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Impact of sprinkler irrigation management on the Del Reguero river (Spain). I: Water balance and irrigation performance

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ABSTRACT

Irrigated agriculture notably increases crop productivity, but the generated irrigation return flows may induce surface water pollution by nutrients if irrigation water and fertilization management are inadequate. In this study, the Del Reguero watershed (Huesca, Spain) was characterized, and irrigation performance was assessed to identify sprinkler irrigation water management impact on surface and subsurface water losses during the 2008 and 2009 hydrological years. Farmers were interviewed, and soil and water use surveys were performed. The main water inputs and outputs of the system were measured (irrigation, precipitation, filter cleaning, and outflow surface drainage) or estimated (municipal waste waters, actual evapotranspiration, wind drift losses, and evaporation losses) and the evaluation of the irrigation performance was performed using various water management indexes. Thirty-two percent of the area contained platform soils or cambisols characterized by a small depth, high stoniness, and limited value of total available water. The main cultivated crops were corn, barley, alfalfa, and sunflower, occupying more than 83% of the irrigated area. The annual average water inputs were 3.1% higher than water outputs. However, the error balance is considered acceptable and its resulted inputs and outputs parameters values can be used to calculate nutrients mass balance. The annual average irrigation efficiency was low (72%), due to the fact that alfalfa and corn were inadequately irrigated. The average annual consumptive water use efficiency was high (91%), indicating that a high percentage of available water was destined for crop evapotranspiration. However, irrigation management was inadequate because there was an annual average water deficit of 9%, indicating that not all the water requirements of crops were met. This high deficit was justified by the reduced irrigation allocation received by sunflower and barley. These two crops were under-irrigated by 90 and 168 mm below their respective net irrigation requirements. At a watershed scale, the average annual seasonal irrigation performance index (SIPI) was 87%, which could indicate that all crops were water satisfied. However, the calculation of SIPI at field scale, revealed that alfalfa and corn were water satisfied (SIPI = 81% and 78%, respectively) and that barley and sunflower were water stressed (SIPI = 132% and 200%, respectively).

1. Introduction

The expansion of irrigated agriculture has greatly increased crop productivity, stability, and diversification in semiarid areas (Causapé et al., 2004). On average, one irrigated hectare produces approximately six times more than non-irrigated agriculture and generates an income four times higher (MARM, 2009). In addition, the 3.68 million ha irrigated land in Spain (i.e., 13.2% of arable land) contributes to more than 50% of total agricultural production (MARM, 2009). While irrigation provides significant benefits to society, it has also generated an increasing environmental impact. Irrigated agriculture is considered a major contributor to the diffuse pollution of surface water and groundwater bodies (Aragüés and Tanji, 2003).

Nowadays, conservation of the environment and protection of natural resources are important objectives in addition to agricultural production itself. Hence, the principal challenge facing the productivity and sustainability of irrigated agricultural systems is to achieve an appropriate equilibrium between optimizing agricultural production and minimizing negative environmental

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Abbreviations: ETa, actual crop evapotranspiration; CWUE, consumptive water use efficiency; DRW, Del Reguero watershed; DF, drainage fraction; Pef, effective precipitation; FC, filter cleaning; HY, hydrological year; I, irrigation; IE, irrigation efficiency; ISg, irrigation sagacity; IS, irrigation season; MW, municipal wastewater; NIR, net irrigation requirements; NIS, non-irrigation season; ETc, potential crop evapotranspiration; P, precipitation; ET_0, reference evapotranspiration; SIPI, seasonal irrigation performance index; Q, surface outflow; TAW, total available water; WD, water deficit; WFD, Water Framework Directive; WDEL, wind drift and evaporation losses.

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impacts. Therefore, diverse European directives have advocated achievement and maintenance of the existing ecological state of water bodies (Causapé, 2009). In particular, the Water Framework Directive (WFD) requires the achievement of "good ecological status" for all waters of the European Union by 2015 (Water Framework Directive European Union, 2000). The WFD requires member states of the European Union to establish programs for the monitoring of water status to establish a coherent and comprehensive overview of water status within each basin. The objective of achieving good water status should be pursued at the watershed scale (Water Framework Directive European Union, 2000). Thus, there is a need for a greater integration of qualitative and quantitative aspects of water bodies that belong to the same watershed. Therefore, it is necessary to analyze the characteristics of an irrigated watershed and the contribution of agricultural practices in the process of water quality impairment.

To satisfy the main objective of the WFD, the Ebro River Basin Authority (Confederación Hidrográfica del Ebro, CHE) has supported studies to characterize water quality in the Ebro River Basin in recent years (CHE, 2006, 2007, 2008). Such studies are based on monitoring programs controlling the water quality in the main rivers located in the Ebro River Basin. On the other hand, the Alto Aragon Irrigation District (AAID) started several monitoring programs in 2005 to control the water quality of irrigation return flows coming from irrigated watersheds (CGRAA, 2007).

The analysis of irrigation performance is usually conducted with a set of indices (Burt et al., 1997; Clemmens and Burt, 1997). These indices quantify water management, and serve to identify problematic areas within an irrigated area (Dechmi et al., 2003). However, the indices do not inform on the reasons of the observed level of performance or provide guidance on how to improve it (Dechmi et al., 2003). Irrigation performance studies have been conducted in several semiarid areas (Faci et al., 2000; Dechmi et al., 2003; Lorite et al., 2004a,b; Lecina et al., 2005). High variability in irrigation performance among farmers indicates a substantial potential for improvement even if average performance values are reasonable (Fernández et al., 2007).

The objective of this research is to provide a better understanding of the processes that govern phosphorus diffuse pollution induced by sprinkler irrigation management systems. The water use and irrigation performance in Del Reguero watershed (Huesca, Spain) at field and watershed scale, as well as the identification of the main water inputs and outputs in the system are presented in this paper. A companion paper focuses on irrigation return flows quality.

2. Material and methods

2.1. Description of the study area

The Del Reguero watershed (DRW) is a sprinkler irrigation agricultural system situated in the Alto Aragon Irrigation District, which represents the largest irrigated area in the Middle Ebro River Valley. An important program of irrigation system modernization (transformation from a surface irrigation system to a sprinkler irrigation system) is currently being executed in this district. The Del Reguero stream is an affluent of the Alcanadre River located in the left bank of the middle Ebro River Basin in Spain (Fig. 1). A total of 1865 ha are drained by the Del Reguero stream, and are situated within the Alconadre Irrigation District (AID) boundaries (41°54′N and 3°34′W). The Pertusa canal crosses the entire Del Reguero watershed and separates the irrigated land (1355 ha) from the non-irrigated land (Fig. 1). A dense network of open ditches collected the drainage water from the irrigated lands. The majority of the cultivated fields also had subsurface drains, especially the fields located in the lower part of the area near the stream. The main irrigated crops were corn, alfalfa, sunflower, barley, and several horticultural crops.

