Agricultural Water Management 158 (2015) 277–287

Contents lists available at ScienceDirect

Agricultural Water Management

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

Assessment of a newly implemented irrigated area (Lerma Basin, Spain) over a 10-year period. I: Water balances and irrigation performance

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ARTICLE INFO

Article history:
Received 19 September 2014
Accepted 23 April 2015
Available online 1 June 2015

Keywords:
Irrigation efficiency
Irrigation drainage fraction
Evaporation and wind drift losses
Water deficit

ABSTRACT

Implementation of irrigated agriculture is common in semi-arid areas around the world. An assessment of irrigation performance is presented herein for a hydrological basin with an area of 7.38 km^2, representative of pressurized irrigated areas within the Ebro Basin (Spain). The study covers ten hydrological years, comprehending periods before (2004–2005), during (2006–2008) and after (2009–2013) transformation to irrigated land. Water balances were carried out for each of the 55 agricultural plots and for the totality of irrigable area. Once the water balance for the basin is validated, indicators of irrigation performance were obtained from the soil water balances for the vegetative cycle of the crops in each plot. Water balances presented good results, with balance errors below 10.0% for most of the studied years and an error of 1.2% across the entire study period. After implementation of irrigation, irrigation became the main water input to the basin (approximately 60%) whereas actual evapotranspiration accounted for the major output (approximately 70%). Irrigation efficiency reached 76.1%, while the losses of efficiency were due to evaporation and wind drift of sprinkler irrigation (13.5%) and drainage fraction (10.4%). A water deficit of 17.8% was estimated. The irrigation efficiency increased (1.05% year^{-1}), while the irrigation drainage fraction decreased (0.95% year^{-1}). However, improvements in irrigation performance were not guaranteed as water deficits also increased (0.95% year^{-1}). Optimal water use could be achieved through adequate design of irrigation schedules, i.e., irrigation rates adjusted to the requirements of crops and minimization of evaporation and wind drift losses.

1. Introduction

During the last decades, transformation of rainfed areas into irrigated agriculture areas is a common process reported in several locations around the world (FAO, 2003a). Transformed areas experience an increase in productivity, crop stability and diversity. Hydrological basins with a significant proportion of surface affected by this land use experience changes in hydrological behaviour from quantitative and water quality perspectives (e.g., Abrahão et al., 2011a, 2011b). For example, irrigation return flows play an important role in water balances of hydrological basins, especially in arid and semi-arid climates, where perennial lakes or streams rely on inputs from irrigation return flows (Scott et al., 2011; Merchán et al., 2013).

The progressive water scarcity reported in many areas of the globe implies in a great effort to evaluate all different water uses. Irrigated agriculture is recognized as the main consumer of water resources worldwide (FAO, 2003b). Consequently, studies have addressed the efficiency of water use in irrigated agriculture through several irrigation quality indexes (e.g., Skhiri and Dechmi, 2012; Soto-García et al., 2013).

Quantitative comparison between studies on irrigation efficiency – and other indexes – is difficult, since different definitions are adopted across studies (Lankford, 2012). Definitions range from irrigation efficiency at a plot level (Setegn et al., 2011; Ahadi et al., 2013) to irrigation district level (Jia et al., 2013), or even economic definitions dealing with mass of harvest or income generated by water volume applied (Soto-García et al., 2013). However, in a study area with a long record of data and consistent study

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http://dx.doi.org/10.1016/j.agwat.2015.04.016
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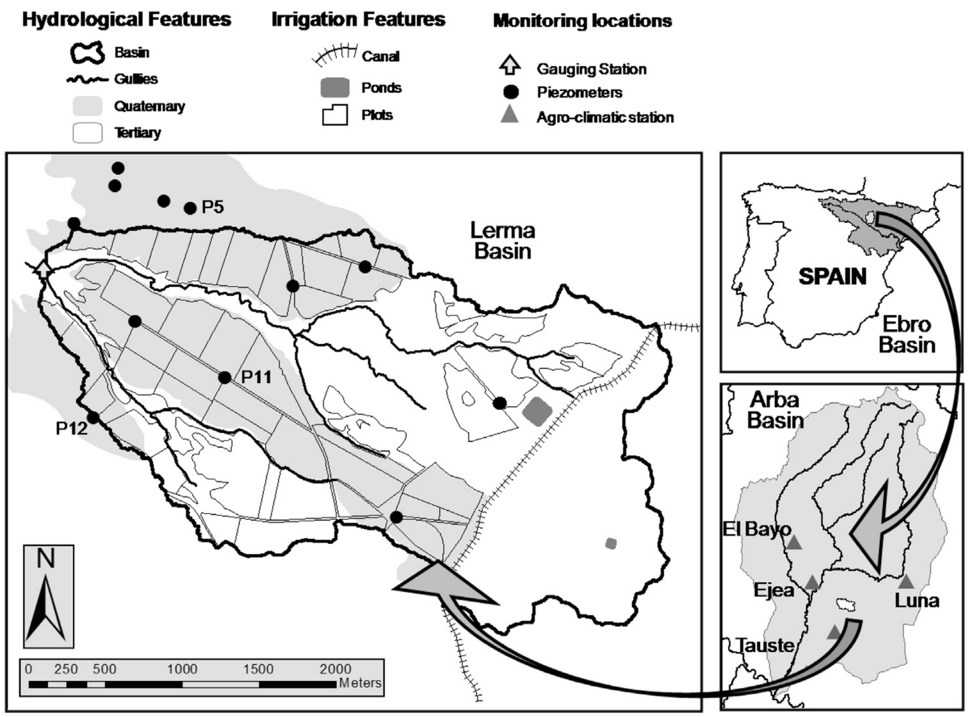

Fig. 1. Location of the Lerma Basin, Arba and Ebro River Basins. Hydrological and irrigation features, monitoring locations. Agro-climatic stations in the proximity of the Lerma Basin.

methodology, quantitative comparison and assessment of the evolution of irrigation performance is feasible. Even though there are differences in the results produced by different irrigation performance definitions, qualitative comparison between studies may be of use (Lankford, 2012), as an idea of the better irrigation scenarios can be provided.

On-plot irrigation efficiency depends on various on-farm design and management factors such as soil type, field length, crop type, crop cultural practices and irrigation scheduling (Ahadi et al., 2013). Thus, irrigation efficiency is both spatially and temporally variable. Consequently, a standard set of mandatory best management practices (BMP) has no utility, as these BMP should be adapted to the particular study case (Hernández and Uddameri, 2010).

Moreover, it is expected that in its first years of operation, a newly developed irrigation area would not achieve optimal performance levels that are typical of the utilized irrigation system. Farmers that have been accustomed to different systems (i.e., different agricultural practices such as those developed in rainfed areas) need time to adapt to the new technology and possibilities of irrigated systems. In fact, a similar statement could be made regarding modernization of irrigation structures, such as the shift from flood to pressurized irrigation. In both cases, such evolutions are especially interesting as the improvement of irrigation performance influences individual farmers (water savings) and the water management authority of the basin (modification of irrigation return flows downstream; Jia et al., 2013). Besides, irrigation performance severely affects the leaching of pollutants from irrigated agriculture (e.g., salts, Duncan et al., 2008; nitrate, Quemada et al., 2013).

