Short Research Article

Water, energy, food and environment nexus in six irrigation districts from the Spanish Duero basin

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ABSTRACT

Background and objective: Duero is the second largest Spanish river which supplies water to a larger and depopulated area where agriculture is the major economic sector. The irrigated area has doubled in the last fifteen years and consumed 85% of total water resources at present. Perspectives for the near future highlight the need to foster rural development and settle population. The challenge ahead is to maintain irrigation but tackling the issues on water scarcity, energy prices and fertilizer cost. This work is aimed at providing some clues on the water-energy-food-ecosystem nexus in rural areas of the Duero basin.

Methodology: Six Duero irrigation districts (ID) (Adaja, Tordesillas, Aranda-Tordesillas, Tordesillas-Zamora, Villalar de los Comuneros and Carracillo) have been selected and the study focuses on the evolution of water and energy consumption, as well as the main crops production, the ecosystems' status and the major municipalities population trends across the IDs, from 2010 to 2020.

Results and conclusion: the annual average water supply was different among ID; the highest value corresponded to "Tordesillas" (6895 m^3/ha) and "Adaja" (6287 m^3/ha). The energy consumption was very high in all IDs. Likewise, the highest water productivity and total gross income indices corresponded to potato and sugar beet and the lowest to barley and sunflower. The total production costs in the last two crops were higher than the gross income and consequently, it would result in economic losses in the case of subsidies lack. The population in the main municipalities of the six IDs has decreased in the study period and does not meet the goal of the Spanish Plan for modernizing irrigation systems of maintaining/increasing population in rural areas. The results would be a valuable tool to develop sustainable solutions (at regional scale) for fair and sustainable sharing food production resources that will affect the water, energy, food and ecosystem (WEFE) nexus.

Keywords: Duero basin; Water Energy Food and Environmental nexus; Irrigation sustainability

1. INTRODUCTION

Irrigated areas continue to increase worldwide and, in particularly, in Spain since the need to provide food for an increasing population (MAPA, 2020). In Spain, irrigation fosters economic development of rural areas and settles population (MAPA, 2008). It contributes about the 69% of total agricultural production in Spain (FENACORE, 2021). Likewise, it is also a valuable socio-economic sector with the development of agri-food companies in the rural areas and the creation of jobs which employs 4% of the Spanish population (Berbel and Gutiérrez-Martin, 2017; Gómez-Lion and Gutiérrez-Martin, 2017). However, irrigation is the Spanish economy sector with the highest water consumption (about 15500 hm^3) 70% of the country's total consumption in 2018 (Instituto Nacional de Estadística, 2020) and it strongly impacts surface and subsurface water resources.

In addition, pressure irrigation systems demand high energy consumption which has been estimated between 0.3 and 0.4 KWh/m^3, regarding on the system. This value can reach 4 KWh/m^3 in desalinated water (Corominas, 2010; Cabrera et. Al., 2010; Camacho, 2012; Camacho et al., 2017; Omedas, 2020). Therefore, it raises concern on how to produce such an energy and the generation of greenhouse gases. In addition, it should be highlighted that, at present, the Plan for modernizing irrigation has changed gravity irrigation methods into more water efficient systems (pressure methods) but demanding energy (Camacho Poyato et al., 2017; Fernandez Garcia et al., 2018; Rodríguez Diaz, 2019); therefore, at present, the sustainability of irrigation sector depends not only on water efficiency but energy efficiency systems and energy cost. Likewise, energy consumption increased in areas of aquifer's overexploitation, that occurs when the ratio between pumping and recharging is higher than 0.8 (MAPA, 2008); water tables move deeper and consequently, the pumping equipment efficiency reduces and energy requirements increase (Moreno et al., 2010; Corominas, 2010). Moreover, the overexploitation leads to water quality and ecosystem deterioration and loss of wetlands and bird/fish species as in the southern Spanish basins (Esteban et al., 2017). It should also be noted that water resources and soils contamination produced by infiltration of agrochemicals and/or the use of unconventional water (wastewater and desalinated water) is another key issue on the impact of irrigation in the ecosystems.

