Agricultural Water Management 102 (2011) 97–104

Contents lists available at SciVerse ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Implementing irrigation: Water balances and irrigation quality in the Lerma basin (Spain)

R. Abrahao[a,*], J. Causapé[b], I. García-Garizábal[b,c], D. Merchán[b]

[a] MIRARCO – Mining Innovation, Rehabilitation and Applied Research Corporation, Laurentian University, 935 Ramsey Lake Road, Sudbury, ON, Canada P3E 2C6
[b] Instituto Geológico y Minero de España (IGME), C/ Manuel Lasala no. 44, 9◦B, Zaragoza 50.006, Spain
[c] Universidad de Zaragoza, C/ Pedro Cerbuna no. 12, Zaragoza 50.009, Spain

ARTICLE INFO

Article history:
Received 23 February 2011
Accepted 13 October 2011
Available online 8 November 2011

Keywords:
Irrigation management
Transition to irrigated land
Water use
Ebro basin
Lerma basin

ABSTRACT

The growing necessity to develop more productive agriculture has encouraged the expansion of new irrigated lands. However, water use in agriculture may affect the natural regimes of water systems. This study aims to analyze, for the first time, water use and its dynamics during the creation of a newly irrigated land. Water use was studied through the development of water balances and subsequent application of quality indices for irrigation in two unirrigated years (2004–2005) and three years of gradual implementation of irrigation (2006, 2007 and 2008) in the Lerma basin (752 ha, Spain). Increases in evapotranspiration, drainage and water content in the aquifer were verified during the gradual transformation into irrigated land. Water balances closed adequately, giving consistency to the results and enabling the application of quality indices for irrigation. Irrigation quality analysis showed a use of available water resources equal to 84%. However, the estimated irrigation efficiency presented lower values, mainly due to irrigation drainage (15%) and combined losses by both evaporation and wind drift of sprinkler irrigation systems (13%). The results indicate that the use of water in the Lerma basin is at the same management level of other modern irrigation systems in the Ebro basin, although there is still margin for improvement in irrigation management, such as reducing the irrigation drainage fraction and the evaporation and wind drift losses of sprinkler irrigation systems.

1. Introduction

In many areas of the world, especially in arid and semi-arid regions, irrigated agriculture is essential to achieve the desired production. Forty percent of global agrarian production is obtained from the 20% of cultivated areas that are irrigated (FAO, 2003a). Currently, over 250 million hectares are irrigated throughout the world, which is more than five times the area irrigated in the early twentieth century (Rosegrant et al., 2002). Because of the higher yields from irrigated agriculture compared to unirrigated agriculture, it is expected that this proportion of irrigated areas will continue to increase in the future.

The introduction of irrigation in an agricultural area involves a major change in water use. Irrigation water in many cases exceeds the total volume of all other inputs of water to the system (Charbonneau and Kondolf, 1993) and is added to the previously available water resources (precipitation and natural flows).

Due to the large amount of water used in irrigation activities (70% of the total water extracted from natural resources (FAO, 2003b)) and potential negative impact resulting from drainage, there is growing interest in studying and quantifying irrigation management (Clemmens and Burt, 1997). However, it is essential to develop water balances to check the level of accuracy of the measured and estimated components of the water cycle (Burt et al., 1997). Accuracy is crucial to further validate the irrigation management assessment.

Among the several existing irrigation quality indices, those evaluating the use of water resources and the volume of water applied that is not used for crops stand out. It is also important to ascertain the degree with which irrigation is meeting the needs of crops, so as to balance high water productivity (i.e. high crop yield per unit of applied water) and low environmental impacts.

The assessment of water use and quality of irrigation has been the subject of several studies conducted in hydrological basins or experimental plots (Chaudhry, 1978; Zalidis et al., 1997; Faci et al., 2000; Al-Jamal et al., 2001; Tanji and Kielen, 2002; Causapé et al., 2004; Isidoro et al., 2004; Lecina et al., 2005; García-Garizábal et al., 2009). However, until the present date, no study has had the opportunity to start an agroenvironmental monitoring in an area before its transition into irrigated land (i.e. monitoring drainage flow, water use, crops implementation, agricultural management, etc.). This was the objective of the work reported in this paper.

---

* Corresponding author. Tel.: +1 705 675 1151x5107.
E-mail address: raphaelprodema@yahoo.com.br (R. Abrahao).

0378-3774/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2011.10.010

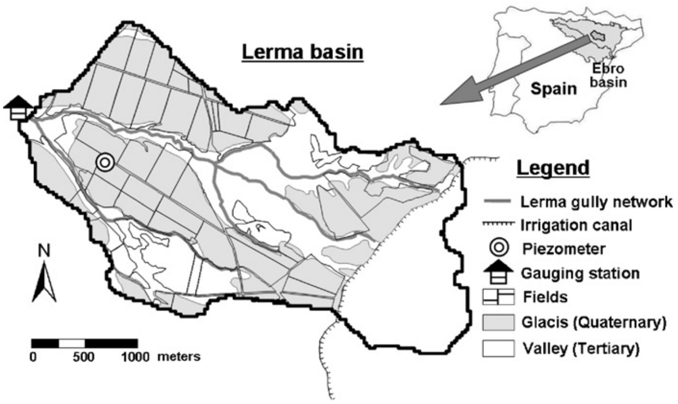

Fig. 1. Geomorphology (Beltrán, 1986) and fields of the Lerma basin, with the location of the gully network, irrigation canal, piezometer and gauging station.