The irrigation performance in Spain has been deeply studied (e.g., Lorite et al., 2004; Farré and Faci, 2009; Salvador et al., 2011; Soto-García et al., 2013), as the climatic conditions and high population density in some areas make water scarcity a great problem. Particularly, irrigated agriculture in the Ebro Basin has received wide attention (Isidoro et al., 2004; Playán et al., 2005; García-Garizábal and Causapé, 2010; Barros et al., 2011; Andrés and Cuchí, 2014).

In this context, the objective of this study was: (i) to assess the changes in the water balance after transformation from rainfed to pressurized irrigated agriculture; and (ii) to study the evolution of irrigation performance during the years after the transformation. This paper presents the first part of a study that also assessed the agro-environmental impact caused by salts and nitrate from this newly implemented irrigated area.

2. Description of the study area

The study area is the hydrological basin of the Lerma Gully (7.38 km^2, Fig. 1), located on the left side of the Middle Ebro River Valley, in Northeast Spain, in the Arba River Basin. In the early 2010s, the original project was to transform half of its surface in irrigated land, with water originating from the Yesa Reservoir (located in a neighbour hydrological basin, Aragón River Basin). The irrigated surface increased gradually between 2006 and 2013 (Table 1). The main increase was observed between 2006 and 2008, although complete transformation was not reached until 2013 (352 ha), the last year included in this study.

Before implementation of irrigation, the main crops were wheat and barley, which were seeded in winter and harvested in June or July. Production relied on meteorological conditions, with good harvest in wet years. An interruption in cultivation occurred between 2003 and 2005, when construction for the implementation of irrigation took place (new distribution of plots, building of access ways, main pipe network and ponds installation). After the installation of on-farm equipments, maize (44%), barley (12%), sunflower (9%), pea (9%), wheat (7%) and tomato (6%) were the main crops in the area (Table 1). Sprinkler irrigation accounted for 93% of the irrigated surface, with drip irrigation used for the remaining area. Irrigation water rates (average of 5680 m^3 ha^{-1}) were influenced by the annual crop pattern and its water requirements, as well as by the presence of double cropping (16% of the cultivated surface, on average).

Table 1
Dynamics of the transition into irrigated land for the Lerma Basin.

		2006	2007	2008	2009	2010	2011	2012	2013	Average[a]
Irrigated area	ha	127	269	316	319	322	331	331	352	–
	%[b]	36.1	76.3	89.6	90.5	91.2	93.8	93.8	100	–
Irrigation system	Sprinkler (%)	91.2	97.9	94.5	90.8	90.6	97.5	88.2	90.8	92.6
	Drip (%)	7.8	2.1	5.5	9.2	9.4	2.5	11.8	9.2	7.4
	$m^3 ha^{-1}$ irrigated	4860	5750	5750	6200	5660	5320	6630	4900	5680
Crops	Summer extensive (%)	71.1	64.2	48.2	65.0	34.9	60.9	57.0	43.2	53.2
	Vegetables (%)	28.9	8.0	21.6	19.7	34.5	17.2	20.7	26.9	22.4
	Winter extensive (%)	0.0	27.8	25.6	9.7	23.2	15.5	18.9	18.2	18.8
	Grass (%)	0.0	0.0	3.7	4.5	5.1	3.9	0.8	9.6	4.0
	Fruit trees (%)	0.0	0.0	0.9	1.1	2.3	2.5	2.6	2.1	1.6
	Maize (%)	64.8	64.3	41.8	49.5	28.2	46.5	44.9	35.9	44.3
	Barley (%)	0.0	17.1	19.0	7.6	10.1	4.6	11.5	15.2	11.6
	Sunflower (%)	6.3	0.0	6.4	15.6	6.7	14.5	12.1	7.2	8.9
	Pea (%)	0.0	0.0	11.8	6.0	21.6	7.9	6.3	6.6	8.7
	Wheat (%)	0.0	10.7	6.6	2.1	13.1	10.9	7.4	3.0	7.2
	Tomatoes (%)	7.8	2.1	5.5	8.1	7.1	0.0	9.2	7.1	5.8
	Broccoli (%)	21.1	2.5	1.7	2.1	1.7	0.0	0.0	6.6	3.1
	Onion (%)	0.0	3.4	2.6	3.5	0.0	0.8	5.2	4.1	2.6
	Leek (%)	0.0	0.0	0.0	0.0	4.1	8.5	0.0	2.4	2.2
	Almond tree (%)	0.0	0.0	0.9	1.1	2.3	2.5	2.6	2.1	1.6
	Vetch (%)	0.0	0.0	0.0	0.0	0.0	3.9	0.8	4.1	1.3
	Ray grass (%)	0.0	0.0	0.0	4.5	5.1	0.0	0.0	0.0	1.3
	Alfalfa (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.5	0.9
	Sorghum (%)	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.5
	Double cropping (%)	0.0	2.5	27.1	8.7	26.3	14.2	10.9	23.9	15.7

[a] Weighted average considering the transformed area.
[b] Percentage of total irrigable area.

The geology of the study area is composed by Tertiary materials consisting of relatively thin layers of marls, clays, limestone and gypsum (66% of the surface, Fig. 1), covered locally (34%) by Quaternary glacis consisting of gravels with loamy matrix (ITGE, 1988). A network of twelve piezometers and a geophysical study provided data on the thickness of the Quaternary materials, with a maximum of 12 m, and more frequent thickness values between 1 m and 6 m (Plata, 2011). Soils developed on the glacis (Calcixerollic Xerochrepts, Soil Survey Staff, 2014) display loamy textures, with an effective depth of 60–90 cm. The low salinity (electrical conductivity of the saturation extract: $EC_e < 4\,dS\,m^{-1}$) and small risk of erosion (slope < 3%) characterized these zones as suitable for conversion into irrigated land (Beltrán, 1986), and therefore most of the irrigated area covers the Quaternary surface (Fig. 1). In contrast, soils developed in the valleys of the Lerma Basin (Typic Xerofluvent, Soil Survey Staff, 2014) have a lower effective depth (between 30 and 45 cm), limited by limestone or tabular gypsum levels, which provide slow drainage. These Tertiary valleys were classified as not appropriate for irrigation due to higher salinity values (EC_e between 4 and 8 $dS\,m^{-1}$) and steep slopes (>10%) (Beltrán, 1986).

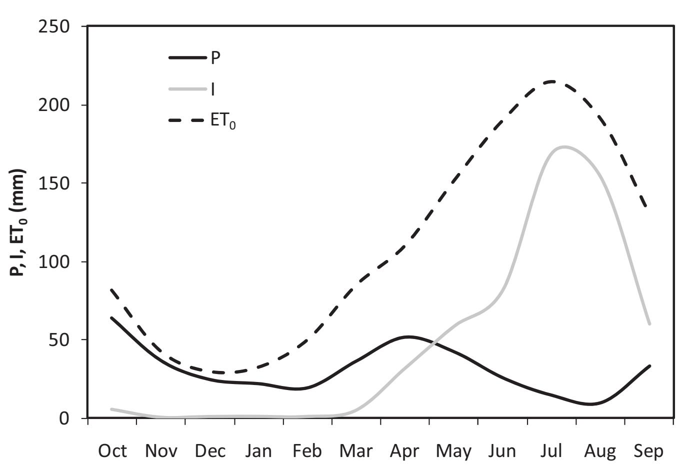

Fig. 2. Average monthly precipitation (*P*), irrigation (*I*) and reference evapotranspiration (ET_0) of the Lerma Basin during 2004–2013. For irrigation, only the years 2009–2013 were used.

