AGRICULTURAL WATER MANAGEMENT 96 (2009) 179–187

available at www.sciencedirect.com

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

Agro-environmental evaluation of irrigation land
I. Water use in Bardenas irrigation district (Spain)

Jesús Causapé Valenzuela *

Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), Avda. Montañana 930, C.P. 50.059 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 21 February 2008
Accepted 12 August 2008
Published on line 20 September 2008

Keywords:
Irrigation district
Water balance
Irrigation efficiency
Water deficit
Water use index

ABSTRACT

Non-point agrarian contamination makes its allocation to a specific territory difficult. This first part of the study seeks to analyze contamination resulting from water use in 54,438 ha of Bardenas irrigation district included in the Arba basin (BID–Arba). To this end, water balances were carried out in BID–Arba by means of measuring or estimating the main inputs, outputs and water storage between 1 April 2004 and 30 September 2006. Also, the spatial-temporal variability in water use was analyzed.

The semester error balances were acceptable (between 11% and −6%), which permits the attribution of the mass of pollutants exported in drainage to the irrigation area evaluated, the objective of the second part of the study. Irrigation efficiency (IE) in BID–Arba was high (90%) despite the fact that Irrigation Sub-District VII (ISD-VII), with considerable flood irrigation drainage (27%), and ISD-XI with considerable losses due to evaporation and wind drift in sprinkler irrigation systems (15%), brought down the average ($IE_{VII} = 73\%$; $IE_{XI} = 83\%$). Irrigation management was inadequate as there was a water deficit (WD) of 9%, partly affected by the 2005 drought ($WD_{Apr\text{-}05/Sep\text{-}05} = 21\%$) and the low irrigation doses applied in ISD-XI ($WD_{XI} = 12\%$).

To sum up, intense re-use of water caused a water use index (percentage of water used by the crops) of 85% which surpassed 90% in periods of drought. Nevertheless, irrigation management should be improved in order to annul the water deficit and to maximize the productivity of the agrarian system.

1. Introduction

Agriculture is the main use of fresh water in the world, with 69% of extractions and 93% of total consumption (FAO, 2003). Nevertheless, the expansion of irrigated agriculture during the second half of the 20th century has made a considerable contribution towards meeting the nutritional needs of a growing world population.

Whilst in the developing world, with deaths from malnutrition, the main priority is still to meet the most basic necessities, in developed countries such as Spain, water management has to go farther. However, besides securing adequate satisfaction of water resources, the aquatic ecosystems should be preserved in a sound ecological state and the quality of water resources should be protected.

Non-point agrarian contamination makes its allocation to a specific territory difficult. Therefore, evaluation and agro-environmental surveillance of irrigation land is not a simple task. Nevertheless, water loss and pollutants in agricultural drainage can be assigned to the hydrological basin and therefore, in association with its climatic, geological and agronomic characteristics, agro-environmental diagnosis of the irrigation area studied can be offered.

---

* Tel.: +34 976716324; fax: +34 976716335.
E-mail address: jcausape@jcausape.es.
URL: http://www.jcausape.es

0378-3774/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2008.08.004

In the Ebro basin (Spain), numerous studies have been carried out to determine the amount of water used in different irrigation areas. A synthesis of the results (Causapé et al., 2006) shows that the average irrigation efficiency in flood-irrigated plots on unsuitable soils with high infiltration rates and low water holding capacity is only 51%. This value increases to 79% if the flood-irrigated plots have suitable soil, and up to 94% if sprinkler irrigation systems are used.

Nevertheless, to compare the results of some areas with others leads to some uncertainty, since the scale and methodology of the work carried out are usually different. Causapé et al. (2006) concluded that those based on the observation of small hydrological irrigated basins are of special interest, since apart from obtaining results regarding the use of irrigation water, they also contributed information concerning pollutant loads exported by irrigation in relation to their climatic, geological and agronomic characteristics. However, the area of the hydrological basins of irrigation land studied were small ranging from 100 to 3000 ha. This made a more detailed analysis possible than what can be done for areas that are 10–100 times larger. The agro-environmental surveillance of a basin such as the River Ebro (Spain), which has more than 800,000 irrigated hectares, requires studies of hydrological irrigation sub-basins to be undertaken on the level of large irrigation districts (≈50,000 ha), in such a way that with a manageable number of sub-basins, most of the irrigated area is covered.

The objective of this work is to study the agro-environmental impact of a large irrigation district in the Ebro valley (Spain), through the study of the hydrological basin which contains it. This first part of the study seeks to analyze water use in 54,438 irrigated hectares of the Bardenas irrigation district included in the Arba basin, which is the pilot experience for the establishment of the agro-environmental control network of the Ebro irrigation land.

2. Description of the study area

The study area is located on the left riverbank of the middle Ebro valley in Spain. It is made up of Bardenas irrigation district included in the River Arba basin (BID–Arba, Fig. 1). The area has glacis and alluvial quaternaries, superficial aquifers lying on impermeable tertiary materials that are considered to be the main natural source of dissolved salts in the drainage water generated by agriculture within the basin (Causapé et al., 2004a).

Irrigation began in Bardenas irrigation district in the middle of the 20th century, with water supplied by Yesa reservoir via the Bardenas canal. This canal supplies irrigation water to 78,500 ha located mainly in the southern half of the Arba basin. The same source of water also is used by villages, mainly Ejea (16,000 inhabitants), and to generate electricity.