2. Description of study area

The study area corresponds to the Lerma hydrological basin (752 ha), located on the left side of the Ebro river valley in Northeast Spain (Fig. 1). The transition project delimited 405 ha of the Lerma basin to be irrigated, divided into 55 fields (irrigable area of the basin). The agroenvironmental monitoring of the basin began in the hydrological year 2004, before transformation of the area. The first fields were irrigated in 2006, with a gradual increase in irrigated area until reaching 85% of irrigated land in 2008, the last year included in this study.

Fifty nine percent of the soils in the Lerma basin are underlain by two layers (Fig. 1): the first layer is quaternary glacis consisting of layers of gravel with loamy matrix and a maximum thickness of 10 m; below are layers of tertiary materials consisting of limestone, clay and gypsum. The remaining 41% of the land area consists of emerged tertiary materials.

The gravel layers provide excellent pathways for subsurface drainage. The drainage water feeds into lower areas through a network of intermittent streams that flow through, and on top of, the tertiary layers. Before irrigation, flows in these streams occurred mainly during fall and spring, as a consequence of rainfall.

The soils developed on the glacis (Calcixerollic Xerochrepts, Soil Survey Staff, 1992) display loamy textures, with an effective depth of 60–90 cm. The low salinity (electrical conductivity of the saturation extract: $EC_e < 4$ dS/m) and small risk of erosion (slope < 3%) of the soils developed on the glacis allowed for identifying these zones as suitable for conversion into irrigated land (Beltrán, 1986), and therefore most of the irrigation occurs in these zones. In contrast, soils developed in the valleys of the Lerma gullies (Typic Xerofluvent, Soil Survey Staff, 1992) have a much lower effective depth (between 30 and 45 cm), limited by limestone or tabular gypsum levels, which confers slow drainage. Salinity (EC_e between 4 and 8 dS/m) and steep slopes (>10%) are the reasons why these zones are classified as not appropriate for irrigation (Beltrán, 1986).

According to the agro-climatic stations of the Integrated Irrigation Advisory Service (SIAR Network: http://oficinaregante.aragon.es), average rainfall for the five study years (hydrological years 2004–2008) was 408 mm/year with a high annual variability as can be seen in Fig. 2 (coefficient of variation: CV = 37%). The average reference evapotranspiration (ET_0) calculated by Penman–Monteith (Allen et al., 1998) was three times higher (1261 mm/year) than rainfall and was much less variable (CV = 6%). A typical year consists of two dry seasons (summer and winter) and two wet seasons (spring and autumn).

Before irrigation, wheat and barley were grown in winter. After irrigation was established, the typical cropping pattern (Table 1) for 82% of the irrigated fields consists of maize (April to October), winter cereals (November to July), and tomato (May to September). The area under irrigation increased from 124 ha in 2006 to 346 ha in 2008. Sprinkler irrigation accounts for 86% of the applied water with drip irrigation used for the rest of the area (Table 1). The implementation of irrigation not only resulted in a progressive increase of irrigated area, but also in an increase in the amount of water applied annually per hectare, mainly due to double cropping practices (Table 1). Finally, the salinity of the irrigation water, 0.3 dS/m, does not pose any limitations on to the type of cultivated crops.

3. Methodology

3.1. Water balances

Annual water balances were calculated for the irrigable area of the Lerma basin for 2004 through 2008 using EMR 2.0 (Irrigation Land Environmental Evaluation Tool – in Spanish, EMR: Causapé, 2009).

3.1.1. Soil water balance

Data on precipitation (P), irrigation (I), combined losses by both evaporation and wind drift (EWDL), and potential evapotranspiration (ET_0) were utilized by EMR to develop daily water soil balances to estimate actual evapotranspiration (ET_a), soil drainage (D_s) and soil water storage (ΔS) in each of the 55 irrigated fields in the Lerma basin:

$$(P + I) - (ET_a + D_S + EWDL) = \Delta S \quad (1)$$

The daily weather data necessary to calculate the water balances was obtained from two agro-climatic stations of the SIAR Network (Tauste and Ejea). EMR software interpolates the climatic variables of the different stations to obtain a daily value for Lerma using the inverse square distance technique (Isaaks and Srivastava, 1989). Irrigation volumes were measured daily with flow meters installed by the Irrigation District Authority in the 55 irrigated fields of the basin.

The percentage of losses, calculated by EMR in accordance with Playán et al. (2005), was applied to the volume of irrigation to quantify the combined losses by both evaporation and wind drift of sprinkler irrigation, using the following equation:

$$EWDL = 20.34 + 0.214 WS^2 - 2.29 \times 10^{-3} RH^2 \quad (2)$$

The wind speed 2 m above the surface (WS, m/s) and relative humidity 1.5 m above ground level (RH, %) were also provided by the SIAR Network. The last dataset obtained from the SIAR Network was the reference evapotranspiration (ET_0), which was derived according to Penman–Monteith (Allen et al., 1998). With ET_0 and the monthly crop coefficients (k_c) obtained from Martínez-Cob (2004) for the study zone, the daily crop evapotranspiration (ET_C) was calculated according to the methodology proposed by Allen et al. (1998):

$$ET_C = ET_0 \times k_c \quad (3)$$

The water holding capacity in the soil (WHC, mm) available for plants was estimated from the average apparent electrical conductivity of the soil (EC_a, dS/m) of each field, which depends on soil water content. EC_a was derived from 43,433 measurements taken in about two weeks, after rainfall (soil at field capacity). A mobile geo-referenced electromagnetic sensing system (Urdanoz et al., 2008) was used for these measurements and the WHC of 10 soil samples (representative of the EC_a range of Lerma soils) was analyzed in the laboratory according to the methodology of the Soil Survey Laboratory (1995) (WHC = field capacity at 0.33 bar minus

Table 1
Dynamics of the transition into irrigated land of the Lerma basin, irrigation systems implemented, established crops, double cropping and irrigation volumes applied.