According to the agro-climatic stations of the Integrated Irrigation Advisory Service (SIAR Network: http://oficinaregante.aragon.es), temperatures ranged from monthly averages of approximately 4 °C (February) to 22 °C (August), with a yearly average of 14 °C. Average rainfall for the ten study years (hydrological years 2004–2013) was 382 mm $year^{-1}$ with a high annual variability (coefficient of variation: CV = 31%). A typical year consists of two dry seasons (summer and winter) and two wet seasons (spring and autumn) (Fig. 2). The average reference evapotranspiration (ET_0) calculated by the Penman–Monteith method (Allen et al., 1998) was three times higher (1307 mm $year^{-1}$) than rainfall, less variable (CV = 6%) with no even distribution throughout the year, presenting 75% of ET_0 occurring between April and September (Fig. 2).

3. Methodology

Daily water balances for the irrigable area of Lerma Basin were carried out for each of the 55 plots throughout the period 2004–2013. An assessment of irrigation performance through the computation of indices was also accomplished. Calculations were automated through the utilization of EMR 2.0 (Irrigation Land Environmental Tool – EMR –, from its Spanish abbreviation, Causapé, 2009a). This methodology has been applied to several irrigated areas in the Middle Ebro River Basin (Causapé, 2009b; García-Garizábal et al., 2009, 2011; Abrahão et al., 2011a; Skhiri and Dechmi, 2012; Andrés and Cuchí, 2014).

3.1. Water balances

3.1.1. Soil water balances

The meteorological data required for calculation for the water balances was obtained from four agro-climatic stations of the SIAR

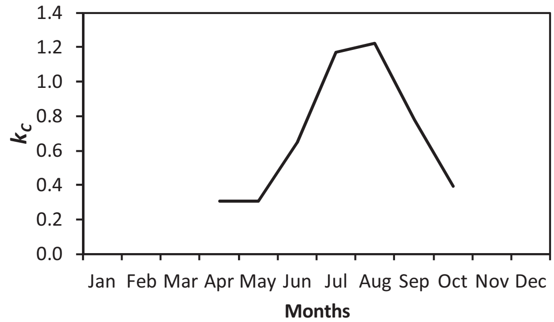

Fig. 3. Crop coefficient (k_C) used for maize, covering the period between early April and early October (Martínez-Cob, 2004).

Network, located between 4 and 18 km away from the study zone in all directions (El Bayo, Ejea, Luna and Tauste, Fig. 1). The EMR software utilizes the inverse square distance technique to interpolate the climatic variables from the different stations to obtain a daily value for every plot in Lerma. Daily irrigation volumes were provided by the Irrigation Authority XI of the Bardenas Irrigation District, obtained from flow metres at the plot level.

Data on precipitation (P), irrigation (I), combined losses due to evaporation and wind drift of sprinkler irrigation (EWDL), and potential evapotranspiration (ET_0) were utilized to develop daily soil water balances (SWB) to estimate actual evapotranspiration (ET_a), soil drainage (D_{SWB}) and soil water storage (ΔS) in each of the 55 irrigated plots:

$$(P + I) - (ET_a + D_{SWB} + EWDL) = \Delta S \quad (1)$$

A percentage of losses was applied to the irrigation volume to quantify the combined losses by evaporation and wind drift of sprinkler irrigation, based on wind speed 2 m above the surface (WS, m s^{-1}) and relative humidity 1.5 m above ground level (RH, %) (Playán et al., 2005):

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

The daily crop potential evapotranspiration (ET_C) was calculated (Allen et al., 1998), from reference evapotranspiration (ET_0) and the monthly crop coefficients (k_c) obtained from Martínez-Cob (2004) for the study zone:

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

It is not the objective of this work to present a detailed explanation of the crop cycle and irrigation management for every crop or plot, nor its influence on the estimation of ET_C. However, maize deserves a more detailed explanation since it is predominating crop with high water demands (Table 1). In the study area, maize is sowed in early April (as a single crop) or mid-June (as a secondary crop), and harvested in October (Fig. 3). It is irrigated approximately every week between April and June, when three or four irrigation events per week are conducted until late August-early September, when the crop coefficients peak (Fig. 3).

The water holding capacity of the soil (WHC, mm) for plants was estimated from the average apparent electrical conductivity of the soil (EC_a, dS m^{-1}) (Causapé et al., 2009; Grisso et al., 2009) for each field, which depended on the water content of the soil. EC_a was derived from 43,433 measurements made throughout two weeks after significant rainfalls (soils at field capacity). A mobile geo-referenced electromagnetic sensing system (Urdanoz et al., 2008) was utilized for these measurements and the WHC of 10 soil samples (representative of the EC_a range of Lerma) was analyzed in the laboratory according to the methodology of the Soil Survey Laboratory (1995) – WHC: field capacity (0.33 bar of soil water tension) minus wilting point (15 bar). The statistically significant relationship established between EC_a and WHC was:

$$WHC = 415.7\,EC_a + 2.42; \quad R^2 = 0.91; \quad p < 0.001 \quad (4)$$

Due to the uncertainty in this estimation, in a preliminary stage a range of WHC values were used for each plot, consisting of the 20% higher and 20% lower values of WHC. The impact of utilizing this range of values was assessed, as in turn, WHC influences the estimated components from the soil water balance.

Therefore, starting from an initial volume of available water for plants in the soil (AW), EMR adds the daily inputs by net irrigation ($I - EWDL$) and precipitation (P). EMR considers that $ET_a = ET_C$ if $AW_{initial} + P + I - EWDL > ET_C$, but otherwise $ET_a = AW_{initial} + P + I - EWDL$; hence, the soil has a wilting point level of moisture at the end of that day (AW = 0). However, if $AW_{initial} + P + I - EWDL - ET_a > WHC$, the programme interprets that the field soil capacity has been surpassed, and drainage from soils (D_{SWB}) occurs in amounts equal to $D_{SWB} = AW_{initial} + P + I - EWDL - ET_a - WHC$, which means that the soil presents field capacity (maximum AW = WHC) at the end of that day. The calculation of water balances started one year before the beginning of the study (October 1st, 2002), assuming the water content was equal to ½ WHC in the first day.

The effective precipitation (P_{ef}, share of precipitation that contributes to the water requirements of crops) was estimated for each day and each field, considering that if $P < WHC + ET_a - AW$ then $P_{ef} = P$, and otherwise $P_{ef} = WHC + ET_a - AW$. This estimate does not consider the existence of preferential flows or the runoff that could be generated. Nevertheless, it is a valid estimate as the fields in the study area are terraced and intense rain is needed to generate runoff or fast percolation.

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 $D_I = [I - EWDL] - [WHC - (AW + P - ET_a)]$. This means that, on any given day, rainfall will always occur before irrigation and, thereby, irrigation drainage has priority over rainfall drainage. It is assumed that a farmer should take rainfall into consideration when deciding whether to irrigate, and thus drainage is assigned preferentially to irrigation rather than to precipitation.