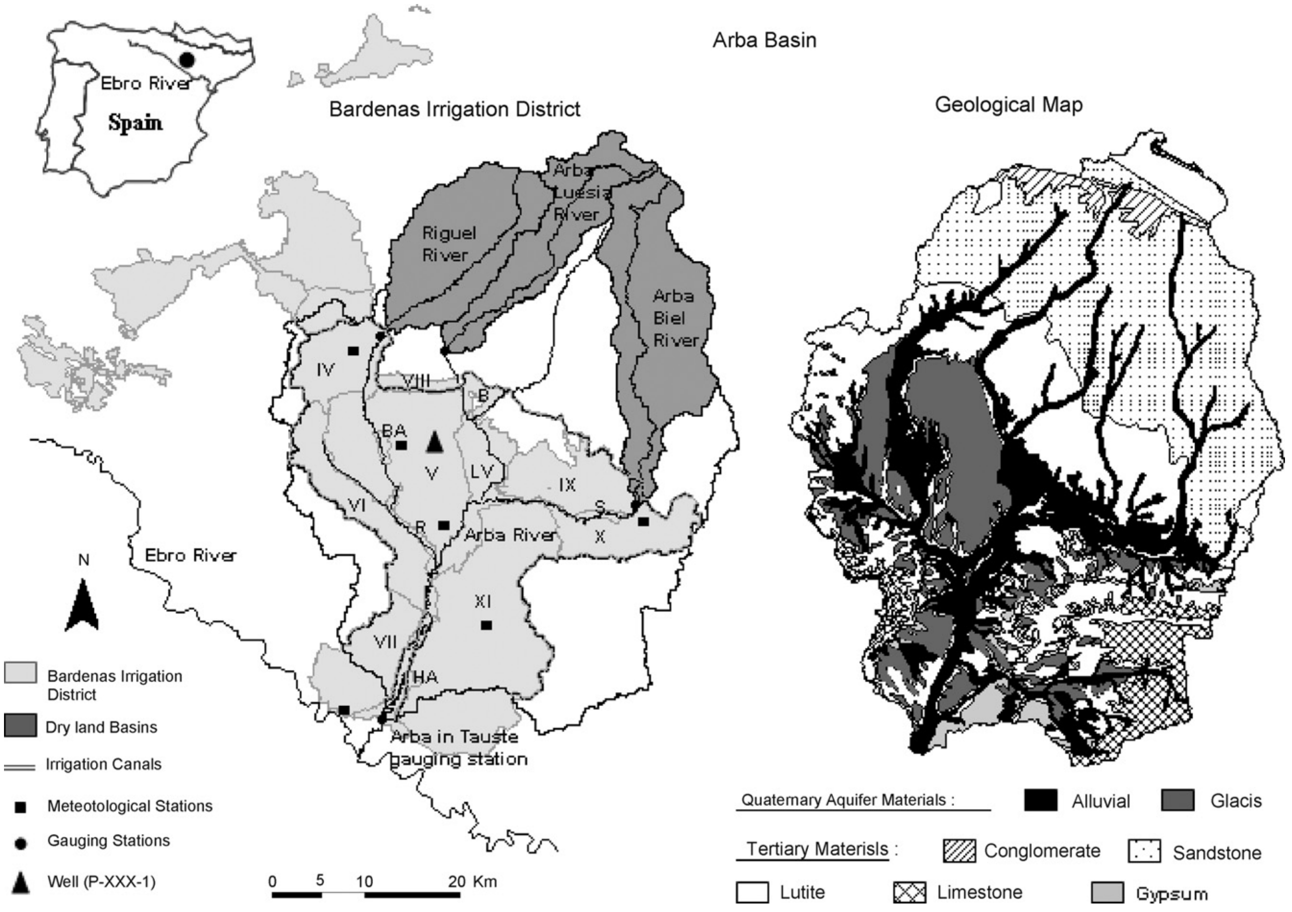

Fig. 1 – Bardenas irrigation district and Arba basin geological map. Location of main irrigation canals, Riguel, Arba de Luesia, and Arba de Biel basins; meteorological and gauging stations; and well P-XXX-1.

The generated drainage water drains into the River Arba into which converge the tributaries Riguel, Arba de Luesia and Arba de Biel (Fig. 1).

The irrigated land studied (BID–Arba) is managed by 14 irrigation sub-districts (ISDs: IV, V, VI, VII, VIII, IX, X, XI, San Bartolomé-B, Las Vegas de Ejea-LV, Huertas Altas de Tauste-HA, Riguel-R, El Bayo-BA and Santía-S) of the 20 which make up the Bardenas irrigation district. These 14 irrigation sub-districts manage a territory of 1011 km^2, of which 880 km^2 is in the Arba basin (40% of its basin). The area of irrigated land has increased slightly in the 3 years covered in this study: 535 km^2 in 2004, 544 km^2 in 2005 and 550 km^2 in 2006. The remaining area (344 km^2 in 2004, 335 km^2 in 2005 and 330 km^2 in 2006) within in the domains of the 14 irrigation sub-districts was not irrigated (barren land, tracks, villages, etc.). The hydrological years covered in the study presented significant differences in rainfall. Whereas 2004 was a very rainy year (607 mm), 2005 was extremely dry (240 mm) and 2006 could be considered an average hydrological year (468 mm, http://oficinaregante.aragon.es). The ET$_0$ (Penman-Monteith method, Allen et al., 1998) was 1147 mm in 2004; 1336 mm in 2005; and 1298 mm in 2006 based on climatic data measured in the study area (http://oficinaregante.aragon.es).

The most widely adopted irrigation system was flood irrigation (87% of the evaluated surface) followed by sprinkler irrigation systems (12%), and lastly, drip irrigation (1%) (Table 1). The groundwater pumping in this area is not significant. The typical crops grown were alfalfa, winter cereal, maize, rice, grass, sunflowers, and vegetables (tomatoes, peppers, leeks, and onions). Crop distribution in the 3 years studied varied according to the availability of irrigation water and according to the new conditions of the Common Agricultural Policy. Therefore, the 2005 drought caused restricted irrigation water supplies while the year 2006 was characterized by being the first one during which Common Agricultural Policy subsidies were not dependent exclusively on the crop distribution (Atance et al., 2006).

