrigation requirements of 1209 m^{3}ha^{-1} (18 %). On average, crop irrigation water requirements have only decreased by 4 % while the reduction in water diverted for irrigation was up to 23 %. Hence, return flows have been reduced.

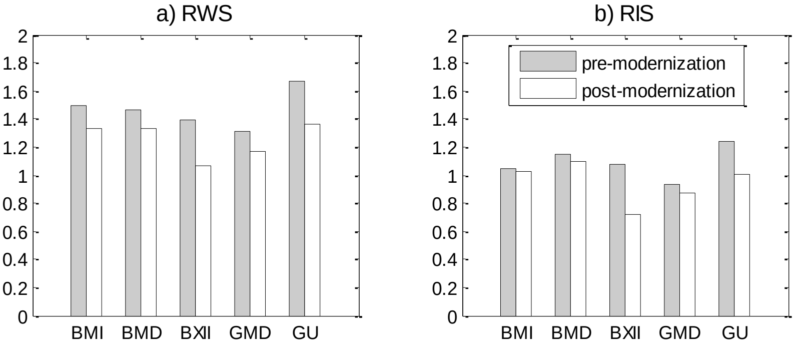

Fig. A.5.a RWS and **b** RIS for the irrigation districts before and after the modernization

However, adequacy indicators are needed to understand whether an improvement in the water use has occurred (Fig. A.5). The value of *RWS* has diminished in all irrigation districts. Likewise, *RIS* value, which relates irrigation water supply and theoretical irrigation water requirements (Rodríguez Díaz *et al.* 2008), has also been reduced in all irrigation districts: from 1.05 to 1.03 in BMI, from 1.15 to 1.10 in BMD, from 1.08 to 0.72 in BXII, from 0.93 to 0.87 in GMD and from 1.24 to 1.01 in GU. Theoretically, *RIS* values around 1.0 show that the full irrigation requirements were met. *RIS* indicator in BMI, BMD and GU showed values around 1 which means that water is used efficiently. In BXII and GMD, *RIS* was lower than 1, which entails deficit irrigation (Rodríguez Díaz *et al.* 2012b).

A.3.2. Water costs

Water cost has three items (Table A.2): the cost related to the water agency tariff, C_C, the maintenance cost, C_M and the energy cost, C_{EA} o C_{EW}. The amortization costs of the water distribution networks and on-farm irrigation systems are not included in the analysis.

Relating to C_C, an increase has been observed in all irrigation districts: 20.1 €ha^{-1} (40 %) in BMI, 16.8 €ha^{-1} (33 %) in BMD, 1.5 €ha^{-1} (2 %) in BXII and 1.8 €ha^{-1} (3 %) in GMD. However, in GU, C_C has reduced by 24 % (21.4 €ha^{-1}) since this irrigation district has now assumed responsibility for maintaining the hydraulic infrastructure. This task was previously carried out by the water authorities and the cost was included in C_C.

Table A.2. Water costs before and after the modernization process

	BMI		**BMD**		**BXII**		**GMD**		**GU**	
	pre	post	pre	post	pre	post	pre	post	pre	post
C_C, €ha^{-1}	49.9	70.0	50.2	66.9	87.5	89.0	64.5	66.2	88.3	66.9
C_M, €ha^{-1}	43.9	77.0	70.5	76.5	69.0	95.6	42.9	96.1	80.1	106.4
C_{EA}, €ha^{-1}	0.0	124.3	2.9	140	115.4	147.6	*	*	14.1	48.9
C_{TA}, €ha^{-1}	93.9	271.3	123.6	283.5	271.9	332.2	107.4	162.3	182.4	222.2
C_{EW}/C_{TW}, %	0	46	2	49	42	45			8	22

* Not available

The maintenance cost, C_M (Table A.2), has increased after the modernization because the upkeep of pressurized networks is more expensive and skilled labour is required (Rodríguez Díaz *et al.* 2012a). Thus, C_M has increased 33 €ha^{-1} (75 %) in BMI, 6 €ha^{-1} (9 %) in BMD, 53.2 €ha^{-1} (124 %) in GMD and 26.3 €ha^{-1} (33 %) in GU. In BXII, C_M has also risen by 26.6 €ha^{-1} (39 %) because of the maintenance of the new infrastructure to measure the volume of water used and the purchase of agricultural machine. Energy cost has evolved from values close to 0 in GU, BMD and BMI to values of 0.01, 0.02 and 0.03 €m^{-3}, respectively (Fig. A.6). In BXII, energy cost has increased from 0.02 to 0.03 €m^{-3}. The significant increment of energy cost is due to the combined effect of higher energy requirements of pressurized systems and the rise of energy price, that has been increased more than 100 % in the last years (Rodríguez Díaz *et al.* 2012c). In this regard, energy is the main contributor to irrigation cost in almost all the irrigation districts. Energy represents up to 50 % of the total water costs (e.g. BMD).

