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Assessment of irrigation and environmental quality at the hydrological basin level I. Irrigation quality

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Abstract

Irrigated agriculture notably increases crop productivity, but consumes high volumes of water and may induce off-site pollution of receiving water bodies. The objectives of this paper were to diagnose the quality of irrigation and to prescribe recommendations aimed at improving irrigation management and reducing the off-site pollution from a 15,500 ha irrigation district located in the Ebro River Basin (Spain). Three hydrological basins were selected within the district where the main inputs (irrigation, precipitation, and groundwater inflows) and outputs (actual crop's evapotranspiration, surface drainage outflows, and groundwater outflows) of water were measured or estimated during a hydrological year. The highest volume of water (I = 1400 mm/year) was applied in the basin with highly permeable, low water retention, flood irrigated soils where 81% of the total surface was planted with alfalfa and corn. This basin had the lowest consumptive water use efficiency (CWUE = 45%), the highest water deficit (WD = 5%) and the highest drainage fraction (DF = 57%). In contrast, the lowest I (950 mm/year), the highest CWUE (62%), and the lowest WD (2%) and DF (37%) were obtained in the basin with 60% of the surface covered with deep, high water retention, alluvial valley soils, where 39% of the cultivated surface is sprinkler irrigated and with only 48% of the surface planted with alfalfa and corn. We concluded that the three most important variables determining the quality of irrigation and the volume of irrigation return flows in the studied basins were (i) soil characteristics, (ii) irrigation management and irrigation system, and (iii) crop water requirements. Therefore, the critical recommendations for improving the quality of irrigation are to (i) increase the efficiency of flood-irrigation, (ii) change to pressurized systems in the shallow and highly permeable soils, and (iii) reuse

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of drainage water for irrigation within the district. These management strategies will conserve water of high quality in the main reservoir and will decrease the crop water deficits and the volume of irrigation return flows, therefore, minimizing the off-site pollution from this irrigation district.

Keywords: Water; Irrigation efficiency; Hydrological basin; Soil; Drainage

1. Introduction

Increased food demand has led to the growth of agricultural production through new land development and increased crop productivity by improving crop management practices and intensifying agricultural inputs (water and agrochemicals). Irrigated agriculture has greatly increased crop's productivity, stability and diversification in water-limiting arid and semiarid areas. Thus, the 3.4 million ha of irrigated land in Spain (i.e., 15% of the arable land) contributes to more than 60% of total agricultural production (Fereres and Ceña, 1997).

However, more than 24 km^3 of water is used for irrigation, equivalent to 68% of the total water consumption in Spain (MMA, 2000), and the irrigation return flows are a major non-point contributor to the pollution of surface and groundwater bodies (Aragüés and Tanji, 2003). Thus, salinity increases in the middle reaches of the Ebro River (Spain) amount to 9 mg of total dissolved solids/l year (Quílez, 1998), and the load of nitrogen exported to the Mediterranean Sea by this River amounts to 10^4 Mg/year (Cruzado et al., 2002).

The control of irrigation-induced environmental problems implies a change in focus from a "water resource development" to a "water resource management" approach. The first step towards this conceptual change is an in-depth knowledge and diagnosis of the actual quality of irrigation, which may be best quantified through a water balance analysis at the hydrological basin scale. Thus, several agricultural basins have been studied in the Ebro River Basin that collect information on suspended and dissolved solids concentrations and loads (Donézar, 2001), as well as salt and nitrate concentrations and loads (Faci et al., 1985; Basso et al., 1991; Tedeschi et al., 2001; Isidoro et al., 2003; Cavero et al., 2003). The aim of these studies is to relate the quantity and quality of irrigation return flows with the physical characteristics and input management practices (irrigation and nitrogen fertilization) in the study areas.

We focused our study in the irrigation district no. V (CR-V) of Bardenas I, an area developed in the fifties that contributes to half of the salts present in the Arba River (tributary of the Ebro River; Fig. 1) (Basso et al., 1991). This district has increasing problems of water scarcity due to an insufficient capacity of the Yesa Reservoir (the supply water of the Bardenas system; Fig. 1), an increase in irrigated land, and the change from winter crops to higher water demand corn, alfalfa and horticultural crops.

Within this water-scarce and source-contaminating district, we selected three irrigated hydrological basins for the analysis of irrigation management (part I) and the volume and quality (salts and nitrates) of their irrigation return flows (part II), as related to climate, geology and agronomic characteristics. Part I of this study focuses on (i) the diagnosis of the quality of irrigation, (ii) the identification of the main inefficiencies in irrigation