The usual crop distribution in 2004 was typical of that during the previous decade: 29% alfalfa, 21% winter cereal, 19% maize, 11% rice, and 5% fallow changed. Because of the drought in 2005 the distribution changed to one with a lower water requirement: 30% winter cereal, 23% alfalfa, 10% maize, 9% rice, and 13% fallow. The reduction of alfalfa was smaller because it is a multi-year cultivation, and that of rice remained level because of the high subsidies received, and because of the impossibility of introducing another crop in the saline soils where it is produced. In the year 2006, irrigation allocations were normal: the area of cultivated alfalfa (27%) increased and fallow (8%) decreased. Nevertheless, it was significant that maize did not recover the terrain lost to winter cereal, possibly due to the adjustment of subsidies from the Common Agricultural Policy, which meant that farmers, receiving almost the same level of subsidy but with lower production costs, decided to cultivate winter cereal instead of maize.

3. Methodology

3.1. *Water balance*

In order to carry out the water balance in the Arba basin irrigation area, it was necessary to measure, or estimate, the

Table 1 – Crops and irrigation systems (IS) average area (ha) in the 14 irrigation sub-districts included in the Arba basin (IV, V, VI, VII, VIII, IX, X, XI, San Bartolomé-B, Las Vegas de Ejea-LV, Huertas Altas de Tauste-HA, Riguel-R, El Bayo-BA, and Santía-S), in the years 2004, 2005, and 2006

	IV	V	VI	VII	VIII	IX	X	XI	B	LV	HA	R	BA	S	Total (ha)
Crops															
Alfalfa	1158	4,255	1251	1353	107	1100	1470	1072	123	1423	455	227	225	179	14,399
Maize	237	2,879	405	336	29	462	577	894	96	809	139	119	19	24	7,025
Winter cereal	2917	3,624	924	1141	625	845	1284	1263	461	1317	490	77	34	60	15,062
Rice	439	689	2135	0	0	477	104	152	0	849	163	146	0	10	5,163
Grass	246	1,616	934	101	0	68	37	85	2	659	23	36	63	66	3,937
Sunflower	179	421	78	0	97	91	101	54	26	35	12	0	0	0	1,094
Pepper	6	202	10	6	20	3	0	5	4	0	1	0	0	0	258
Tomatoes	2	153	33	35	0	2	0	167	0	7	15	10	0	0	424
Leek	2	123	3	2	0	0	0	19	0	0	0	0	0	0	149
Onion	0	4	0	33	0	0	0	241	0	0	16	0	0	0	295
Broccoli	7	87	0	8	0	12	0	21	0	21	9	0	0	0	166
Pea	164	333	62	17	149	94	36	113	6	5	0	0	25	0	1,003
Fruit tree	12	53	29	17	0	21	20	57	15	8	6	0	0	0	238
Vineyard	0	12	0	0	5	0	0	0	0	0	0	0	0	0	16
Other crops	11	126	11	0	11	11	8	197	0	44	30	0	0	0	449
Fallow	477	894	493	340	244	703	343	611	39	412	0	20	14	43	4,635
IS															
Flood	5582	14,672	6294	3235	1286	3798	2566	562	737	5582	1355	636	376	375	47,054
Sprinkler	275	665	68	148	0	94	1400	4125	34	0	5	0	4	8	6,826
Drip	1	135	7	5	0	0	13	264	0	5	0	0	0	0	429
Total	5858	15,471	6369	3389	1286	3893	3980	4952	771	5587	1360	636	380	383	54,314

main inputs, outputs and storage of water in BID–Arba from the beginning until the end of the balance (1 April 2004 to 30 September 2006).

Inputs were considered to be precipitation (*P*), irrigation (*I*), water used to generate electricity and later discharged into the Arba without being used for irrigation (*E*), supply to small villages without a wastewater treatment plant (*V*), water discharged from the Ejea wastewater treatment plant (TP), water discharged from the Bardenas Canal into the Arba when there is too much water (BC), the input via the rivers Riguel (RI), Arba de Luesia (AL) and Arba de Biel (AB), and lastly, the estimated drainage from the remaining non-irrigated land in the Arba basin (RNI). Outputs were considered to be actual evapotranspiration (ET_a), evaporation and wind drift losses in sprinkler irrigation systems (EWDL), drainage via the River Arba in Tauste (AT), outputs via two small canals of the River Arba (*C*) and the groundwater outflow through the Arba alluvial (GO). The error balance was calculated as input minus output minus the increase of water in the system (ΔW):

$$\text{inputs} - \text{outputs} - \Delta W = \text{error balance}$$
$$(P + I + E + V + TP + BC + RI + AL + AB + RNI) - (ET_a + EWDL + AT + C + GO) - (\Delta W) = \text{error balance}$$

and the error balance percentage was calculated as

$$\text{error balance}\ (\%) = 200 \times \frac{\text{inputs} - \text{outputs} - \Delta W}{\text{inputs} + \text{outputs} + \Delta W} \quad (2)$$

3.1.1. *Inputs*

Rainfall, like other necessary climatic variables in this study, was estimated for the 14 ISDs involved based on the interpolation (inverse-square distance technique; Isaaks and Srivastava, 1989) of data obtained at six meteorological stations (Sádaba, Ejea, Luna, Santa Engracia, Bayo and Tauste; Fig. 1) of the Network of the Ministry of Agriculture (SIAR, http://oficinaregante.aragon.es).