Within this context and keeping in mind the goal of fixing/increasing population in rural areas, the sustainability of the irrigated agriculture sector requires a proper management of water and energy resources, especially if we take into account the climate change effects such as: the reduction of precipitation, the increase in crops water needs caused by the increase in temperature and droughts (Sánchez-Mora, 2020). Several studies have studied the water, energy, food and environment nexus (Willaarts and Mayor, 2017; Hardy and Garrido, 2010; Hardy et al., 2012; Fernández García et al., 2018). This study aims at assessing the sustainability of IDs in several Duero basin exploitation systems, specifically on the irrigation areas: Adaja, Tordesillas, Aranda-Tordesillas, Tordesillas-Zamora, Villalar de los Comuneros and Carracillo. The study has analyzed the evolution of water and energy resources consumption, crops water productivity and gross income on the main crop during the last ten years, the results are a valuable information to be taking into account in decision-making of WEFE nexus planning in the area.

2. MATERIAL AND METHODS

This work was carried out in six IDs: "Adaja", "Tordesillas", "Aranda-Tordesillas", "Tordesillas-Zamora", "Villalar de los Comuneros" and "Carracillo", which have been modernized to pressure irrigation since the beginning of the XXI century. Table 1 shows information on water sources, exploitation system, irrigable area, main municipalities and natural areas.

The information was compiled from different sources as presented in Table 2 and regards to water supply, total annually irrigated area, main crops area and crops yield; likewise, economic indices such as gross income and total cost of production were also gathered but do not include subsidies or taxes.
Gross income was calculated as the difference between revenue and total costs, which includes the costs of machinery, labour, crop production inputs, irrigation and capital invested in the productive process.

The water consumption's analysis was addressed by the evolution of the annual water supply within the last ten years as in Hardy and Garrido (2010), Willaarts and Mayor, (2017) and Willarts et al., (2016).
The water supply was calculated as the ratio between water volume and the total irrigated area per year. The total annual energy consumption was estimated as the total consumed water volume times the average energy consumption per cubic meter in Spain (0.35 kW/m^3); this value has been highlighted by different studies (Camacho et al., 2017; Omedas, 2020). In addition, the total annual energy requirement per unit area was determined as the ratio between the total annual energy consumption and the irrigated area, and it was classified as described by "Instituto para la Diversificacion y ahorro de la Energia" (IDEA) in Table 3.

The crop water productivity was calculated as the production over the water volume supply. The irrigation impact on natural areas was assessed by the exploitation index, which monitor groundwater water bodies and the concentration of the chemical substances (ammonia and/ or ammonium). if the exploitation index is below 0.80, the quantitative status of water bodies is considered poor.

Finally, the impact of irrigation on the settlement of population was assessed by looking at the population trend in the major IDs' municipalities during the last decade.

Table 1. General information of the irrigation areas

Irrigation district	**Water source**	**Exploitation system**	**Irrigable area (ha)**	**Main municipalities**	**Natural areas**
Adaja	Superficial	Cega-Eresma-Adaja	6530	Arévalo, Langa, Nava de Arévalo	wetland of Arenales, Tierra de Campiñas
Tordesillas	Superficial	Bajo Duero	2310	Tordesillas, San Miguel del, Pino, El Montico	Riberas de Castronuño, Riberas del Río Duero and tributaries
Aranda-Tordesillas	Ground water	Riaza-Duratón	794,03	Laguna de Duero, Tordesillas, Tudela de Duero	Carrascal, Riberas of river Riaza, Riberas of river Douro and tributaries
Tordesillas-Zamora	Ground water	Bajo Duero	590,26	Zamora, Toro, Tordesillas	Riberas of Castronuño, Riberas Douro river and tributaries La Nava-Rueda
Villalar de los Comuneros	Ground water	Bajo Duero	16.674,39	Toro, Tordesillas, Morales de, Toro	Riberas of Castronuño, Tierra del Pan
Carracillo	Ground water	Cega-Eresma-Adaja	2.590,83	Cantalejo, Villacastín, Cantimpalos	Valles of Voltoya and Zorita – ZEPA, Sierra of Guadarrama – ZEPA, Encinares of Adaja river and Voltoya, Lagunas of Cantalejo, Encinares of Adaja river and Voltoya – ZEPA, Sierra of Guadarrama, Lagunas of Cantalejo – ZEPA, vallys of Voltoya and Zorita, Lagunas ofSanta María la Real of Nieva