The rise of energy cost has led to higher total irrigation costs, C_{TA} (Table A.2). C_{TA} has risen 177.4 €ha^{-1} (189 %) in BMI, 159.9 €ha^{-1} (130 %) €ha^{-1} in BMD, 60.3 (22 %) €ha^{-1} in BXII, 54.9 €ha^{-1} (51 %) in GMD and 39.7 €ha^{-1} (22 %) in GU.

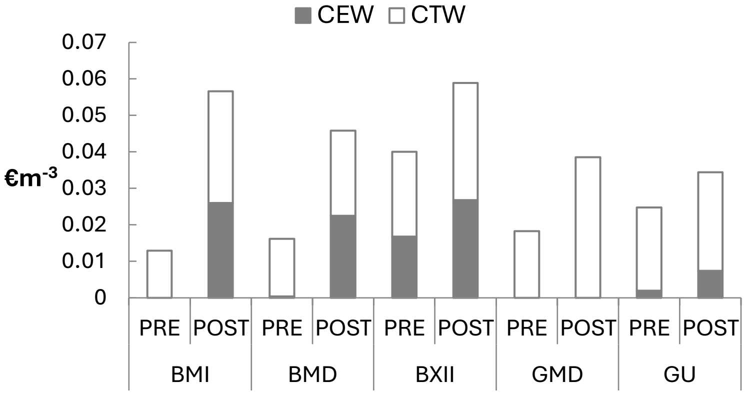

Fig. A.6. Energy cost (C_{EW}) and total irrigation cost (C_{TW}) in pre-modernization and post-modernization periods.

A.3.3. Productivity

The productivity indicators are shown in Table A.3. In BMI, BMD and GMD, the change to more profitable crops has entailed greater outputs per unit irrigated area. By contrast, in BXII and GU (irrigation districts with traditional crops) outputs per unit irrigated area have decreased mainly due to the market prices. In this work, possible increments in crop yield due to the adoption of pressurized irrigation systems, in which water use by crops is more efficient, have not been taken into account. Better irrigation systems increase the water availability, uniformity and flexibility and consequently, crop transpiration. Lecina *et al.* (2010b), estimated that the land productivity (€ha^{-1}) in sprinkler irrigation, with more intensive cropping patterns, was around 51 % higher than in surface irrigation. However, in some of the studied districts there was a significant percentage of drip irrigation before modernization (mainly for irrigation of fruit trees and citrus) and it has not been possible in our survey to distinguish between the previous and the current situation in terms of unit yields.

Table A.3. Apparent productivity indicators (output per unit irrigated area, OA, output per unit irrigation supply, OS; output per unit crop water demand, OETc; apparent productivity of the labour, PL) before and after the modernization processes

	O_A, € ha^{-1}		**O_S,** € m^{-3}		**O_{ETc},** € m^{-3}		**P_L,** € AWU^{-1}	
	pre	post	pre	post	pre	post	pre	Post
BMI	2,946	4,315	0.40	0.93	0.34	0.62	45,311	27,507
BMD	3,955	4,509	0.53	0.80	0.47	0.55	37,651	30,379
BXII	3,341	3,120	0.49	0.66	0.40	0.35	52,599	42,151
GMD	3,799	4,235	0.70	1.09	0.43	0.57	31,183	23,911
GU	2,740	2,029	0.37	0.36	0.37	0.24	41,974	34,363

Output per unit irrigation supply has also increased since the irrigation water supply was significantly reduced in all irrigation districts and the output per unit irrigated area increased in some cases. Carrasco *et al.* (2010), in their study about crop water productivity in the Guadalquivir river basin, obtained an increase of this indicator from 1989 to 2005 due to, among other factors, the more efficient use of irrigation water.

The value of output per unit crop water demand has increased after the modernization in BMI, BMD and GMD mainly due to the increase of output per unit irrigated area. In contrast, in BXII and GU, this indicator has reduced because of the increase of ETc and the reduction of output per unit irrigated area.

