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Three study decades on irrigation performance and salt concentrations and loads in the irrigation return flows of La Violada irrigation district (Spain)

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ABSTRACT

Irrigation district salt balances identify the main sources and sinks of salts and quantify salt loads in irrigation return flows. Salt balances were performed in La Violada Irrigation District during the 80's (1982-1984), 90's (1995-1998) and 00's (2006-2008) decades. Total Dissolved Solids (TDS) and loads in irrigation return flows were related with changes in irrigation performance and infrastructures during these decades. TDS increased linearly to increases in Irrigation Consumptive Use Coefficient (ICUC) ($P < 0.01$), and decreased with increases in Drainage Fraction (DRF) ($P < 0.001$). The salt balances revealed that 82% of the exported salts originated from soil gypsum dissolution. Annual salt yields in return flows were high and similar in the 80's and 90's (about 19.3 Mg/ha year), and halved in the 00's (9.9 Mg/ha year) due to comparable reductions in irrigation and drainage volumes derived from a better irrigation performance. Irrigation season salt yields were high and steady around 14.1 Mg/ha for ICUC $<$ 51% and DRF $>$ 66%, and decreased exponentially for values above and below these thresholds, respectively. Therefore, the key management strategy to reduce salt discharge to downstream areas is to decrease drainage volumes by improving irrigation management.

Keywords: irrigation; salt balance; diffuse salt pollution; drainage fraction; soil gypsum; water quality

1. Introduction

Irrigated agriculture is the major world's water consumer and a significant diffuse source of contamination (Ongley, 1996; Tanji and Kielen, 2002). Although an adequate drainage is critical to prevent soil salinization and waterlogging, the contaminants (salts, agrochemicals, trace elements and sediments) exported by the irrigation return flows (IRF) may damage the quality of the receiving water bodies and restrict its municipal, industrial, agricultural and environmental uses.

Salts (i.e., total dissolved solids, generally referred as Electrical Conductivity, EC) are one of the major irrigation-induced contaminants in arid and semi-arid environments due to mineral weathering that increases salt concentrations and loads in IRF (Aragüés and Tanji, 2003; El-Ashry et al., 1985). An example of the negative effects of salts on ecosystems is the steady salinity increments in the Great Menderes River (Turkey) that resulted in the extinction of carp (*Cyprinus carpio*) and wells catfish (*Silurus glanis*) (Koç, 2008). Excessive salt concentrations have also shown to be deleterious to crops, soils and human health (Tanji, 1990). The EU has set limits for electrical conductivity (EC, 1 dS/m; indicative), sulphate (SO_4^{2-}, 250 mg/L), and chloride (Cl^-, 200 mg/L; indicative) in waters allocated to human consumption (EU, 1998).

The type, concentration and mass of salts in IRF depend basically on the salinity of the irrigation water, the minerals present in the soil and subsoil, the hydrogeology, and the management of irrigation and drainage waters (Tanji and Kielen, 2002). Salt concentrations in IRF may be one to ten fold those in irrigation waters, depending on the leaching fraction (evapo-concentration effect) and the presence of soluble minerals in the soil (weathering effect) (Aragüés and Tanji, 2003). However, the impact of salts in IRF on the receiving water bodies is determined by its mass rather than its concentration. Hence, assessment of the off-site salinity impact of irrigated agriculture requires the determination of IRF volumes and salt concentrations for quantification of salt loads.

A main objective of the European Framework Directive (EU, 2000) is the achievement of a good quality status of water bodies in Europe in year 2015. Since salts originated by irrigated agriculture may have a negative quality impact on these water bodies, quantifying salt loads, understanding the processes that contribute to salt discharges in IRF, and identifying best management practices (BMP) for its control are crucial issues to comply with this objective and to minimise salinity impacts on downstream users and ecosystems (Duncan et al. 2008).

Hydrosalinity balances have been performed in the last decades in several irrigated areas around the world for appraisal of salt loads in IRF (Australia: Prendergrast et al., 1994; India: Sharma, 1999; Iran: Noory et al., 2011; México: Palacios et al., 1978; Spain: Faci et al., 1985; Tunisia, Turkey: Aragüés et al., 2011; USA: Schoups et al., 2005). However, most studies were performed for short periods of time and did not allow identifying the effects of long-term agronomic changes and climatic variability on salt load trends. Moreover, BMP are site-specific and depend on the dominant salt mobilisation processes in a given irrigation district (Thayalakumaran et al. 2007). Hence, an efficient application of these BMP requires the analysis of existing irrigation and drainage management and an in-depth information about salt pollution, its temporal trends, and its relations with the hydrological processes and agricultural practices in the study area.

