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Application of the Irrigation Land Environmental Evaluation Tool for flood irrigation management and evaluation of water use

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ABSTRACT

Irrigated zones worldwide suffer from water deficits, making it necessary to analyze irrigation management and to study alternatives to maximize adequate partitioning and distribution of irrigation water. The objective of this study is to compare the water use efficiency before (2001) and after (2002–2008) implementation of a new irrigation management plan in an area operating with traditional methods.

To this end, annual water balances were carried out in a pilot basin (95 ha) in Northeast Spain during the period between 2001 and 2008. From these, the evolution of irrigation quality (Net Hydric Needs, Irrigation Efficiency, and Water Deficit) was analyzed in climatically different years and after changes in irrigation management (i. assignment of irrigation allowances, ii. on-demand flood irrigation system, and iii. creation of water consumption accounts).

The changes in irrigation management contributed to a better adjustment between water consumption and net hydric needs of crops, translating into improved irrigation efficiency and drainage reduction, although years with greater net hydric needs presented greater water deficits.

Assignment of irrigation allowances and billing according to the volume of irrigation water consumed contributed to raising awareness of farmers about the value of water, especially in dry years. These facts, along with the flexibility in the time of irrigation granted by an "on-demand" management, led to an optimization of irrigation water applications to levels seldom exceeded by gravity irrigation in such permeable soils.

1. Introduction

The basic supply of water and food to populations makes water resource management a fundamental requirement for society. During the last 50 years, worldwide water extraction for consumption has increased more than 150% (FAO: Food and Agriculture Organization of the United Nations, 2002), therefore it is increasingly necessary to know the water requirements for the different consumers and to develop a plan to optimize distribution and use of this resource.

The agrarian sector is by far the greatest consumer of water resources. Three quarters of the planet's withdrawal of freshwater is for agricultural irrigation, increasing production and allowing for a greater stability in food supply (especially in regions where development of crops is limited by available precipitation). Forty percent of global agrarian production is obtained from the 20% of cultivated areas that are irrigated (FAO: Food and Agriculture Organization of the United Nations, 2003). In Spain, where irrigated lands have increased 24% in the last 20 years (MAPA: Ministerio de Agricultura Pesca y Alimentación, 2006), the relationship between production and area is even greater, with more than 50% of the production coming from 14% of the agrarian area that consumes 75% of the country's water resources (MMA: Ministerio de Medio Ambiente, 2007; MARM: Ministerio de Medio Ambiente y Medio Rural y Marino, 2008). Within Europe, Spain has the second highest area of agricultural land (after France) and has the greatest area under irrigation in the EU (EU: European Union, 2008).

Climate change studies developed in the Mediterranean environment (Díaz et al., 2007; CIHEAM: Centre International des Hautes Etudes Agronomiques Méditerranéennes, 2008; Perez and Boscolo,

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Abbreviations: AW, available water for plants in the soil; AW_{end}, available water contained in the soil at the end of the balance; $AW_{initial}$, available water contained in the soil in the beginning; CV, coefficient of variation; D, soil drainage; D_I, drainage from irrigation; D-XIX-6, drainage; EC_a, apparent electrical conductivity; ET_0, reference evapotranspiration; ET_a, actual evapotranspiration; ET_C, potential evapotranspiration; h, water height; I, irrigation; ID-V, Bardenas Canal Irrigation District nº V; IE, irrigation efficiency; K_C, crop coefficient; LSC, lateral subterranean contributions; MGESS, Mobile Geo-referenced Electromagnetic Sensing System; HNn, net hydric needs; P, precipitation; P_{ef}, effective precipitation; Q, flow; S_a, water's storage in aquifer; S_s, water's storage in soil; WD, water deficit; WHC, water holding capacity.

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2010) suggest a future increase in crop evapotranspiration along with a decrease in precipitation. If such a trend is verified, greater water extractions will be necessary to satisfy crop irrigation demands, which according to these studies could increase up to 23%.

In general, irrigation supply comes from surface waters and inadequate management of these extractions can have serious environmental consequences (Ji et al., 2006). For example, deviations of the flows of the Amu-Danya and Syr-Danya rivers have resulted in continuous recession in the Aral Sea and progressive salinization of its waters since 1960, with important environmental and economic consequences (Aladin and Plotnikov, 2003; Cai et al., 2003).

In order to achieve a high agrarian productivity while maintaining a good environmental quality, it, is necessary to develop studies that evaluate irrigation water management to identify issues and propose management alternatives (FAO: Food and Agriculture Organization of the United Nations, 2002).

Monitoring of irrigated hydrological basins, development of water balances and consequent evaluation of irrigation quality, have been considered as an adequate methodology for analyzing irrigation management in agrarian districts (Tedeschi et al., 2001; Cavero et al., 2003; Isidoro et al., 2004). This allows for an evaluation of the degree of water usage and a quantification of the share not utilized by crops.

Nevertheless, a common flaw in previous studies is the disregard for subterranean components (lateral flows and storage in soils and aquifers) in water balances. Traditionally, closed hydrological basins have been assumed to have stationary annual hydric regimes where initial and final water storage is the same. This has resulted in significant errors in water balances that affect the analyses of irrigation management.