3.1.2. Water balances in the irrigable area

Water balances were obtained for the irrigable area considering also the incoming water flows (IWF), water drained through the Lerma Gully (LG) and the storage of water in the aquifer (ΔA) to complete a basin water balance:

$$(P + I + IWF) - (ET_a + LG + EWDL) - (\Delta S + \Delta A) = \text{Balance error} \quad (5)$$

The water evacuated via drainage was quantified by a gauging station (Fig. 1) equipped with continuous monitoring instruments, which allowed for the registry of water height (h, m) measurements every 10 min. These measurements were converted into flow units (Q, m^3 s^{-1}) according to the equations provided by the software Winflume (Wahl, 2000):

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

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

From the beginning of the study (October 1st, 2003) until the gauging station was operational (August, 2005), the flow of Lerma Gully was estimated from precipitation data and based on a runoff coefficient of 10.1% and on the shape of the recession curves obtained for the period when the gauging station was available and the first irrigation season had not started (October, 2005 to March, 2006).

IWF was constituted of the runoff generated in the unirrigated area, channel filtrations, and several leakages (from broken pipes) that produced increases in the discharge. For the unirrigated area, the aforementioned runoff coefficient was applied to estimate the incoming water flows. Irrigation channel filtrations were estimated through chemical gauging in several locations and seasons. A high-resolution hydrograph was utilized to estimate the amount of water generated by pipe breakages.

Finally, the annual water storage in the aquifer was estimated based on the aquifer area (251 ha) and on the saturated thickness provided by three representative piezometers located in each independent groundwater body (Fig. 1). An effective porosity of 5% was considered, which was obtained from pumping tests performed in the piezometers. The effective porosity obtained was within the range provided for the lithology of the aquifer (Custodio and Llamas, 1983). In March, 2008, eight piezometers were installed, and in April, 2010, four additional piezometers were installed, completing the piezometers network. Therefore, storage in the aquifer could only be estimated for the hydrological years 2009–2013. Given the uncertainty embedded in the effective porosity estimation, initially the balance calculations were performed with different values of porosity to assess the sensitivity of the global results to this parameter. A "double and half" approach was used, testing porosities of 2.5, 5.0 and 10.0%.

The difference between inputs (IN), outputs (OUT) and storage (ST) constituted the balance error (BE), which was evaluated in percentage terms (Causapé, 2009a):

$$BE\,[\%] = 200 \times \left[\frac{(IN - OUT - ST)}{(IN + OUT + ST)}\right] \quad (8)$$

As several components of the water balance were roughly estimated, BE of approximately 10% are generally accepted in this type of studies.

3.2. Water use and irrigation performance indices

Analysis of irrigation performance involved the computation of net hydric needs (HNn), irrigation efficiency (IE), irrigation drainage fraction (IDF), and water deficit (WD). These indices were calculated for each field and during crop cycles, from data provided by water balances in the soil (Causapé, 2009a):

$$HN_n = (ET_C + AW_{final}) - (AW_{initial} + P_{ef}) \quad (9)$$

$$IE = \left[\frac{1 - (D_I + EWDL)}{I}\right] \times 100 \quad (10)$$

$$IDF = \left(\frac{D_I}{I}\right) \times 100 \quad (11)$$

$$WD = \left[\frac{(ET_C - ET_a)}{ET_C}\right] \times 100 \quad (12)$$

HNn estimates the volume of irrigation water necessary to avoid crop yield losses due to water stress. IE quantifies the percentage of irrigation that has been used to either meet the water requirements of the crops or be stored as soil water. IDF 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, WD evaluates the extent to which the water requirements of crops have not been met.

High quality irrigation is experienced when WD and IDF are close to zero and IE approaches 100%. It must be noted that some irrigation events are not intended to meet water requirements, but to optimize humidity in the soil for specific agronomic activities (e.g., seed irrigation, tillage, testing irrigation equipment). Conversely, it may be necessary to apply excessive irrigation under certain circumstances to promote the leaching of salts with the subsequent generation of drainage and, therefore, loss of irrigation efficiency (Corwin et al., 2007). Furthermore, controlled deficit irrigation techniques might be applied to cause an intended water deficit (Farré and Faci, 2009).

During the years 2007, 2008 and 2012, surveys were conducted (by phone and face-to-face enquiries) with all farmers included in the Lerma Basin. Information regarding crops, times of sowing and harvest, and yields were registered to better understand the results of the irrigation performance indicators.

4. Results and discussion

4.1. Water balances

The total amount of the input components in the water balance for the irrigated area of the Lerma Basin was significantly modified with the implementation of irrigation (Table 2, Fig. 4). Overall inputs values ranged from 262 mm (dry year) to 711 mm (wet year) during the rainfed period. During the irrigated period, inputs exceeded 800 mm even in dry years (Table 2), which demonstrates the relevance of irrigation. The temporal distribution was also affected, shifting from precipitation- to irrigation-controlled, i.e., the main inputs were centered in the rainy months for the rainfed period whereas inputs were centered in the irrigated season for the irrigated period (Fig. 2).

Precipitation ranged between 227 and 632 mm $year^{-1}$, with an average of 382 mm $year^{-1}$ (CV = 31%). Opposing extreme situations occurred before implementation of irrigation (Table 2). During the irrigated years, precipitation was, in general, closer to average values. Effective precipitation averaged 85%, ranging from 58 to 96% throughout the different years (Fig. 4); this value was higher than what is generally obtained from theoretical estimation (75%), typically used in other studies (Cuenca, 1989).

Although precipitation was the greatest input during 2004–2006 (which covers the unirrigated period and the first irrigated year), it was surpassed by irrigation in the year 2007 (Table 2, Fig. 4). Annual irrigation reached 618 mm (in 2012) with an average of 401 mm for the entire study period. Average annual irrigation was 567 mm for the period when irrigation was consolidated (2009–2013, Table 2). The irrigation season comprehends the period April–September, but July and August presented more intense irrigation (Fig. 2). Irrigation was also the most important input in other semi-arid irrigated areas in the Ebro Basin (García-Garizábal et al., 2011; Andrés and Cuchí, 2014) as well as around the world (e.g., Scott et al., 2011).

Incoming water flows (IWF) from the unirrigated area had to be considered in the estimation of the balance in the irrigable area. IWF included runoff generated over the unirrigated area (80% of IWF), filtration along the channel (17%) and some localized leaks in the pipe system (3%). Throughout the study period, leaks supposed 7% of inputs, ranging from 4 to 13% in the different years (Table 2).

The main output was actual evapotranspiration, accounting for 73% (CV = 9%) of the outputs, ranging from 64 to 84% (Table 2). The highest ET_0 were recorded in the driest years (2005 and 2012). ET_C greatly increased its values with the expansion of irrigation (Table 2). Consequently, ET_a increased progressively throughout the study period. However, ET_a never reached the potential ET_C values due to scarcity of available water in the soil during specific periods. ET_a was the most affected variable when different water holding capacities were tested; nevertheless, 20% variations in WHC resulted in very small differences in ET_a (between 1.8 and 2.3%).

The flow in Lerma Gully accounted for 22% of outputs (Table 2), ranging from 15% in dry years (2005 and 2012) to 29% (2009), possibly as a consequence of the installation of artificial drainage to avoid

Table 2
Annual and cumulative water balance components (in mm) for the irrigable area of the Lerma Basin. In: inputs [precipitation (*P*), irrigation (*I*), incoming water flows (IWF) from unirrigated area]; Out: outputs [actual evapotranspiration (ET_a), potential evapotranspiration (ET_C); water drained through the Lerma Gully (LG), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL)]; St: storage [soil (ΔS), aquifer (ΔA)]; and balance errors (BE) for years 2004–2013.