Irrigation return flows in the Ebro River Basin (located in North East Spain and with about 800000 irrigated ha, 28% of them affected by salinity) are significant contributors to the salinization of water courses (Quílez et al., 1992). The studies performed in the middle Ebro Basin indicate that salt loads in IRF are basically due to the presence of geologic salts dissolved and mobilised by deep-percolation waters towards the drainage courses due to an inefficient irrigation management (Tedeschi et al., 2001; Isidoro et al., 2004). The attainment of higher irrigation efficiencies would reduce these salt loads, although a sufficient leaching fraction is required to maintain a favourable salt balance in the crop's root zone to prevent soil salinization. Hence, the development of relationships between irrigation performance and salt concentrations and loads in IRF would be a significant contribution to target salt load limits.

La Violada irrigation district (VID), located in the middle Ebro River Basin, has been the focus of several hydrology, irrigation and mass balance studies since the beginning of the 80's. Under the National Irrigation Modernization Program being developed in the last decade in Spain (Lecina et al., 2010), VID has implemented several structural and management irrigation improvements that are detailed in the next section. These changes offered a unique opportunity to assess its impact on off-site salt pollution by comparing the historical (80's and 90's decades, before modernization) and actual (00's decade, after modernization) water and salt balances performed in the District.

The VID water balances and irrigation performances were presented by Quilez (1985) for the 80's (1982-1984 hydrological years), and by Barros et al. (2011a,b) for the 90's (1995-1998 hydrological years) and 00's (2005-2008 hydrological years) decades. In the current article, we updated and compared the historical salt balances obtained in the 80's and 90's (Faci et al., 1985; Quilez, 1985; Aragüés et al., 1990; Isidoro, 1999) with the new salt balances obtained in the 00's. Further, based on the historical and new information on hydrology, irrigation management and salt balances in VID, we related the Total Dissolved Solids (TDS) and loads in the VID irrigation return flows with the changes in irrigation performance and infrastructures that took place during these decades. In a parallel article (Barros et al., 2012), a similar approach is taken for the assessment of N off-site pollution.

The objectives of our work are (1) to update the historical salt balances performed in VID in the 1980's and 1990's and compare them with the new salt balances carried out in the 2000's, and (2) to relate the IRF salt concentrations and loads with changes in irrigation infrastructures and irrigation performance that have occurred in VID during these decades.

2. Materials and methods

2.1. Summary description of La Violada irrigation district

VID is located in the lower reaches of La Violada Gully watershed (north-east Spain; latitude: 41°59' – 42°04' N; longitude: 0°32' – 0°40' W) and is underlain by a Tertiary impervious clay layer that prevents deep percolation, so that all or most of the return flows are intercepted by the gully which is the single drainage outlet for the district. VID is mostly surrounded by dry land and is delimited by three lined irrigation canals forming a closed hydrological system very adequate to perform mass balances (Faci et al., 1985; Aragüés et al., 1990; Isidoro et al., 2006; Barros et al., 2011a) (Fig. 1).

VID occupies an area of 5282 ha and has about 4000 ha of irrigable land, 94% of it flood irrigated until 2008, when transformation works into solid set sprinkler systems started. The climate is Mediterranean, dry, subhumid and mesothermic, with precipitations concentrated in spring and autumn. Mean annual values for the period 1986-2008 were 438 mm (precipitation), 13.8 °C (air temperature) and 1166 mm (Penman-Monteith reference evapotranspiration, ET_0). The soils in the northeast VID are shallow, coarse-textured, stony and low (< 50 mm) in water retention capacity. The soils in the valley fills are deeper, stone-free and with higher (up to 100 mm) water retention capacity. The soil profiles are generally composed of alternating layers of marl, dolomitic limestone (average content = 30%) and gypsum (average content = 3.6%), and the subsurface drainage waters flowing towards La Violada Gully are at or close to gypsum and calcite saturation (Isidoro et al., 2006). A dense, open-ditch drainage network was implemented since the 1940's following waterlogging problems after the start of irrigation.

Besides the irrigation transformation works started in 2008, some structural and management improvements have taken place in VID during the last decade: (i) Construction of the elevated La Violada Irrigation Canal that replaced the old Canal seriously affected by seepage losses. The new Canal entered in service just before the 2003 irrigation season, reducing or eliminating its seepage losses; (ii) Intense reuse of drainage waters for irrigation in the water-scarce 1999, 2005 and 2006 years; (iii) Better control of tail-waters from irrigation ditches due to new rules enforced by Confederación Hidrográfica del Ebro (CHE); and (iv) Construction of five internal reservoirs that allowed for a better irrigation performance. All these factors affected the hydrologic regime in VID and the volume, salt concentrations and loads in their return flows, providing for a unique opportunity to asses the impact of these changes on VID off-site salt pollution.