	2004	2005	2006	2007	2008	Average[a]
Irrigated area						
ha	–	–	124	274	346	–
%	–	–	31	68	85	–
Irrigation system						
Sprinkler (%)	–	–	90	92	79	86
Drip (%)	–	–	10	8	21	14
Crops						
Maize (%)	–	–	61	63	40	52
Winter cereal (%)	–	–	–	25	23	20
Tomato (%)	–	–	10	4	14	10
Broccoli (%)	–	–	24	4	2	6
Pea (%)	–	–	–	–	10	5
Sunflower (%)	–	–	4	–	5	3
Onion (%)	–	–	–	4	3	3
Sorghum (%)	–	–	–	–	2	<1
Double cropping (%)	–	–	–	4	24	13
Irrigation						
m^3/ha irrigated	–	–	4790	5870	6180	5839

[a] Weighted average considering the transformed area.

wilting point at 15 bar). The statistically significant relationship established between EC_a and WHC was:

$$\mathrm{WHC} = 415.7\mathrm{EC_a} + 2.42; \quad R^2 = 0.91; \quad n = 10; \quad p < 0.001 \qquad (4)$$

Therefore, starting from an initial volume of available water for plants in the soil (AW), EMR adds the daily inputs by net irrigation ($I-\mathrm{EWDL}$) and precipitation (P), and $\mathrm{ET_C}$ is subtracted only if there is sufficient AW in the soil. EMR considers that $\mathrm{ET_a} = \mathrm{ET_C}$ if $\mathrm{AW_{initial}} + P + I - \mathrm{EWDL} > \mathrm{ET_C}$, but otherwise $\mathrm{ET_a} = \mathrm{AW_{initial}} + P + I - \mathrm{EWDL}$—hence, the soil has a wilting point level of humidity at the end of each day (AW = 0). On the other hand, if $\mathrm{AW_{initial}} + P + I - \mathrm{EWDL} - \mathrm{ET_a} > \mathrm{WHC}$, the program interprets that the field soil capacity has been surpassed, and drainage (D_{SWB}) occurs in amounts equal to $D_{\mathrm{SWB}} = \mathrm{AW_{initial}} + P + I - \mathrm{EWDL} - \mathrm{ET_a} - \mathrm{WHC}$, leaving the soil at the termination of each day at field capacity (maximum AW = WHC).

In order to obtain an approximate value of the water content in the soil at the beginning of the study (October 1, 2003), the calculation of water balances was started one year before (October 1, 2002), assuming the water content was equal to ½ WHC.

With the information generated by the soil water balance (SWB), EMR estimates the direct components of the water balance in the basin ($\mathrm{ET_a}$ and ΔS) and soil drainage (D_s). Using the information provided by the SWB, the effective precipitation (P_{ef}, portion of precipitation that contributes to crop water requirements) was estimated for each day and each field, considering that if $P < \mathrm{WHC} + \mathrm{ET_a} - \mathrm{AW}$ then $P_{\mathrm{ef}} = P$, and otherwise $P_{\mathrm{ef}} = \mathrm{WHC} + \mathrm{ET_a} - \mathrm{AW}$. This estimate does not consider the existence of preferential flows or the runoff that could be generated.

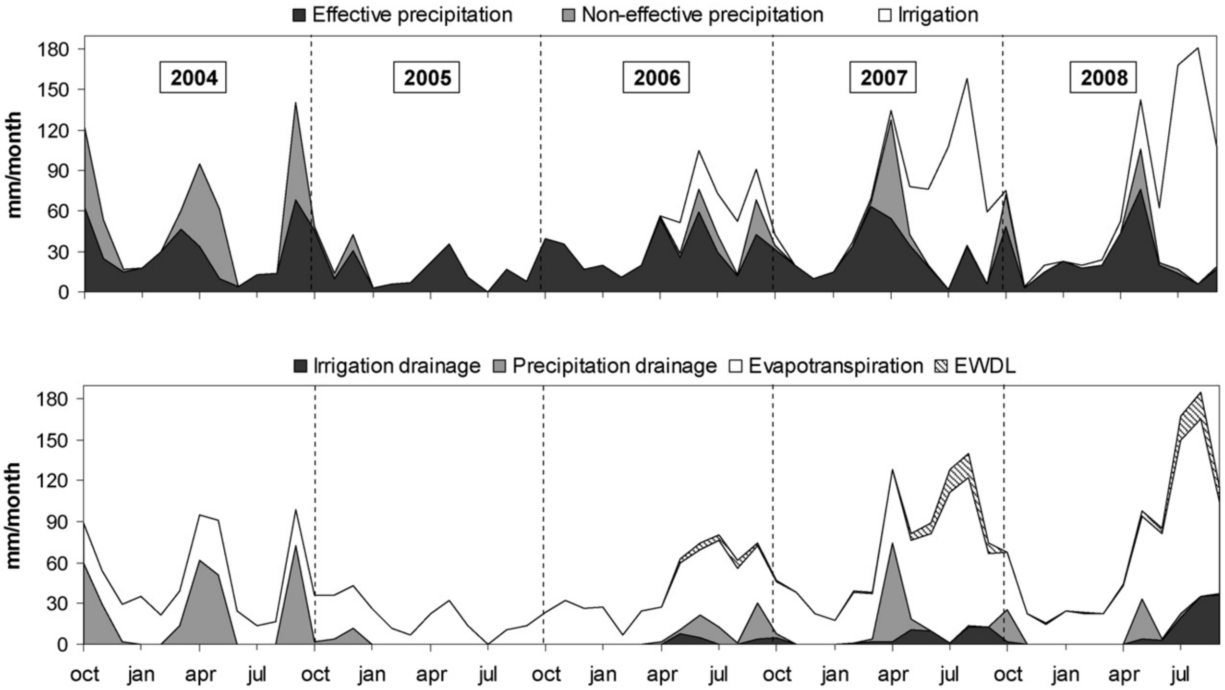

Fig. 2. Monthly dynamics of inputs (effective precipitation, non-effective precipitation and irrigation) and outputs (irrigation drainage, precipitation drainage, evapotranspiration and combined losses by both evaporation and wind drift-EWDL) obtained from water balances in the soil during the five study years (2004–2008).