The monthly values of I, E, V, BC for each of the ISDs involved were obtained from data collected by the Ebro Basin Authority (Confederación Hidrográfica del Ebro, CHE), which measured these water volumes with a flowmeter network in the main canals of BID–Arba.

Similarly, average daily flows measured by gauging stations on the three rivers and reported by the CHE Hydrology Service were used for RI, AL and AB. The estimation of RNI needed the extrapolation proportional to surface of the average flow controlled in the Riguel basin (196 km^2), Arba de Luesia basin (144 km^2) and Arba de Biel basin (262 km^2) to the rest of the surface of the Arba basin not included in the irrigated area and without gauging stations to measure the flow (991 km^2).

Finally TP was measured by the Aragonese Water Institute.

3.1.2. *Outputs*

Values used for AT were reported by the CHE Hydrology Service; GO was estimated by applying Darcy's law, whereby flow equals the result of the permeability (100 m/day) multiplied by the area of saturated section (15,000 m^2, and by the hydraulic gradient (0.0033 m/m) based on the hydro-geological information reported by ITGE (1985).

EWDL was calculated daily for each irrigation sub-district working from values estimated by means of the relationship reported by Salvador (2003) with wind speed 2 m above ground level (WS, m/s) and the relative humidity 1.5 m above ground level (RH, %) obtained from the interpolation of the six meteorological stations (Fig. 1):

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

The outputs of water via two lateral canals coming from the Arba, which irrigate ISD_{HA} and leave the study area bypassing the Arba gauging stations in Tauste (C), was estimated based on an average flow of 200 l/s (ISD_{HA} authority, personal communication).

ET_a was calculated daily for each irrigation sub-district by means of a daily soil water balance (SWB). For this, the potential evapotranspiration (ET_C) was calculated previously for each crop in each irrigation sub-district as the result of the reference evapotranspiration (ET_0) multiplied by crop coefficient (Kc) (Allen et al., 1998).

The ET_0 was obtained for each irrigation sub-district based on the interpolation of the ET_0 calculated in the meteorological stations using the Penman-Monteith method (Allen et al., 1998). The average monthly values of Kc and vegetative period for each crop were obtained from Martinez-Cob (2004) for the agrarian districts of Ejea (ISDs: V, VI, VIII, IX, X, XI, B, LV, HA, R, BA, S), Sádaba (ID: IV), and Tauste (ID: VII). For uncultivated periods and areas, a coefficient of the bare soil was assigned following the methodology proposed by Allen et al. (1998) for the calculation of the initial Kc depending on soil type, precipitation regime and average ET_0 values obtained from the agrarian districts of Ejea, Sádaba, and Tauste (Martinez-Cob, 2004). For minority crops classified as "other crops" a value of Kc = 1 was assigned throughout the year.

Development of the soil water balances in each irrigation sub-district started with an initial volume of plant available water in the soil (AW) which, being an unmeasured quantity, was estimated to be half of the soil water holding capacity (WHC). WHC for BID–Arba soils was assumed to be 100 mm, which corresponds to a representative value of soils in the Ebro valley (Martinez-Cob, 2004). Consequently AW for 1 April 2004 was assumed to be 50 mm. Inputs of water from irrigation ($I - \text{EWDL}$) and precipitation (*P*) were added to AW, and ET_C was subtracted provided there was enough AW. Therefore, it was considered that $ET_a = ET_C$ if the $AW_i + P + I - \text{EWDL} > ET_C$ and if not, $ET_a = AW_i + P + I - \text{EWDL}$, the soil having the same water content at the end of the day as at the wilting point (AW = 0). On the other hand, when the $AW_i + P + I - \text{EWDL} - ET_a > \text{WHC}$, it was interpreted that the field capacity of the soil had been surpassed, thus causing drainage (D_{SWB}) equal to $D_{SWB} = AW_i + P + I - \text{EWDL} - ET_a - \text{WHC}$ and leaving the soil at the end of the day at field capacity (AW = WHC). In this way, soil water balance was developed for 1 day after another, generating estimates of the ET_a, D_{SWB} and AW for every day and sub-district.

By carrying out the soil water balance at the sub-district level, ET_a could be overestimated and D_{SWB} underestimated, because drainage at one location and time in a sub-district can be interpreted to satisfy the water needs of another location, which at the same time, is in hydric stress. To a certain extent, this situation is what happens in Bardenas irrigation district, as, faced with the water shortage of recent years, re-use of drainage water is a very well-developed practice.

3.1.3. *Storage*

Water balances were developed for semesters (October–March and April–September) and for the whole period of the study (1 April 2004 to 30 September 2006). Water storage in BID–Arba was estimated as the difference in water content in the aquifers between the initial and final day of a given period. For this, the water volume contained in the aquifers on 1 April and 30 September (semester change) was considered, assuming the measurements of phreatic level carried out in the well P-XXX-1 (Fig. 1) and an effective porosity of 10% to be representative of BID–Arba aquifers. Water storage in the soils was not considered.

3.1.4. *Drainage associated to irrigation land evaluated*

Drainage associated with irrigation (*D*; Eq. (3))) was calculated by deducting from the total drainage of the basin the water not associated with the irrigation. In this group, *V* was included since most of it is discharged into the river:

$$D = (\mathrm{AT} + \mathrm{C} + \mathrm{GO}) - (E + V + \mathrm{TP} + \mathrm{BC} + \mathrm{RI} + \mathrm{AL} + \mathrm{AB} + \mathrm{RNI}) \tag{3}$$

3.2. *Water use index and water management indices*

To evaluate the extent the water resources (*I* and *P*) were being used by BID–Arba in a given period, the water use index (WUI) was calculated as

$$\mathrm{WUI} = \left[1 - \left[\frac{\mathrm{D} + \mathrm{EWDL}}{I + \mathrm{P}}\right]\right] \times 100 \tag{4}$$

WUI depends just as much on irrigation management as it does on the capacity of flow regulation in the hydrological basin.

