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Evolution of the efficiency and agro-environmental impact of a traditional irrigation land in the middle Ebro Valley (2001-2007)

I. García-Garizábal[1]*, J. Causapé Valenzuela[2] and R. Abrahão[1]

[1] Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA). Ctra. Montañana nº 930, 50059-Zaragoza. Spain
[2] Instituto Geológico y Minero de España (IGME), C/ Manuel Lasala 44 9º B. 50006-Zaragoza. Spain.

Abstract

Alternatives in irrigation management can lead to the creation of irrigation lands that are more efficient and more respectful towards the environment. The objective of this work is to analyze the evolution of the agro-environmental impact in a traditional irrigation land of the middle Ebro Valley (Spain) which has experienced changes in its management. For such, water, salt and nitrate balances were accomplished in a hydrological basin (95 ha) in 2001, 2005, 2006 and 2007. The drought of 2005 caused more intensive water use (86%), increasing in 33% the irrigation efficiency when compared to 2001 (53%), even though a high hydric deficit (24%) was caused. Changes in the flood irrigation system management (from rotation to on-demand), maximum allocations of irrigation water, billing for the volume of irrigation water consumed and the expansion of crops with lower water and fertilization needs made it possible to achieve irrigation efficiencies of approximately 73% (an increase of 20%) and to halve salt (1.3 Mg ha^{-1} year^{-1}) and nitrate (25 kg NO_3^--N ha^{-1} year^{-1}) loads exported in the drainage. The evaluated management changes have been efficient, but nevertheless, crops still suffer certain hydric stress and since 2005 a slight but worrying negative agro-environmental tendency has been observed and should be reversed.

Additional key words: contamination, irrigation management, nitrate, salts, water quality.

Resumen

Evolución de la eficiencia e impacto agroambiental de un regadío tradicional en el valle medio del Ebro (2001-2007)

Alternativas en la gestión pueden conducir a generar regadíos más eficientes y respetuosos con el medioambiente. El objetivo de este trabajo es analizar la evolución del impacto agroambiental de un regadío tradicional del valle del Ebro (España) que ha introducido variaciones en su gestión. Para ello, se desarrollaron balances de agua, sales y nitratos en una cuenca hidrológica (95 ha) durante 2001, 2005, 2006 y 2007. La sequía de 2005 provocó un mayor aprovechamiento del agua (86%), incrementando la eficiencia de riego un 33% respecto a la de 2001 (53%), si bien, también condicionó un elevado déficit hídrico (24%). El cambio en el manejo del riego por inundación (de turnos a la demanda), la asignación de dotaciones máximas de riego, la facturación por volumen consumido, y la expansión de cultivos con menores necesidades de agua y fertilización han permitido alcanzar eficiencias de riego en torno al 73% (20% superiores) y disminuir las masas de sales (1,3 Mg ha^{-1} año^{-1}) y nitrato (25 kg NO_3^--N ha^{-1} año^{-1}) exportadas a la mitad. Los cambios de gestión evaluados han sido eficientes, no obstante, los cultivos aún sufren cierto estrés hídrico y desde 2005 se ha observado una suave pero preocupante tendencia agroambiental negativa que sería conveniente invertir.

Palabras clave adicionales: calidad del agua, contaminación, gestión del riego, nitrato, sales.

* Corresponding author: igarciaga@aragon.es
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Abbreviations used: CAP (common agricultural policy), D (drainage associated with the hydrological basin), D_I (irrigation drainage), D_{Salts} (mass of salts associated with the hydrological basin), $D_{Nitrate}$ (mass of nitrate associated with the hydrological basin), EC (electrical conductivity), EC_{NI} (EC in nonirrigated season), ECa (apparent EC: hc-horizontal configuration, vc-vertical configuration), EMR (environmental land evaluation tool; in Spanish: evaluador medioambiental de regadíos), ET_0 (reference evapotranspiration), ET_a (actual ET), ET_C (potential ET), EWDL (losses due to evaporation and wind drift from sprinkler irrigation), GI (groundwater inflow), h (water height), HD (hydric deficit), HNn (net hydric needs), I (irrigation), ICU (irrigation-crop units), IDF (irrigation drainage fraction), ID-V (Irrigation District nº V of the Bardenas Canal), IE (irrigation efficiency), IN (INputs), m.a.s.l. (meters above sea level), NCI (nitrate contamination index), NFN (nitrogenous fertilization needs), OU (OUtputs), P (precipitation), P_{ef} (effective precipitation), Q (flow), S (storage), SCI (salt contamination index), SO (surface drainage outflow), TDS (total of dissolved solids), VC (variation coefficient), WHC (water holding capacity), WUE (water use efficiency).