Productivity of labour has shown lower values in the post- modernization period in all irrigation districts. In BMI, BMD and GMD, the migration to citrus has involved a rise of input labour whereas in BXII and GU, the lower value of the output per unit irrigated area after the modernization, has entailed the reduction of the productivity of labour.

A.3.4. Perspectives about future cropping patterns and theoretical water requirements

In this analysis, the cropping patterns corresponding to the 2001/2002 and 2010/2011 seasons were assumed as representative of pre-modernization and post-modernization periods, respectively. The likely distribution of the key crops in 2020 was estimated from managers' perceptions about the evolution of the crop area in 2020 (Table A.4). The area devoted to citrus has significantly increased from 3511 ha in 2001/2002 to 8900 ha in 2010/2011 (153 %). The area devoted to citrus rises yearly (Montesinos *et al.* 2011) and the predictions for 2020 show an additional increase of 1063 ha (12 %) compared to the area devoted to citrus in 2010/2011. Consequently, traditional irrigated crops in these irrigation districts such as cotton, sunflower, wheat or sugar beet, will suffer substantial reductions. Considering only the influence of the cropping patterns change on evapotranspiration and irrigation requirements, an average hydrological year has been selected for every district (data taken from the long-time climate series). Thus, the cropping patterns of 2001/2002, 2010/2011 and the future scenarios were analyzed for the same climate conditions. Fig. A.7 shows that the progressive incorporation of citrus in the cropping patterns produces an increase in the maximum irrigation requirements when the trees reach their mature stage.

Table A.4. Predictions of change (%) in the irrigated areas devoted to the main crops for 2020 compared to the 2010/2011 irrigation season

%	BMI	BMD	BXII*	GMD	GU	Collectively
Cotton	10	-10	0	-10	-10	-2
Sunflower	-10	0	0	-25	0	-2
Wheat	10	0	0	-25	-25	-11
Maize	10	10	0	-25	0	5
Olive tree	-20			5	10	-2
Citrus	10	10		20	20	12
Sugar beet			0			0

* The manager of BXII estimated the same cropping pattern for 2010/2011 and 2020.

Comparing the 2010/2011 and 2001/2002 cropping patterns, the *ETc* decreases in BMI and BMD, remain constant in GMD and GU and increases in BXII. Collectively, the crop water requirements (*ETc*) increased by 2 %. Theoretical irrigation water requirements (*Ir*) are lower in 2010/2011 than in 2001/2002 for all irrigation districts, with the exception of BXII due to the replacement of sugar beet by cotton (Table A.1). For all districts jointly, *Ir* is reduced in 3 %. Thus, it can be assumed that the crop water requirements and irrigation needs remain practically constant in the short term. The result of our research regarding the behaviour of *Ir* and *ETc* is congruent with the results of the agro-economic model developed by Berbel and Mateos (2014) which analyses the impact of modernization in water use and consumption.

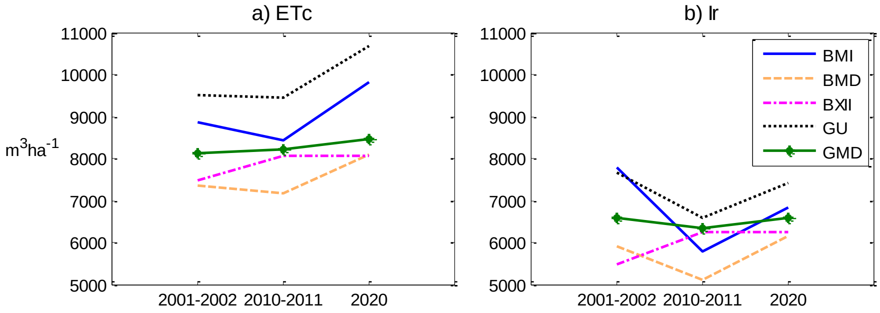

Fig. A.7. Crop water requirements (ETc) and irrigation water requirements (Ir).