Moreover, most investigations cover a short period of time (1 or 2 hydrological years), which does not allow for the development of analyses considering the influence of climatic variability that exists in irrigated lands or to contrast significant agronomic changes. Therefore, this investigation includes a long-term monitoring (8 hydrological years) of a pilot basin, with the objective of analyzing the dynamics of irrigation quality in climatically different years and throughout significant changes in management of a traditional irrigated land.

2. Study zone description

The study area corresponds to the experimental hydrological basin of drainage ditch D-XIX-6 of Bardenas Canal Irrigation District n° V (ID-V, Fig. 1). The irrigation canal network that surrounds drainage ditch D-XIX-6 constitutes the surficial water divide, delimiting a hydrological basin of 95 ha (Fig. 1), of which 96% are soils subjected to flood irrigation with surficial Pyrenean waters coming from the Yesa reservoir (Aragón river).

The Spanish Institute of Geomining Technology (SIGT, in Spanish ITGE) classifies the climate of the study zone as Mediterranean warm weather (ITGE: Instituto Tecnológico Geominero de España, 1985). Average precipitation was 394 mm/year, with a notable annual variability (CV = 36%). During the study period (2001–2008), two rainy years were registered (2001 and 2004), two dry years (2003 and 2005) and four years with intermediary precipitation (Table 1).

Rain was seasonally distributed, with highs during autumn/spring and lows during winter/summer (Fig. 2). Nevertheless, monthly variability was very high, with months such as September having a coefficient of variation of 100%, in which precipitation for this month exceeded 150 mm (2004) and others in which it hardly rained (2007). This prevents the assumption of stationary annual hydric regimens commonly accepted by other studies that, like this one, are based on the comparison of water balances by hydrological years.

Annual average reference evapotranspiration (ET_0) for the eight study years was 1315 mm/year (CV = 13%). Lowest ET_0 (1093 and 1152 mm/year) were registered in the wettest years (2001 and 2004), while the highest ET_0 (1645 mm/year) was produced in 2002, resulting in a record low storage in the Yesa reservoir (CHE: Confederación Hidrográfica del Ebro, 2009). ET_0 also showed an annual seasonality, with minimum values in winter and maximums in summer when it far exceeded precipitation (Fig. 2), making irrigation indispensable for the adequate development of summer crops.

Geologically, 75% of the basin is located on a glacis of gravel with loamy matrix which constitutes a free aquifer. On this glacis, drainage D-XIX-6 was found flowing from north to south and forming a valley where lutitic tertiary substratum surfaced.

When a network of 15 piezometers was built in 2006 (Fig. 1), it was verified that the maximum thickness of the glacis reached 5.5 m at the north of the basin, with saturated thicknesses of 4 m in the summer (irrigation period). Towards the south, the thickness of the glacis decreased progressively to values less than 2 m and piezometers were occasionally dry in winter. The effective porosity of the aquifer at a regional scale was quantified by ITGE: Instituto Tecnológico Geominero de España (1995) to 10–15%. Interpretation

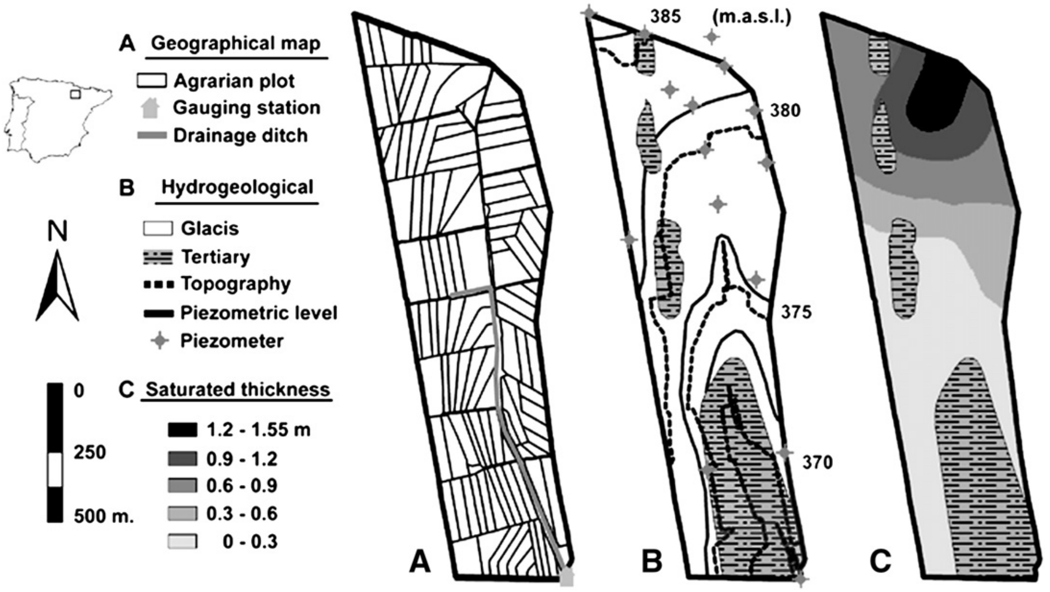

Fig. 1. Localization of the experimental hydrological basin drained by D-XIX-6 ditch: (A) distribution of agrarian plots, gauging station and D-XIX-6 drainage ditch; (B) geology, topography and piezometric level; (C) average saturated thickness in the aquifer (2006–2008).