The water requirement (WR) and four water managements indices were calculated from daily soil water balances carried out for each sub-district. WR (mm) equals crop needs assuming the soil water content is the same at the end of the season as it is at the beginning; it was the difference between potential evapotranspiration ($\mathrm{ET_C}$) plus available water contained in the soil at the end of the period ($\mathrm{AW_e}$) and effective precipitation (P_{ef}) plus available water contained in the soil at the beginning of the period ($\mathrm{AW_i}$):

$$\mathrm{WR} = (\mathrm{ET_C} + \mathrm{AW_e}) - (\mathrm{AW_i} + \mathrm{P_{ef}}) \tag{5}$$

Effective precipitation (P_{ef}) for everyday in each irrigation sub-district was estimated considering that if $P < \mathrm{WHC} + \mathrm{ET_a} - \mathrm{AW}$ then $P_{\mathrm{ef}} = \mathrm{P}$ and otherwise $P_{\mathrm{ef}} = \mathrm{WHC} + \mathrm{ET_a} - \mathrm{AW}$. This approximation does not take into consideration the existence of preferential flows in the soil or the runoff which could be generated. Nevertheless, it is considered to be a sufficiently valid approximation bearing in mind that the plots are terraced, so that very intense rains are needed to generate runoff.

Consumptive water use efficiency (CWUE, %) refers to the fraction of water used by crops. It is calculated as the actual evapotranspiration ($\mathrm{ET_a}$) plus $\mathrm{AW_e}$ divided by the sum of available resources, that is to say, $\mathrm{AW_i} + P_{\mathrm{ef}} + I$:

$$\mathrm{CWUE} = \left[\frac{\mathrm{ET_a} + \mathrm{AW_e}}{\mathrm{AW_i} + \mathrm{P_{ef}} + I}\right] \times 100 \tag{6}$$

Water deficit (WD, %) is calculated as the difference between $\mathrm{ET_C}$ and $\mathrm{ET_a}$ divided by $\mathrm{ET_C}$. WD is the extent irrigation, as a complement to $\mathrm{P_{ef}}$ and $\mathrm{AW_{i,}}$, has been unable to satisfy the water requirement of the crops:

$$\mathrm{WD} = \left[\frac{\mathrm{ET_C} - \mathrm{ET_a}}{\mathrm{ET_C}}\right] \times 100 \tag{7}$$

Irrigation drainage fraction (IDF, %) was calculated as a percentage of drainage from irrigation (D_{I}) with respect to *I*:

$$\mathrm{IDF} = \frac{D_{\mathrm{I}}}{I} \times 100 \tag{8}$$

D_{I} was calculated from soil water balances, considering it occurred on days within irrigation sub-districts as follows: if $\mathrm{AW} + P - \mathrm{ET_a} \geq \mathrm{WHC}$ then $D_{\mathrm{I}} = I - \mathrm{EWDL}$, or otherwise $D_{\mathrm{I}} = I - \mathrm{EWDL} - [\mathrm{WHC} - (\mathrm{AW} + P - \mathrm{ET_a})]$. The interpretation of this calculation is that on any given day rainfall will always be considered previous to irrigation, and therefore irrigation drainage takes priority over rainfall drainage, assuming that to a certain extent the farmer should bear rainfall in mind when deciding about irrigation.

Irrigation efficiency (IE, %) was calculated using:

$$\mathrm{IE} = \left[1 - \frac{D_{\mathrm{I}} + \mathrm{EWDL}}{I}\right] \times 100 \tag{9}$$

A theoretical IE of 100% would indicate that the entire volume of irrigation application has been used to satisfy the water requirement of crops (evapotranspiration) or it has accumulated in the soil's water reserves for use on crops in the following period.

Water management indices were calculated for every irrigation sub-district except for irrigation sub-district introduced previous to the use of Yesa reservoir because of lack of irrigation volume data. These irrigation sub-districts do not use water directly from the Bardenas Canal at all (LV, HA, R, and BA), or only partially (B and S), as they are supplied by rivers in the area where it is not monitored (mostly water proceeding from irrigation returns flows from irrigation sub-districts located on higher land). For the whole BID–Arba, WR and water use efficiency indices were calculated every 6 months and during the whole period of the study.

4. Results and discussion

4.1. *Water balance*

The main inputs of water to the system during the whole period of study were from irrigation (52%) and precipitation

Table 2 – Water balances (inputs: P-precipitation, I-irrigation, RI-Riguel, Al-Arba de Luesia, AB-Arba de Biel, RNI-remaining non-irrigation, E-electricity, V-village, BC-Bardenas Canal, TP-treatment plant; outputs: EWDL-evaporation and wind drift losses, ET-evapotranspiration, AT-Arba in Tauste, C-canals, GO-groundwater outflow; ΔW-increment of water in the system), error balance, drainage associated to irrigation land included in Arba basin (D), and water use index (WUI) of Bardenas irrigation district included in Arba basin during complete period of study (April 2004/September 2006) and by semesters (April–September and October–March)