2.2. Irrigation and outflow water quality characterization

Irrigation water samples were collected manually in the 80's, 90's and 00's periods every 20-24 days in the Monegros Canal (CMO, Fig. 1) for analysis of electrical conductivity (EC) and major ions. Daily outflow water samples were collected with an ISCO 6712C automatic sampler installed at the drainage outlet of VID (D-14 monitoring station in La Violada Gully) (Fig. 1). Additional samples were taken at D-14 every 20-24 days for analysis of major ions. The EC was measured using an Orion 5 Star conductivity meter, and ion concentrations were measured using a Bran+Luebbe AA3 autoanalyzer, except alkalinity that was analyzed by potentiometric titration. The saturation index (SI) for calcite and gypsum minerals was calculated from these analysis using the WATEQ4F program (Hounslow, 1995), to determine the degree of saturation in these mineral of irrigation and outflow waters (Truesdell and Jones, 1974).

The charge balance error (%), given as 200 · (∑Cations – ∑Anions) /(∑Cations + ∑Anions) in meq/L, was used to verify the quality of the analyses. Samples with errors higher than 10% were discarded due to potential analytical errors. Table 1 shows the final number of samples (*n*) selected in each decade to characterize the chemical composition of irrigation and outflow waters.

An analysis of variance was performed on the results of the chemical analyses (mean EC and ion concentrations in each decade) using the Duncan's multiple-range test to establish significant differences between periods.

2.3. Water and salt balances: main inputs and outputs

The mean water inputs (irrigation I, precipitation P, other inputs OI (the sum of canal releases CR, surface runoff SR and municipal waste waters MW), and canal seepages CS) and outputs (outflow Q) in VID for the hydrological years (HY: 1 October to 30 September) and irrigation seasons (IS: 1 April to 30 September) of each decade are summarized in Tables 2 and 3, respectively. Crop evapotranspiration was not included in Table 3 because this water output is free of salts.

The irrigation season ICUC (Irrigation Consumptive Use Coefficient or percent ratio of the volume of irrigation water consumptively used to the irrigation water available for the consumption of crops) was calculated in the 90's and 00' (required data not available in the 80's) as an expression of irrigation performance (i.e., an ICUC of 100% would be the maximum irrigation efficiency). The irrigation season DRF (Drainage Fraction or percent ratio of the volume of IRF to the total water (I+P) delivered to the system) was also calculated in the three decades. Details of these ICUC and DRF calculations were given in Barros et al. (2011b).

We assumed equal salt concentrations in irrigation water (TDS_I), canal releases (TDS_{CR}) and canal seepages (TDS_{CS}), and were determined from the average Monegros Canal EC in each decade and the linear regression equation between EC and TDS established by Isidoro (1999). Salt concentrations in precipitation (TDS_P), surface runoff (TDS_{SR}) and municipal waste waters (TDS_{MW}) were obtained from its average EC values measured in a set of samples in each decade and the accepted conversion factor of 640 (mg/L) · $(dS/m)^{-1}$ for waters with EC values lower than 5 dS/m (Rhoades, 1999). Salt concentrations in other inputs (TDS_{OI}) were calculated as the volume-weighted TDS values of CR, SR and MW. Table 2 summarizes the I, P, OI and CS mean TDS values for the HY and IS of the 80's, 90's and 00's decades.

Daily salt concentrations in outflow waters (TDS_i) were determined from the daily EC_i values measured at D-14 and the linear regression equation developed between EC and TDS [TDS (mg/L) = - 441 + 1150 · EC (dS/m); R^2 = 0.92; n = 72)]. The monthly (m), hydrological year (HY) and irrigation season (IS) flow-weighed average salt concentrations (TDS_Q) were calculated as:

$$TDS_Q = \frac{\sum_{m,HY,IS} TDS_i \cdot Q_i}{\sum_{m,HY,IS} Q_i} \qquad (1)$$

where Q_i is the mean daily flow (m^3/s) at D-14 provided by Confederación Hidrográfica del Ebro (CHE). Table 3 summarizes the mean TDS_Q for the HY and IS of the 80's, 90's and 00' decades.

For a given period, the salt load (SL) in each water input and output was obtained as the product of its salt concentration (TDS), its volume per unit irrigated area (V), the irrigated area (S), and the appropriate conversion factor:

$$SL\ (Mg) = TDS\ (mg/L) \cdot V\ (mm) \cdot S\ (ha) \cdot 10^{-5} \qquad (2)$$

where the irrigated areas were facilitated by the Almudévar Water User Association (CRA).