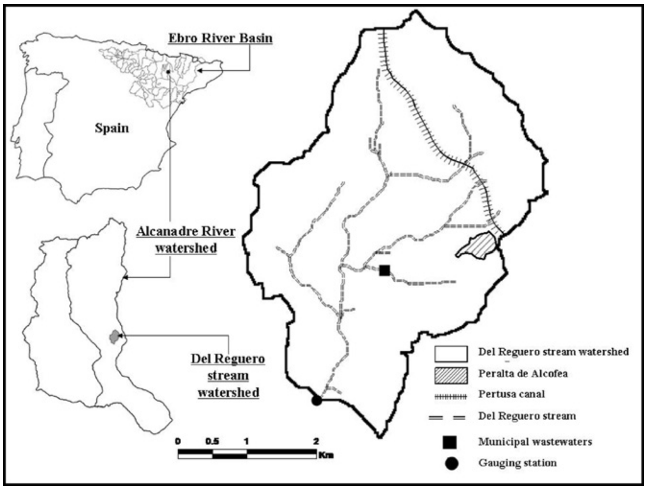

Fig. 1. Location of Del Reguero watershed, monitoring station, drainage network, municipal wastewater point, Peralta de Alcofea village and the Pertusa irrigation water canal.

Considering the Huerto meteorological station daily data (from January 2004 to December 2009) located at 6 km from the study area (41°56′59″N and 00°08′09″W), and according to the Köppen climate classification system (Kottek et al., 2006), the climate is classified as semiarid. The mean annual precipitation is 391 mm, and the mean annual reference evapotranspiration (ET_0), as determined by the Penman and Monteith method (Allen et al., 1998), is 1294 mm. The highest precipitation amount occurred in spring (139 mm), and the highest average monthly ET_0 occurred in July (205 mm; 6.6 mm day^{-1}). The lowest average monthly ET_0 occurred in December (28.3 mm; 0.9 mm day^{-1}). Considering the ombrothermic diagram, the dry period extends from May to late August. The mean temperature is 13.1 °C with a large temperature difference between winter and summer. The average minimum temperature of the coldest month (December) is −0.1 °C, and the average maximum temperature of the warmest month (July) is 31.4 °C.

The Alconadre Irrigation District has a well-developed collective irrigation network managed by Ador management software (Playán et al., 2007). Irrigation practices began in 1982, and excellent quality of water was used for irrigation ($EC = 0.28\ dS\ m^{-1}$; $NO_3 < 2\ mg\ L^{-1}$; and $TP < 0.001\ mg\ L^{-1}$). The average water consumption was considered moderate (501 mm), and the water was delivered mainly by sprinkler irrigation systems (96% solid-set sprinkler irrigation, 3% pivot and 1% drip irrigation systems). The sprinkler models were VYR35, VYR36, and VYR70 (Zapata et al., 2007). The most common sprinkler spacing was triangular with sprinklers at every 21 m or 18 m in the sprinkler line and 18 m between the sprinkler lines (Zapata et al., 2007). The majority of the principal nozzle diameters were 4.0 mm or 4.8 mm, and the diameter of the auxiliary nozzle was 2.4 mm. The solid-set coefficient of uniformity ranged between 60% and 94% with an average value of 79%, which was not considered acceptable (Clemmens and Dedrick, 1994).

A rectangular control section was constructed in the Del Reguero stream bed at the watershed outlet, and the water level (H; cm) was recorded every 15 min using an electronic limnigraph during the study period (from October 2007 to September 2009). Water level daily average values were calculated and converted into flow values (Q; $L\ s^{-1}$) using the elaborated relationship between flow and water level.

The measured streamflow values were separated through hydrograph separation method into baseflow and direct runoff components using the specific electrical conductivity (EC) as a hydrologic tracer (Matsubayashi et al., 1993). This method is based on the assumption that the gully flow (Q_t, with measured concentration C_t) originates from the mixing of a surface runoff component (Q_r) and a baseflow (subsurface drainage) component (Q_b) with known concentrations (C_r and C_b, respectively). The following equations for the conservation of mass for water and solute were used then to estimate the relative contribution of each component to the total flow (i.e., Q_b/Q_t and Q_r/Q_t). The baseflow ECs were characterized during the non-irrigated season in dates without runoff events by EC measurements of the waters sampled daily with the automatic water sampler. The surface runoff ECs were assumed to equal the ECs of irrigation waters (0.28 dS m^{-1}).

$$Q_t = Q_b + Q_r, \qquad C_t \times Q_t = C_b \times Q_b + C_r \times Q_r \tag{1}$$

2.2. Soil characteristics

According to the geomorphologic map constructed by the Instituto Geológico y Geominero de España (www.igme.es) and soil survey conducted by the Alconadre Irrigation District, two geomorphologic units were distinguished in the study zone. The first unit (38% of the total area) corresponded to platform soils or cambisols (locally called “sasos”). These soils were characterized by a shallow depth, presence of calcareous horizon, and a high content of stones. The second unit covered the remaining watershed area and corresponded to alluvial soils, mostly stone-free and with a soil depth varying from 0.6 m to more than 1.2 m. This unit was divided in two sub-units (shallow and deep alluvial units).

A soil sampling survey was performed during the fall of 2008 to determine the main soil physical and hydraulic properties in the study area. Soil samples were taken from 28 plots (7 samples from the cambisols, 6 samples from the shallow alluvial soils, and 15 samples from the deep alluvial soils), and each sample was taken from a depth of 0.3 m to 1.2 m when possible. The sampling sites were chosen covering all the surface of the watershed and all types of crops grown. In total, 92 samples were collected. Soil texture was determined using the USDA system based on the particle size ratio (sand, silt, and clay). Pressure chambers with ceramic plates were used to determine field capacity (FC) and wilting point (WP) using pressures of 0.033 MPa and 1.5 MPa, respectively (Soil Survey Division Staff, 1993). For each soil sample, the bulk density was estimated using a US texture triangle (Saxton et al., 1986). The total available water (TAW; mm) was calculated according to the following equation of Walker and Skogerboe (1987):

$$\mathrm{TAW} = 10^3 p(\theta_{\mathrm{FC}} - \theta_{\mathrm{WP}}) \frac{\rho_b}{\rho_w}(1 - S) \tag{2}$$

where p is the soil depth (m); θ_{FC} is the gravimetric water content ratio at 0.033 MPa (field capacity); θ_{WP} is the gravimetric water content ratio at 1.5 MPa (wilting point); ρ_b is the soil bulk density (Mg m^{-3}); ρ_w is the water density (Mg m^{-3}); and S is the volumetric ratio of stoniness.

The soil survey analytical results indicate that the platform soils are mainly loam textured, characterized by the high stoniness (20% in volume on average), the small soil depth (0.6 m on average) and the existence of soil horizon dominated by calcium carbonate deposits which can limit the soil rooting depth. As a consequence, soil TAW is small (70.0 mm on average). In the second layer (0.3–0.6 m), the coefficient of variation of TAW (10.7%) was three times lower than that found in the topsoil layer (34.5%). In platform soils, textural classes and average gravimetric water contents at field capacity (θ_{FC}) and wilting point (θ_{WP}) were found to be similar in all soil layers.