Nevertheless, it is considered to be a quite valid estimate as the fields in the study area are terraced and intense rain is needed to generate runoff.

The drainage volume proceeding from irrigation (D_I) was estimated by considering for the days and fields with drainage that if $AW + P - ET_a \geq WHC$ then $D_I = I - EWDL$ and otherwise $D_I = [I - EWDL] - [WHC - (AW + P - ET_a)]$. The interpretation of this calculation is that, on any given day, rainfall will always occur before irrigation and thereby irrigation drainage takes priority over rainfall drainage. It is assumed in this study that a farmer takes rainfall into account when deciding whether to irrigate, although evidently weather forecasting is by no means infallible.

3.1.2. Water balances in the basin

Annual water balances were obtained for the irrigable area included in the Lerma basin considering also the incoming water flows from the unirrigable area included in the basin (IWF), water drained through the Lerma gully (LG) and the increase of water in the aquifer (ΔA) to complete a basin water balance.

$$\begin{gathered}\text{Inputs} - \text{Outputs} - \text{Storage} = \text{Balance error}\\ (P + I + \text{IWF}) - (\text{ET}_a + \text{LG} + \text{EWDL}) - (\Delta S + \Delta A) = \text{Balance error}\end{gathered} \quad (5)$$

The water evacuated from the basin via drainage was quantified by the gauging station (Fig. 1) equipped with an electronic limnigraph (Thalimedes, OTT), which allowed for the registration of water height (h, m) measurements every 15 min. These measurements were converted into flow (Q, m^3/s) according to the equations provided by the software Winflume (Wahl, 2000):

$$Q = 1.73 \times (h + 0.00347)^{1.624} \quad \text{for } h \leq 0.5\,\text{m} \quad (6)$$

$$Q = 10.28 \times (h + 0.01125)^{1.725} \quad \text{for } h > 0.5\,\text{m} \quad (7)$$

From the beginning of the study (October 1, 2003) up to when the gauging station was operational (August, 2005), the flow of Lerma gully was estimated from precipitation data and based on a runoff coefficient of 0.087. The coefficient was obtained from the relationship precipitation-flow in the period before the introduction of irrigation (Critchley and Siegert, 1991). Based on the entire dataset available from the gauging station and rainfall data, it was verified that heavy rains yielded a higher runoff coefficient (0.313), which was then applied to daily rainfall events exceeding 25 mm. These runoff coefficients were also applied to estimate the incoming water flows from the unirrigable areas included in the Lerma basin (IWF).

Finally, the annual water storage in the aquifer was estimated based on the aquifer area (310 ha), the saturated thickness of a representative piezometer of the aquifer (Fig. 1), and an effective porosity of 25% corresponding to the average value provided by Custodio and Llamas (1983) to the lithology of the aquifer. As the piezometer was not built until March 2008, the saturated thickness at the end of each hydrological year was estimated from the statistically significant relationship between the saturated thickness (ST, cm) and the flow measured at the Lerma gully (Q_{LG}, m^3/day) between March and September 2008:

$$\text{ST} = 0.046Q_{LG} + 29.78; \quad R^2 = 0.92; \quad n = 10; \quad p < 0.001 \quad (8)$$

3.1.3. Calculation of errors

The difference between inputs (In), outputs (O) and storage (S) constituted the balance error, which in percentage terms was evaluated as

$$\text{Balance error [\%]} = 200 \times \left[\frac{\text{In} - O - S}{\text{In} + O + S}\right] \quad (9)$$

Once the water balance was verified to be satisfactory, the drainage associated with the irrigable area of the Lerma basin was be calculated as

$$D = \text{LG} - \text{IWF} \quad (10)$$

Drainage (D) should be equal to the estimated soil drainage (D_s) minus the storage in the aquifer and the final validation of the developed balances was made by calculating the drainage error as

$$\text{Drainage error [\%]} = 200 \times \left[\frac{D_S - D - \Delta A}{D_S + D + \Delta A}\right] \quad (11)$$

3.2. Water use and irrigation quality indices

The water use index (WUI) proposed by Causapé (2009) was utilized to quantify the use of water in the irrigable area of the Lerma basin:

$$\text{WUI} = \left[1 - \frac{D + \text{EWDL}}{P + I}\right] \times 100 \quad (12)$$

This index, obtained mainly from measured data, quantifies the percentage of water resources (irrigation and precipitation) that were utilized in evapotranspiration.