Introduction

Increment in food needs and the development of new technologies oriented towards the use of biofuels result in an increase in the land area destined for irrigation in the world (FAO, 2006). In Spain, during the period 2002-2005, the irrigated land area increased 4%, accounting for 13.6% of all agricultural land, consuming 75% of the country's hydric resources (MMA, 2007).

Although high volumes of water are destined for agriculture, not all water is well used; a significant percentage returns to the natural environment, contaminated either in a greater or lesser degree. Changes in the chemical composition of the water, due to the evapoconcentration of irrigation water and to the dissolution of the salts present in the soil may be so considerable that water cannot be reused in any agricultural, industrial, urban or ecological activity (Jiménez and Lamo de Espinosa, 1998). Therefore, the contamination of aquatic ecosystems that receive irrigation return flows is an increasing problem due to the introduction of more areas dedicated to irrigated agriculture. Contamination originating from agrarian nitrogen deserves a special mention, as the World Health Organization classified the presence of nitrates derived from nitrogenous fertilization in surface water and groundwater (WHO, 2004) as a very important problem.

The climate and substratum on which agricultural fields lie, as well as the fertilization practices and irrigation management, condition to a great extent the pollutant load exported by irrigation and therefore its potential impact on the systems receiving irrigation return flows. It has been verified that irrigation districts in the Ebro valley with moderate saline soils, presenting low drainage fractions and appropriate nitrogenous fertilization, export masses of the order of 3 Mg salts ha^{-1} $year^{-1}$ and 25 kg NO_3^--N ha^{-1} $year^{-1}$ compared to 20 Mg salts ha^{-1} $year^{-1}$ and 200 kg NO_3^--N ha^{-1} $year^{-1}$ in irrigation lands with saline substratum, in which there is inappropriate irrigation and nitrogenous fertilization management (Causapé *et al.,* 2006).

Therefore, alternatives in irrigation management can lead to the generation of more efficient irrigation lands with greater respect for the environment. Nevertheless, the long term effect changes cause is not usually studied on field and hence it is not evaluated outside particular experimental conditions.

Thus, this study seeks to quantify the efficiency and agro-environmental impact of a traditional irrigation land and to analyze its evolution between 2001 and 2007, a period which encompasses the climatic variability and significant changes in irrigation management in the basin studied.

Material and methods

Description of the study area

The study area is located in the middle Ebro valley (Spain) and it corresponds to the hydrological basin drained by the D-XIX-6 ditch that belongs to the Bardenas Canal Irrigation District nº V (ID-V). The irrigation canal network that encompasses D-XIX-6 constitutes the divide line of waters which limit a hydrological basin of 95 ha parcelled in 30 Irrigation-Crop Units (ICU: group of plots irrigated from the same irrigation canal outlet and with the same annual crop, Fig. 1A).

Geologically, 75% of the basin lies on a glacis of gravel with loamy matrix which constitutes a free aquifer by intergranular porosity. The erosion affects the glacis originating a valley where the Tertiary impermeable lutitic substratum emerges.

Fifteen test drillings were installed in the basin (Fig. 1C), which allowed the detection of the thickness of the glacis. The thickness decreases from 5.5 m in the north (2.2 m saturated in water) until its disappearance in the south central area of the basin (Fig. 1D). Therefore, groundwater flows in a general north-south direction (coinciding with the topography) with a 1% hydraulic gradient, crossing the basin and almost entirely evacuated by D-XIX-6 drainage. The groundwater outflows were not significant in the basin because the D-XIX-6 drainage collects the groundwater flows.

The soil salinity of the study area is low, as indicated by the 25,600 readings average for apparent electrical conductivity at 25ºC in horizontal configuration ($ECa_{hc\ average}$ = 0.16 dS m^{-1}, VC = 59%), measured with a Mobile Geo-referenced Electromagnetic Sensing System (Amézqueta *et al.*, 2007). The greatest ECa for the vertical configuration ($ECa_{vc\ average}$ = 0.25 dS m^{-1}, VC = 69%) indicates that soil salinity increases with depth, as consequence of a greater affection of the tertiary substratum. Therefore, the lowest values correspond to soils developed entirely on the glacis ($ECa_{hc\ min}$ = 0.04 dS m^{-1}) whereas the highest belong to soils on the tertiary with salinity problems ($ECa_{hc\ max}$ = 1.64 dS m^{-1}).