Table 1
Precipitation (P), and reference evapotranspiration (ET_0, Penman-Monteith) during the study period (2001–2008), followed by average of values and coefficient of variation (VC).

Year	2001	2002	2003	2004	2005	2006	2007	2008	Average	VC
	mm	mm	mm	mm	mm	mm	mm	mm	mm/year	%
P	526	426	235	627	211	450	372	305	394	36
ET_0	1093	1645	1384	1152	1363	1327	1260	1298	1315	13

of results from 3 piezometers of the basin resulted in a transmissivity of approximately 15 m^2/day (García-Garizábal, 2010).

Contributions to the aquifer include precipitation, irrigation and lateral subterranean flows. There is a hydraulic gradient of 1% from the North West to the south (Fig. 1).

For the edafic characterization of the basin, 10 soils were sampled (Fig. 3). The soils developed on the glacis (Calcixerollic Xerochrept; Soil Survey Staff, 1992) displayed loamy textures with a stone content between 11 and 13% and an average water holding capacity (WHC) of 111 mm. In contrast, the soils developed on the tertiary substratum (Typic Xerofluvent; Soil Survey Staff, 1992) displayed argillaceous textures and less stone content (from 4 to 18%) with greater values of WHC (158 mm).

The selection of crops used in different study years was influenced by the availability of irrigation water, changes in market prices of raw materials and grains (MARM: Ministerio de Medio Ambiente y Medio Rural y Marino, 2009), and perhaps the changes in the Common Agricultural Policy (Atance et al., 2006). In 2001, almost the entire basin was dedicated equally between alfalfa and corn (Table 2). The water restrictions in 2002, caused by scarce water reserves of the Yesa reservoir, limited irrigation allowances to only 5000 m^3/ha and led farmers to plan their crops in order to reduce irrigation needs. Thus, areas dedicated to winter wheat and sunflower expanded at the expense of corn, with the percentage of irrigable fallow land increasing to up to 18%.

With the greater irrigation water allowances in 2003 and 2004 (7 000 m^3/ha), corn regained cultivated area increasing to 23% although still not reaching its 2001 levels (49%). This increase was sustained until the 2005 drought and partial decoupling of subsidies in 2006, which created an expansion in the trend of winter wheat at the expense of alfalfa and corn that virtually disappeared in 2008.

Based on recommendations from previous studies (Causapé, 2002; Lecina, 2004), irrigation management started to be modified in 2002, offering the opportunity to assess its influence on water use. Prior to 2002, rotation flood irrigation with minimum shifts of 12 days was applied with an irrigation rate of payment only for irrigated area, without any assignment of irrigation allowances. Subsequently, rotation flood irrigation was replaced by a more flexible system of on-demand flood irrigation and invoices accounting for irrigation volume, with the creation of irrigation allowances as a function of water reserves in the Yesa reservoir.

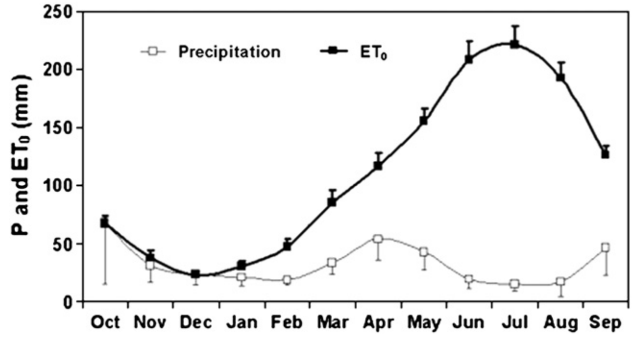

Fig. 2. Dynamics of average monthly precipitation (P) and average monthly reference evapotranspiration (ET_0) in study period (2001-2008). Vertical bars indicate ½ standard deviation.

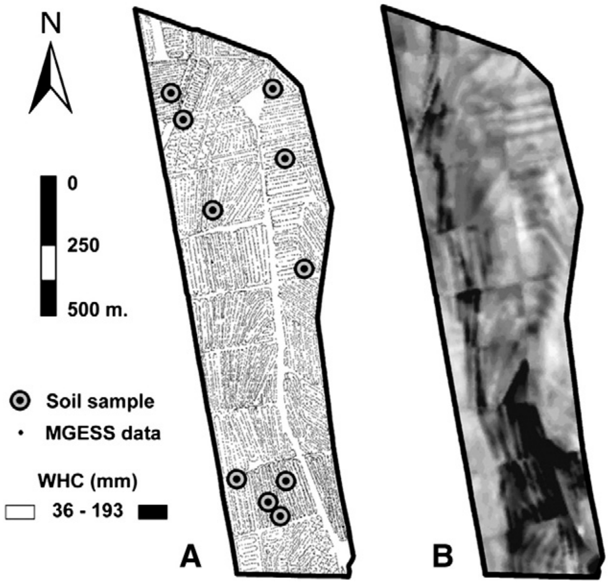

Fig. 3. (A) Readings of the Mobile Geo-referenced Electromagnetic Sensing System (MGESS) and soil sample locations. (B) Water holding capacity (WHC) map of the soils of the experimental basin.