In order to better analyze the irrigation quality, net hydric needs (HNn) and indices evaluating the irrigation efficiency (IE), irrigation drainage fraction (IDF), and water deficit (WD) were utilized. These indices were calculated for each field and during annual crop period, according to the criteria proposed by Causapé (2009) and starting from data provided by water balances in the soil.

$$\text{HNn} = (\text{ET}_C + \text{AW}_{\text{final}}) - (\text{AW}_{\text{initial}} + P_{\text{ef}}) \quad (13)$$

$$\text{IE} = \left[1 - \left(\frac{D_I + \text{EWDL}}{I}\right)\right] \times 100 \quad (14)$$

$$\text{IDF} = \frac{D_I}{I} \times 100 \quad (15)$$

$$\text{WD} = \frac{\text{ET}_C - \text{ET}_a}{\text{ET}_C} \times 100 \quad (16)$$

The HNn estimates the volume of irrigation water necessary to avoid crop yield losses due to water stress. In the presence of crops, the net water requirements divided by the irrigation efficiency would estimate the gross amount of irrigation applied. Irrigation efficiency quantifies the percentage of irrigation that has not left the system, being used to meet the water requirements of the crops or accumulated as soil water storage. The irrigation drainage fraction quantifies the percentage of irrigation lost in drainage and is influenced by the irrigation volume applied and the soil water content when irrigation occurs. Finally, the water deficit evaluates the extent to which irrigation has been unable to satisfy the water requirements of crops.

High quality irrigation is experienced when the WD and the IDF are nil and the IE approaches 100%. It must be noted that there are irrigation events not intended to meet water requirements, but to optimize humidity in the soil for specific agrarian activities (e.g. tillage). Conversely, it may be necessary to apply excessive irrigation in certain circumstances to promote the leaching of salts with the subsequent generation of drainage and irrigation efficiency loss (Tanji and Kielen, 2002). Furthermore, controlled deficit irrigation techniques might be applied to cause an intended water deficit (Doorenbos and Kassam, 1979; Farré and Faci, 2009).

4. Results and discussion

4.1. Water balances

The volume of water involved in the balances of the Lerma basin progressively increased with the introduction of irrigation. After

Table 2
In: inputs [precipitation (P), irrigation (I), incoming water flows (IWF) from the unirrigable area]; O: outputs [actual evapotranspiration (ET_a), water drained through the Lerma Gully (LG), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL)]; S: storage [in the soil (ΔS) and in the aquifer (ΔA)] and balance errors ($In - O - S$ and percentage) for the years 2004–2008.

Year	Inputs (mm/year)				Outputs (mm/year)				Storage (mm/year)			Balance error	
	P	I	IWF	ΣIn	ET_a	LG	EWDL	ΣO	ΔS	ΔA	ΣS	$In - O - S$ (mm/year)	%[a]
2004	628	0	78	706	318	169	0	487	20	–	20	199	32.7
2005	212	0	16	228	237	36	0	273	−42	–	−42	−2	−1.1
2006	426	144	56	626	425	123	20	568	48	9	57	1	0.2
2007	411	397	31	839	643	106	57	806	−36	68	32	1	0.2
2008	361	519	27	907	656	118	59	832	7	69	77	−2	−0.3
2004–2008	408	212	41	661	456	110	27	593	−1	29	29	39	6.1

[a] Balance error [%] = 200 × [$(In - O - S)/(In + O + S)$].

the rainy year of 2004, the volume of water reached a low 230 mm in 2005 and increased with the implementation of irrigation until approximately 900 mm in 2008 (Table 2).

Seasonally, the water involved in the balance shifted from an initial distribution according to precipitation (mainly during spring and autumn) to a distribution according to irrigation patterns. With the transition of the basin, the distribution was centered on the irrigation months, when highest input and output water volumes were registered due to irrigation, evapotranspiration and drainage (Fig. 2)—although the latter was partially regulated by the aquifer.

Precipitation was the main water input component in the Lerma basin, except in 2008, when it was surpassed by irrigation. The highest (628 mm in 2004) and lowest (212 mm in 2005) volumes of water introduced by precipitation occurred in unirrigated conditions. During the transition into irrigated land, less extreme annual precipitations were recorded, which were closer to the average historical records for the area (460 mm/year; http://oficinaregante.aragon.es).

The effective precipitation for the entire study period was 75% of total precipitation, similar to the theoretical value used in other studies (Cuenca, 1989). However, throughout the studied years, this value varied considerably from 54% in the rainy year of 2004 to 92% in the dry year of 2005, indicating the importance of not considering the effective precipitation as a fixed percentage value of total precipitation. The effective precipitation fluctuated less during the irrigation years, ranging between 79% (in 2007) and 86% (in 2006). The greatest non-effective precipitations occurred after saturation of the soil, especially during the spring months. Specifically, in April 2007, the wettest month of the entire irrigation period, non-effective precipitation (73 mm) was 57% of the total (127 mm).

Irrigation was the second greatest input component in the water balance. Its importance increased gradually since its implementation in 2006. In fact, in 2008, when 85% of the area became irrigated, irrigation represented the main component of total water inputs (519 mm, 57% of inputs).

Water flows from unirrigable areas of the Lerma basin (mostly valley zones) accounted for only 6% of the total inputs in the balance. These flows varied temporally according to precipitation, reaching a high of 11% of total inputs in 2004. This component became less significant with the transformation of Lerma into irrigation land, as the contribution of these flows to the total inputs decreased proportionally from 11% in 2004 to 3% in 2008.

In terms of outputs, the ET_a (Table 2) was the main component throughout the entire study period, accounting for 77% of the total outputs. Although the highest ET_0 (1334 mm) was recorded in 2005, lack of irrigation and an intense drought led to a low ET_a (237 mm) during this year. As expected, ET_C increased with the expansion of irrigation, from 564 in 2006, to 736 mm in 2007 and 852 mm in 2008. The last year included the greatest irrigated area and widespread presence of double cropping. The increase in ET_C led to progressive increases in ET_a with the implementation of irrigation, although ET_a never equaled the ET_C due to lack of available water in the soil during certain periods of time.