The relation between the ECa_{hc} and the water holding capacity of the soils (WHC), obtained according to the Soil Survey Laboratory method (1996) (WHC = 83·Ln [ECa_{hc}] +

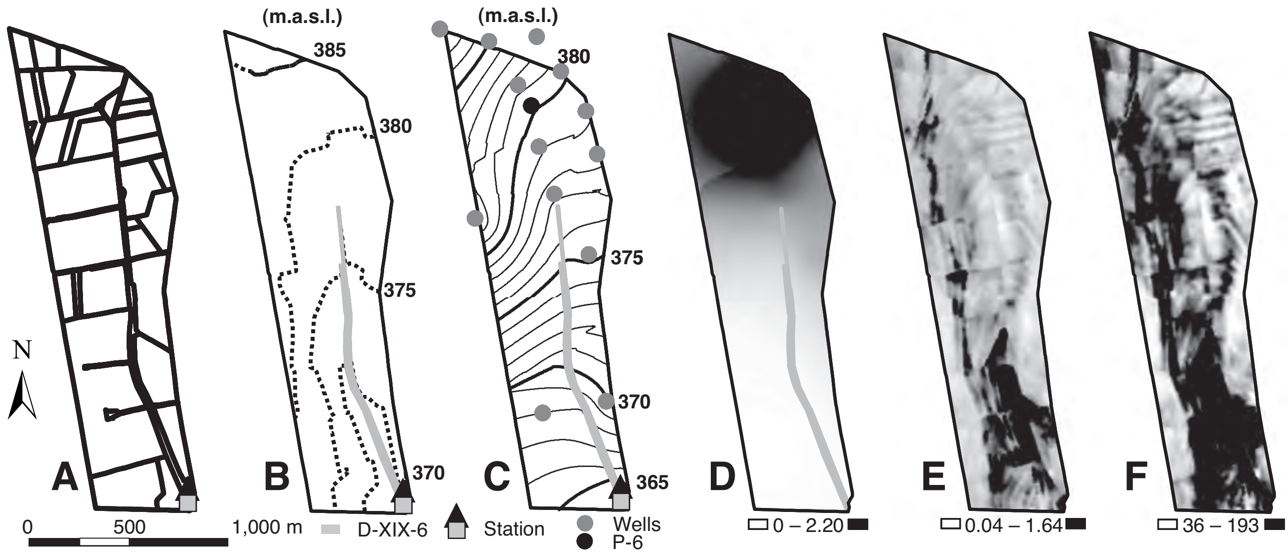

Figure 1. Maps of the hydrologic basin drained by D-XIX-6 ditch (Bardenas Canal Irrigation District nº V): (A) Irrigation-Crop Units distribution; (B) Topography (m.a.s.l.: meters above sea level); (C) Piezometry (m.a.s.l.); (D) Saturated thickness in the aquifer (m); (E) Apparent electrical conductivity (dS m^{-1}); (F) Water holding capacity (mm).

+ 269; n = 10; R^2 = 0.99), allowed to estimate WHC in the 25,600 points. The WHC average for the basin was 106 mm (VC = 30%); nevertheless, stony and shallow soils developed on the glacis present WHC of less than 40 mm and 30% of the soils of the basin do not reach 85 mm.

The hydrological years covered in the study (2001, 2005, 2006, and 2007) were representative of the climatic variability of the area, coinciding that the driest year (2005 with only 211 mm of precipitation) presented the greatest reference evapotranspiration (ET_0 = = 1363 mm) while the rainiest year (2001 with 526 mm of precipitation) presented the lowest ET_0 (1093 mm) (http://oficinaregante.aragon.es, 2007).

Irrigation has been introduced into practically the entire study basin and only 4% of its soils correspond to nonirrigated land (barren land, roads…). The crop pattern has varied, conditioned by the availability of irrigation water and by the changes in the Common Agricultural Policy (CAP) which since 2006 offers subsidies nonrelated to the crop production (Atance *et al.*, 2006).