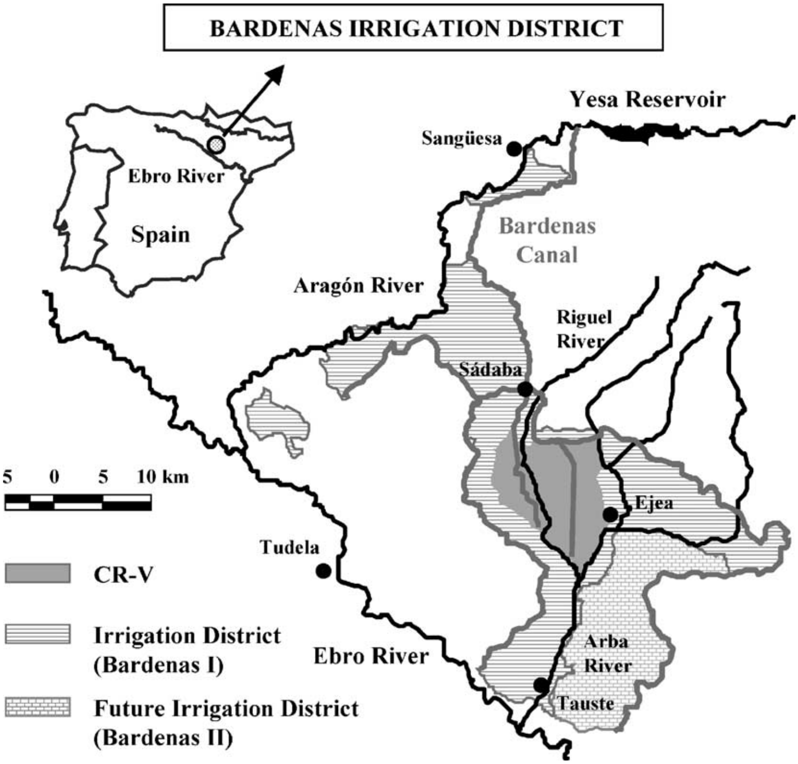

Fig. 1. Location of the CR-V study area in the Bardenas irrigation district (Spain). The main villages, rivers, the Yesa Reservoir, and Bardenas Canal are also shown.

management, and (iii) recommendations aimed at improving the management of irrigation water and reducing the off-site pollution from these hydrological basins.

2. Description of the study areas

The CR-V irrigation district belongs to the 60,000 ha Bardenas I irrigation scheme located in the left bank of the middle Ebro River in Spain (Fig. 1). The climate is characterized by a low precipitation (average 1965–1994 annual precipitation = 419 mm) with two wet (spring and fall) and two dry (summer and winter) seasons, and an elevated evapotranspiration (average 1965–1994 annual reference evapotranspiration = 1084 mm) with peaks during the summer months.

The CR-V has 15,500 hectares irrigated by the Bardenas Canal that originates in the Yesa Reservoir located in the Aragón River (Fig. 1). The irrigation water is of excellent quality (EC = 0.32 dS/m; $[NO_3^-] < 2$ mg/l). Water consumption is high (average = 1100 mm in year 2000) and it is delivered by flooding every 13 days for irrigation of field crops (alfalfa, corn, barley, wheat, sunflower, and horticultural crops).

Seventy percent of the soils are located over a broad glacis system dissected by the alluvial valleys of the Arba and Riguel rivers (Fig. 2). Except for some small areas with internal drainage problems, the soils do not present salinity problems and are adequate for the development of irrigated agriculture. The glacis soils (calcisols) are locally known as ''sasos'', and are characterized by a high stone content (average of 22%;