The shallow alluvial soils occupy 11% of the total area and are located close to Del Reguero stream. The soil depth of shallow alluvial soils varies from 0.6 to 0.9 m. Shallow alluvial soils are loam and silt loam textured, with the existence of some plots with sandy loam texture. Low stoniness was observed (≈4% in volume on the average). The TAW was slightly high, averaging 167.3 mm. The gravimetric water content at field capacity and wilting point showed low variability between soil layers and the highest average values were observed in the upper 0.30 m layer. As soil depth increases both θ_{FC} and θ_{WP} slightly decrease, which can be attributed to the moderate increase in the sand fraction.

The soil depth of the deep alluvial soils exceeded 1.2 m at almost all sampling points. The majority of sampled deep alluvial soils are loam and sandy loam textured, with no coarse fragments. The computed TAW values were high, averaging 179.1 mm. The value of TAW increased slightly at deeper layers (0.6–0.9 m) which can be explained by the moderate increase in the silt fraction. In all soil layers, the coefficient of variation of (θ_{FC}) and (θ_{WP}) was moderate (less than 20%), and therefore the resulting spatial variability of TAW within these soils was also moderate.

2.3. Cropping patterns and water use data

Another field survey was performed to determine crop spatial distribution and the corresponding areas during 2008 and 2009. The farmers irrigation management practices were analyzed from farmers interviews conducted in 2008 (16 farmers) and 2009 (17 farmers). The farmers were randomly selected, and the questionnaire consisted mainly of multiple choice questions about the irrigation systems and water management practices of the most important crops in the irrigated area. The size of surveyed farms ranged from 4.3 ha to 23.5 ha with a total surveyed area of 185 ha in 2008 (16% of irrigated area) and 176 ha in 2009 (15% of irrigated area) covering the entire surface of the watershed. The following information was collected from the surveys: dates of the first and the last irrigation event; number of irrigations; number of days between two irrigations; and volume of water applied for each type of crop.

2.4. Water balance

Annual water balances in the DRW were performed for the two hydrological years of 2008 and 2009. Assuming that the initial and final amounts of soil water were the same, the difference between water inputs and outputs in the system (ΔW) corresponded to the water balance calculated as follows (Eq. (3)):

$$\Delta W = (I + P + \mathrm{MW} + \mathrm{FC}) - (\mathrm{ETa} + Q + \mathrm{WDEL}) \tag{3}$$

where I is the water diverted for irrigation; P is the precipitation; MW is the wastewater discharge from Peralta de Alcofea village; FC is the water used to clean the pumping station pumps and discharged in the drainage canal; ETa is the volume of actual crop evapotranspiration in the entire study area; Q is the drainage outflow measured at the gauging station that includes surface and subsurface runoff; and WDEL are the wind drift and evaporation losses.

The following equation was used to calculate the error balance as a percentage:

$$\text{error balance}\,(\%) = 200 \times \frac{\text{Inputs} - \text{Outputs}}{\text{Inputs} + \text{Outputs}} \tag{4}$$

The global error balance calculated using the above equation could include measurement errors and unmonitored flows in the watershed, such as deep percolation. The irrigation volumes (I) applied in 2008 and 2009 were calculated by multiplying the mean volume of irrigation applied for each crop by the surface occupied by each crop. The summation of total volumes of water consumed by each crop gave the total volume of water incoming by irrigation.

The daily precipitation (P) was measured at the Huerto meteorological station (6 km away from the study area). As monthly P registered in a pluviometer in the watershed (daily data not available in this case) was different from that gathered at the Huerto station, the regression relationship between monthly P in the watershed and monthly P in Huerto was calculated and used to generate daily P data in the watershed. The monthly volumes supplied to municipal users were obtained from the Ebro River Basin Authority (CHE), and the municipal wastewater returns (MW) were calculated as 80% of the supplied water (Isidoro et al., 2004). Finally, the volume of water used to clean the filter in the pumping station (FC) was calculated following Eq. (5). The cleaning system includes 17 sprinklers with a flow rate of $0.5\,\mathrm{L\,s^{-1}}$ and operating during 15 min each hour during the whole irrigation season.

$$\mathrm{FC}(\mathrm{m^3\ day^{-1}}) = 17 \times 0.5(\mathrm{L\ s^{-1}}) \times 0.25 \times 86.4 \quad (5)$$

The annual volumes of actual crop evapotranspiration in the entire study area (ETa) were calculated using the Irrigation Land Environmental Evaluation Tool for daily soil water balance (Causapé and Pérez, 2008). ETa was calculated on a daily basis for the irrigated crops, non-irrigated crops and non-cultivated land in the study area. The average monthly values of crop coefficients (K_c) and vegetative periods were obtained from Martínez-Cob et al. (1998). Non-cultivated lands were considered as bare soils and the corresponding monthly value of coefficient was obtained from Martínez-Cob et al. (1998). The annual drainage outflow (Q) volume was calculated from the recorded data at the gauging station. The volumes of water lost (WDEL) were calculated on a daily basis for the entire sprinkler irrigated area using the following equation (Playán et al., 2005):

$$\mathrm{WDEL} = 20.3 + 0.214U^2 - 2.29 \times 10^{-3}\mathrm{RH}^2 \quad (6)$$

where U is wind speed ($\mathrm{m\,s^{-1}}$); and RH is the relative humidity (%).

2.5. Irrigation performance characterization

Irrigation performance was characterized through various water management indexes calculated at watershed or field level for 2008 and 2009. Three irrigation performance indices as defined in Eqs. (7)–(9) were calculated as described below. Consumptive water use efficiency (CWUE; %), which refers to the fraction of water used by crops (Eq. (7)), was defined as the ratio of the percentage of the ETa to the total water available for evapotranspiration (i.e., irrigation and effective precipitation [P_{ef}]). CWUE evaluates the global efficiency of the crop in the consumptive use of the available soil water. Irrigation efficiency (IE; %) was calculated as the ratio of ETa minus P_{ef} to irrigation (Eq. (8)). A theoretical IE of 100% indicates that the entire volume of irrigation application has been used to satisfy the water needs of crops or that it has accumulated in the water reserves of the soil for use on crops in the following period (Causapé, 2009). Irrigation sagacity (ISg; %) was calculated the same way as IE taking into account the non-agronomic benefits of water use, such as WDEL in the case of sprinkler irrigation (Eq. (9)). Other indexes expressing irrigation performance included drainage fraction (DF; %) and water deficit (WD; %). The DF was calculated as the ratio of the percentage of drainage outflow (Q) volume to I and P (Eq. (10)). The WD was calculated as the difference between crop evapotranspiration (ETc) (or potential crop evapotranspiration) and ETa divided by ETc (Eq. (11)). WD evaluates the global capability of the water resources (I and P) for covering the water requirements of the crop. The seasonal irrigation performance index (SIPI) was also calculated (Bensaci, 1996). SIPI was defined as the ratio of the seasonal net irrigation requirements, which was the difference between ETc and P_{ef}, to the seasonal irrigation dose (I) delivered to the crop (Eq. (12)). The SIPI represents a simplification of the irrigation efficiency standard concept defined by Burt et al. (1997) and Clemmens and Burt (1997). The SIPI is usually used to evaluate water use quality where detailed data for water balance are not available (Faci et al., 2000; Dechmi et al., 2003).