In 2001, almost the entire basin was distributed equally between alfalfa (*Medicago sativa* L.) (46.3%) and corn (*Zea mays* L.) (46.3%) but the drought of 2005 along with the decoupling of CAP subsidies in 2006 caused the continuous ascent of winter wheat in detriment of corn (Table 1). Fallow oscillated between its

Table 1. Allocation of irrigation water and crops distribution, as a percentage of the basin surface, in the basin drained by D-XIX-6 ditch in hydrologic years 2001, 2005, 2006 and 2007

Year	2001	2005	2006	2007
Allocation of irrigation water (m^3 ha^{-1})	Not established	6,500	7,500	7,500
Winter wheat (%)	1.33	23.76	31.29	49.01
Alfalfa (%)	46.30	36.66	38.23	33.82
Corn (%)	46.30	11.01	7.88	2.49
Sunflower (%)	—	8.11	15.37	7.91
Leek (%)	1.26	—	—	—
Pea (%)	—	2.01	—	—
Grass (%)	—	6.60	—	—
Vineyard (%)	—	—	0.5	0.64
Fallow (%)	—	7.02	2.96	1.33

—: Without crop

complete absence in 2001 to 7% in 2005 due to the water restrictions that year.

Irrigation with good quality waters (electrical conductivity = 0.3 dS m^{-1}) was accomplished by using flood irrigation, even though improvements in irrigation management implemented by the ID-V in 2002 facilitated the change from a rotation to an on-demand irrigation system, and also the establishment of a binomial irrigation rate (payment for surface area and consumption) instead of payment only for irrigated area. Also, since 2002, maximum irrigation allowances were assigned for each year (Table 1) according to the water reserves in the reservoir.

Therefore, since 2002, farmers have had to adapt their crop planning, calendars and irrigation doses to the allowances assigned under a more flexible irrigation system with economic penalizations for higher water consumption.

Methodology

The agro-environmental evaluation of the studied irrigation area was executed based on the calculation of water balances and on the quantification of exported pollutants (salt and nitrate) in the basin drained by the D-XIX-6 ditch during the hydrological years 2001, 2005, 2006 and 2007. For such, the computational program Irrigation Land Environmental Evaluation Tool (in Spanish: EMR; http://jcausape.es/investigacion/EMR.htm, Causapé and Pérez, 2008) was utilized.

Water balance

The water balance calculation followed the equation:

$$[\text{Inputs}] - [\text{Outputs} + \text{Storage}] = \text{Error}$$
$$[I + P + GI] - [(ET_a + SO) + (\Delta S + \Delta A)] = \text{Error}$$

where the error associated with the balance consisted in the difference between Inputs (IN: I-irrigation, P-precipitation, GI-groundwater inflow) and outputs plus water storage (OU: ET_a-actual evapotranspiration, SO-surface drainage outflow) in the system, from the initial to the final moment of the balance (S: ΔS-increase of water in the soil, ΔA-increase of water in the aquifer) (Fig. 2). As the groundwater outflow was not significant it was considered nil. With the components of the water balance, EMR calculated the percentage error of the balance as $200 \cdot [(IN - OU - S)/(IN + OU - S)]$.

Daily irrigation volumes were facilitated by the ID-V, and measured by flowmeters in the irrigation canal network and by the control of irrigation time in each ICU. Precipitation was registered daily by the nearby El Bayo meteorological station, that belongs to the Network of the Ministry of Agriculture for Irrigation Support