Nevertheless, an increase of crop evapotranspiration for 2020 is expected compared to 2010/2011 irrigation season in all the irrigation districts excepting BXII, whose manager estimated the same cropping pattern for 2010/2011 and 2020. On average, the value of *Ir* is also expected to increase by 5 %. Although the comparison of 2001/2002 and 2010/2011 cropping patterns shows a decrease of *ETc* and *Ir* in most irrigation districts, it must be considered that high water requirement crops (cotton or maize) have been replaced by young citrus trees. However, in the 2020 scenario, the new citrus trees, that were already planted before the modernization processes plus the additional post modernization increment, will be in full production with maximum water requirements. Thus, the water savings that were obtained after modernization could be dramatically reduced and, in the next ten years, the net water losses (evapotranspirated water that goes to the atmosphere and cannot be reused by other users) could be even higher than before the improvement actions. The fact that water quota has been reduced in these irrigation districts by 25 % from previous levels may avoid the 'rebound' effect producing deficit irrigation as farmers cannot supply full irrigation needs.

The impacts of a changing climate on irrigation demand have not been included in the analysis and, as in other Mediterranean regions, any increase in evapotranspiration, coupled with changes in rainfall distribution, are expected to cause significant increases in irrigation demand. Increase in demand forecasts for the most common crops in the region for 2050 horizon estimates a range from +15 to +25 % for the 2050s and from +25 to +35 % for the 2080s (Rodríguez Díaz and Topcu 2010). These increases can aggravate the current situation.

A.4. Discussion and concluding remarks

In order to evaluate the impacts of irrigation system modernization on water and energy use, five irrigation districts, in the Guadalquivir basin with pressurized networks, have been analyzed.

The results show an average reduction of irrigation water abstraction of 23 %, mainly due to improvement of water distribution efficiency. Contrasting with the reduction of water diverted for irrigation, the energy cost was increased by 149 %, leading to an average rise of water costs of 52 %. Additionally the water tariff after the modernization process has become volumetric instead of the fixed land based (flat rate) previous system. All costs including operation and maintenance of new systems (pressurized distribution, metering etc.) are covered by the new tariff.

Farmers have carried out changes on their cropping patterns in response to the increased irrigation cost and the availability of a more flexible irrigation system. Area of more profitable crops, such as citrus, has increased productivity of land. Similar trends were observed for the outputs per unit of irrigation water supply, which have risen in 44 %. In contrast, these higher value crops require more water when they are irrigated at full requirement. Thus, the comparison of 2001/2002 and 2010/2011 irrigation seasons with the synthetic 2020 scenario, considering a standard hydrological year, shows a rebound effect in most irrigation districts. Current crop water requirements are just 2 % higher than in 2001/2002 irrigation season due to the substantial area devoted to young citrus trees (with reduced water demand). However, on 2020, increased area of citrus and maturity of those crops, will involve an increase in 9 % of crop water requirements compared to 2001/2002.

Thus, the higher water costs and the increased flexibility in the water availability after the modernization process, lead to the incorporation of more profitable crops (Playán *et al.* 2006; Lopez-Gunn *et al.* 2012; Rodríguez Díaz *et al.* 2012a). The adoption of higher water demanding crops has been also indicated by Pfeiffer and Lin (2010), who have highlighted that more efficient irrigation systems improve the effectiveness of water, but the saved water is used to increment the crop yields, adopt more intensive crops or increase the irrigated areas.

Furthermore, the likely increment of crop yields due to the increased operational flexibility in the water conveyance system, which would entail further increase of ETc, has not been taken into account in this work. Therefore, the change to higher water demanding crops will enhance the dependence on irrigation water and the vulnerability of agricultural productions to droughts periods, typical of this region. Berbel *et al.* (2013) have described the process at basin level analysing the trajectory of Guadalquivir towards basin closure.

Modernization will probably not lead to net water savings at basin level as it has been already observed by Molle and Berkoff (2007), because of the change in crop plan and water use intensity. The solution adopted in Spain has been the reduction in water rights allotment that averages 25 % over the previous quota, e.g. most of the irrigation districts analyzed in this research has seen their water right allotment reduced from the previous 8.000 m^3ha^{-1} to 6.000 m^3ha^{-1} after the modernization were completed. This policy controls any possible rebound effect because even if maximum potential irrigation requirements increase, the water supply constraint will force farmers to use deficit irrigation and other water saving technologies.

This research has focused on the impact of water saving technologies (related to water delivery and application efficiency) in large irrigation schemes considering variables such as land use changes, energy use, water cost, and productivity factors. Further research should also study the impact of the reduction of water allocations on the return flows and also it should consider the impact on crop yields of the improvement of water supply, and consequently the higher uniformity and flexibility of water availability for farmers.

Finally, modernization allows the implementation of economic instruments such as those promoted by European Commission (2012) including an increase in water cost and metering as a pre-requisite to use water price as a signal to allow farmers efficient assignation of water resources.

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