Table 2. Characteristics and compiled data sources

Data	Description	Source
Data from the hydrographic Plan of the Duero basin from 2010 to 2020	Annual water consumption, total irrigated area, irrigated area per crop, exploitation rates and pollution of groundwater bodies	Hydrographic confederation of the Douro https://www.chduero.es/
Castilla y León Irrigation monitoring plan from 2011 to 2019	Irrigation dose and yield per crop, gross income, total costs and irrigation costs per crop	Agricultural Technological Institute of Castilla y León (ITACYL) https://www.itacyl.es/
Population evolution from 2010 to 2020	Population of major municipalities in the IDs	National Institute of Statistics https://www.ine.es

Table 3. Classification of irrigation energy consumption (IDEA, 2008)

Group	Description	Specifications
1	Non consumer	EPH = 0
2	Low consumer	0 < EPH ≤ 300
3	Medium consumer	300 < EPH ≤ 600
4	Consumer	600 < EPH ≤ 1000
5	High consumer	EPH > 1000

EPH: energy consumed per irrigated hectare (kWh/ha)

3. RESULTS AND DISCUSSION

Table 4 presents the annual values of the irrigated area, the irrigation water supply and the energy requirement per unit area. The irrigation water supply varied in the range [3774-7924] m^3/ha among IDs and years thus, Adaja and Aranda-Tordesillas presented the highest coefficient of variation CV (16%-18 %). The average values range by IDs was [4881- 6895] m^3/ha, and agree with the ones presented for modernized irrigation by Corominas (2010), Rodríguez Diaz (2011), Fernandez Garcia et al. (2018) and Berbel and Espinosa Tazon (2020); however, they were lower than irrigation water consumption per unit area values before the Spanish Plan for the modernization of irrigation. Tordesillas and Adaja were the districts with the highest water consumption with respectively 6894.89 and 6286.97 m^3/ha. Irrigation water supply in pressure irrigated areas demands energy, which consumption has increased in recent years since in the area, the solid set sprinkler and center pivot are used mostly and require higher energy than drip irrigation systems. The average energy requirement per unit area have has moved between 1708.30 and 2413.21 kWh/ha in different years and agree with the values presented by Fernández García et al. (2018). Likewise, according to the energy criteria adopted by IDEA (2008), presented in Table 3, the six IDs are within the classified as high consumer.
Table 5 presents the values of water productivity (WP), gross income (GI) and total production costs (TPC) of the main crops in the area. These indexes have varied among crops thus, the average WP index ranged between 0.44 and 1.37 €/m^3, which is lower than

the one presented by Aldaya (2020) for alfalfa and, higher than the one presented by Exposito and Berbel (2017) for sugar beet, and Salvador et al. (2011) for barley, wheat, alfalfa, corn and sunflower. The average GI range was between 722.05 and 7280.82 €/ha, which is higher than those obtained by Lecina et al. (2010) for corn, alfalfa and wheat. The average highest economic indices (WP and GI) corresponded to potato (WP = 1.37€/m^3 and GI = 7280.82 €/ha) and sugar beet (WP = 1.10 €/m^3 and GI = 6730.39 €/h). However, barley and sunflower crops presented a TPC higher than the GI, that would result in economic losses if no subsidies were applicable.
The exploitation of water resources has led to the progressive decline in water tables. Thus, the exploitation index for the study areas varied between 0.28 and 1.55. In Aranda-Tordesillas and Tordesillas-Zamora, the exploitation index varied between 0.28 and 0.46, respectively but in the other IDs it was above 0.8, which highlight a poor quantitative groundwater status. Likewise, from the qualitative point of view, a high nitrate concentration has been found in the natural areas: “Los Arenales”, “Campo de Medina”, “Los Aluviales de Aranda-Tordesillas”, “Los Aluviales de Tordesillas-Zamora”, and also a high ammonium concentration in the Tordesillas.
The population’s trend has slightly decreased in the major municipalities, across the IDs, in the period studied (see Figure 1). Likewise, the ratio between the number of man and women has not changed. These results highlight that even though irrigation has contributed to the economic development of the surrounding areas it has not help to settle down population which has still moved to nearby areas with better facilities to improve social wellness such as: availability of health care centers and schools and better access to internet.