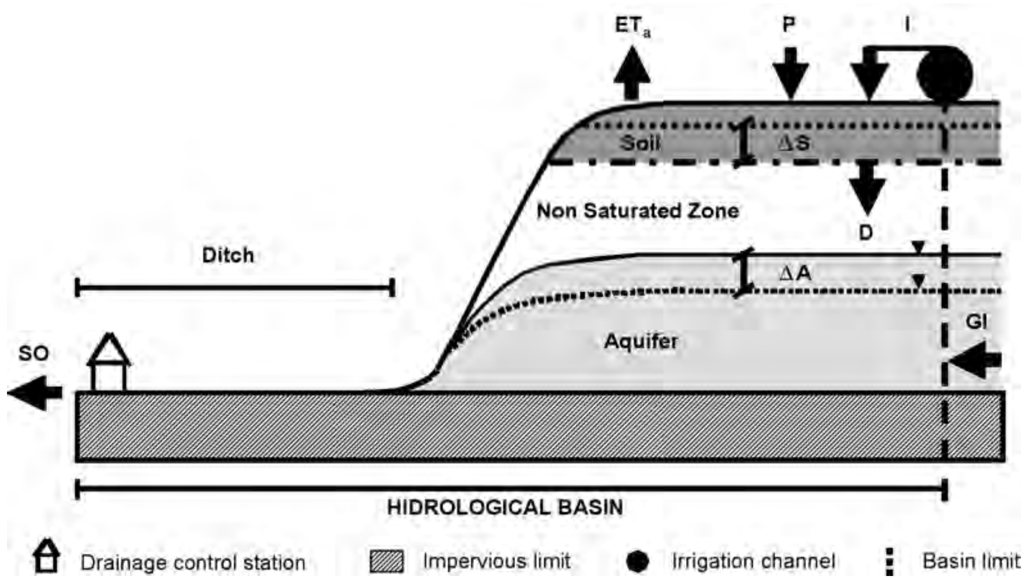

Figure 2. Hydrological sketch where the different water balance components of the system drained by D-XIX-6 ditch are represented: Irrigation (I), precipitation (P), actual evapotranspiration (ET_a), drainage associated to the hydrological basin (D), groundwater inflow (GI), surface outflow (SO), increase of water in the soil (ΔS) and increase of water in the aquifer (ΔA).

(http://oficinaregante.aragon.es) whose climatic data also aided in the calculation of ET_0, using the Penman-Monteith method (Allen *et al.*, 1998).

The daily I, P and ET_0 data, along with an hypothetical available initial soil water for plants which, being unknown, was estimated as half of the WHC, constituted the EMR inputs (Causapé and Pérez, 2008) for the development of a water balance in the soil for each ICU, using the daily ET_a, available soil water stored and soil water drainage. The crop coefficients and vegetative periods of each crop, necessary to estimate the ET_a, were obtained from Martínez-Cob (2004) for the study area agrarian district (Ejea, Zaragoza).

The surface drainage outflow through D-XIX-6 was measured by a flowmeter, long throated flume type (data length per section at bottom profile: approach section 100 cm, converging transition 60 cm, control section 70 cm; vertical dimensions: upstream channel depth 56 cm, height of sill 15 cm, bed drop 10 cm and abrupt expansion diverging transition) with rectangular control section (bottom width 82 cm) located in the drainage control station (Fig. 1C). Water height (h, cm) was recorded every 15 min with an electronic limnigraph and converted into flow (Q, L s^{-1}) using the equation:

$$Q = 0.17\ h^2 - 1.95\ h - 17.89;\ R^2 = 0.99$$

obtained with nine propeller current meter measure.

With the establishment of the piezometer network in 2006 (Fig. 1C), the flow in D-XIX-6 ditch during the nonirrigation period was related to the saturated thickness registered in piezometer P-6 (Fig. 1C; piezometer located in the main entrance of groundwater flows area); the saturated thickness measured manually every 21 days at piezometer P-6 was used to estimate GI in the basin ($GI = 190 \cdot e^{0.58 \cdot \text{Saturated Thickness P-6}}$; n = 22; $R^2 = 0.95$).

The 15 piezometers' saturated thickness readings, together with the estimated effective porosity (15%), based on the lithologic material of the aquifer (Custodio and Llamas, 1983), allowed the calculation of the aquifer water content in the initial and final dates of the balances (1 October of the corresponding years) and thereby to estimate ΔA during the years that the piezometer network was available (2006 and 2007).

Evaluation of irrigation quality

The irrigation quality evolution was analyzed starting from the EMR calculations (Causapé and Perez, 2008) of the net hydric needs (HNn), water use efficiency (WUE), hydric deficit (HD), irrigation drainage fraction (IDF) and irrigation efficiency (IE) for each ICU and for the entire basin during the four study years. These equations are described below.

The HNn estimates the irrigation water necessary to prevent crops from suffering hydric stress. It was calculated as the difference between potential evapotranspiration (ET_C) plus available water contained in the soil at the end of the balance (AW_e) and effective precipitation (P_{ef}) plus available initial soil water (AW_i).

$$HNn = (ET_C + AW_e) - (AW_i + P_{ef})$$

The WUE refers to the extent of the use of water (irrigation, rain and water stored in the soil) by crops. It is calculated as ET_a plus AW_e divided by the sum of the available water resources for plants, that is, AW_i, P_{ef} and I.

$$WUE = [(ET_a + AW_e) / (AW_i + P_{ef} + I)] \cdot 100$$

The HD evaluates to what extent the hydric resources were unable to satisfy the crops' hydric needs. It is calculated as the difference between ET_C and ET_a divided by ET_C.