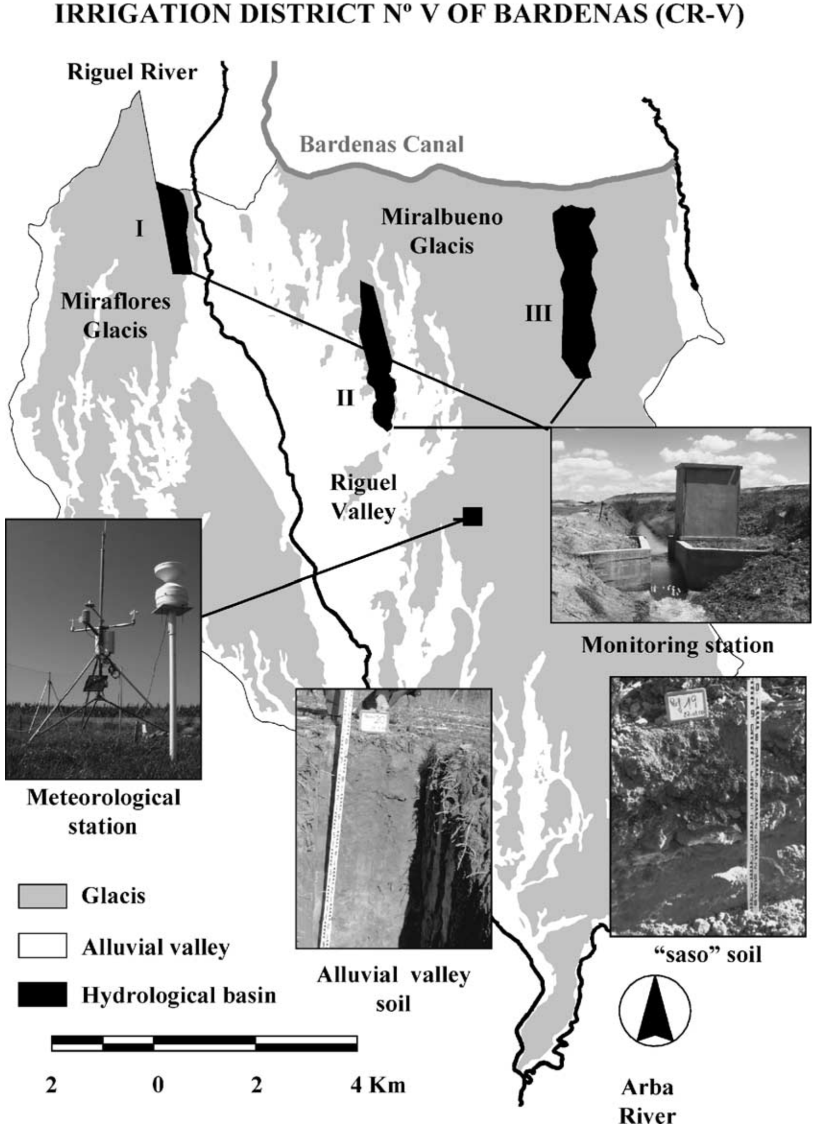

Fig. 2. Location of the three hydrological basins (I, II, and III), and the weather station in the CR-V study area. Photographs of a gauging station and typical soil profiles of the two main soil types identified (''saso'' and alluvial valley) are also shown.

Causapé, 2002), and the presence of a petrocalcic layer at a depth of approximately 0.5 m. The alluvial soils (fluvisols) are deeper, fine-textured and without gross elements (Fig. 2).

The main aquifers are quaternary deposits associated to the Miralbueno (120 km^2) and Miraflores (50 km^2) glacis and to the Arba and Riguel alluvial valleys that lie over impermeable clay, silt and sandstone tertiary formations. These aquifers are recharged by irrigation and precipitation and discharge through a dense drainage network towards the Riguel and Arba rivers (Fig. 1).

Three hydrological basins (I, II and III in Fig. 2) were selected representing the physical characteristics and agronomic management of the CR-V irrigation district. The drainage waters of each basin are characteristic of the three most important drainage water types identified in CR-V (Isidoro et al., 2002). These basins are isolated from external surface runoff, but collect groundwaters that flow in the North-South direction (Causapé, 2002). The base of basins I and II fully penetrate into impermeable tertiary materials so that its outlets drain all the groundwater fluxes. In contrast, the base of basin III partially penetrates quaternary gravels and its outlet does not collect all the groundwater fluxes.

Thirty three percent of the soils in basin I (total surface area = 97 ha) are on alluvial valleys and all the fields are flood irrigated. Sixty percent of the soils in basin II (149 ha) are located on alluvial valleys and 39% of the fields are sprinkler irrigated. The average field size in basins I and II is similar (1 ha). The larger size of the sprinkler irrigated fields in basin II is compensated by the smaller flood irrigated fields located in the hill slopes. In basin III (216 ha), all the soils are "sasos", the average field size is 3.3 ha, they are unlevelled and all of them are flood irrigated. The volumes of irrigation water delivered per unit of cultivated area during the 2001 irrigation season (April–September) were 1150 mm (basin I), 950 mm (basin II) and 1400 mm (basin III).

3. Materials and methods

3.1. Water balance

A simplified water balance was performed in each basin for the 2001 hydrological year by means of the equation:

$$\Delta CW = (I + P + GI) - (ET_a + SO + GO) \tag{1}$$

where ΔCW is the change in the volume of stored water in the basin, the inputs are the volumes of irrigation (I), precipitation (P) and groundwater inflow (GI) and the outputs are the volumes of actual crop's evapotranspiration (ET_a), surface drainage outflow (SO) and groundwater outflow (GO). This equation was further decomposed into two equations dealing with the water balances for the soil and the aquifer systems. The soil system extends from the soil surface to the effective soil depth defined by the maximum depth of root development, whereas, the aquifer system extends from the effective soil depth to the impermeable tertiary layer.

3.1.1. Soil water balance; the BAS program

A soil water balance was calculated on a daily basis for each of the irrigated fields and the non-irrigated surface in each basin. The equation used was:

$$\Delta SW = [I + P] - [ET_a + D] \tag{2}$$

where D is the volume of soil drainage and ΔSW is the daily change in stored soil water. The estimated values of ΔSW include possible computational uncertainties associated with the measurements or estimations of the different variables. The estimated daily values of ΔSW, ET_a, and D were aggregated to obtain the annual values for the period from 1 October 2000 to 30 September 2001.

The BAS program was developed to simulate the soil water fluxes and provide the daily estimates of ΔSW, D, and ET_a. The input variables to BAS are (i) meteorological data (daily precipitation, average air temperature and reference evapotranspiration (ET_0), (ii) soil parameters (field capacity, wilting point and initial soil water content), and (iii) agronomic data (daily irrigation depth, sowing data, base temperature, cumulative degree-days to reach the different phenological stages for each crop, and crop coefficients for the initial, mid-season, and late season stages (Allen et al., 1998)).