	April/September 2004 (mm)	October 2004/March 2005 (mm)	April/September 2005 (mm)	October 2005/March 2006 (mm)	April/September 2006 (mm)	April 2004/ September 2006 (mm)
I-Inputs						
P	299	127	114	198	275	1013
I	517	97	419	37	598	1668
RI	25	1	2	2	3	33
AL	21	3	1	9	4	37
AB	28	5	3	9	7	53
RNI	123	15	9	32	23	203
E	79	0	0	0	0	79
V	7	40	4	27	0	78
BC	3	1	0	0	0	4
TP	3	2	2	2	2	11
O-Outputs						
EWDL	10	2	11	1	14	37
ET	634	234	538	207	666	2279
AT	309	210	53	83	174	829
C	6	6	6	6	6	28
GO	2	2	2	2	2	8
ΔW Δ Water	209	−189	−85	15	51	1
I $\sum$ Inputs	1104	293	554	316	913	3179
O $\sum$ Outputs	960	452	610	299	861	3182
ΔW Δ Water	209	−189	−85	15	51	1
$I - O - \Delta W$	−65	29	29	2	0	−5
Error[a] (%)	−6	11	5	1	0	0
D[b]	28	149	39	10	142	368
WUI[c] (%)	95	33	91	95	82	85

[a] Error balance (%) = $200 \times [(\text{inputs} - \text{outputs} - \Delta W)/(\text{inputs} + \text{outputs} + \Delta W)]$.

[b] $D = (AT + C + GO) - (E + V + TP + BC + RI + AL + AB + RNI)$.

[c] $WUI = [1 - [(D + EWDL)/(I + P)]] \times 100$.

(32%). Irrigation (92%) was applied in the three summer semesters whilst 76% of precipitation was concentrated between April 2004/September 2004 and October 2005/September 2006 (Table 2). It should be noted that irrigation periods with most precipitation (April 2004/September 2004: 299 mm and April 2006/September 2006: 275 mm) also registered the highest irrigation volumes (299 and 275 mm, respectively). In contrast, the period of irrigation with lowest precipitation (April 2005/September 2005: 114 mm) and therefore with greatest water requirement, registered the lowest irrigation volumes (419 mm) affected by low irrigation water availability because of the drought.

External flows (RI, AL, AB and RNI) made up 10% of the inputs, distributed spatially according to the surface of each basin and temporally, according to the distribution of precipitation. The intense rains of September 2004, which led to serious floods, created external hydric flows between April and September 2004 five times greater than those registered between April and September 2006, although the climatic conditions of the periods was similar. Flows direct from Bardenas Canal (E, CB) and the supply to small villages (V) made up 5% of the inputs, thus highlighting the importance of *E* in April and May of 2004 (79 mm) because Yesa reservoir was full. This circumstance allowed the release of water, in order to generate electricity and to flow into the river without being used for irrigation. The contribution of treated wastewaters (TP) from the main village in BID–Arba (16,000 inhabitants) was only 0.3%.

As for outputs, the most important were ET_a (72%) and AT (26%). ET_a in the 6-month irrigation periods were three times higher than those without irrigation (Table 2), and between irrigation semesters, the lowest ET_a was registered between April and September 2005 as a consequence of crop distribution because of the drought. The highest AT was between April and September 2004 (309 mm) when high values of input components were registered. It should be noted that the lowest AT took place in an irrigation semester (April 2005/September 2005: 53 mm) although in this semester, affected by the drought, the lowest precipitation and irrigation volume of the summer semesters were registered. The outputs in EWDL (1.2%), C (0.9%) and GO (0.3%) were inferior by far to those of ET_a and AT.

As for the increase of water in the system, three semesters presented positive water storage ($\Delta W > 0$), while the other two had a loss ($\Delta W < 0$). For the whole period studied, the increase of water in BID–Arba was practically nil, therefore, the water content in the aquifers at the beginning and at the end of the balance was similar. The capacity of hydric regulation, mainly in the aquifers, influenced the ΔW and the drainage associated with BID–Arba registered in each semester. This way, April 2004/September 2004, with intense precipitation at the end of the semester, propitiated the highest ΔW (209 mm) and lower than expected D (28 mm) if it is compared with the semester April 2006/September 2006 (D = 142 mm) with similar irrigation and precipitation volumes (Table 2). Also, a great part of the volume stored in April 2004/September 2004 (209 mm) became volume exiting the aquifer the following semester (189 mm), and the water which was not re-used in BID–Arba contributed to the semester D (149 mm), a priori too high if only the input for irrigation and precipitation of that semester are considered.

The D of semesters with a water loss ($\Delta W < 0$; October 2004/March 2005 and April 2005/September 2005), was inferior to the water loss from the aquifers, a consequence of the fact that a great part of the volume of water stored in the aquifers was re-used over and over again from the aquifer or once incorporated into the ditch network. These semesters were also very dry, which intensified the re-use of water for irrigation.

The 6-month error balances obtained (between 11% and −6%) can be assumed normal for this type of study and the precision with which some of the components of the balance were obtained. Also, for the whole period the error balance is practically nil, which indicates satisfactory accounting of the components of water balance, especially in the long term when components that are difficult to quantify accurately, such as the increase of water in the system, are less important than other components.

Traditionally, studies based on water balances in irrigated basins do not take into account the increase of water in the system from the initial to the final moment of the balance, assuming stationary annual and even 6-month regimens, because of the difficulty in quantification of ΔW. Although in this study, water storage in the system has not been quantified in a precise way, the relationship existent for each semester between the difference in the phreatic level of the well P-XXX-1 and the difference between inputs and outputs (Fig. 2) justifies to a great extent the water storage in the system.