$$HD = [(ET_C - ET_a) / ET_C] \cdot 100$$

The IDF evaluates the irrigation water "losses" from deep percolation and is calculated as the percentage of irrigation drainage (D_I) respect to I.

$$IDF = (D_I / I) \cdot 100$$

And lastly, IE was calculated as one minus the relation between the volume of irrigation water leaving the system without being used in evapotranspiration by crops (D_I plus losses due to evaporation and wind drift from sprinkler irrigation -EWDL) and I. In our study case, EWDL is nil because there are no sprinkler irrigation systems.

$$IE = \{1 - [(D_I + EWDL) / I\ ]\} \cdot 100$$

A theoretical IE of 100% would indicate that the entire volume of applied irrigation has been used to satisfy the hydric needs of the crops or was accumulated in the water reserves for later use.

This series of indices allows the evaluation of irrigation quality in each of the "subareas" and for the group of irrigation areas assessed in a certain period of time. Therefore, high irrigation quality will be achieved when the HD and the IDF are nil and as WUE and IE approach 100%. Those indices are broadly explained in Causapé (2008).

Quantification of salt and nitrate masses associated with the drainage of the basin

To quantify the mass of pollutants exported through the drainage associated with the hydrological basin (D), salt and nitrate concentrations were assigned to SO, GI and ΔA.

$$D = SO - GI + \Delta A$$

D-XIX-6 drainage control station (Fig. 1C) was equipped with an auto-sampler collector programmed for the collection of a daily water sample. Later, the electrical conductivity at 25ºC (EC) and nitrate content were determined in the laboratory. To calculate the mass of salts in the drainage waters, the daily EC was transformed into total of dissolved solids [TDS (mg L^{-1}) = = 704 · EC (dS m^{-1}) + 90; n = 31; R^2 = 0.97] and multiplied by the daily volume water drainage. In the case of nitrate the procedure was the same used for salts, using the daily nitrate water content instead of the daily TDS.

The spatial-temporal variability of the groundwater quality made it impossible to obtain representative water samples of the groundwater inflow. Therefore, given the similar agriculture and geology outside the basin, it was estimated that the GI had the same salt and nitrate concentrations as the ones measured in SO.

The mass of salts and nitrates stored in the aquifer were obtained starting from the analysis of manual samples taken from the 15 piezometers on October 1st of the corresponding year. In 2001 and 2005, when the piezometer network had not yet been installed, the mass of pollutants drained into the basin was estimated according to the average SO/D proportion for 2006 and 2007.

Environmental evaluation of irrigation

The temporal evolution of the environmental impact on irrigation land was analyzed starting from the calculation of the salt contamination index (SCI) and the nitrate contamination index (NCI) of the basin for the four study years. Both indices, defined by Causapé (2008), correct the unitary masses of pollutants exported (masses exported per surface unit) by factors related to "natural and socioeconomic" influence, such as geology and the agronomic possibilities of a specific irrigation area. Thus, SCI was calculated as the salt mass exported (D_{Salts}) divided by the average EC of the drainage for nonirrigation seasons (October-March) (EC_{NI}) during the whole study period, being SCI a representative parameter of the geologic materials salinity of the studied irrigation land.

On the other hand, the NCI was calculated as the nitrate mass associated with the basin drainage ($D_{Nitrate}$), divided by the nitrogenous fertilization needs of the system (NFN). Nitrogenous fertilization needs were calculated annually, starting from crop production and crop nitrogen extractions (Orús and Sin, 2006), except for leguminous plants which were considered null because of their capacity to fix nitrogen symbiotically.

Results and discussion

Water balance

Irrigation was the main water contributor to the basin during the four study years, highlighting the fact that changes in irrigation management after 2001 contributed to nearly a 50% irrigation volume reduction (Table 2). Precipitation was the second most important water input into the basin, oscillating between 526 mm in the rainiest year (2001) and only 211 mm in the driest year (2005). Water inputs through groundwater inflows, monitored after the installation of the piezometer network, were significant, accounting for 21% of the inputs in 2006 and 24% in 2007.

As far as the outputs are concerned, 2001 stands out by presenting the highest volume of SO (928 mm) and 10% less ET_a (836 mm). In the other three years (2005, 2006 and 2007), the introduction of crops with smaller hydric needs (expansion of winter cereal in detriment of corn) produced a decrease in ET_a (approximately 10%) although to a smaller extent than the decrease in the water exported through D-XIX-6 (approximately 50%). Therefore, the ET_a represented, respectively, 67%, 66% and 61% of the water outputs from the basin in 2005, 2006 and 2007.