ET_0 was estimated by the Penman–Monteith method (Allen et al., 1998) using the meteorological data gathered in a Campbell automatic meteorological station located in the geographic centre of CR-V (Fig. 2). The crop coefficients for the initial, mid and late season were taken from Martínez-Cob et al. (1998) and the base temperatures and cumulative degrees-day to reach the different stages of development (Allen et al., 1998) were provided by Martinez-Cob (personal communication). The sowing dates of each plot were obtained by farmer's surveys. The irrigation depths given to each field were supplied by the CR-V irrigation district that measured the flow rate at the head of each irrigation ditch and the irrigation time of each plot (only one plot is irrigated at each time). The maximum depths of the crop's root system were measured in 50 pits (40 in saso and 10 in alluvial valley soils). Soil samples of each horizon were taken and the stone content, bulk density and water retention at 0.03 MPa (field capacity, FC) and 1.5 MPa (wilting point, WP) were determined in the laboratory. The average water holding capacity (WHC) of the saso (WHC = 85 mm, CV = 54%) and alluvial (WHC = 176 mm, CV = 18%) soils was estimated according to the Soil Survey Laboratory (1996). The initial soil water content was not measured and was assumed to be equal to WP + [(FC − WP)/2] in all fields. This approximation does not affect significantly the balance results because WHC is much lower than the remaining variables.

After gathering of the required data in each hydrological basin, the BAS program first calculates the potential crop's evapotranspiration (ET_c) following the FAO methodology (Allen et al., 1998). In periods without crops, BAS uses the monthly K_c for bare soil. Next, the daily I and P are added to the initial soil water content to give the actual soil water content (SWC). The plant's available water (AW) is then estimated from the difference (SWC − WP). If $ET_c \leq$ AW, the actual evapotranspiration (ET_a) is set equal to ET_c, and the new computed SWC is decreased by ET_c. If $ET_c >$ AW, ET_a is set equal to AW, and the new computed SWC is set equal to WP. Finally, if SWC > FC, BAS estimates the soil drainage (D) as the difference (SWC − FC), whereas if SWC $\geq$ FC, D = 0.

3.1.2. Aquifer water balance

An aquifer water balance was calculated on a daily basis by means of the equation:

$$\Delta A = [\mathrm{GI} + D] - [\mathrm{SO} + \mathrm{GO}] \tag{3}$$

where ΔA is the change in the volume of stored water in the aquifer and the rest of variables have been previously defined. The input D corresponds to the output D estimated by BAS.

Three flume gauging stations were built at the outlets of each basin to collect the surface drainage waters (SO). Water height (h, cm) was recorded every 15 min with an electronic limnigraph and converted into flow (Q_{SO}, l/s) using the equation:

$$\mathrm{Q_{SO}} = [0.969 + 0.907h]h^{0.645}; \quad R^2 = 0.99 \tag{4}$$

obtained with the Winflume program (Wahl, 2000) from the geometric characteristics of the flume.

As previously indicated, the drainage outlets of basins I and II collect all the water outputs (surface and groundwater). However, the outlet of basin III does not collect all the groundwater outflows (GO). The groundwater discharge (Q_{GO}, $\mathrm{m^3}$/day) in the southern section of basin III was, therefore, estimated by Darcy's law:

$$\mathrm{Q_{GO}} = KAi \tag{5}$$

where K (m/day) is the permeability of the aquifer, A ($\mathrm{m^2}$) is its saturated section, and i (m/m) is the hydraulic gradient.

The value of $K = 400$ m/day was estimated from the superposition on the Breddin curves of the particle size distribution of a sample of the aquifer's gravels (Custodio and Llamas, 1983). The daily saturated section (A) was estimated from the aquifer's outlet width (600 m) and the saturated thickness that was continuously recorded with a limnigraph installed in well P-XXX-1 located close to the outlet of basin III (Fig. 3). The average hydraulic gradients for the irrigation (i = 1.15%) and non-irrigation (i = 1.06%) seasons were estimated from the isolines map of the mean irrigation and non-irrigation periods groundwater heights obtained from the groundwater depths measured every 21 days in 11 wells (Fig. 3). Based on the similar saturated thicknesses measured at the initial (01/10/00) and final (01/10/01) dates of the 2001 hydrological year (Fig. 3) and on the small water content changes of the non-saturated section of the aquifer (i.e., absence of precipitation and similar irrigation regimes on the last days of meteorological years 2000 and 2001), it was concluded that the change in the volume of stored water in the aquifer (ΔA) during the 2001 hydrological year was insignificant. Therefore, groundwater inflows (GI) in each basin were estimated from the aquifer water balance equation as:

$$\mathrm{GI} = [\mathrm{SO} + \mathrm{GO}] - D \tag{6}$$

3.2. Water management indexes

Two water management indexes (consumptive water use efficiency, CWUE and water deficit, WD) were calculated for each irrigated field during the crop's cycle periods. A third index (drainage fraction, DF) was calculated for the 2001 hydrological year.