For comparison purposes among the study years and to take into account differences in irrigated acreage, these salt loads were also given in terms of salt yields (L) (i.e., salt loads per unit irrigated ha). The mean SL and L values for the HY and IS of each decade are given in Tables 2 (inputs) and 3 (outputs).

The outflow (Q) measured in La Violada Gully D-14 monitoring station results from the sum of the IRF originated in VID (drainage flows plus canal seepage flows) and the OI components. Since one aim of this work is to assess salt concentrations and loads in the IRF, the volume of IRF originated in VID (Q*) was obtained as Q* = Q – OI (Barros et al., 2011), and the corresponding salt concentrations (TDS_{Q*}) were calculated as:

$$TDS_{Q^*} = \frac{TDS_Q \cdot Q - TDS_{OI} \cdot OI}{Q - OI} \quad (3)$$

Based on the Q* and TDS_{Q^*} values, the corresponding mean salt load (SL_{Q^*}) and salt yield (L_{Q^*}) values in the IRF of VID were calculated for the HY and IS of each decade (Table 3).

After calculation of salt yields in the input and output waters, the salt balance (SB = inputs - outputs) equation shown in Table 3 allows to assess if salts are being accumulated (SB > 0) or leached (SB < 0) in VID in a given period assuming steady-state conditions.

2.4. Salt Pollution Indices

Two salt pollution indices were calculated to assess the impact of changes in irrigation infrastructures and irrigation performance on salt concentrations and loads in the IRF of VID during the three studied decades:

(1) The salt balance index (SBI) defined by Wilcox (1963) that allows to identify if there is a net salt export (SBI > 1), an equilibrium between exported and imported salts (SBI ~ 1), or a net salt accumulation (SBI < 1) in VID. The SBI was calculated for each irrigation season as the ratio of salt loads in IRF (SL_{Q^*}) to salt loads in irrigation (SL_I), precipitation (SL_P) and canal seepages (SL_{CS}).

(2) The irrigation water concentration factor (CF) that allows to identify the relative increase in salt concentrations in the IRF (TDS_{Q^*}) over those in irrigation waters (TDS_I) due to the coupled evapoconcentration and mineral dissolution effects.

Besides these two pollution indices, salt yields in total outflows (L_Q) and in IRF (L_{Q^*}) were also taken as salt pollution index for comparison purposes among study areas and study years with different irrigated areas. As indicated in the introduction section, salt yield is the critical parameter to evaluate salt pollution load and its impact on the salinity of the receiving water bodies.

3. Results and discussion

3.1. Water balances and irrigation management

A short summary is given first on crop distributions, irrigation management and water balances in VID during the three study decades to facilitate the interpretation of subsequent results. Further details are given in Barros et al. (2011a,b).

The total irrigated area in VID was similar in the 80's and 90's, and decreased by about 15% in the 00' (Table 2). In the 80's the most important crops were winter cereals (close to 60% of the irrigated area) followed by alfalfa and corn, in the 90's the corn acreage increased to 50% at the expense of winter cereals, and in the 00's alfalfa and winter cereals increased to 38% and 30%, respectively, at the expense of corn (Barros et al., 2011b).

The annual average volumes of irrigation water (I) were similar in the 80's and 90's (about 1000 mm) and halved in the 00's (550 mm) (Table 2) due to water shortages in 2005 and 2006, a shift from high (corn and alfalfa) to low (winter grains) water-demanding crops, and higher ICUC values. Accordingly, the annual average outflow volumes (Q) were also quite similar in the 80's and 90's (about 1000 mm) and halved in the 00's (520 mm) (Table 3) due to lower inputs of water, an intensification of drainage water reuse in some water-shortage years and, in particular a drastic decrease in canal seepages from irrigation season values of about 200 mm in the 80's and 90's to only 77 mm in the 00's (Table 2).

Monthly irrigation depths (I) during the year followed a similar pattern: low values outside the irrigation season that increased during irrigation to maximum values in July and August, when crop water needs were highest (Fig. 2a). The only exception was May, with lower depths than April in the 80's and 90's because corn is heavily irrigated in April to promote its emergence and is only slightly irrigated in May because it takes the water stored in the previous month. Fig. 2a also shows that the monthly I values in the IS of the 00's were much lower than in the other two decades for reasons given above. The relatively low standard deviations show that the monthly depths were quite similar among years of a given decade.