3. Methodology

Management of water resources was evaluated in the study basin for 8 hydrological years (2001–2008). For this, the computer program Irrigation Land Environmental Evaluation Tool (Causapé, 2009) was utilized to automate calculations for the development of water balances in irrigated hydrological basins as well as to provide a series of indices capable of evaluating irrigation quality.

Hydrological monitoring of the basin during the last three study years allowed for calibration (2006) and validation (2007–2008) of annual water balances developed by Irrigation Land Environmental Evaluation Tool. Once validated, the computer program was executed with data from the other study years (2001–2005) to obtain irrigation quality indices for the entire study period (2001–2008), which allowed for the analysis of irrigation dynamics over time in terms of physical and agronomic variables.

3.1. Water balances

Development of annual water balances was carried out by either measurement or estimation of the main inputs, outputs and storage of

Table 2
Allocation of irrigation water and distribution of crops in the hydrological basin drained by D-XIX-6 during the study period (2001–2008, eight hydrological years).

Year	Allocation of irrigation water	Winter wheat	Alfalfa	Corn	Grass	Sunflower	Other crops	Fallow
	m^3/ha	%	%	%	%	%	%	%
2001	–	1	49	49	0	0	1	0
2002	5000	25	44	2	0	11	0	18
2003	7000	26	44	23	3	0	0	4
2004	7000	15	36	23	13	5	0	8
2005	6500	25	39	11	7	8	2	8
2006	7500	33	39	8	0	15	1	4
2007	7500	51	31	3	5	8	1	1
2008	8000	55	24	0	10	8	2	1

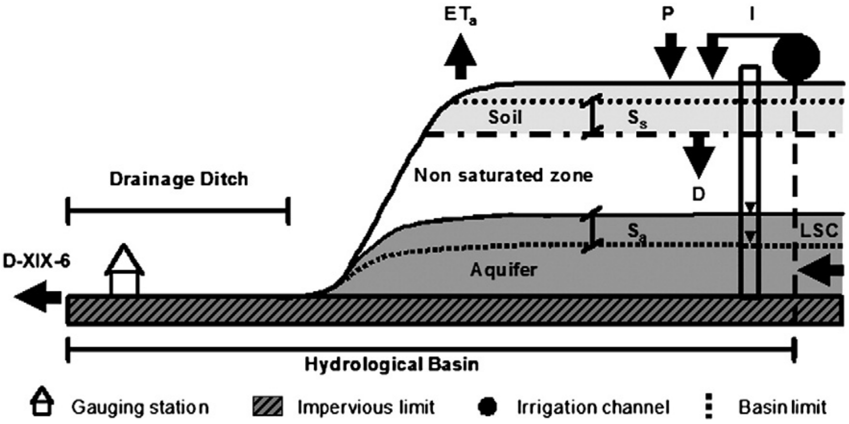

Fig. 4. Hydrological sketch where the different water balance components of the system drained by D-XIX-6 ditch are represented: irrigation (I), precipitation (P), actual evapotranspiration (ETa), drainage associated to the hydrological basin (D), lateral subterranean contributions (LSC), drainage (D-XIX-6), storage in soil water (S_s) and in the aquifer (S_a).

water in the basin (Fig. 4). The equation that determines this balance is:

$$Inputs(IN)–Outputs(OU)–Storage(S) = Error$$

$$(I + P + LSC)–(ET_a + D–XIX–6)–(S_s + S_a) = Error \tag{1}$$

where the inputs via irrigation (I), precipitation (P) and lateral subterranean contributions (LSC), minus outputs by actual evapotranspiration (ET_a) and drainage (D-XIX-6), minus water storages in soil (S_s) and in aquifer (S_a) result in the balance error.

The Irrigation Land Environmental Evaluation Tool initially developed a daily water balance for the soil of each agrarian plot using as direct inputs the daily irrigation volumes (provided by the Irrigation District) and the precipitation values recorded by nearby weather stations (GA: Gobierno de Aragón., 2009). The development of soil water balances with the Irrigation Land Environmental Evaluation Tool requires a representative value of WHC soil for each agrarian plot. For this, 25,600 measurements were taken (Fig. 3) in homogeneous moisture conditions close to field capacity (after heavy rainfall) with a Mobile Geo-referenced Electromagnetic Sensing System (MGESS) in horizontal configuration, which integrates apparent electrical conductivity (EC_a) up to 1 m in depth (Amezketa, 2007).

Apparent electrical conductivity values were transformed to WHC based on the relationship obtained between water holding capacity in 10 soil samples (Fig. 3) and its respective EC_a values,

$$WHC(\mathrm{mm}) = 276 \cdot EC_a(\mathrm{dS/m}) + 78; \mathrm{n} = 10; \mathrm{R}^2 = 0.93; **\mathrm{p}<0.01 \tag{2}$$

which allowed for the development of the WHC map for the entire basin (Fig. 3) and consequently the average WHC values to be introduced into the Irrigation Land Environmental Evaluation Tool for each agrarian plot.

Daily ET_0 data obtained by Penman-Monteith (GA: Gobierno de Aragón., 2009), along with crop coefficients for the area (K_C; García Vera and Martínez-Cob, 2004) enabled the calculation of daily potential evapotranspiration (ET_C) as $ET_C = ET_0 \cdot K_C$ (Allen et al., 1998), which in turn was used to estimate real evapotranspiration. This allowed for the calculation of water output by evapotranspiration of the general water balance for the basin as well as the soil moisture necessary to execute the balance of the following day.