$$\mathrm{CWUE} = \left[\frac{\mathrm{ETa} + \mathrm{WDEL}}{I + P_{\mathrm{ef}}}\right] \times 100 \quad (7)$$

$$\mathrm{IE} = \left[\frac{\mathrm{ETa} - P_{\mathrm{ef}}}{I}\right] \times 100 \quad (8)$$

$$\mathrm{ISg} = \left[\frac{(\mathrm{ETa} - P_{\mathrm{ef}}) + \mathrm{WDEL}}{I}\right] \quad (9)$$

$$\mathrm{WD} = \left[\frac{\mathrm{ET_c} - \mathrm{ET_a}}{\mathrm{ET_c}}\right] \times 100 \quad (10)$$

$$\mathrm{DF} = \left[\frac{Q}{I + P}\right] \times 100 \quad (11)$$

$$\mathrm{SIPI} = \left[\frac{(\mathrm{ETc} - P_{\mathrm{ef}})}{I}\right] \quad (12)$$

All water management indexes were calculated for the irrigation season (IS = April–September) and entire hydrological year (HY) (except for the SIPI). The SIPI was computed for each representative crop (alfalfa, corn, sunflower, and barley) and year considered. Daily ETc was calculated from the reference evapotranspiration ($\mathrm{ET_0}$), and the respective crop coefficients (K_c) obtained from a previous report (Martínez-Cob et al., 1998). Reference evapotranspiration was calculated using standard FAO procedures as previously described by Allen et al. (1998) and using meteorological data recorded at the Huerto station. Daily P_{ef} was estimated using the ETa, TAW, and available water (AW) of the soil. The initial available water was estimated to be half of the soil water holding capacity. Effective precipitation was estimated considering the following parameters: if $P < (\mathrm{TAW} + \mathrm{ETa} - \mathrm{AW})$ then $P_{\mathrm{ef}} = P$; otherwise $P_{\mathrm{ef}} = (\mathrm{TAW} + \mathrm{ETa} - \mathrm{AW})$ (Causapé, 2009).

To better understand factors affecting water use and the SIPI, Duncan's multiple means comparison was applied to study the interaction between quantitative and categorical variables. This procedure determined which means were significantly different from the others. The seasonal water use indexes and the SIPI were the dependent variables considered in this analysis. The independent categorical variables (factors) were as follows: type of crop, class of soil, and class of plot area. Four crops were considered in this analysis, including corn, alfalfa, sunflower, and barley. The sampling was done selecting between 5 and 7 plots for each considered crop. In 2008, 47 plots were sampled at random to perform the statistical analyses, whereas in 2009, 57 plots were considered. Three soil classes were tested as follows: platform soils, shallow alluvial soils, and deep alluvial soils. Finally, the following three classes of plot areas were considered: class A with surface area less than 5 ha; class B with surface area ranging between 5 ha and 12 ha; and class C with surface area greater than 12 ha.

3. Results and discussion

3.1. Hydrological regime of Del Reguero stream

Table 1 summarizes the main statistical parameters of streamflow measured in the drainage outlet of the study area during the 2008 and 2009 hydrological years. The streamflow variability was more pronounced during the irrigation season (IS). The coefficient of variation (CV) was 97% during the IS and 80% during the non-irrigation season (NIS). These results were expected because the study area was mostly fed by rainfall during the NIS. During the IS, however, irrigation in addition to rainfall water contributed to water in the system resulting in more variable streamflow discharge. Streamflows recorded during 2009 were significantly ($P < 0.001$) higher than those recorded during

Table 1
Maximum ($L\,s^{-1}$), minimum ($L\,s^{-1}$), average ($L\,s^{-1}$), median ($L\,s^{-1}$) and coefficient of variation (CV, %) of surface outflows (*Q*) measured in drainage outlet of Del Reguero watershed during the non-irrigation season (NIS), the irrigation season (IS), and the hydrological year (HY) of the years 2008 and 2009. Mean values of both years were also calculated.

	2008			2009			2008 + 2009		
	NIS	IS	HY	NIS	IS	HY	NIS	IS	HY
Maximum	55.5	225.5	225.5	478.4	941.0	941.0	478.4	941.0	941.0
Minimum	15.2	20.9	15.2	42.7	47.5	42.7	15.2	20.9	15.2
Average	28.3	62.6	50.6	78.1	98.7	88.4	60.6	80.6	71.9
Median	27.9	62.7	40.0	64.2	72.3	69.0	56.8	68.9	64.4
CV	23.1	48.1	58.4	67.4	105.3	93.8	80.5	97.3	94.4

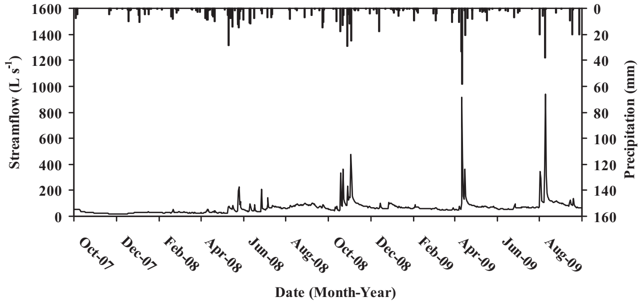

Fig. 2. Evolution of the average daily streamflow recorded in the Del Reguero stream and average daily precipitation during the period of October 2007–September 2009.

Table 3
Components of water balance: water inputs (In) as precipitation (*P*), irrigation (*I*), municipal wastewaters (MW) and filter cleaning (FC); water outputs (Out) as actual crop evapotranspiration (ETa), surface outflow (*Q*) and wind drift and evaporation losses (WDEL). Difference between inputs and outputs (ΔW) and error of the balance are calculated. Mean values of the whole study period are also calculated.