Table 4. Irrigated area, irrigation water supply and energy requirement evolutions in different irrigation area.

	Irrigated area (ha)				**Irrigation water supply (m^3/ha)**				**Energy requirement (KWh/ha)**			
Irrigation District	Average	Range	Typic Dev.	CV (%)	Average	Range	Typic Dev	CV (%)	Average	Range	Typic Dev.	CV (%)
Adaja	4848.39	2.65 - 6323.33	2440.98	50.35	6286.97	3774 - 7924	1173.11	18.66	2200.44	1320.75 - 2773.49	410.59	18.66
Tordesillas	1569.86	1216.45 - 1655.84	115.99	7.39	6894.89	5452 - 7735	634.36	9.20	2413.21	1908.39 - 2707.11	222.02	9.20
Aranda-Tordesillas	708.80	534.71 - 783.36	71.31	10.06	4880.86	3209 - 5961	789.15	16.17	1708.30	1123.06 - 2086.52	276.20	16.17
Tordesillas-Zamora	395.15	340.43 - 411.26	18.85	4.77	5025.14	4251 - 5575	392.28	7.81	1758.80	1488.01-1951.40	137.30	7.81
Villalar de los Comuneros	18677.08	14708.03 - 19566,27	1279.52	6.85	5337.45	4640-5872	395.58	7.41	1868.11	1623.95 - 2055.32	138.45	7.41
Carracillo	3209.87	2766.25 - 3612.88	321.78	10.02	4941.50	4694-5653	247.14	5.00	1729.52	1643.01 - 1978.62	86.50	5.00

Table 5. Water productivity WP, gross income GI and total production cost TPC by crops.

	WP (€/m³)				GI (€/ha)				TPC (€/ha)			
Crops	Average	Range	Typic Dev.	CV (%)	Average	Range	Typic Devi.	CV (%)	Average	Range	Typic Dev.	CV (%)
Sunflower	0.48	0.32 - 0.7	0.17	35.03	1113.21	707.93 - 1724.6	392.52	35.26	1307.57	927.09 - 1935.85	443.29	33.90
Potato	1.37	0.44 - 2.35	0.67	48.60	7280.82	2458.1 - 12163.9	3506.21	48.16	3902.35	3589.91 - 4558.55	335.78	8.60
Alfalfa	0.44	0.32 - 0.55	0.07	16.84	1957.36	1475.0 - 2282.93	249.51	12.75	1607.98	1554.11 - 1785.49	81.03	5.04
Sugar beet	1.10	0.76 - 1.31	0.20	18.65	6730.39	4437.0 - 8885.64	1606.81	23.87	2494.83	2185.07 - 2715.64	177.02	7.10
Corn	0.46	0.42 - 0.52	0.04	7.84	2392.60	2142.7 - 2698.03	179.65	7.51	1690.87	1489.86 - 1849.89	116.84	6.91
Barley	0.62	0.37 - 1.04	0.21	34.32	722.05	493.44 - 1052.38	158.98	22.02	928.10	876.41 - 959.94	27.18	2.93
Wheat	0.63	0.43 - 0.98	0.19	29.66	1209.30	982.69 - 1783.32	247.49	20.47	1096.92	1018.67-1263.83	93.58	8.53