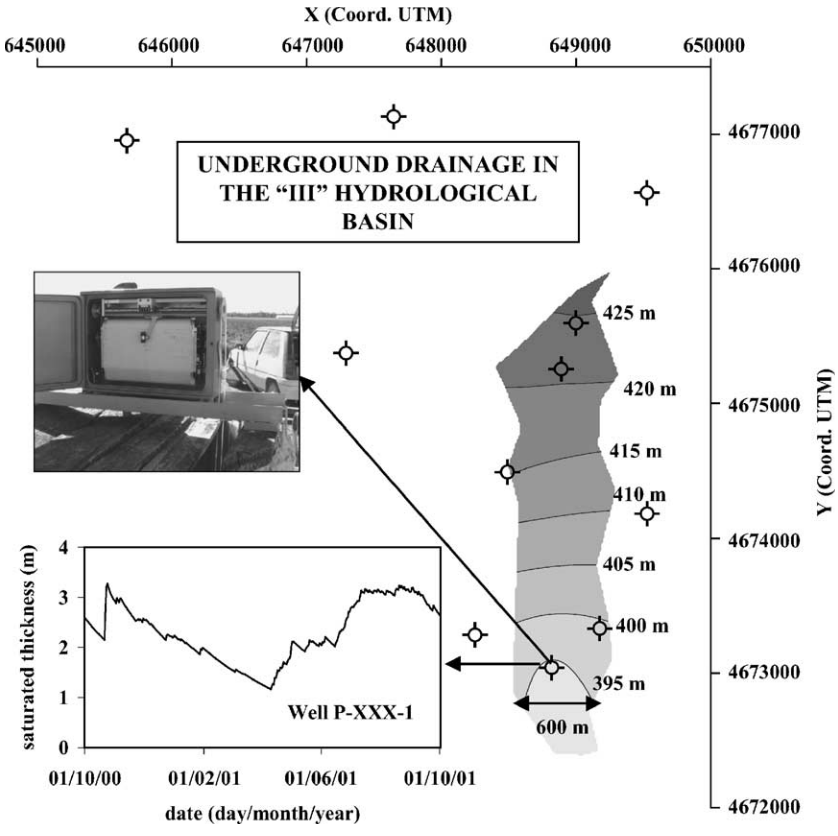

Fig. 3. Isolines map of the mean annual groundwater height estimated in hydrological basin III from the groundwater depths measured every 21 days in 11 wells. The daily saturated thickness of the aquifer measured with a limnigraph at the outlet of basin III during the hydrological year 2001 is also shown.

The consumptive water use efficiency (CWUE, %) is the ratio of the percentage of the actual crop's evapotranspiration (ET_a) to the total water available for evapotranspiration (i.e., irrigation, I; precipitation, P; and available soil water at the beginning of the vegetative cycle, AW_{sowing}):

$$\mathrm{CWUE} = \frac{\mathrm{ET_a}}{I + P + \mathrm{AW_{sowing}}} \times 100 \quad (7)$$

This index evaluates the crop's global efficiency in the consumptive use of the available soil water. Monthly CWUE values were also calculated using monthly values of ET_a, I, P, and the differences between the initial and final soil water contents for the given month.

The water deficit (WD, %) is the percentage of the potential crop evapotranspiration (ET_c) that is not evapotranspired due to a lack of available water in the soil:

$$\mathrm{WD} = \frac{\mathrm{ET_c} - \mathrm{ET_a}}{\mathrm{ET_c}} \times 100 \quad (8)$$

This index evaluates the global capability of the water resources (I, P, and AW_{sowing}) for covering the crop's water needs. Corresponding monthly WD values were also calculated.

The drainage fraction (DF, %) is the ratio of the percentage of the volume of drainage water (D) to the total water available for evapotranspiration:

$$DF = \frac{D}{I + P + AW} \times 100 \qquad (9)$$

where AW is the available soil water at the beginning of the hydrological year (for the global DF) or at the beginning of the given month (for the monthly DF).

The indexes obtained for each individual field were averaged on a surface-weighted basis to obtain the mean hydrological basin values. Although these indexes depend on management, climatic, crop, and soil factors, an "ideal" irrigation management will be characterized by values close to CWUE = 1, WD = 0 and (neglecting crop's leaching requirement) DF = 0.

4. Results and discussion

4.1. Hydrological regime

Surface outflows (SO) measured in the drainage outlets of basins I, II, and III had a similar general pattern along the 2001 hydrological year: (i) low and relatively constant flows during the October–April non-irrigated season, with instantaneous flow increases due to precipitation events, and (ii) higher flows during the March–September irrigated season due to return flows from irrigation, with flow peaks resulting from surface runoff and fast drainage of each field as well as direct spill-over of irrigation water into the drainage ditches. Thus, the mean surface outflows were, depending on basins, between two and four times higher in the irrigated than in the non-irrigated season (Table 1). This flow seasonality has been typically found in other semiarid irrigated districts of the Ebro River Basin (Faci et al., 1985; Tedeschi et al., 2001; Isidoro et al., 2003), in contrast with the distinctive dynamics in rivers with higher flows during the snowmelt and high precipitation autumn and spring seasons.