	Inputs (hm^3)				Outputs (hm^3)			In–Out ΔW (hm^3)	Balance error (%)
	P	*I*	MW	FC	ETa	*Q*	WDEL		
2008	6.92	7.13	0.06	0.04	12.22	1.43	0.89	−0.40	−2.8
2009	9.47	7.82	0.05	0.04	12.21	2.79	1.03	1.35	+8.1
Mean	8.20	7.47	0.06	0.04	12.22	2.11	0.96	0.47	+3.1

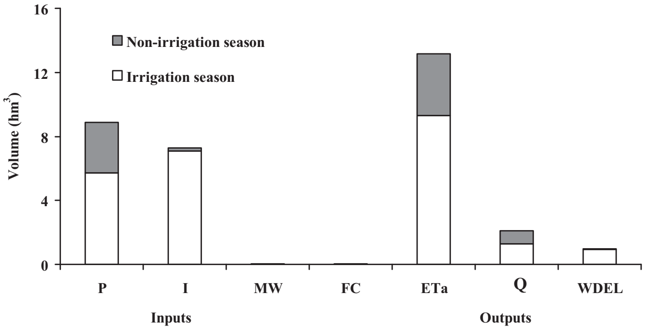

Fig. 3. Mean volumes of precipitation (*P*), irrigation (*I*), municipal wastewater (MW), filter cleaning (FC), actual crop evapotranspiration (ETa), surface outflow at P11 gauging station (*Q*) and wind drift and evaporation losses (WDEL) in the 2008 and 2009 hydrological years, irrigation and non-irrigation season of Del Reguero watershed.

2008 ($88\,L\,s^{-1}$ *vs.* $51\,L\,s^{-1}$, respectively). Moreover, the maximum streamflow reached during 2009 ($941\,L\,s^{-1}$, 08/09/2009) was more than four times higher than the maximum streamflow reached during 2008 ($226\,L\,s^{-1}$, 05/25/2008). This peak in streamflow was generated on May 2008, after three rainy days (total precipitation = 37 mm). For 2009, the maximum streamflow was recorded during August (08/09/2009) and was generated by a rainfall event of 38 mm. Fig. 2 shows that the lowest streamflow values were recorded at the end of the NIS in both hydrological years. In addition, the streamflow smoothly decreased during the NIS, except for the period when floods caused by rainfall events altered this trend (during 2008).

The largest difference between both years was derived from the lower streamflow in 2008 (average streamflow was $51\,L\,s^{-1}$ with an annual contribution of $1.43\,hm^3$) when compared to 2009 (average streamflow was $88\,L\,s^{-1}$ with an annual contribution of $2.79\,hm^3$). This difference was mainly due to increased volumes of rainfall and irrigation water in 2009. The total precipitation in 2008 was 395.8 mm and 556.9 mm in 2009. The height of irrigation water applied was 601 mm in 2008 and 654 mm in 2009. The increase of the irrigation water applied in 2009 is mainly due to the increase of corn area (405 ha in 2008 and 480 ha in 2009).

Hydrograph separation revealed that most of the streamflow (77%) during the study period was represented by the baseflow that included throughflow and interflow (Table 2). The contribution of baseflow to total streamflow varied between the 2008 (81%) and 2009 (76%) hydrological years. This result was expected because there were more peaks of streamflow generated by precipitation in 2009. The majority of those peaks were originated from direct runoff or overland flow.

3.2. Water balance

The main average annual water inputs during the years 2008 and 2009 in the DRW were precipitation (52.0% of total inputs) and irrigation (47.4% of total inputs) and the main average water output was ETa (79.9% of total outputs) (Table 3). The average volumes of *P*, *I*, and ETa were 45%, 97%, and 63% higher, respectively, during the IS than the NIS (Fig. 3). The remaining measured or estimated average annual inputs and outputs were much smaller (less than 1% of total inputs and 6.8% of total outputs).

The typical random nature of precipitation was observed in 2008 and 2009. The total precipitation during 2009 was 28% higher than the total precipitation during 2008 and was mainly recorded during the irrigation seasons. The majority of water inputs had higher values during the IS when compared to the NIS. The irrigation seasons had a positive water storage ($\Delta W > 0$), and the non-irrigation seasons had a negative water storage ($\Delta W < 0$).

Slight increases were found in the applied seasonal irrigation water during 2009 (Table 3). A small difference in the ETa between 2008 and 2009 was observed. This result was expected because

Table 2
Volumes of total surface outflow (TSO) divided in baseflow and direct runoff calculated for 2008 and 2009 hydrological years (HY) and their respective irrigation season (IS) and non-irrigation seasons (NIS). Between parentheses represent their respective percentage. Values of total period were also calculated.

Component (hm^3)	2008			2009			2008 + 2009		
	NIS	IS	HY	NIS	IS	HY	NIS	IS	HY
TSO	0.44	0.99	1.43	1.23	1.56	2.79	1.66	2.55	4.21
Baseflow	0.41 (94)	0.75 (75)	1.16 (81)	1.02 (83)	1.09 (70)	2.11 (76)	1.43 (86)	1.83 (72)	3.26 (77)
Direct runoff	0.03 (6)	0.24 (25)	0.27 (19)	0.21 (17)	0.47 (30)	0.68 (24)	0.23 (14)	0.72 (28)	0.95 (23)

Table 4
Irrigation efficiency (IE), irrigation sagacity (ISg), consumptive water use efficiency (CWUE), drainage fraction (DF), water deficit (WD), and seasonal irrigation performance index (SIPI) for global DRW for the hydrological years (HY) 2008 and 2009 (except for SIPI) and their respective irrigation seasons (IS). Mean values for the whole study period are also presented.

	2008		2009		2008 + 2009	
	HY	IS	HY	IS	HY	IS
IE (%)	81	76	63	63	72	69
ISg (%)	93	88	76	76	85	82
CWUE (%)	95	91	88	85	91	88
DF (%)	1	6	17	16	9	11
WD (%)	11	3	7	9	9	6
SIPI (%)	–	86	–	87	–	87

there was a small variability in crop distribution within the watershed between the study years.

The surface outflow (*Q*) was much higher in 2009 than in 2008 (48.7% higher). The higher *Q* was the result of the increase in the volumes of irrigation and precipitation during 2009. During the IS of 2008, the monthly outflow volumes had a positive correlation with the monthly irrigation volumes ($r = 0.86$) and a negative correlation with the monthly precipitation ($r = -0.33$). During the IS of 2009, however, the monthly outflow volumes were more positively correlated with monthly precipitation volumes ($r = 0.68$) than with monthly irrigation volumes ($r = 0.48$). This indicates that surface outflow can be influenced by both irrigation and rainfall waters. Nevertheless, if the IS is rainy, precipitation will contribute more than irrigation waters to surface outflow.

Volumes of municipal wastewater (MW) and filter cleaning water (FC) contributed the least to the water balance final result. The volumes of wind drift and evaporation losses were similar in 2008 and 2009 (0.89 hm^3 for 2008 and 1.03 hm^3 for 2009). This result was expected because WDEL is directly related to the irrigation volumes applied, relative humidity (RH; %), and wind speed (U; m s^{-1}). The mean values of both RH and U during the irrigation seasons were similar (RH = 63% and 61% for 2008 and 2009, respectively; and $U = 2.6$ m s^{-1} for both 2008 and 2009).