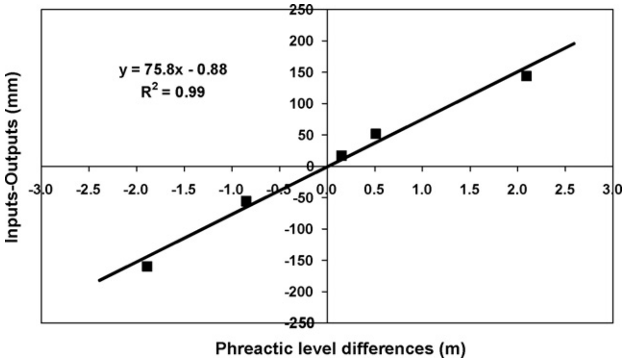

Fig. 2 – Relation between phreatic level differences in P-XXX-1 well and inputs minus outputs in semester water balances.

The greatest 6-month WUI was registered between April and September 2004 (95%) while the following semester was the smallest (33%). This fact was affected by the important volume of water accumulated between April and September 2004, which to a great extent was evacuated the following semester and exported from the basin without regulation. If the calculation is made annually (between April and March) in a way which responds to irrigation administration in a certain year, it is observed that the WUI of April 2005/March 2006 (92%) was notably superior to periods April 2004/March 2005 and April 2006/September 2006 (82%) because of the drought, indicating that the need to obtain hydric resources increased efficient water use in the basin by means of more appropriate irrigation management and the intensification in the re-use of drainage water.

The WUI in the whole period studied was high (85%). This fact contrasts with irrigation efficiency data of approximately 50% obtained at plot level (Lecina et al., 2005) or small hydrological basin (Causapé et al., 2004b) in the evaluated area. The explanation for this fact resides in the intense re-use of water which is carried out in Bardenas irrigation district, considerably elevating the global irrigation efficiency of the system compared to the low efficiency in its more habitual plots with very permeable soils. This way, the WUI for the whole BID–Arba evaluated was similar to those registered in modern sprinkler-irrigated districts such as Monegros II (Cavero et al., 2003) where irrigation efficiency was quantified up to 94%, from which evaporation and wind drift losses in sprinkler irrigation systems should be deducted.

4.2. *Water management indices*

The WR of the BID–Arba in the whole period ascends to 1742 mm (Table 3) although there are differences between irrigation sub-districts associated with differences crop distributions which are conditioned to a greater or lesser degree by the climatic, geological and agronomic characteristics of each irrigation sub-district. Therefore, ISD-VI had greatest WR (2199 mm) because the saline soils therein favour growing rice (34% of the surface) as almost the only crop alternative. On the other hand, ISD-VIII with deficient irrigation infrastructures favour the introduction of winter cereal and the fallow (49% and 19% of the surface, respectively) presenting the lowest WR (1132 mm). It should be stressed that ISD-X, located in the north of the system (more rains and lower temperatures), presented 5% less WR than the ISD-HA (located in the south of the system), despite having crops with greater irrigation needs (37%, 14%, and 32% alfalfa, maize, and winter cereal, respectively in the ISD-X compared to 33%, 10%, and 36% of ISD-HA).

Seasonally, there is a difference between the three irrigation periods (average WR April–September = 532 mm) compared to the periods without irrigation (average WR October–March = 73 mm). Among the irrigation periods it should be noted that April 2004/September 2004 (483 mm) had the lowest WR, because it was the rainiest irrigation period, while April 2005/September 2005, being a much drier period than April 2006/September 2006, presented some lower WR (545 *versus* 568 mm).

Table 3 – Water requirement (WR), consumptive water use efficiency (CWUE), water deficit (WD), irrigation drainage fraction (IDF), and irrigation efficiency (IE) in the 14 irrigation sub-districts (IV, V, VI, VII, VIII, IX, X, XI, San Bartolomé-B, Las Vegas de Ejea-LV, Huertas Altas de Tauste-HA, Riguel-R, El Bayo-BA, and Santía-S) and for global Bardenas irrigation district included in Arba Basin, by semesters (April–September and October–March) and during the complete period of study (April 2004/Septemer 2006)

ISD	WR (mm)	CWUE (mm)	WD (mm)	IDF (mm)	IE (mm)
IV	1429	97	4	5	95
V	1958	93	5	9	90
VI	2199	96	5	5	95
VII	1707	78	0	27	73
VIII	1132	91	3	14	86
IX	1522	97	3	3	96
X	1511	96	6	1	93
XI	1566	89	12	2	83
B	1218	–	–	–	–
LV	1696	–	–	–	–
HA	1597	–	–	–	–
R	1839	–	–	–	–
BA	1956	–	–	–	–
S	1750	–	–	–	–

Bardenas irrigation district included in Arba basin

Period	WR (mm)	CWUE (mm)	WD (mm)	IDF (mm)	IE (mm)
April 2004/September 2004	483	92	5	11	87
October 2004/March 2005	91	96	2	10	88
April 2005/September 2005	545	97	21	1	97
October 2005/March 2006	54	98	9	10	88
April 2006/September 2006	568	92	5	9	89
April 2004/September 2006	1742	94	9	7	90

BID–Arba had a CWUE of 94%, indicating that a high percentage of available water ($AW_i + P_{ef} + I$) was destined for crop evapotranspiration. Four of the irrigation sub-districts (ISDs: IV, VI, IX, and X) presented CWUE above 95% and the lowest value was quite high ($ISD_{VII} = 78\%$). Despite this, irrigation management in the system was inadequate, as the system had a WD of 9% indicating that not all the water requirement of crops was met. Surprisingly, the highest WD occurred in ID-XI (WD = 12%) which is the only irrigation sub-district which totally transformed to sprinkler irrigation. This high WD was justified by the reduced irrigation allocation received by ISD-XI, which obliges farmers to save their corn crops (18% of the surface) with yields of 14 Mg/ha, at the cost of the lower yields from two to three cuttings of alfalfa (22% surface). The WD of the other irrigation sub-districts was lower, presenting values between 0% and 6%. Seasonally, it is of interest that the WD during 2005 irrigation season (21%) was far greater than the other semester periods (between 2% and 9%) because of the drought.