		Annual balance (mm)										Cumulative balance (mm)									
	Year	04	05	06	07	08	09	10	11	12	13	04	05	06	07	08	09	10	11	12	13
In	*P*	632	227	444	406	367	380	307	336	240	480	632	430	434	427	415	409	395	387	371	382
	I	0	0	177	452	539	559	562	569	618	528	0	0	59	157	234	288	327	357	386	401
	IWF	79	35	59	53	49	54	57	47	34	65	79	57	58	57	55	55	55	54	52	53
	ΣIn	711	262	681	910	955	992	927	951	892	1073	711	487	551	641	704	752	777	799	809	835
Out	ET_a	335	260	466	687	697	747	664	760	688	763	335	397	354	437	489	532	551	577	589	607
	(ET_C)	(354)	(416)	(584)	(765)	(902)	(880)	(852)	(950)	(985)	(856)	(354)	(385)	(451)	(530)	(604)	(650)	(679)	(713)	(743)	(754)
	LG	133	51	141	122	135	337	289	227	133	286	133	92	109	112	117	153	173	179	174	185
	EWDL	0	0	25	68	68	78	84	86	86	60	0	0	8	23	32	40	46	51	55	56
	ΣOut	469	311	632	878	900	1161	1038	1074	907	1109	469	390	470	572	638	725	770	808	819	848
St	ΔS	30	−52	56	−41	7	−16	16	−14	8	7	30	−11	11	−2	0	−3	0	−2	−1	0
	ΔA	–	–	–	–	–	−3	−14	−38	−6	36	–	–	–	–	–	−1	−2	−7	−7	−3
	ΣSt	30	−52	56	−41	7	−20	2	−51	2	43	30	−11	11	−2	0	−3	−2	−9	−7	−2
	BE	213	3	−8	73	47	−149	−112	−71	−17	−80	213	108	69	70	66	30	10	0	−2	−10
	%[a]	35.2	1.2	−1.2	8.4	5.1	−14.0	−11.4	−7.2	−1.9	−7.2	35.2	25.0	13.4	11.6	9.8	4.1	1.2	−0.1	−0.3	−1.2

[a] Balance error [%] = 200 × [(In-Out-St)/(In + Out + St)].

plot flooding. A shift was observed in the monthly distribution of gully discharge, changing from a precipitation-driven pattern to one controlled by precipitation and irrigation.

The combined losses by evaporation and wind drift of sprinkler irrigation, absent in the unirrigated period, ranged from 4 to 10% of outputs during the irrigated period, averaging 7% (Table 2).

Water storage in the soil ranged from −52 to 56 mm $year^{-1}$ across the study period (Table 2). This parameter is very dependent on the specific hydrologic conditions of a particular year, as the amount of water stored in soils can vary significantly with irrigation or precipitation in the last days of the hydrological year.

The water table in the aquifers varied considerably during the irrigation season (Fig. 5), rising sharply at the end of the irrigation season and decreasing during the remainder of the year. Although aquifer storage could not be estimated for the first five years, it ranged from −38 to 36 mm $year^{-1}$ during the period 2009–2013 (Table 2). The accumulated value of aquifer storage was −3 mm $year^{-1}$, which can be explained by the construction of drains, as reported by farmers (Irrigation Authority XI, personal communication). Given the proximity of a low permeability layer in large areas of the basin (Plata, 2011), several plots experienced problems related to the rise of water table and consequently, artificial drainage was installed in different plots. Aquifer storage was utilized to close the balance in the period 2004–2008, providing an average storage of 30 mm $year^{-1}$ throughout the study period, which is in line with the change from intermittent to perennial gullies dependent on groundwater (Merchán et al., 2013). It is probable that the saturated thickness in the aquifer increased during the first years of the study.

Balance error (Table 2) was within the interval ± 10% for most of the studied years and thus is considered an acceptable balance closure. Testing different WHC and porosities did not produce relevant changes in balances errors (between ± 0.3%), as soils and aquifer storage were negligible in comparison with other components. In addition, the cumulative water balance improved with time, resulting in ± 1.2% in the last years. Finally, the difference observed between the drainage estimated from the soil water balance and drainage from the difference between the discharge and incoming water flows of Lerma Gully for the entire study period was 10%. This demonstrated that the estimated drainage from soil water balances is of the same order of magnitude than the drainage measured in the gully. Therefore, the water balances were acceptable, allowing for the quantification of irrigation performance indices.

4.2. Irrigation performance

The expansion of the irrigated area resulted in increases in the net hydric requirements, from 0.59 hm^3 in 2006 up to 2.28 hm^3 in the dry year of 2012 (Table 3). Nevertheless, in a wet year such as 2013, with irrigation completely implemented (100%) and similar crop distribution, HNn were 1.55 hm^3. Specific HNn for crops were higher than the average reported by Salvador et al. (2011) for large irrigation districts in the Ebro Basin. This is probably due to the specific climatic characteristics of the study zone (i.e., lower precipitation and higher ET_0) as well as differences in the distribution of crops.

Average irrigation efficiency reached 76.1% (ranging from 75.1 to 77.0% with ± 20% WHC tested). No significant trends were observed in the annual dynamics due to inter annual variation (ranging from 64.4% in 2006 to 80.7% in 2012). However, cumulative annual irrigation efficiency presented a significant upward trend (1.05% $year^{-1}$, Table 3).

The IE reported in other sprinkler irrigation districts in the Ebro Basin presented similar figures (72%, Skhiri and Dechmi, 2012; 76%, Andrés and Cuchí, 2014). These values were higher than

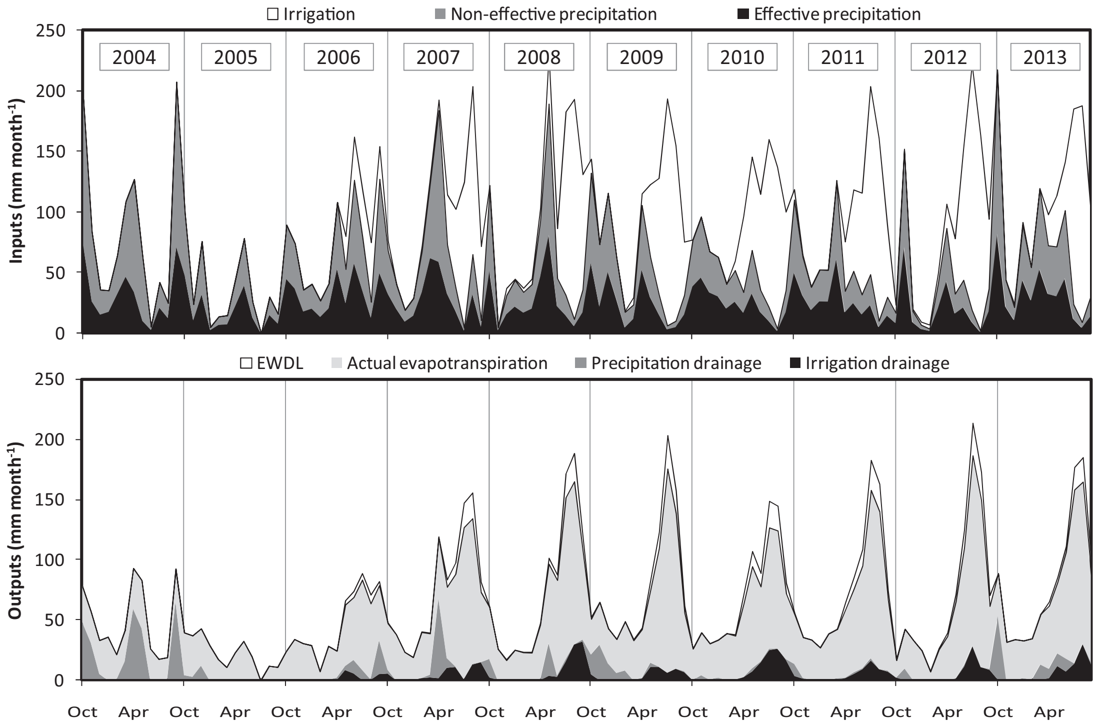

Fig. 4. Monthly inputs (irrigation, non effective precipitation and effective precipitation) and outputs (combined losses by both evaporation and wind drift-EWDL, actual evapotranspiration, precipitation drainage and irrigation drainage) during hydrological years 2004–2013.