Water outputs were higher than water inputs in 2008, and water inputs were higher than water outputs in 2009. The mean annual water inputs during 2008 and 2009 were 3.1% higher than water outputs. This excess (0.47 hm^3) in mean annual water inputs may have been due to various processes, such as an underestimation of actual crop evapotranspiration or an overestimation of irrigation volumes, because the average values of water consumed per crop were considered. The crop water consumption data in each cropped field should have been specified to reduce the difference between inputs and outputs. Another possible source of error may have been the weather data. The climate station used in this work was 6 km from the watershed. Thus, precipitation volumes used to calculate the water balance may have been higher than the actual volumes of rainfall in the watershed. Nevertheless, for the level of approximation of this district-scale balance, the closing error can be regarded as acceptable.

3.3. Irrigation water use performance at watershed level

Table 4 shows the irrigation quality indexes obtained for the 2008 and 2009 hydrological years and their respective irrigation seasons (except for SIPI index). The irrigation efficiency (IE) of the DRW during the entire study period was relatively low (IE = 72%). The IE of the 2008 hydrological year (81%) was approximately 22% higher than the IE of the 2009 hydrological year.

Regarding the global SIPI for the entire watershed, the calculated values were 86% and 87% for 2008 and 2009, respectively, with an average interannual SIPI of 87%. These results indicate that the volumes of irrigation water were approximately 15.3% and 19.3% higher than the net irrigation requirements of crops in 2008 and 2009, respectively. However, these global SIPI values should be handled with great caution due to the large differences between the crops as previously highlighted.

The IE and SIPI values calculated for alluvial soils (data not shown) were the same for the irrigation seasons of both years. In the platform soils, however, the SIPI values were much higher than the IE values for the irrigation seasons of both years. In the platform soils, the ETa was lower than the ETc (the mean ETa was 17% lower than the mean ETc) in the two study years, indicating that the applied water was unable to meet the maximum crop evaporative demand. In the alluvial soils, however, the ETa was equal to the ETc, indicating that the maximum crop evaporative demand was satisfied for this soil type.

The water use was inadequate during 2009, which explained the high drainage fraction value reached in 2009. In fact, 17% of the applied water left the system through drainage in 2009, which was high when compared to the drainage value in 2008 (DF = 1%). These results reflect how the drought conditioned the maximum use of irrigation water.

The system had a mean WD value of 9%, indicating that not all crop water requirements were met. The highest WD occurred during 2008 (11%). Additionally, crops grown in alluvial soils had a value of WD equal to zero. The 2009 hydrological year with abundant volumes of rains (6.92 hm^3 in 2008 compared to 9.47 hm^3 in 2009) and applied irrigation volumes (7.12 hm^3 in 2008 compared to 7.82 hm^3 in 2009) had the lowest value of IE (IE = 63%) even though the actual crop evapotranspiration values were similar for both years (715 mm and 736 mm for 2008 and 2009, respectively).

Irrigation appeared to be more effective when the irrigation performance was characterized by the ISg rather than by the IE (85% compared to 72%, respectively) due to the importance of the WDEL in the study area (Table 4). The Del Reguero watershed had a

Table 5
Area (%), water use (WU), irrigation interval (II), net irrigation requirement (NIR) and Seasonal Irrigation Performance Index (SIPI) of the main crops in the 2008 and 2009 irrigation seasons. Coefficients of variation for average WU and SIPI are included in parenthesis. Total number of irrigation events for II is included in parenthesis.

Crop	Area (%)	WU (mm)			II (days)			NIR (mm)	SIPI (%)
	Ave.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Ave.
2008									
Corn	39.1	796 (09)	940	654	2 (59)	3	1	621	79 (09)
Alfalfa	15.6	898 (16)	1150	651	2 (57)	3	1	692	79 (17)
Sunflower	11.1	474 (24)	626	300	3 (32)	4	2	527	117 (28)
Barley	18.3	241 (38)	450	129	18 (4)	20	15	390	183 (35)
2009									
Corn	42.0	864 (11)	1067	690	2 (64)	3	1	650	76 (11)
Alfalfa	14.6	898 (12)	1043	743	2 (62)	3	1	738	83 (12)
Sunflower	6.7	473 (08)	537	350	3 (32)	4	2	600	129 (15)
Barley	19.4	189 (29)	264	100	18 (4)	20	15	376	217 (33)

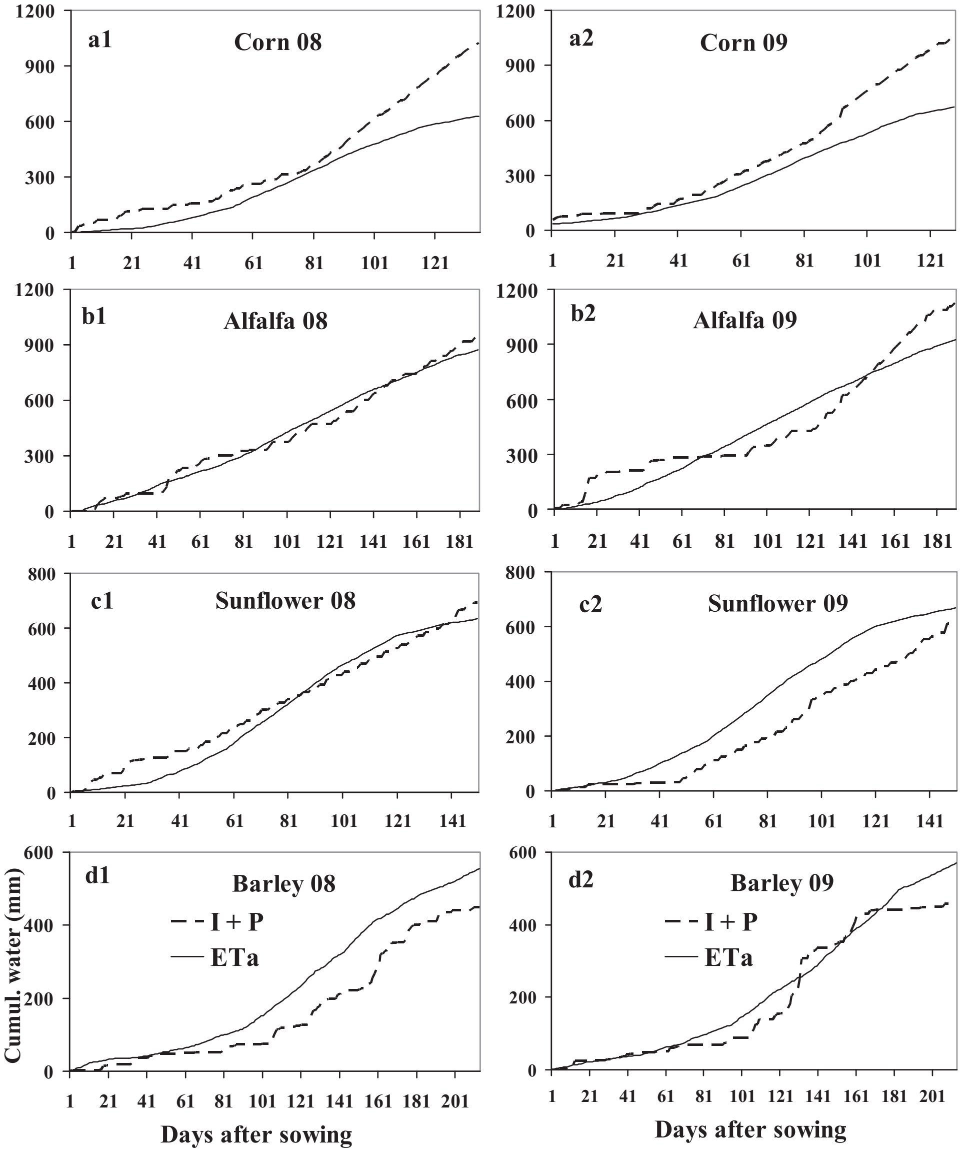

Fig. 4. Time evolution of cumulative irrigation dose plus precipitation ($I+P$) and actual evapotranspiration (ETa) for corn (a1 and a2), alfalfa (b1 and b2), sunflower (c1 and c2) and barley (d1 and d2) during the 2008 and 2009 hydrological years.