The water drained through the Lerma gully corresponded to 19% of the outputs in the entire study period (Table 2). The lowest value was recorded in the dry year of 2005 (36 mm, 13% of outputs), while the highest occurred in the rainy year of 2004 (169 mm, 35% of outputs). Drainage gradually changed over the transition years from an intermittent pattern solely due to precipitation in 2004/2005 to a continuous flow with a clear influence of irrigation thereafter. With the transformation into irrigated land, the median of daily flow at the Lerma gully increased significantly from 4.3 l/s in 2006, to 7.6 l/s in 2007 and up to 9.4 l/s in 2008 ($p < 0.05$, Mann–Whitney). The percentage of the total drainage due to irrigation was 22% in 2006, increasing to 39% in 2007 and reaching 63% in 2008. Seasonally, 66% of the water evacuation by the Lerma gully occurred between April and September, during which 97% of irrigation was applied.

The losses due to evaporation and wind drift from sprinkler irrigation, absent in the unirrigated period, accounted for between 4% (2006) and 7% (2007 and 2008) of the outputs during the years under irrigation. Although seemingly small volumes in the balance, these values are significant from an agronomic perspective, corresponding to 11–14% of total irrigation and 14–16% of applied sprinkler irrigation. These values were similar to those found in experimental trials in areas with weather conditions similar to those of the Lerma basin (Playán et al., 2005).

Storage in the soil varied with the annual regime and seasonality of irrigation and rain, such that some years were offset by others. Gradual implementation of irrigation progressively increased

Table 3
Soil drainage volume (D_S), drainage of irrigated area (D), water storage in the aquifer (ΔA) and drainage error associated with water balances.

Year	D_S (mm/year)	D (mm/year)	ΔA (mm/year)	Error[a] (%)
2004	290	91	–	104.4
2005	18	20	–	−12.8
2006	78	68	9	1.4
2007	144	76	68	0.9
2008	158	91	69	−1.6
2004–2008	137	69	29	33.3

[a] Drainage error [%] = 200 × [$(D_S - D - \Delta A)/(D_S + D + \Delta A)$].

Table 4
Net hydric needs (HNn), irrigation (*I*), irrigation efficiency (IE), irrigation drainage fraction (IDF), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL) and water deficit (WD) during the period 2006–2008 in the Lerma basin.

Year	HNn (hm^3/year)	*I* (hm^3/year)	IE (%)	IDF (%)	EWDL (%)[a]	WD (%)
2006	0.54	0.58	74.5	11.8	13.7	15.3
2007	1.33	1.61	72.1	13.5	14.4	11.6
2008	1.90	2.10	70.3	18.3	11.3	19.5
2006–2008	1.26	1.43	72.1	14.7	13.1	15.6

[a] Percentage expressed with respect to the total irrigation volume.

Table 5
Area percentage, net hydric needs (HNn), irrigation (*I*), irrigation efficiency (IE), irrigation drainage fraction (IDF), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL) and water deficit (WD) during the period 2006–2008 for the three main crops of the Lerma basin.

Crop	Area (%)	HNn (m^3/ha year)	*I* (m^3/ha year)	IE (%)	IDF (%)	EWDL (%)	WD (%)
Maize	52	5950	7400	71.6	13.3	15.1	10.0
Winter cereal	20	2510	1535	70.8	15.4	13.8	26.9
Tomatoes	10	5550	5520	86.6	13.4	0.0	14.4

storage in the aquifer (Tables 2 and 3), and, at the end of the study, it could not be verified that the system was in equilibrium.

Water storage in the aquifer is not considered in many studies due to a claimed periodicity of irrigation and rainfall. However, in Lerma basin, water storage in the aquifer accounted for up to 8% of the water involved in the balance of 2007 and 2008, and explains the high balance error in 2004 (32.7%) when it could not be quantified. For the rest of study years, and in particular for the last three in which the water storage in the aquifer was quantified, the balances closed properly.

The precipitation events in 2004 influenced the balance estimation of soil drainage to a high 290 mm, while the measured drainage of the irrigated area itself was only 91 mm (Table 3). This would imply a theoretical storage in the aquifer of 199 mm, which when not considered leads to an unacceptable drainage error (104.4%). Once the storage in the aquifer was considered, annual errors fell below ±2%, giving consistency to the results of the balance and enabling the implementation of irrigation quality indices based on those results.

4.2. *Water use and irrigation quality indices*

In unirrigated conditions, the quantity of water drained through the gully ranged from 14% of precipitation in the rainy year of 2004 to 9% in the dry year of 2005 (which also could have drained previous rainfalls). With the transformation into irrigated area, the water use index was 84%, ranging from 85% in 2006 to 83% in 2008. This translates into only 16% of the available water resources (rainfall plus irrigation) leaving the basin in the form of drainage or wind drift and evaporation losses (thus unused by crops).

The volume of irrigation applied was 13% higher than the net hydric needs (Table 4), a proportion that is not considered excessive because an irrigation efficiency of 87% would have been sufficient to meet the crop requirements. However, the calculated efficiency of Lerma stood at only 72%, producing a crop water deficit of 16%. The latter value might be an overestimation though, since the growth stages of the crops did not always coincide with the average values of the region of Ejea de los Caballeros (used by EMR). According to information provided by farmers, production yields did not correspond to the maximum potential of the area, which could in part be justified by a possible water deficit.

The irrigation efficiency is within the range verified in irrigation lands around the world (between 54 and 80%: Zalidis et al., 1997; Al-Jamal et al., 2001). However, it differs from what was quantified in other pressurized irrigation lands of the middle Ebro valley. Tedeschi et al. (2001) and Cavero et al. (2003) quantified efficiencies above 90% in irrigation areas of the Ebro river basin, although it is important to note that those authors do not discount the losses by evaporation and wind drift, which, as indicated by Playán et al. (2005), may account for 8–15% of sprinkler irrigation applied in the climatic conditions of the Ebro valley.