those obtained for flood irrigated areas (45–62%, Causapé et al., 2004; 67%, García-Garizábal and Causapé, 2010). However, simple alternatives in irrigation management (García-Garizábal et al., 2011) or improvements in irrigation infrastructure (Barros et al., 2011) can significantly increase flood irrigation efficiency, up to values of the same order of those obtained for pressurized irrigation. In these cases, the goal is to control runoff and the irrigation drainage fraction.

One of the reasons why well-managed flood irrigated plots can reach high IE values, close to those obtained in sprinkler irrigated plots, is the absence of evaporation and wind drift losses. In the case of the Lerma Basin, EWDL averaged 13.5% of total irrigation (Table 3) and 14.7% of applied sprinkler irrigation. No significant trends were detected for either annual or cumulative data.

The second component responsible for the loss of irrigation efficiency was irrigation drainage fraction (IDF), with an average value

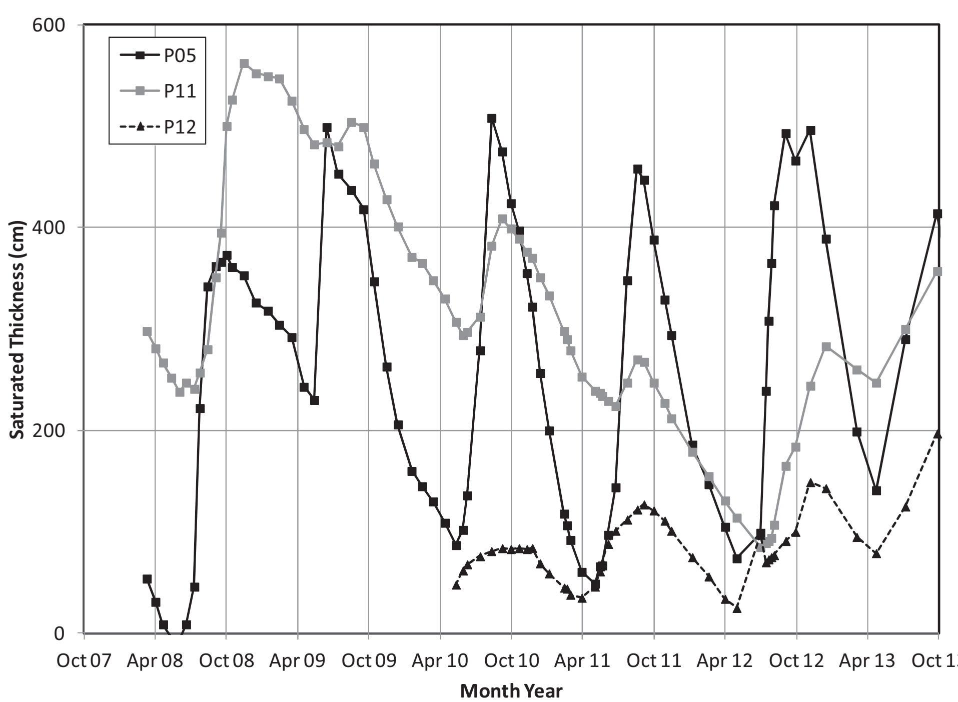

Fig. 5. Saturated thickness in selected piezometers in for the years 2007–2013.

Table 3
Annual and cumulative net hydric needs (HNn), irrigation efficiency (IE), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL), irrigation drainage fraction (IDF) and water deficit (WD) during the irrigated period for the Lerma Basin.

Year	HNn (hm^3 $year^{-1}$)	IE (%)	EWDL (%)	IDF (%)	WD (%)	Cumulative	HNn (hm^3 $year^{-1}$)	IE (%)	EWDL (%)	IDF (%)	WD (%)
2006	0.59	64.4	13.1	22.5	13.1	06	0.59	64.4	13.1	22.5	13.1
2007	1.31	73.6	14.7	11.7	11.5	06–07	0.95	70.6	14.3	15.1	12.0
2008	1.83	78.1	12.7	9.2	20.4	06–08	1.25	74.0	13.5	12.5	15.8
2009	1.83	78.5	13.6	7.9	15.8	06–09	1.39	75.3	13.6	11.1	15.8
2010	1.71	74.4	14.0	11.6	20.0	06–10	1.46	75.1	13.7	11.2	16.8
2011	1.94	80.7	14.5	4.8	22.0	06–11	1.54	76.3	13.7	10.0	17.8
2012	2.28	78.1	13.9	8.0	24.7	06–12	1.64	76.5	13.9	9.6	18.9
2013	1.55	73.6	11.5	14.9	11.5	06–13	1.63	76.1	13.5	10.4	17.8
Trend[a]	ns	ns	ns	ns	ns	Trend	***	**	ns	*	**
Slope[a]	–	–	–	–	–	Slope	+0.11	+1.05	–	–0.97	+0.95

ns: non significant trend ($p > 0.1$); *: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$.
[a] Significant trend and slope with Mann–Kendall test and Sen's slope (Helsel and Hirsch, 2002).

of 10.4% (ranging from 9.6 to 11.5% with ± 20% WHC tested). The cumulative values presented significant downward trend (0.97% $year^{-1}$, Table 3), which could be related to the decreasing trends detected in the flow when irrigation was consolidated (Merchán et al., 2013). IDF values were similar to those of other pressurized irrigation areas (11%, Skhiri and Dechmi, 2012; 12%, Andrés and Cuchí, 2014). Flood irrigation areas with low WHC soils can present higher IDF (44%, García-Garizábal et al., 2011), although the implementation of management improvements decreased IDF to 11–24%.

The water deficit obtained was 17.8% (ranging from 16.6 to 19.3% with ± 20% WHC tested). The cumulative data presented an upward trend of 0.95% $year^{-1}$. WD values were higher than those reported in other irrigation systems (9%, Skhiri and Dechmi, 2012; 13%, Andrés and Cuchí, 2014; 14%, García-Garizábal et al., 2011) and this was probably related to, among other factors, the lower water holding capacity of the soils in the Lerma Basin.

The irrigation performance of Lerma Basin is within the observed values for other pressurized irrigation areas in the Ebro Basin. Regarding its temporal evolution, the trends for the different variables show a progressive increase in IE and decrease in IDF. Farmers that originally used rainfed or flood irrigation schemes may have adapted to new pressurized irrigation equipment and possibilities, and obtained a better knowledge of the system. However, an increase in WD was observed, requiring further knowledge to elucidate the causes.