Table 1
Mean and coefficient of variation of surface outflows (SO) measured in drainage outlets of basins I, II, and III during the 2001 hydrological year, the irrigated and the non-irrigated seasons

Basin	Hydrological year (October 2000/September 2001)				Irrigation season		Non-irrigation season	
	Mean (l/s)	CV (%)	Maximum (l/s, date)	Minimum (l/s, date)	Mean (l/s)	CV (%)	Mean (l/s)	CV (%)
I	34	102	531 (01/07/01)	4 (15/04/01)	51	81	17	54
II	68	63	644 (21/10/00)	10 (06/10/00)	86	56	51	56
III	54	125	1229 (21/10/00)	0 (5–25/03/01)	87	78	21	226

The year maximum and minimum outflows and the date of occurrence are also presented.

The smallest basin I (surface area = 95 ha) had the lowest mean surface outflow (34 l/s for the 2001 hydrological year). The largest mean outflow (68 l/s) was measured in basin II (surface area = 149 ha), likely due to the Bardenas canal filtrations that increased the base flow throughout the year (Fig. 4). In contrast, the mean outflow (54 l/s) of the largest basin III (surface area = 216 ha) was lower than that of basin II because of the significance of the groundwater outflows (GO) not collected by the drainage outlet of basin III. Thus, drainage outflows in basin III were negligible towards the end of the non-irrigated season (Fig. 4 and Table 1) and most of the outflows in that period were in the form of groundwater only.

The variability of the mean surface outflows was high (coefficients of variation of the hydrological year mean between 63% and 125%, Table 1). The largest variability was obtained in basin III as a consequence of the larger outflow variations along the year and during one irrigation day (data not given).

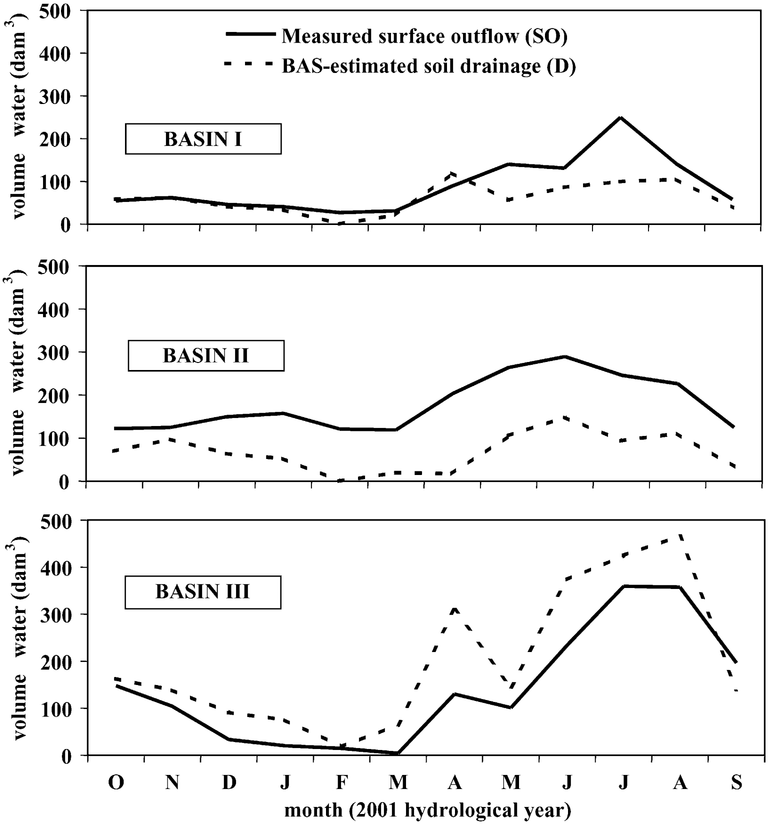

Fig. 4. Monthly measured surface outflows (SO) and BAS-estimated drainage volumes (*D*) in basins I, II, and III during the 2001 hydrological year.

4.2. Water balance

4.2.1. Soil water balance

Total precipitation (*P*) during the 2001 hydrological year was 526 mm (i.e., 26% higher than the historic mean *P*). The volume of irrigation in basin II was slightly higher than *P*, while in basins I and III they doubled and almost tripled, respectively, the volume of *P* (Table 2).

Crop's evapotranspiration (ET_a) depended on its distribution in each basin. The highest ET_a was found in basin I (ET_a = 859 mm), where the main crops were corn (47% of the total surface) and alfalfa (46%), and with only 5% of the area non-cropped. ET_a in basin III was also high (ET_a = 810 mm) due to the presence of corn (55%), alfalfa (26%), winter cereals (8%) and horticultural crops (8%), and with only 2% of the area non-cropped. In contrast, ET_a in basin II was much lower (ET_a = 681 mm) because 26% of the surface was non-cropped, the acreage of corn (32%) and alfalfa (16%) was lower than in basins I and III, and there were also other less water-consumptive crops as pasture for livestock production (13%), sunflower (6%) and winter cereals (4%).

The BAS-estimated soil drainage volumes (*D*) basically depended on irrigation depths. Thus, *D* was highest in basin III (1113 mm), intermediate in basin I (755 mm) and lowest in basin II (495 mm).