According to Tanji and Kielen (2002), a well managed sprinkler irrigation system can achieve a maximum application efficiency of 90%. The loss of irrigation efficiency in Lerma was divided between drainage losses and combined losses by both evaporation and wind drift (sprinkler irrigation). Thus, the irrigation drainage fraction was 15%, while the wind drift and evaporation losses were 13% of the total irrigation applied.

The increase in irrigated area resulted in increases in the net hydric requirements of the basin, which nearly quadrupled in three years (from 0.54 hm^3 in 2006 to 1.90 hm^3 in 2008) (Table 4). The unit net hydric needs increased from 4401 m^3/ha irrigated in 2006 to 4910 m^3/ha irrigated in 2007 and 5509 m^3/ha irrigated in 2008, showing that as irrigation is implemented, farmers opt for more profitable crops or double crops, which in turn have higher water requirements.

The annual performance of the irrigation quality indices shows a continuous decline in irrigation efficiency (from 74% in 2006 to 70% in 2008), which is mainly due to increasing irrigation drainage fraction (from 12% in 2006 to 18% in 2008). Season-wise, April registered irrigation efficiencies of approximately 80%, decreasing to 62% in May as a result of irrigation in the rainy season (Fig. 3). In other sprinkler-irrigated areas of the Ebro river basin, Tedeschi et al. (2001) found lower irrigation efficiencies in the months of April and

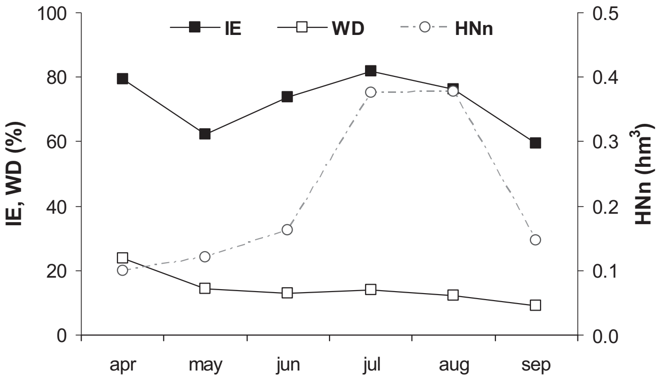

Fig. 3. Monthly dynamics of irrigation efficiency (IE), water deficit (WD), and net hydric needs (HNn) between April and September of the period 2006–2008 in the Lerma basin.

May as a result of precipitation and frequent irrigation applied after planting maize in an attempt to stimulate emergence and reduce crust formation in soils. Planting maize, which in general occurs later in the Lerma basin, caused this effect in May. After May, as water requirements continued to increase, irrigation efficiency values also increased to approximately 80%. Efficiency only began to decrease in September when the water needs decreased and rainfall increased (Fig. 3). Water deficit, which significantly increases during the summer months in flood irrigation systems (Causapé et al., 2004; García-Garizábal et al., 2011), remained practically constant in the Lerma basin as there was the possibility of more frequent application of pressurized systems to meet water requirements over this period.

Among the three main crops in the basin (82% of the irrigated area), tomatoes presented an irrigation efficiency of 87%, 15% higher than that of maize and winter cereal (72 and 71%, respectively). The fraction of irrigation drainage was similar among these three crops (between 13 and 15%), indicating that differences between the efficiencies were mainly due to wind drift and evaporation losses from sprinkler irrigation, which ultimately demonstrates the higher efficiency of drip irrigation systems (Table 5).

The lower hydric needs of winter cereal did not prevent it from suffering the greatest water deficit (27%), which was due to longer intervals between irrigation applications—similar management to that of flood irrigation with high irrigation applications sparsely divided.

The results indicate that an increase in irrigation efficiency could be achieved by better planning around timetables and schedules of irrigation application, so as to reduce drainage and minimize combined losses by evaporation and wind drift. A greater fractioning of irrigation according to the hydric needs of crops and consideration of precipitation would reduce irrigation drainage.

With regard to wind drift and evaporation losses, switching to drip irrigation wherever possible would nullify these losses. But knowing that for many crops this switch is not possible, some authors suggest the possibility of reducing these losses with a rigorous schedule of irrigation (Dechmi et al., 2003). In this sense, Playán et al. (2005) show that wind drift and evaporation losses of nocturnal irrigation can become almost half of those occurring during diurnal irrigation, and Zapata et al. (2007, 2009) suggest the use of programmable irrigation with built in wind speed sensors, making it possible to choose the ideal time for irrigation. Therefore, during the next years of consolidation of irrigation in the basin, there is the possibility of an improvement in water use in addition to higher crop yields.

5. Conclusions

The results indicate that the use of water in the Lerma basin is at the same level of other modern irrigation systems in the Ebro basin, although there is still margin for improvement in irrigation management. For instance, adjusting the doses and schedules of irrigation can have substantial impact on maximizing efficiency and minimizing water deficit.

Acknowledgments

The authors are thankful to the support of European Union Program of High Level Scholarships for Latin America (Raphael Abrahao Alβan Scholarship No. E07D400318BR), to the projects CGL2009-13410-C02-01 (MICINN) and PMO19/2006 (DGA), to the Bardenas Canal Irrigation District no. XI Authority and to the farmers for their valuable collaboration.

References

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO, Rome, Italy (FAO Irrigation and Drainage Paper No. 56).

Al-Jamal, M.S., Ball, S., Sammis, T.W., 2001. Comparison of sprinkler, trickle and furrow irrigation efficiencies for onion production. Agric. Water Manage. 46 (3), 253–266.