Of the main crops (87% of irrigated surface), barley, sunflower and wheat presented net hydric needs higher than irrigation rates, generating expected water deficits (over 20%, Table 4). In the case of winter cereals, the deficit occurred mainly at the end of the vegetative cycle. This water deficit may have affected yields (approximately 4500 kg ha^{-1}, according to surveys with the farmers). However, the decrease in yield produced by the water deficit depends absolutely on the phase within the cycle, as increased productivity has been observed when small water deficits occurred in specific moments. Sunflower was traditionally under-irrigated, and cultivated with strong subsidies from the Common Agricultural Policy; in 2003 the subsidies were "decoupled" for particular crops (http://ec.europa.eu/agriculture). Although these associated subsidies are no longer available since 2003, farmers still experience "inertia" regarding shifts in the traditional management of sunflower.

Maize and tomato, for which HNn were lower than irrigation rates, presented relevant water deficits (11.0 and 16.1%, respectively). This indicates an inappropriate irrigation schedule. Tomatoes presented maximum IE (83.7%), mainly due to the absence of EWDL, which supports the higher efficiency of drip irrigation systems (Table 4). However, tomatoes also presented the highest IDF due to excessive application of irrigation in punctual moments.

Maize, the predominant crop, deserves a detailed assessment. Maize presented the lowest IE (77.0%) and irrigation surpassed HNn for all years, with values between 6 and 29% higher (Table 5). Such over-irrigation of maize is reported in several other location of the irrigated area of the Ebro Basin (Skhiri and Dechmi, 2012; Andrés and Cuchí, 2014) and is a general pattern for the entire Ebro Basin (average of 20%, Salvador et al., 2011). This is related to the sensitivity of maize to water stress, a fact that is well-known by the farmers (Barros et al., 2011), who try to avoid water stress through excessive irrigation.

Irrigation efficiency ranged from 74.1 to 80.2% and losses by EWDL ranged from 15 to 16%, presenting low variability (CV = 3%). However, IDF ranged between 4 and 12% (CV = 35%) and was related to the net hydric needs ($R^2 = 0.78$, $p < 0.01$): the higher the HNn (dry and hot years), the lower the IDF. This is due to a dryer state of soils in those years, along with a major effort from the farmers to achieve good water use in years of scarcity as also reported in other studies (Soto-García et al., 2013).

The water deficit for maize averaged 11.0% (ranged from 6.4 to 14.4%, CV = 25%), and was negatively correlated with the over-irrigation ratio (I/HNn, $R^2 = 0.87$, $p < 0.01$), i.e., the more irrigation applied exceeding the crop requirements, the lower the water deficit. The obtained WD for maize was slightly lower than what was reported in other irrigated areas of the Ebro Basin (13%, Andrés and Cuchí, 2014; 14%, Barros et al., 2011).

A detailed analysis of the irrigation schedule followed by different farmers is beyond the scope of this paper. Instead, as a conclusive summary, the most common examples of inadequate

Table 4
Number of plots available for each crop (N), area percentage, net hydric needs (HNn), irrigation (I), irrigation efficiency (IE), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL), irrigation drainage fraction (IDF) and water deficit (WD) during the period 2006–2013 for the main crops of the Lerma Basin.

Crop	N	Area (%)[a]	HNn (mm $year^{-1}$)	I (mm $year^{-1}$)	IE (%)	EWDL (%)	IDF (%)	WD (%)
Maize	155	44.3	647	740	77.0	15.2	7.8	11.0
Barley	31	11.6	271	177	81.2	13.6	5.2	25.9
Sunflower	26	8.9	609	527	80.7	15.3	4.0	25.8
Wheat	22	7.2	349	295	78.4	14.3	7.3	21.0
Tomatoes	24	5.8	637	645	83.7	0.0	16.3	16.1

[a] Proportion of the irrigated area.

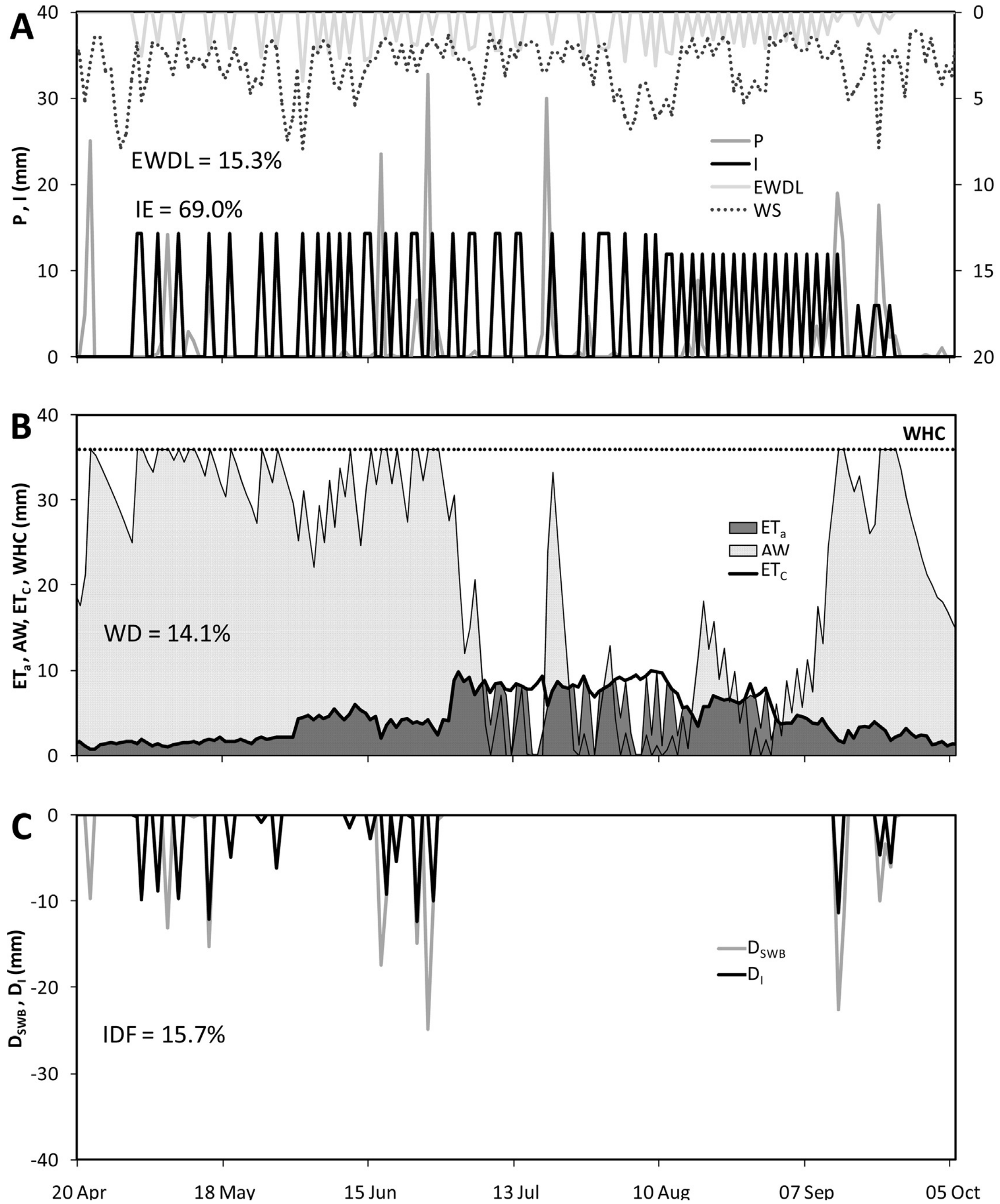

Fig. 6. Components of the soil water balance during the maize crop cycle in 2006 for a selected plot. (A) Precipitation (*P*), irrigation (*I*), wind speed (WS) and evaporation and wind drift losses (EWDL). (B) Actual evapotranspiration (ET_a), available water in the soil (AW), potential evapotranspiration (ET_C) and water holding capacity (WHC). (C) Total drainage from soil water balance (D_{SWB}) and irrigation drainage (D_I).