In this way, starting from an initial volume of available water for plants in the soil (AW), the Irrigation Land Environmental Evaluation Tool adds the daily inputs by irrigation and precipitation, and ET_C is subtracted only if there is sufficient available water in the soil. The computer program considers that $ET_a = ET_C$ if $AW_{initial} + P + I > ET_C$, but otherwise $ET_a = AW_{initial} + P + I$, hence, the soil has a wilting point level of humidity at the end of the day (AW = 0). On the other hand, if $AW_{initial} + P + I - ET_a > WHC$, the program interprets that the field soil capacity has been surpassed, obtaining drainage equal to $Drainage = AW_{initial} + P + I - ET_a - WHC$, leaving the soil at the termination of the day at field capacity (AW = WHC).

Because no data was available on the initial water content in the soil of each plot, the value was estimated to be ½ WHC and the execution of balances was initiated 1 year before the starting date of the study (in order to achieve a better approximation of the initial water content in the soil in the beginning of the study).

With the information generated by the soil water balance, the Irrigation Land Environmental Evaluation Tool estimates the direct components of the water balance in the basin (ET_a and S_S) and soil drainage. Taking advantage of the information provided by the soil water balance, effective precipitation (P_{ef}) was estimated for each day and each plot, 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 considered to be a quite valid estimate as agricultural plots are usually 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 plots with drainage that if $AW + P - ET_a$ WHC then $D_I = I$ and otherwise $D_I = I - [WHC - (AW + P - ET_a)]$. 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.

Going back to the general water balance equation, the water leaving the basin via drainage was quantified starting from the flow (Q) measured in a gauging station (Fig. 1), where a limnigraph measured water height (h) every 15 min (Thalimedes, OTT).

$$\text{Rating curve}: Q(\mathrm{l/s}) = 0.17 \cdot h^2(\mathrm{cm}) – 1.95 \cdot h(\mathrm{cm}) – 17.9; \quad \mathrm{n} = 9; \mathrm{R}^2 = 0.99; ***\mathrm{p}<0.001 \tag{3}$$

Water storage in soil was estimated from the variation of moisture quantified by the Irrigation Land Environmental Evaluation Tool, while water storage in the aquifer was estimated from monthly monitoring of water table levels in the piezometer network and the assumption of an aquiferous effective porosity of 15% (ITGE: Instituto Tecnológico Geominero de España, 1995).

Because lateral subterranean contribution is difficult to quantify, it was selected as the variable to calibrate the balance. For this, monthly balances were executed for the first year of piezometric records (2006). The difference between inputs and outputs-storage was attributed to lateral subterranean contributions and related to irrigation and precipitation, leading to the following equation:

$$LSC = 0.018 + 0.26 \cdot P + 0.36 \cdot I; R^2 = 0.52; **p<0.01 \tag{4}$$

From this equation lateral subterranean contributions were estimated, validating the calibration for the year of 2006 with the results of 2007 and 2008. Accuracy of the water balance was quantified by the calculation of the percentage error of the balance with the Irrigation Land Environmental Evaluation Tool:

$$Error(\%) = [(IN – OU – S) / (IN + OU + S)] \cdot 200 \tag{5}$$

3.2. Irrigation quality indices

Net hydric needs, irrigation efficiency and water deficits were calculated in order to evaluate irrigation quality in the 8 study years (2001–2008). These three indices were based on soil water balances accomplished by the Irrigation Land Environmental Evaluation Tool and proposed by Causapé (2009).

The Net Hydric Needs (HNn) estimates the volume of irrigation water necessary to avoid crops from suffering hydric stress and for the soil to sustain the same soil moisture conditions. Net hydric needs are calculated as the difference between potential evapotranspiration plus available water contained in the soil at the end of the balance (AW_{end}) and available water contained in the soil in the beginning ($AW_{initial}$) plus effective precipitation. Effective precipitation was estimated by the Irrigation Land Environmental Evaluation Tool from daily soil water balances as rainfall retained in the soil available for crops.

$$HNn(\text{mm}) = (ET_C + AW_{end}) – \left(AW_{initial} + P_{ef}\right) \tag{6}$$

Irrigation Efficiency (IE) quantifies the percentage of irrigation that has not been drained, and is calculated as one minus the relationship between drainage from irrigation (estimated by the Irrigation Land Environmental Evaluation Tool from the soil water balances) and the irrigation volume applied to the crops.

$$IE(\%) = [1 – (D_I / I)] \cdot 100 \tag{7}$$

The Water Deficit (WD) evaluates the extent to which irrigation was unable to satisfy the hydric needs of crops, and is derived from the following equation:

$$WD(\%) = [(ET_C – ET_a) / ET_C] \cdot 100 \tag{8}$$

An adequate irrigation management maximizes irrigation efficiency while minimizing water deficit affecting crops. However, in certain circumstances it is necessary either to apply excessive irrigation to promote leaching of salts with a consequent loss of irrigation efficiency or to *under*-irrigate to cause a water deficit. Moreover, based on the values of annual irrigation allowances, net hydric needs, irrigation efficiency and water deficit, the eight study years were classified by multivariate cluster analysis with standardized data, using the Ward method to obtain cluster hierarchy (Hair et al. 1999). In 2001, irrigation allowances were estimated based on the total volume of water applied to the basin.