The surface outflows (SO) measured in the drainage outlets of basins I (SO = 1070 dam^3) and II (SO = 2150 dam^3) were 1.5 (basin I) and 2.9 (basin II) times higher than the BAS-estimated soil drainage values due to significant groundwater inflows (GI) that were fully intercepted and exported by the drainage outlets. In basin II, the higher SO line was drawn parallel to the lower *D* line along the 2001 hydrological year (Fig. 4) because of the almost constant contribution of the Bardenas canal filtrations along the study period. In contrast, basin I was not influenced by the Bardenas Canal because its seepage waters were intercepted by the Riguel River (Fig. 2). Thus, the SO and *D* lines were very close during the non-irrigated season, whereas SO was higher than *D* during the irrigated season (Fig. 4) due to GI arising from drainage of the irrigated fields located in the north area of the Miraflores Glacis.

Although basin III also received seepage waters from the Bardenas Canal, the BAS-estimated soil drainage (*D*) was 40% higher than the surface outflow (SO) along the 2001 hydrological year (Fig. 4) because the drainage outlet did not collect all the groundwater outflows (GO). The maximum difference between *D* and SO occurred at the beginning of the irrigated season (April, Fig. 4), when the saturated thickness of the aquifer was lowest (Fig. 3).

Table 2
Components of the soil water balance $\Delta SW = [I + P] - [ET_a + D]$: volume of irrigation (*I*), precipitation (*P*), actual evapotranspiration (ET_a), drainage (*D*), and the difference between inputs and outputs (ΔSW) computed in the studied basins during the hydrological year 2001

Basin	Inputs (In)		Outputs (Out)		In–Out (ΔSW, mm)
	I (mm)	*P* (mm)	ET_a (mm)	*D* (mm)	
I	1112	526	859	755	+23
II	669	526	681	495	+18
III	1396	526	810	1113	−1

Table 3
Components of the global water balance $\Delta CW = [I + P + GI] - [ET_a + SO + GO]$: volume of irrigation ($I$), precipitation ($P$), groundwater inflow (GI), actual evapotranspiration (ET_a), surface drainage outflow (SO), groundwater outflow (GO), and the difference between inputs and outputs (ΔCW) computed in the studied basins during the hydrological year 2001

Basin	Inputs (In)			Outputs (Out)			In–Out (ΔCW, dam^3)
	I (dam^3)	P (dam^3)	GI (dam^3)	ET_a (dam^3)	SO (dam^3)	GO (dam^3)	
I	1055	499	353	816	1070	0	+22
II	996	784	1413	1014	2150	0	+27
III	3018	1138	1531	1752	1704	2235	−3

4.2.2. Global water balance

Groundwater inflows (GI) in basins II and III were similar and four times higher than those estimated in basin I (Table 3). As previously indicated, GI arose from drainage of irrigated fields northern of the three basins and from seepage of the Bardenas Canal in basins II and III. Thus, in relation to the total water inputs ($I + P +$ GI), GI represented only 19% of total water inputs in basin I, as compared to 44% in basin II and 27% in basin III.

The groundwater outflow (GO) estimated in basin III during the 2001 hydrological year was 2235 dam^3 (Table 3), representing 39% of total water outputs (ET_a + SO + GO). As previously indicated, GO in basins I and II were negligible due to hydrogeological reasons. Therefore, the surface outflows (SO) measured in basins I and II were the most important water outflows (57% and 68% of total outflows, respectively), whereas SO in basin III only represented 30% of total water outflows.

4.3. Water management indexes

The average consumptive water use efficiency (CWUE) was low in the three studied basins (Table 4) and, on the average, only 53% of the available water was used by the crops. The highest value was found in basin II (CWUE = 62%) due to the relatively high CWUE values of the sprinkler irrigated fields located in the deep alluvial valley soils. Although both basins I and III were flood irrigated and quite similar in crops, the average CWUE was significantly lower in basin III than in basin I (45% and 56%, respectively). This difference was due to a higher proportion of permeable soils (sasos) in basin III and the presence of larger fields not levelled by laser. Even though the higher average irrigation flow in basin III

Table 4
Average and coefficient of variation of the consumptive water use efficiency (CWUE), water deficit (WD), and drainage fraction (DF) estimated in the three studied basins during the 2001 hydrological year

	Hydrological basin					
	I		II		III	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
CWUE (%)	56	3	62	5	45	3
WD (%)	3.4	22	6.7 (2.0)[a]	50	4.6	14
DF (%)	45	4	37	6	57	1

[a] In parenthesis: excluding a sunflower field with WD = 57%.

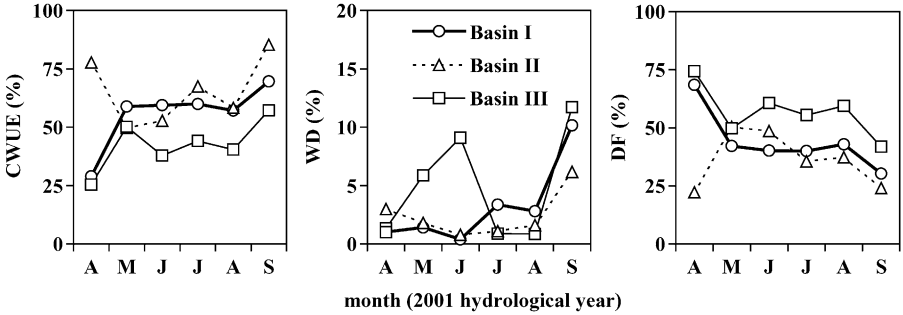

Fig. 5. Monthly consumptive water use efficiency (CWUE), water deficit (WD) and drainage fraction (DF) in the three study basins during the 2001 irrigation season.