Finally, water storage in the soil and in the aquifer was the least important component of the balance, mainly due to the annual seasonality of irrigation and precipitations, and also to the scarce thickness and high permeability of the aquifer system associated with the basin. Nevertheless, annual storage has accounted for between 5% and 10% of the volume of water involved in the balance and it

Table 2. Water balance in the hydrological basin drained by D-XIX-6 ditch in hydrologic years 2001, 2005, 2006 and 2007. Components of the balance: water inputs (IN) as irrigation (I), precipitation (P) and groundwater inflow (GI), water outputs (OU) as actual evapotranspiration (ET_a) and surface drainage outflow (SO) and water storage (S) in the soil (ΔS) and in the aquifer (ΔA). Error was calculated as 200 [(IN-OU-S)/(IN+OU-S)]

Year	Inputs (mm)			Outputs (mm)		Storage (mm)		Error (%)
	I	P	GI	ET_a	SO	ΔS	ΔA	
2001	1139	526	—	836	928	-6	—	-5
2005	570	211	—	729	359	-38	—	-29
2006	567	450	276	808	417	65	35	-2
2007	512	372	277	733	469	-42	23	-2

should be considered in this type of balance, since only the WHC of the soils (maximum volume of water which can be held in the soils) can be of the same order of the precipitations during the driest years.

The high error in the balance of 2005 (-29%) demonstrates the need to take into consideration GI and ΔA. Casually, the lack of consideration of these components in 2001 did not lead to a high error balance (-5%), justified by the possible compensation of errors and components not taken into account. In the years 2006 and 2007, when the estimation of GI and ΔA were taken into consideration, error balances of only -2% were obtained, which highlight the good quality of the balances developed and allow the association of the mass of pollutants exported to the studied basin.

Irrigation quality indices

The net hydric needs registered significant differences associated to the crops introduced and to the climatic characteristics of each year (Table 3). In 2005, with the lowest registered precipitation, 716 mm of irrigation water had to be applied to satisfy the hydric needs of the crops, whilst in 2007, with greater development of crops with low hydric demands (Table 1), only 430 mm had to be applied. The use of hydric resources quantified by the WUE was moderate-low in 2001 when the crops only used 63% of the available hydric resources. The drought of 2005 and the improvements in the irrigation management imposed by the ID-V from 2002 onwards contributed to increase the WUE, which oscillated between 82% in 2007 and 90% in 2005.

Table 3. Net hydric needs (HNn), water use efficiency (WUE), hydric deficit (HD), irrigation drainage fraction (IDF) and irrigation efficiency (IE) in the basin drained by D-XIX-6 ditch in hydrologic years 2001, 2005, 2006 and 2007

Year	HNn (mm)	WUE (%)	HD (%)	IDF (%)	IE (%)
2001	611	63	1	47	53
2005	716	90	24	14	86
2006	569	87	14	23	77
2007	430	82	10	32	68

The year 2001, with abundant rains and applied irrigation volume, presented a HD of only 1%. However 2005, with a severe drought and important irrigation water restrictions, registered the greatest HD (24%), demonstrating that the effort of farmers in planning their crops was not enough to annul the hydric stress of the crops. In 2006 (HD = 14%) and 2007 (HD = 10%) the changes in irrigation management did not avoid the disappearance of hydric stress. Concerning the water loss through irrigation drainage, 2001 presented the greatest loss (IDF = 47%) conditioning a low IE (53%), while the drought of 2005 caused the least loss (IDF = = 14%) and therefore the greatest IE (86%). However, the true consequences of the changes in irrigation management imposed by the ID-V are observed in 2006 and 2007 (years without drought) when the IE registered values of 77% and 68% compared to only 53% in 2001.

Environmental evaluation of irrigation

The low salinity in the basin soils (EC_{NI} = 1.05 dS m^{-1}) caused the salt mass associated with its drainage to be only 1.6 Mg ha^{-1} $year^{-1}$, lower than the 14 Mg ha^{-1} $year^{-1}$ of modern irrigation with saline subsoils in Monegros II (Tedeschi *et al.*, 2001) or the 20 Mg ha^{-1} $year^{-1}$ of gypsiferous traditional irrigation lands in Monegros I (Isidoro *et al.*, 2006a) located in the Central Ebro basin. Inadequate irrigation management led to higher salt masses exported in 2001 (2.5 Mg ha^{-1}) and therefore a higher salt contamination index (2.4 Mg ha^{-1} dS^{-1} m $year^{-1}$). The improvements in irrigation management diminished appreciably the salt mass associated with drainage in 2005, 2006 and 2007 (Table 4), obtaining saline contamination indices similar to those registered in well managed modern irrigation such as Monegros II (1.6 Mg ha^{-1} dS^{-1} m year^{-1}; Causapé, 2008).