4. Results and discussion

4.1. Water balance

4.1.1. Calibration and validation of water balance

The water balances accomplished were satisfactory as the annual percentage error of validated years resulted in only −1% in 2007 and 2% in 2008 (Table 3). In addition, the soil drainage (D) estimated by the balance in the 2 years of validation (2007–2008) plus water storage in the aquifer (322 mm) differed by only 5% of what was calculated as water exported (D-XIX-6 minus LSC, 338 mm).

Lateral subterranean contributions during calibration and validation years accounted for approximately 25% of the inputs, indicating the need for their consideration in the water balance of the hydrological basin. Although water storage in soils and aquifers from irrigation cyclicity and precipitation were not as significant in most years, in years such as 2006 these accounted for 10% of inputs, preventing the assumption of a stationary annual water regime.

The adequate closure of the water balance in the basin validated the soil water balance executed by the Irrigation Land Environmental Evaluation Tool, allowing for the extrapolation of remaining study years and for evaluation of irrigation quality by means of the derived indices.

4.1.2. Soil water balance

Throughout the eight study years, irrigation was the greatest water contributor (61%), with an average of 627 mm/year, although since 2002 it has been reduced by almost half (Table 4) due to decreased availability of irrigation water and changes made in irrigation management.

The average precipitation was 394 mm/year, contributing 27% to total entries in the driest year (2005), and 52% in the wettest year (2004). According to the Irrigation Land Environmental Evaluation Tool criterion, effective precipitation was 92% of the total amount (Fig. 5), ranging from 72% in 2001 (year with greatest irrigation) to 98% in 2003 (very dry year).

Regarding water outputs, the main output was due to ET_a (77%), with an average of 788 mm/year. Despite the influence of other variables, the evolution towards crops with lower water requirements conditioned a progressive decrease in ET_a, so that in 2008 it was 19% lower than in 2001.

Average drainage was 234 mm/year, with a high annual variability (CV = 101%). The greatest volumes of water by irrigation and precipitation were experienced in 2001, leading to the largest drainage outputs (784 mm). Conversely, 2005 experienced lower inputs, which then led to the smallest drainage (71 mm). An average of 72% of drainage was irrigation drainage, ranging between 45% in the wettest year (2004) and 96% in the year with the highest effective precipitation (2003; Fig. 5).

Soil storage was substantially less significant, although some variability occurred. Very rainy years following dry years had highest

Table 3
Water inputs [IN: precipitation (P), irrigation (I), and lateral subterranean contributions (LSC)], water outputs [OU: evapotranspiration (ET_a) and drainage (D-XIX-6)] and water storage [S: soil (S_s) and aquifer (S_a)] in the hydrological basin drained by D-XIX-6 during water balance calibration (2006) and validation (2007-2008). Water balance error was calculated as 200 · (IN − OU − S) / (IN + OU + S).

Year	IN			OU		S		Error
	P	I	LSC	ETa	D-XIX-6	Ss	Sa	
	mm	mm	mm	mm	mm	mm	mm	%
2006(1)	450	567	332	830	417	65	42	0
2007(2)	372	512	291	753	469	−39	4	−1
2008(2)	305	559	291	686	451	13	−16	2

[1] Calibration year; [2] Validation year.

Table 4
Water inputs [precipitation (P) and irrigation (I)], outputs [actual evapotranspiration (ET_a) and soil water drainage (D)] and water storage in soil (S_s) in the hydrological basin drained by D-XIX-6 during the study period (2001–2008), followed by average of values and coefficient of variation (VC).

Year	Inputs		Outputs		Storage
	P	I	ET_a	D	S_s
	mm/year		mm/year		mm/year
2001	526	1139	843	784	38
2002	426	508	811	154	−31
2003	235	581	785	72	−41
2004	627	579	810	335	60
2005	211	570	786	71	−75
2006	450	567	830	121	65
2007	372	512	753	169	−39
2008	305	559	686	165	13
Average	394	627	788	234	−1
VC (%)	36	33	6	101	4191

Table 5
Net hydric needs (HNn), irrigation efficiency (IE), and water deficit (WD) in crops periods during the study period (hydrological years 2001–2008), and average in the hydrological basin drained by D-XIX-6.

		2001	2002	2003	2004	2005	2006	2007	2008	Average
HNn	Hm^3/year	0.57	0.61	0.69	0.44	0.64	0.54	0.40	0.55	0.56
IE	%	56	81	86	76	89	84	82	78	73
WD	%	0	30	24	5	19	13	8	19	14

soil storage, while very dry years followed by rainy years had highest water evacuation.

The monthly volume of inputs was equivalent to the volume of outputs plus small differences caused by the variation in soil water. Both inputs and outputs adapted to the vegetative cycle of summer crops and therefore adapted to increased irrigation requirements, ET_a and drainage, with maximums reached in the summer and minimums in the winter. Consequently, it is important to note that 92% of irrigation was applied between April and September, with the same period registering 76% of ET_a and 74% of drainage. In addition, this soil drainage was temporally stored in the aquifer delaying its exit from the basin through the ditch, as demonstrated by the highest water levels recorded in the summer and its progressive decline over autumn-winter.