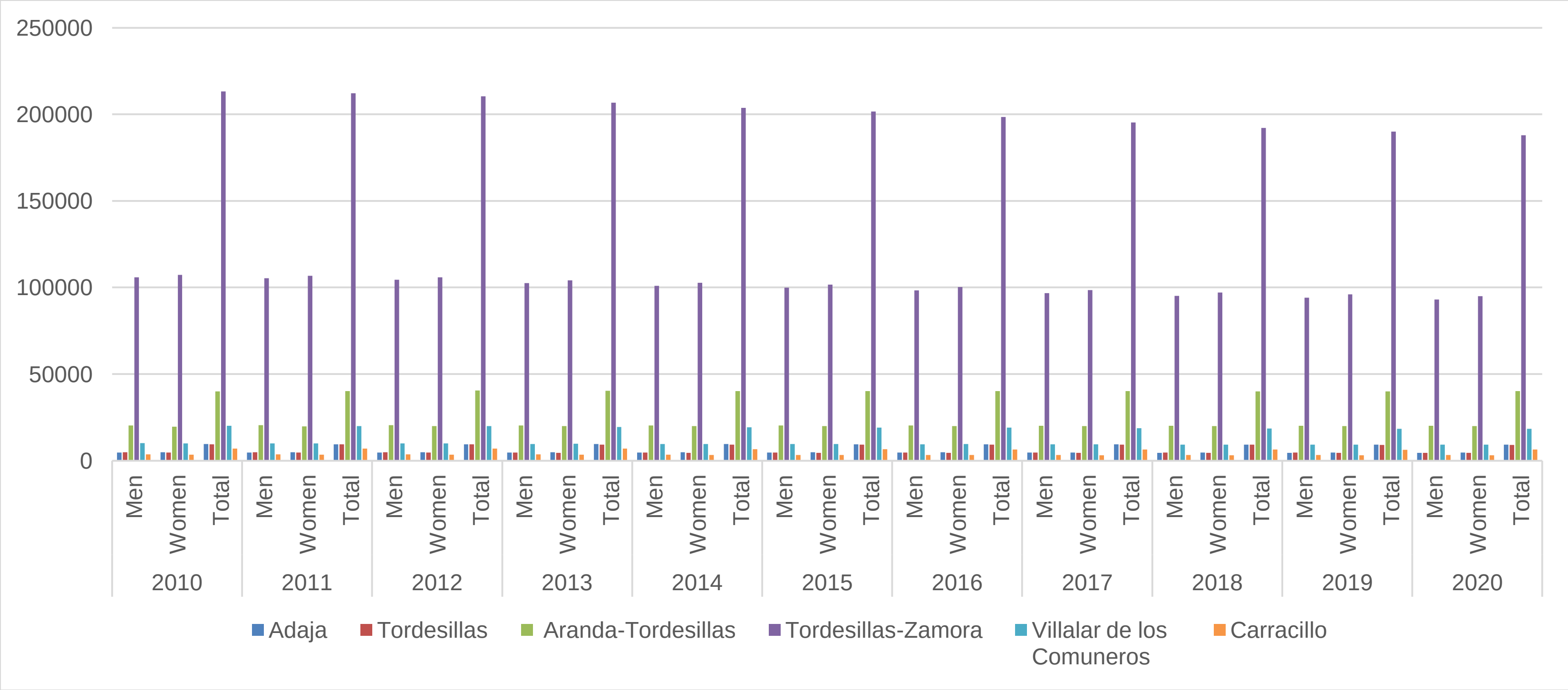

Figure 1. Population trends in the major municipalities, across the IDs

4. CONCLUSION

The WEFE nexus has been assessed in six irrigation districts of the Duero basin from 2010-2020; it focused on the evolution of water and energy consumption, as well as the main crops production and ecosystems status and population evolution. The annual average water supply was different among ID; the highest value corresponded to “Tordesillas” (6895 m^3/ha) and “Adaja” (6287 m^3/ha). The energy consumption was very high in all IDs. Likewise, the highest water productivity and total gross income indices corresponded to potato and sugar beet and the lowest to barley and sunflower. The total production costs in the last two crops were higher than the gross income and consequently, it would result in economic losses in the case of subsidies lack. Likewise, irrigation has drawdown water tables and has increased ammonia or ammonium concentrations, thus, the groundwater of the natural areas in “Los Arenales”, “Campo de Medina” and “Tordesillas” showed poor quantitative and qualitative condition. The population in the main municipalities of the six IDs has decreased in the study period and does not meet the goal of the Spanish Plan for modernizing irrigation systems of maintaining/increasing population in rural areas.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

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