Beltrán, A., 1986. Estudio de suelos de la zona regable de Bardenas. II. Sectores: VIII, XI, X, XII y XIII. Instituto Nacional de Reforma y Desarrollo Agrario, Ministerio de Agricultura, Pesca y Alimentación, Spain.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E., 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Eng.-ASCE 123 (6), 423–442.

Causapé, J., Quílez, D., Aragüés, R., 2004. Assessment of irrigation and environmental quality at the hydrological basin level. I. Irrigation quality. Agric. Water Manage. 70 (3), 195–209.

Causapé, J., 2009. A computer-based program for the assessment of water-induced contamination in irrigated lands. Environ. Monit. Assess. 158 (1–4), 307–314.

Cavero, J., Beltrán, A., Aragüés, R., 2003. Nitrate exported in drainage waters of two sprinkler-irrigated watersheds. J. Environ. Qual. 32 (3), 916–926.

Charbonneau, R., Kondolf, G.M., 1993. Land use change in California, USA: nonpoint source water quality impacts. Environ. Manage. 17 (4), 453–460.

Chaudhry, F.H., 1978. Nonuniform sprinkler irrigation application efficiency. J. Irrig. Drain. Div.-ASCE 104 (2), 165–178.

Clemmens, A.J., Burt, C.M., 1997. Accuracy of irrigation efficiency estimates. J. Irrig. Drain. Eng. 123 (6), 443–453.

Critchley, W., Siegert, K., 1991. Water Harvesting: A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production. FAO, Rome, Italy.

Cuenca, R.H., 1989. Irrigation System Design. An Engineering Approach. Prentice Hall, New Jersey, United States.

Custodio, E., Llamas, M., 1983. Hidrología Subterránea. Ediciones Omega, Barcelona, Spain.

Dechmi, F., Playán, E., Cavero, J., Faci, J.M., Martínez-Cob, A., 2003. Wind effects on solid set sprinkler irrigation depth and yield of maize (*Zea mays*). Irrig. Sci. 22 (2), 67–77.

Doorenbos, J., Kassam, A.H., 1979. Yield Response to Water. FAO, Rome, Italy (FAO Irrigation and Drainage Paper No. 33).

Faci, J.M., Bensaci, A., Slatni, A., Playán, E., 2000. A case study for irrigation modernisation. I. Characterisation of the district and analysis of water delivery records. Agric. Water Manage. 42 (3), 313–334.

FAO, 2003a. Unlocking the Water Potential of Agriculture. Food and Agriculture Organization of the United Nations, FAO, Rome, Italy.

FAO, 2003b. World Agriculture Towards 2015/2030. An FAO Perspective. Food and Agriculture Organization of the United Nations, FAO, Rome, Italy.

Farré, I., Faci, J.M., 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. Agric. Water Manage. 96 (3), 383–394.

García-Garizábal, I., Causapé, J., Abrahao, R., 2009. Evolution of the efficiency and agro-environmental impact of a traditional irrigation land in the middle Ebro valley (2001–2007). Span. J. Agric. Res. 7 (2), 465–473.

García-Garizábal, I., Causapé, J., Abrahao, R., 2011. Application of the irrigation land environmental evaluation tool for flood irrigation management and evaluation of water use. Catena 87, 260–267.

Isaaks, E., Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University, New York, United States.

Isidoro, D., Quílez, D., Aragüés, R., 2004. Water balance and irrigation performance analysis: La Violada irrigation district (Spain) as a case study. Agric. Water Manage. 64 (2), 123–142.

Lecina, S., Playán, E., Isidoro, D., Dechmi, F., Causapé, J., Faci, J.M., 2005. Irrigation evaluation and simulation at the irrigation district V in Bardenas (Spain). Agric. Water Manage. 73 (3), 223–245.

Martínez-Cob, A., 2004. Revisión de las necesidades hídricas netas de los cultivos de la cuenca del Ebro. CHE internal document.

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sánchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric. Water Manage. 76 (3), 139–159.

Rosegrant, M.W., Ximing, C., Cline, S.A., 2002. Global Water Outlook to 2025. Averting an Impending Crisis. International Food Policy Institute, Washington DC, United States.

Soil Survey Laboratory, 1995. Information Manual. Soil Survey Investigations Report No. 45. Version 1.0. United States Department of Agriculture, Washington DC, United States.

Soil Survey Staff, 1992. Keys to Soil Taxonomy. Pocahontas Press, Blacksburg, United States.

Tanji, K.K., Kielen, N.C., 2002. Agricultural Drainage Water Management in Arid and Semi-arid Areas. FAO, Rome, Italy (FAO Irrigation and Drainage Paper No. 61).

Tedeschi, A., Beltrán, A., Aragüés, R., 2001. Irrigation management and hydrosalinity balance in a semi-arid area of the middle Ebro river basin (Spain). Agric. Water Manage. 49 (1), 31–50.

Urdanoz, V., Amezqueta, E., Clavería, I., Ochoa, V., Aragües, R., 2008. Mobile and georeferenced electromagnetic sensors and applications for salinity assessment. Span. J. Agric. Res. 6 (3), 469–478.

Wahl, T., 2000. Winflume User's Manual. United States Department of the Interior.

Zalidis, G., Dimitriads, X., Antonopoulos, A., Geraki, A., 1997. Estimation of a network irrigation efficiency to cope with reduced water supply. Irrig. Drain. Syst. 11 (4), 337–345.

Zapata, N., Playan, E., Martinez-Cob, A., Sanchez, I., Faci, J.M., Lecina, S., 2007. From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agric. Water Manage. 87 (2), 187–199.

Zapata, N., Playán, E., Skhiri, A., Burguete, J., 2009. Simulation of a collective solidset sprinkler irrigation controller for optimum water productivity. J. Irrig. Drain. Eng. 135 (1), 13–24.