(187 l/s) than in basin I (129 l/s) could be beneficial in terms of uniformity of flood irrigation, the irrigation times were similar in both basins (2.9 h/ha) and, therefore, the amount of water applied was substantially higher in basin III.

The CWUE trends along the 2001 irrigated season were similar in the three basins (i.e., lowest values at the beginning and highest values at the end of the irrigation season), except for the high value found in April in basin II (i.e., April CWUE = 78% in basin II as compared to 25% in basin III and 32% in basin I) (Fig. 5). This difference was due to pre-sowing flood irrigations given to the shallow "saso" soils planted with corn in basins I and III, as compared to the absence of pre-sowing sprinkler irrigations in the deep alluvial soils in basin II.

Water deficits (WD) of the individual fields varied from 0% to 16% (excluding a sunflower field with a high WD of 57%), and 80% of the fields presented deficit irrigation (WD > 0). The highest WD values were found in the low water holding capacity saso soils (average WHC = 85 mm) that were flood irrigated with large irrigation time intervals. The average WD in these soils was 4.8%, as compared to WD = 0 in the high WHC (average of 176 mm) alluvial valley soils. Therefore, average water deficits at the basin level (Table 4, WD basin III > basin I > basin II discounting the sunflower field) depended primarily on their proportions of saso soils (saso soils basin III > basin I > basin II).

The WD trends were in general similar in the three basins, increasing towards the end of the irrigated season (September) due to the early interruption of irrigation provoked by the lack of water in the Yesa Reservoir. Water deficits in April and June were significantly higher in basin III due to an improper delay of the first irrigation in some corn fields.

Irrigation distribution in the CR-V district is based on almost fixed irrigation depths and intervals that do not take into account climatic or soil characteristics. Thus, the irrigation depths given to the alluvial valley soils were generally lower than their WHC, whereas they were higher in the permeable, shallow and low WHC saso soils. Therefore, irrigation produced important drainage losses in the saso soils. In consequence, the basin-average drainage fractions (DF) were highest in basin III (100% of the area with saso soils), intermediate in basin I (67% with saso soils) and lowest in basin II (40% with saso soils) (Table 4). The general DF trends in the three basins were similar along the 2001 irrigation season, with higher values at the beginning of the season and lower values at the end (Fig. 5). These trends, as well as the low DF found in April in basin II have been justified before.

5. Conclusions and recommendations

The water balance performed in the three studied basins shows that groundwater inflows were an important component of the total surface drainage outflows, and that groundwater outflows were only relevant in basin III. In consequence, the measured surface drainage outflows were not representative of the cumulative soil drainage, which is the important variable for assessing the quality of irrigation. Thus, soil drainage at the hydrological basin scale was estimated through a daily soil water balance in each field. In a study carried out in an irrigated area of California (USA), Tanji et al. (1975) also concluded that the hydrogeology of the area had an important effect on the volume of the irrigation return flows, so that a simple water balance based only on surface water inputs and outputs could lead to erroneous conclusions. In summary, the assessment of the quality of irrigation at the hydrological basin level should be based on surface and subsurface water balances in those basins where groundwater is significant with respect to the other water components.

Irrigation quality basically depended on the irrigation system and soil characteristics. The highest consumptive water use efficiency (CWUE = 62%) and the lowest water deficit (WD = 2%) were found in the sprinkler irrigated and alluvial valley soils basin, whereas the lowest CWUE (45%) and the highest WD (5%) were found in the flood irrigated, ‘‘saso’’ soils without laser levelling. Similar results were obtained by Lecina et al. (2001) in 50 irrigation evaluations performed in the CR-V district.

The first irrigation applied to the ‘‘saso’’ soils was the least efficient and produced the largest drainage fractions (DF = 65–75% in April). The basin-average drainage fractions were directly related to the irrigation depths applied in each basin. Average DF = 45–57% were found in the flood irrigated basins I and III, similar to the value of 50% found in the flood irrigated La Violada district (Isidoro et al., 2003). A lower DF (37%) was found in basin II, where 39% of the area was sprinkler irrigated. Tedeschi et al. (2001) found DF of around 10% in the Monegros II district, where 100% of the area is sprinkler irrigated.

Based on the results obtained in our work, the following recommendations should be considered for improving the presently poor irrigation quality in the CR-V district: (i) improve management of water delivery (adapt the water conveyance and distribution network to crop’s water requirements, construct regulation reservoirs to increase flexibility in water delivery; prevent bypass losses); (ii) optimize farm water applications (adapt field sizes to irrigation flows; laser levelling in flood irrigated fields, reduce surface run-off through appropriate time water-cuts); (iii) change to pressurized systems in the permeable, shallow, low water retention saso soils where the actual flood-irrigation systems produce inevitable and very high drainage fractions; and (iv) reuse of drainage waters for irrigation.

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