For nitrates, the average mass associated with the drainage of the basin studied was 37 kg NO_3^--N ha^{-1} year^{-1}, a lower value compared to the 111 kg NO_3^--N ha^{-1} year^{-1} of Monegros I (Isidoro *et al.*, 2006b) and slightly higher than the 31 kg NO_3^--N ha^{-1} year^{-1} of Monegros II (Cavero *et al.*, 2003). However, the nitrogenous fertilization needs of the hydrological basin drained by D-XIX-6 ditch (85 kg N ha^{-1} year^{-1}) were only 57% of the nitrogenous fertilization needs of Monegros I and II (150 kg N ha^{-1} year^{-1}; Causapé, 2008).

In 2001, 60% of nitrogenous fertilization needs were leached, while in 2005 and 2006 this proportion decreased by half. In 2007 a worrying increase in nitrate losses (45% of fertilization needs) was registered, however it did not reach the levels of 2001.

The NCI in 2001 (0.63) was similar to that registered in traditional irrigation lands in Monegros I (0.71; Causapé, 2008) while in the later years of study, with more appropriate irrigation management and nitrogenous fertilization, NCIs (0.32, 0.25 and 0.48) were very close to the values obtained in the modern well managed irrigation lands in Monegros II (0.22; Causapé, 2008).

Conclusions

The annual water balances accomplished in the drainage basin D-XIX-6 were satisfactory, particularly in the hydrological years of 2006 and 2007 (error = -2%), when the groundwater inflows into the basin and the water stored in the system between the initial and final moment of the balances were taken into consideration.

The inadequate irrigation management executed in 2001 caused low irrigation efficiency (IE = 53%) although it led to a low hydric deficit in crops (HD = 1%). The drought of 2005 maximized WUE (90%) although crop planning did not decrease sufficiently the hydric needs of the crops, which presented high hydric deficit (24%). The effects of the changes implanted by the ID-V were noticeable in 2006 and 2007, when IE increased from 53% in 2001 to 77% in 2006 and 68% in 2007, although the hydric deficit also increased (14% in 2006 and 10% in 2007, compared to 1% in 2001). As a consequence of the changes in the irrigation management after 2001, the salt mass associated with drainage decreased by half (from 2.5 Mg ha^{-1} year^{-1} in 2001 to 1.3 Mg ha^{-1} year^{-1} in 2005-2007) and nitrate mass decreased to a third (from 72 kg NO_3^--N ha^{-1} year^{-1} in 2001 to 25 kg NO_3^--N ha^{-1} year^{-1} in 2005-2007). Improvements have caused a decrease in 50% of the salt and nitrate contamination indices, approaching those obtained in well managed modern irrigation land.

Finally, the results shown demonstrate that changes in the irrigation management imposed by ID-V since 2002 have been efficient in increasing water and fertilizer use and in reducing the potential impact of irrigation returns flows. Nevertheless, crops still suffer certain hydric stress which affects their productivity and since 2005 a slight but worrying negative tendency has been observed (decrease in water use efficiency and increase of saline and nitrate contamination indices), so it is necessary to reverse this trend in the future by new improvements in irrigation management.

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Table 4. Salt mass associated with drainage water (D_{Salts}), Electrical conductivity in nonirrigation season (EC_{NI}), salt contamination index (SCI), nitrate mass associated with drainage water ($D_{Nitrate}$), nitrogenous fertilization needs (NFN) and nitrate contamination index (NCI) in the basin drained by D-XIX-6 ditch in hydrologic years 2001, 2005, 2006 and 2007

Year	D_{Salts} (Mg ha^{-1})	EC_{NI} (dS m^{-1})	SCI (Mg ha^{-1} dS^{-1} m)	$D_{Nitrate}$ (kg NO_3^--N ha^{-1})	NFN (kg N ha^{-1})	NCI
2001	2.5	1.05	2.4	72	115	0.63
2005	1.0	1.05	1.0	22	68	0.32
2006	1.2	1.05	1.1	21	84	0.25
2007	1.6	1.05	1.5	32	67	0.48

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