Only 7% of the water used in irrigation exited the BID–Arba through the drainage. The lowest IDF (1 and 2%) occurred n the irrigation sub-districts that had converted to pressurized irrigation (ISD-X and ISD-XI). On the other hand, the highest IDF (27%) occurred in ISD-VII which registered the lowest CWUE (78%). Seasonally, all the semesters presented IDF between 9% and 11%, except for the 2005 irrigation period (a very dry year) when the IDF was only 1%.

The global IE of the BID–Arba during the whole period of study was 90%. Five of the eight evaluated irrigation sub-districts presented IE above 90%. However, ISD-VII with lowest CWUE (78%) and highest IDF (27%) also obtained the lowest IE (73%). It is noteworthy that the ISD-XI (totally converted to pressurized irrigation) had an IE of 83% with an IDF of only 2%. This was because the EWDL was 15% of volume irrigation applied, habitual value of the Ebro irrigation lands (Playán et al., 2005).

The IE of 2005 irrigation period (97%) was about 10% superior to that of the other semester periods, which reflects how the drought conditioned maximum use of irrigation water and establishes the margin of improvement of irrigation management when water is more abundant.

5. Conclusions

The main inputs of water into BID–Arba during the period of study were irrigation (52%) and precipitation (32%) while the main outputs were evapotranspiration (72%) and drainage through the River Arba (26%). The other components contributed to a lesser extent to the water balance, although its correct determination was important when quantifying drainage associated to BID–Arba.

The water balances closed acceptably (error semester balances between 11% and −6%) taking into account the estimate of the storage of water in the system in each semester. For the whole period, the error balance was practically nil, which will allow the assignation of concentrations to the different components attributing the mass of pollutants exported in irrigation return flow to the irrigation land evaluated.

As for BID–Arba, it had a water use index of 85%, which surpassed 90% in drought periods. Although the CWUE of the BID–Arba was high (94%), irrigation management was not appropriate, as there was a WD of 9%, partly conditioned by the drought of 2005 ($WD_{Apr\text{-}05/Sep\text{-}05} = 21\%$) and the low irrigation allocations in ID-XI (WD = 12%). The global IE was high (90%) although for it was lower for ISD-VII (IE = 73%), resulting from a high amount of drainage generated by irrigation (IDF = 27%), and for ISD-XI (IE = 83%) resulting from considerable evaporation and wind drift losses in sprinkler irrigation systems (EWDL = 15%). All things considered, intense re-use meant that water use in global BID–Arba (WUI = 85%) was higher than studies from the Bardenas irrigation district obtained from small plots (IE $\approx$ 50%, Lecina et al., 2005). In spite of this, irrigation management should be improved to annul the water deficit and to maximize productivity. It is possible to apply the methodology proposed in this work to different scales allowing the comparison of water use in different irrigation lands.

Acknowledgements

The work has been financed by the Ebro Basin Authority, which, together with the Bardenas irrigation district Authority and the Water Institute of Aragón have facilitated the basic data for the execution of this study.

REFERENCES

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper no. 56. FAO, Roma, Italy, 300 pp.

Atance, I., Barco, E., Benito, I., Compés, R., Langreo, A., 2006. La reforma de la Política Agraria Común: preguntas y respuestas en torno al futuro de la agricultura. Eumedia y Ministerio de Agricultura, Pesca y Alimentación, Madrid, Spain, 242 pp.

Causapé, J., Auqué, L., Gimeno, M^{a}.J., Mandado, J., Quílez, D., Aragüés, R., 2004a. Irrigation effects on the salinity of the Arba and Riguel rivers (Spain): present diagnosis and expected evolution using geochemical models. Environmental Geology 45 (5), 703–715.

Causapé, J., Quílez, D., Aragüés, R., 2004b. Assessment of irrigation and environmental quality at the hydrological basin level. I. Irrigation quality. Agricultural Water Management 70, 195–209.

Causapé, J., Quílez, D., Aragüés, R., 2006. Irrigation efficiency and quality of irrigation return flows in the Ebro River Basin: an overview. Environmental Monitoring and Assessment 117, 451–461.

Cavero, J., Beltrán, A., Aragüés, R., 2003. Nitrate exported in the drainage water of two sprinkler irrigated watershed. Journal of Environmental Quality 32, 916–926.

FAO, 2003. Gestión del agua hacia el 2030. www.fao.org/ag.

Instituto Tecnológico Geominero de España, 1985. Investigación de los recursos hidráulicos totales de la cuenca del Arba. Unpublished.

Isaaks, E., Srivastava, R.M., 1989. An Introduction to Applied Geostatistics. Oxford University, New York, 561 pp.

Lecina, S., Playán, E., Isidoro, D., Dechmi, F., Causapé, J., Faci, J.M^{a}., 2005. Irrigation evaluation and simulation at the Irrigation District V in Bardenas (Spain). Agricultural Water Management 73, 223–245.

Martinez-Cob, A., 2004. Revisión de las necesidades hídricas netas de los cultivos de la cuenca del Ebro. 111 pp. Documento interno CHE. Unpublished.

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. Agricultural Water Management 76 (3), 139–159.

Salvador, R., 2003. Estudio de las pérdidas por evaporación y arrastre en los sistemas de riego por aspersión: Diferencias entre riegos diurnos y nocturnos. Proyecto fin de carrera de Ingeniería Agrónoma, Universidad de Lérida, Departamento de Medio Ambiente y Ciencias del Suelo, 206 pp.