irrigation management are presented in Fig. 6: components of the soil water balance in a maize plot with sprinkler irrigation. IE in this plot reached 69.0% with EWDL losses (15.3%) similar to those of IDF (15.7%). EWDL were related to high wind speeds in the study zone. As observed in Fig. 6A, there are irrigation events in days with high wind speed, with an extreme case of 8 m s^{-1} on June 2nd. Tarjuelo et al. (1992) consider 3 m s^{-1} as a threshold for sprinkler irrigation: above this wind speed value, sprinkler irrigation should not be applied. However, this threshold is hard to implement in windy areas such as the Lerma Basin (average wind speed 3.2 m s^{-1}, Fig. 6A). Nevertheless, it would be advisable to irrigate during the night (lower average wind speed and higher relative humidity, Playán et al., 2005) and to avoid irrigation in extremely windy days to minimize EWDL. Additional measures, such as upgrading to drip irrigation in applicable crops could reduce EWDL.

IDF was related to irrigation events that exceeded the water requirements of the crop, when the available water in the soil was close to its water holding capacity (Fig. 6B and C). Also, some irrigation events were carried out just after important precipitation events (July 20th, after a rainfall event of 30 mm). However, this problem presents difficult solution as farmers must require water two days in advance. After irrigation is scheduled, there are difficulties to cancel the event due to operational system limitations (distance to Yesa reservoir, storage capacity of ponds). An ambitious objective would be to achieve null irrigation drainage although some drainage will always occur in connection with precipitation events, limiting the

Table 5
Number of plots available each year (*N*), net hydric needs (HNn), irrigation volume (*I*). Annual and cumulative irrigation efficiency (IE), combined losses by both evaporation and wind drift of sprinkler irrigation (EWDL), irrigation drainage fraction (IDF) and water deficit (WD) for maize in the irrigated period.

Year	*N*	HNn (mm year^{-1})	*I* (mm year^{-1})	IE (%)	EWDL (%)	IDF (%)	WD (%)	Cumulative	IE (%)	EWDL (%)	IDF (%)	WD (%)
2006	13	595	645	75.6	15.2	9.2	14.4	06	75.6	15.2	9.2	14.4
2007	24	619	760	74.1	15.8	10.1	9.2	06–07	74.6	15.6	9.8	10.9
2008	19	591	761	74.2	14.7	11.1	6.4	06–08	74.4	14.4	10.2	9.4
2009	21	681	757	80.0	15.1	4.9	10.3	06–09	76.0	15.3	8.7	9.7
2010	12	712	872	76.3	15.9	7.8	8.8	06–10	76.1	15.3	8.6	9.6
2011	25	681	725	79.4	15.5	5.1	14.0	06–11	76.8	15.4	7.8	10.5
2012	21	735	803	80.2	16.1	3.7	11.9	06–12	77.3	15.5	7.2	10.7
2013	20	560	618	75.0	13.4	11.6	12.8	06–13	77.0	15.2	7.8	11.0
Trend[a]	ns	ns	ns	ns	ns	ns	ns	Trend	*	ns	*	ns
Slope[a]	–	–	–	–	–	–	–	Slope	+0.40	–	−0.37	–

ns: non significant trend ($p > 0.1$); *: $p < 0.1$; **: $p < 0.05$; ***: $p < 0.01$.
[a] Significant trend and slope with Mann–Kendall test and Sen's slope (Helsel and Hirsch, 2002).

accumulation of salts in soil profiles, and consequently compromising yields.

Finally, ET_a did not reach ET_C in some periods of the crop cycle (Fig. 6B), and water deficit occurred (14.1%) as a consequence of irrigation rates slightly below crop requirements and lack of available water in those periods. The average yields obtained were approximately 11,500 kg ha^{-1} (farmer surveys), with maximum yields of 14,000 kg ha^{-1}, which could be partially due to this water deficit.

The exposed facts imply in the existence of margins of improvement through the implementation of measures to decrease both IDF and EWDL. Adjustment of irrigation rates to the water requirements of the crop, according to the stage of its vegetative cycle, will not only minimize water deficit but also reduce drainage and increase efficiency. For instance, the automation of irrigation in accordance with soil humidity and climatic sensors would enable the adjustment of irrigation to the water requirements of the crop, provided that the irrigation infrastructures allows for it.

5. Conclusion

After the transition was completed (100% implementation), irrigation was the main water input in the basin (approximately 60%) whereas the main output was actual evapotranspiration (73%). Other outputs were the discharge through the Lerma Gully (22%) and the evaporation and wind drift losses of sprinkler irrigation (5%). Soil and aquifer storage were accounted for, but negligible in comparison with other components of the water balance. Differences between inputs and outputs were minimal, averaging −1.2% across the study period, allowing for a trustworthy estimation of irrigation performance.

The irrigation performance of Lerma Basin was within the observed values for other pressurized irrigation areas of the Ebro Basin. Irrigation efficiency reached 76.1%, while the losses of efficiency were due to evaporation and wind drift losses (13.5%) and drainage fraction (10.4%). A water deficit of 17.8% was estimated. The irrigation efficiency increased (1.05% year^{-1}) while irrigation drainage fraction decreased (0.95% year^{-1}) throughout the period 2006–2013. No significant changes in evaporation and wind drift losses of sprinkler irrigation were detected. Despite these facts, an improvement in irrigation performance was not verified, as water deficit also increased (0.95% year^{-1}).

It is necessary to improve irrigation management in order to continue increasing irrigation efficiency, while decreasing evaporation and wind drift losses, drainage fraction, and water deficit. Optimal water use could be achieved if irrigation rates were adjusted to the requirements of crops, if the irrigation infrastructure allows for it.

Irrigation performance is important not only because it prevents water deficit or saves water. An adequate management of irrigation increases the good use of water resources and decreases the environmental impacts in irrigated areas, especially the leaching of salt and nitrates from irrigated soils, which is the objective of the second part of this study, presented in a companion manuscript.

Acknowledgements

This work was carried out within project CGL2012-32395 (Spanish Ministry of Economy and Competitiveness – Feder-EU Funds) and benefited from grant BES2010-034124 (Spanish Ministry of Economy and Competitiveness). Dr. Iker García-Garizábal was supported by PROMETEO grant from SENESCYT-Ecuador. The authors are thankful to Juan Plata, Felix Rubio and Antonio Azcón, from the Geological Survey of Spain. Thanks are also extended to the Irrigation Authority XI of Bardenas Irrigation Scheme, for facilitating irrigation data and providing help in several field-related issues.

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