CWUE of 91%, indicating that a high percentage of available water (irrigation and effective precipitation) was destined for crop evapotranspiration (Table 4). A difference in the CWUE between the study years was observed with the highest CWUE (95%) occurring in 2008.

3.4. Irrigation water use performance at field scale

The seasonal irrigation dose was 601 mm (2008) and 654 mm (2009). Analyzed for the representative crops, the seasonal irrigation dose was 830 mm, 898 mm, 473 mm, and 202 mm for corn, alfalfa, sunflower, and barley crops, respectively. These values indicated that the sunflower and barley net irrigation requirements were not met (Table 5). Therefore, no surface runoff was generated if irrigation was adequately distributed. However, only 43% of evaluated farms showed irrigation events classified as adequate (Christiansen coefficient of uniformity >84%) (Zapata et al., 2007). This result may explain a part of the water surface drainage volume that left the watershed.

The Duncan's multiple comparison analysis indicated that less water was used in corn, sunflower, and barley fields when compared to alfalfa fields ($P<0.1$). However, the difference between alfalfa and corn was not significant ($P<0.1$) in 2009 (Table 6). Differences in irrigation water use between soil types and plot area classes were not significant ($P<0.1$) for both years, which indicate that farmers did not take into account the soil type and plot size when irrigating. The farmers did not apply additional irrigation water to platform soils when compared to alluvial soils when using solid-set sprinkler irrigation systems. They applied frequent irrigations with an average irrigation depth of 13 mm for all types of soils. On average, this irrigation dose did not exceed the total available water of platform soils. Dechmi et al. (2003) found that the large plots have a potential to conserve water. In the case of DRW, the large plots had less water applied when compared to the small plots. This is due to the fact that the majority of small plots are located in cambisols where the value of TAW is very low (average TAW = 70%). Therefore, farmers need to apply more water to meet crop requirements. However, the differences in the DRW between the classes of plot areas were not significant ($P<0.1$).

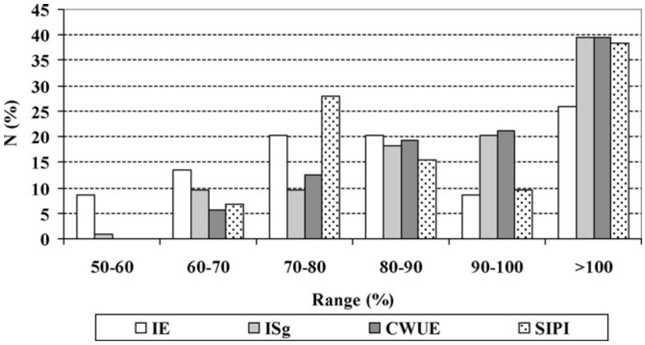

Fig. 5. Irrigation efficiency (IE), irrigation sagacity (ISg), consumptive water use efficiency (CWUE), and seasonal irrigation performance index (SIPI) frequency distribution for a total of 102 plots in DRW. *N* is the average number of plots (%).

Average SIPI values were lower than one for corn and alfalfa crops, indicating that the WU clearly exceeded the calculated net irrigation requirement of these crops (Table 5). In contrast, the mean SIPI values of the sunflower and barley crops were higher than one, indicating that the WU did not fulfill the needs of these crops. Fig. 4 shows that the corn and alfalfa crops were over irrigated and that irrigation of the sunflower and barley crops was deficient. The SIPI values varied considerably among irrigators with the CV values ranging from 9% for corn to 35% for barley. A large variability in the SIPI values indicates a substantial potential for irrigation improvement. The shape of the frequency distribution of the SIPI values (Fig. 5) showed that 39% of the plots had SIPI values higher than one and that 22% of the plots had satisfactory SIPI values (80% < SIPI < 100%).

Barley was the most water-stressed crop during the two study years with an interannual average SIPI of 200% (Table 5). Moreover, the average WU values for barley were 38% and 50% lower than the NIR during 2008 and 2009, respectively. The SIPI values of barley showed the largest variability when compared to the other crops, and barley had the lowest number of irrigation events, which may be due to the low economic revenue of the crop yield. Moreover, 93% of the total barley plots presented SIPI values higher than 100% (Fig. 5), and only one plot presented a satisfactory value of SIPI (SIPI = 87%).

Table 6
Results of the Duncan's multiple comparison procedure used to characterize the factors affecting the water use (WU) and the seasonal irrigation performance index (SIPI) in the years of study.

Variable	Level	WU ($m^3\ ha^{-1}$)		SIPI ($m^3\ ha^{-1}$)	
		2008	2009	2008	2009
Crop	Alfalfa	0	0	0.00	0.00
	Corn	1016^{*}	331^{ns}	0.004^{ns}	0.08^{ns}
	Sunflower	3981^{*}	4248^{*}	-0.47^{*}	-0.51^{ns}
	Barley	6565^{*}	7220^{*}	-1.38^{*}	-2.51^{*}
Soil type	Platform soils	0	0	0.00	0.00
	Shallow alluvial soils	1894^{ns}	954^{ns}	-0.37^{ns}	0.09^{ns}
	Deep alluvial soils	897^{ns}	724^{ns}	-0.09^{ns}	-0.26^{ns}
Plot area	A ($S < 5$ ha)	0	0	0.00	0.00
	B (5 ha $< S >$ 12 ha)	-433^{ns}	-2062^{ns}	-0.06^{ns}	0.21^{ns}
	C ($S > 12$ ha)	-1418^{ns}	-1263^{ns}	0.23^{ns}	0.37^{ns}

ns: non significant.

* $0.05 \geq P > 0.01$.

The same behavior was also observed for sunflower crops with an interannual average SIPI of 123%. The average WU values for sunflower were 10% and 21% lower than the NIR during 2008 and 2009, respectively. The sunflower SIPI values were variable with CV values of 28% and 15% for 2008 and 2009, respectively. Fig. 5 shows that 79% of the plots occupied by sunflower crops presented SIPI values higher than one. The same results have been reported in a similar sprinkler irrigation district (Dechmi et al., 2003) where farmers regularly stressed their crops, especially sunflower crops, which had an interannual average SIPI of 142%. It seems that farmers did not consider yield as the main source of income because the sunflower subsidies were comparatively high in the years of study.