4.2. Irrigation quality

The average hydric needs of the basin for the eight study years was 0.56 Hm^3/year (Table 5), with the driest years of 2003 and 2005 having the greatest hydric needs. The year of 2003 experienced the lowest precipitation (235 mm), an elevated ET_0 (1384 mm) and the largest area of corn-alfalfa (67%) compared to winter wheat-sunflower (26%), thus registering the greatest net hydric needs (0.69 Hm^3). Conversely, 2007 had low precipitation (372 mm), lower ET_0 (1260 mm) and a smaller surface of corn/alfalfa (39%) compared to winter wheat/sunflower (59%), thus registering the lowest hydric needs (0.40 Hm^3).

Average irrigation efficiency was relatively high (73%) considering it was performed via flood irrigation. However, irrigation did not meet its primary goal of completely addressing the hydric needs of crops as the average water deficit for the study period was 14%, which decreased the potential yield of crops.

The years following 2001 (when changes in irrigation management occurred) demonstrated an average increase of 23% in irrigation efficiency, although also registering some water deficit (nil in 2001). After 2001, irrigation efficiency ranged between 76% in the wettest year (2004) and 89% in the driest year (2005), indicating that scarce rain led to better utilization of irrigation water even though hydric needs were not completely satisfied. Pertaining to water deficit, values ranged from 30% in 2002 (year with lower water reserves in the Yesa reservoir) and 5% in the rainiest year (2004).

The years with highest irrigation efficiency also presented highest water deficit (Table 5), indicating that planning efforts to avoid water stress in crops was not sufficient. Conversely, years with lowest irrigation efficiency (2001 and 2004) registered the lowest water deficit (Table 5).

Multivariate cluster analysis classified the eight years of study into 3 groups (Table 6). The first group was constituted solely by year 2001, which had the highest irrigation allowance (11,000 m^3/ha year), the lowest irrigation efficiency (56%) and an absence of water deficit.

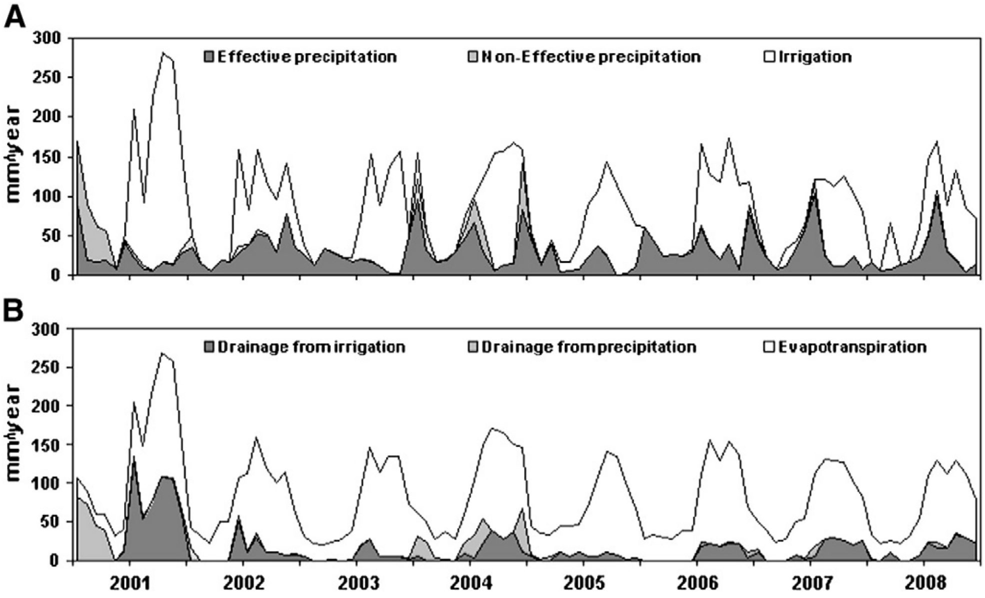

Fig. 5. Monthly dynamics of water inputs (a: irrigation, effective precipitation and non-effective precipitation) and water outputs (b: actual evapotranspiration, drainage proceeding from irrigation and drainage proceeding from precipitation) obtained by soil water balances in the experimental basin during the study period (2001–2008).

Table 6
Group classification by cluster analyses in study years (200-2008) according to allocation of irrigation water, net hydric needs (HNn), irrigation efficiency (IE), and water deficit (WD) in the hydrological basin drained by D-XIX-6.

Years	Allocation of irrigation water	HNn	IE	WD
	m^3/ha year	Hm^3/year	%	%
2001	11,000	0.57	56	0
2002, 2003, 2005	6167	0.65	85	24
2004, 2006, 2007, 2008	7500	0.45	80	11

The second group was constituted by hydrological years 2002, 2003 and 2005, experiencing the greatest net hydric needs (0.65 Hm^3/year) with the lowest irrigation water allowance (6167 m^3/ha year), reaching maximum irrigation efficiency (85%) but also highest water deficit (24%).