However, the interannual average of the SIPI values for alfalfa and corn were 81% and 78%, respectively, indicating that all crop water needs were satisfied. The annual average of water applied was 25% and 27% higher than the NIR for corn and alfalfa, respectively. The average SIPI value for corn was the lowest among all crops. The shape of the frequency distribution of the SIPI values showed that 95% of alfalfa plots and 100% of corn plots presented SIPI values lower than 100% (Fig. 5). Moreover, 50% of the plots showed acceptable SIPI values.

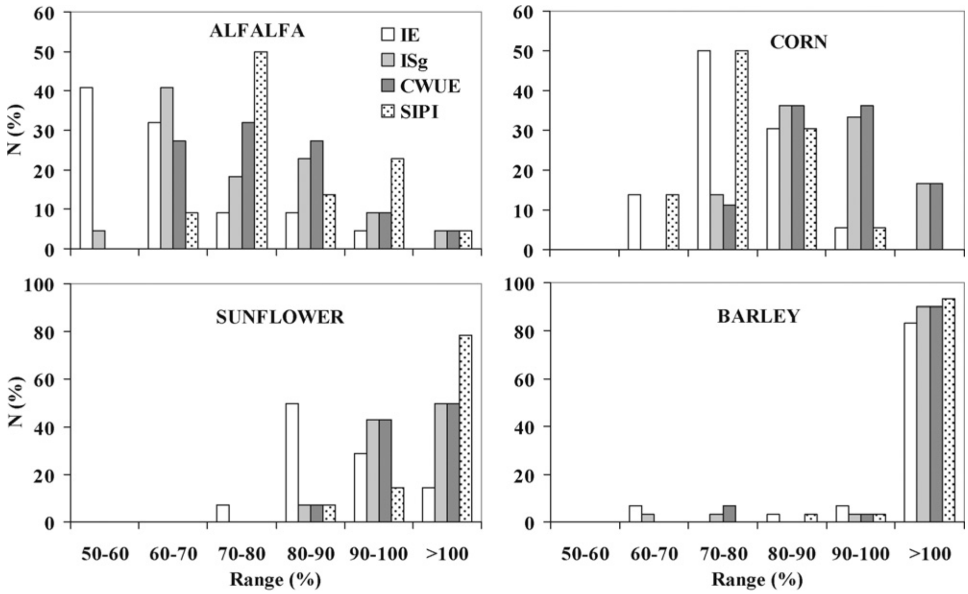

Fig. 6. Irrigation efficiency (IE), irrigation sagacity (ISg), consumptive water use efficiency (CWUE), and seasonal irrigation performance index (SIPI) frequency distribution for the main crops grown in DRW. *N* is the average number of plots (%).

These data suggest that farmers tried to optimize irrigation water use by restricting application on drought resistant crops (sunflower and barley) and by limiting water stress on drought sensitive crops (corn). Alfalfa is a drought-resistant crop. Nevertheless, the water requirements were met during the two study years, indicating that farmers applied less water to crops where yield reductions produced less damage to their economies.

The Duncan's multiple means comparison analysis indicated that crop type was the only significant variable for both 2008 and 2009 irrigation seasons (Table 6). The SIPI of sunflower and barley crops were significantly ($P < 0.05$) different from that of alfalfa in the 2008 irrigation season, and barley was the only crop showing significant ($P < 0.05$) differences with alfalfa in regard to SIPI in the 2009 irrigation season. The corn SIPI values were 6% smaller than the alfalfa SIPI values. The relationship found between the soil type and SIPI values indicated no significant ($P < 0.05$) differences. Moreover, the relationship between classes of plot area and SIPI values indicated no significant differences. Similar findings have been reported (Dechmi et al., 2003) where no relationship existed between plot area and SIPI values for the studied years and no significant differences were found between soil type and SIPI values.

Considering the irrigation efficiency index, 24% of the plots had IE values lower than 70% (Fig. 5), indicating that the irrigation management was unsatisfactory. In fact, the irrigation was inadequate in 77%, 14%, and 7% of the alfalfa, corn, and barley plots, respectively (Fig. 6). Moreover, 30% of the plots had satisfactory irrigation performance (Fig. 5) if irrigation sagacity (ISg) was considered (80% < ISg < 100%). The shape of the frequency distribution showed that 42% of the corn plots and 32% of the alfalfa plots presented satisfactory ISg values (Fig. 6). In addition, 30% of the plots had satisfactory values of CWUE (Fig. 5), and 39% of the plots had a CWUE value higher than 100% (mainly for barley with CWUE values higher than 100% in 93% of the plots) (Fig. 6). These results indicate that no deep percolation losses occurred in almost all of the barley plots. During 2009, however, excess water application during a period of barley growth induced water percolation losses (Fig. 4d2). Additionally, corn was over-irrigated during the growing season of both years (Fig. 4a1 and a2).

4. Conclusions

The study indicates that Del Reguero stream discharge variability was more pronounced during the IS (CV = 97%) than the NIS (CV = 81%) reflecting the contribution of irrigation to streamflow. The hydrograph separation revealed that subsurface flow was the most relevant flow path (77% of total flow).

The water balance performed for DRW in 2008–2009 hydrological years allowed to calculate the volumes of the inputs and outputs from which various performance indices were derived. The average annual water inputs were 3.1% higher than outputs (15.8 hm^3 *vs.* 15.3 hm^3). This excess 0.47 hm^3 output volume was quite small for a district-scale study and may be ascribed to an overestimation of irrigation volumes or an underestimation of crop evapotranspiration volumes.

The annual average IE in the Del Reguero catchment was inadequate (72%) during the hydrological years 2008 and 2009, indicating that there was an excess application of irrigation water. The CWUE was high with an average annual value of 91%. Moreover, the irrigation management was inadequate because there was an annual WD of 9%.

The SIPI showed important irrigation problems in DRW. For sunflower and barley, the mean SIPI was 123 and 200%, respectively, indicating that the seasonal volumes of irrigation water were lower than the net sunflower and barley irrigation requirements. For corn and alfalfa, the mean SIPI was 78 and 81%, respectively, indicating that the seasonal volumes of irrigation water were higher than the net corn and alfalfa irrigation requirements. This is due to the high economic value of corn and alfalfa where irrigation water is applied with non-limiting rates.

In the sprinkler irrigation system, the water management appeared to be more effective when the performance was characterized by the ISg rather than by the IE (85% compared to 72%, respectively) due to the importance of WDEL.

Surface water quality depends a lot on the magnitude of irrigation return flows. However, the irrigation performance analysis at watershed scale does not identify the actual loss of water in the form of surface and subsurface flows. Therefore, irrigation performance should be studied at field scale to better identify the plots contributing more in the generation of irrigation return flows.

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