Finally, the analysis distinguished a third group that included the most recent years (2004, 2006, 2007 and 2008) and demonstrated that the lowest net hydric needs (0.45 Hm^3/year) adapted better to a relatively low allowance (7500 m^3/ha year), while reaching adequate irrigation efficiencies (80%) and reducing water deficits to 11%.

Considering monthly variations during crop season, the greatest irrigation efficiency was recorded in the months of higher evapotranspiration demand (June, July and August; Fig. 6), when crops consumed a higher percentage of available water in the soil before irrigation. Alternatively, irrigation applied to soils with higher moisture content caused reduced irrigation efficiency over spring, even when taking into account that irrigation was applied to presowing and emergence of corn.

The dynamics of irrigation efficiency after changes in irrigation management (2002–2008) remained parallel to those before changes (2001, Fig. 6), with greatest increases in irrigation efficiency recorded in the spring (April–May) when changes in management allowed for greater flexibility in the choice of irrigation days.

In contrast, the smallest increases in irrigation efficiency occurred in the summer, when high irrigation demand exceeded the delivery capacity of the irrigation network leading to less than optimal timing of irrigation water, influencing the choice of irrigation days.

The greatest water deficits occurred in summer months, when crops demanded more water and precipitation was scarce. Conversely, the lowest water deficit occurred in May when the greatest amounts of precipitation were recorded.

Nevertheless, the temporal evolution of irrigation quality indices was influenced by the distribution of crops. Among the three main crops, irrigation efficiency of corn (69%) was lower than that of winter wheat (74%) and alfalfa (76%) due to irrigation efficiency in its presowing and emergence. Regarding water deficit, farmers were concerned with maintaining deficits low for corn (5%), whereas alfalfa and winter wheat (which have lower economic losses associated with lack of irrigation) were allowed to have significantly higher water deficit (13% and 20%, respectively), especially during drought years.

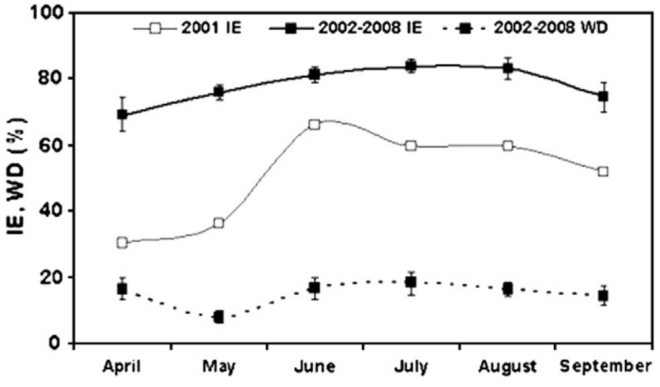

Fig. 6. Monthly dynamics of irrigation efficiency (IE) and water deficit (WD) in the experimental basin in year 2001 and during the period 2002–2008. Vertical bars indicate ½ standard deviation.

In contrast to what was expected, no significant relationship ($p>0.1$) was found between irrigation efficiency and water holding capacity in the soils of the agrarian plots, indicating that high and low application efficiencies could be obtained for any given soil depending on irrigation management.

Consequently, changes in irrigation management occurring after 2001 facilitated the achievement of high irrigation efficiency (82%), close to those recorded in pressurized irrigation systems (Caballero et al., 2001; Cavero et al., 2003), which can reach 90%. Evaporation and wind drift losses in sprinkler irrigation systems have to be discounted, and in the Ebro valley these values are in the order of 15–20% (Dechmi et al., 2003; Playán et al., 2005).

In accordance with the values of Tanji and Kielen (2002), the irrigation efficiency obtained herein are at the maximum attainable by flood irrigation, being exceeded only in very permeable soils and with the change to pressurized irrigation systems. However, such a change would alter the type of crops that, according to the different scenarios considered by Lecina et al. (2009), would lead to increased productivity of irrigation water at the cost of increased consumption.

5. Conclusions

Subterranean water components, particularly lateral contributions not usually considered in studies of this type, contributed significantly to the annual water balances (approximately 25% of the water involved). Therefore, quantification of subterranean water components becomes fundamental for its discrimination from soil drainage associated exclusively with the study zone.

Annual water balances displayed adequate closure, confirming that the main components were accounted for and properly quantified, which provided consistency to the evaluation of irrigation quality.

Changes in irrigation management contributed to a better adjustment between water consumption and net hydric needs of crops, translating into improved irrigation efficiency and drainage reduction.

However, the years with highest net hydric needs, which also presented highest irrigation efficiencies, registered the greatest water deficits. This demonstrates that in addition to greater flexibility in irrigation, the crop distribution should be better adapted to the availability of irrigation water.

Assignment of irrigation allowances and charging according to the volume of irrigation water consumed contributed to raising awareness of farmers about the value of water, especially in shortage years. These facts, along with the flexibility in the time of irrigation granted by an “on-demand” management, led to an optimization of the irrigation applications to levels seldom exceeded by flood irrigation in such permeable soils.

In accordance with values reported by other studies, the irrigation efficiencies obtained with the management changes implemented by ID-V are at the maximum limit achievable via flood irrigation.

Having longer continuity in studies of this type is fundamental to evaluate irrigation management alternatives and the effect of multi-annual climatic and agronomic variables.

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