Monthly outflow depths (Q) generally resembled monthly I in the IS (Fig. 2b), when other inflows except CS were relatively minor. In contrast, monthly Q values where higher and more variable than monthly I values in the NIS because other inflows as surface runoff and canal releases were more important than in the IS. It is also noticed that the month-to month changes in Q during the IS were less variable than those in I, showing the buffer effect of the soil and the aquifer.

Higher irrigation efficiencies were found in the 00's (average ICUC = 59%) than in the 90's (average ICUC = 47%), whereas drainage fractions where lowest in the 00's (DRF = 50%), intermediate in the 80's (DRF = 58%) and highest in the 90's (DRF = 72%). However, these results do not necessary indicate a better water management in the 00's because crops were subject to a severe water deficit in this decade (Barros et al, 2011b). As previously indicated, ICUC in the 80's was not calculated due to the lack of ET_a estimates.

3.2. Irrigation and outflow water quality characterization

3.2.1. Irrigation water quality

The mean EC (0.37 ± 0.05 dS/m; average ± standard deviation) and SAR [0.43 ± 0.14 $(mmol/l)^{0.5}$] values for the three decades were very low indicating its excellent quality from the point of view of crop production. In contrast, this low EC might impair soil crusting and infiltration and crop's emergence problems in soils susceptible to clay dispersion (Ayers and Westcot, 1985).

Even though EC was very low, it increased significantly ($P < 0.001$) during the three decades (Table 1). A minimum EC of 0.29 dS/m was found in the IS of 1982 and a maximum of 0.50 dS/m in the IS of 2008. These EC increases were attributed to land use changes in the upper ranges of the Gállego River (from which the irrigation waters are diverted), where formerly cropped areas are being replaced by natural vegetation which uses more water leading to less runoff and higher salinity in the water courses. The SAR also increased by 39% during the study period (although this increase was not significant), but the values remained very low and without negative effects on crops and soils.

The main ions were Ca^{2+} and HCO_3^-, and the waters were saturated in calcite but not in gypsum (Table 1). SO_4^{2-} was the only ion showing significant differences ($P < 0.05$) between the 80's (average of 0.65 meq/L) and the other two periods (average of 0.83 meq/L). Although not significantly different, higher concentrations were found for the other ions (except Mg^{2+}) in the 00's than in the other decades.

3.2.2. Outflow water quality

The mean EC for the three decades was 2.14 dS/m (CV = 12%) and quite similar for the NIS (2.03 dS/m, CV = 11%) and the IS (2.09 dS/m, CV = 12%). The highest daily EC value measured during the study period was 3.0 dS/m, and the lowest 0.62 dS/m, when the Monegros Canal was emptied for maintenance purposes through the canal gates that divert directly the water to La Violada Gully. The outflow EC values measured at La Violada Gully D-14 monitoring station were in all cases lower than the threshold level of 3.0 given by Ayers and Westcot (1985) for irrigation use. In fact, these waters have been regularly used downstream for irrigation without salinity problems. The EC-SAR combination of these outflow waters implies that they can be used for irrigation without soil infiltration problems (Ayers and Westcot, 1985).

Average EC was significantly different ($P < 0.001$) between the three decades: $EC_{80's}$ > $EC_{00's}$ > $EC_{90's}$ (Table 1). In the 80's and 90's the average EC in the NIS was significantly higher ($P < 0.001$) than in the IS (Table 1) due to a dilution effect arising from low-EC irrigation losses (canal seepages, bypass and tail waters). However, these differences were much lower than those found in other irrigation districts because they are dominated by gypsum dissolution. During the 00's (excluding 2005) the mean EC in the NIS and IS were the same (2.10 dS/m) due to the lower dilution effect following the decrease in canal seepages after 2003 (when the new elevated La Violada canal rendered in service), and the more severe control of tail-waters from irrigation ditches (Barros et al., 2011b). The 2005 IS had the highest salinity (mean EC= 2.3 dS/m; CV = 7%) because of the low irrigation volumes applied derived from severe water restrictions, and the intense reuse of drainage waters for irrigation that resulted in lower and more salt concentrated drainage volumes.

The predominant ions in outflow waters in the three decades were SO_4^{2-} and Ca^{2+} (Table 1). Even though bicarbonate concentrations were low, these waters were saturated in calcite (SI > 0) and close to gypsum saturation (SI close to zero) due to the dissolution of gypsum present in the VID soils. EC and SO_4^{2-} were significantly correlated ($P < 0.001$), pointing to the relevance of gypsum as the main salinity source in this irrigated district.

3.3. Salt balances: main inputs and outputs

3.3.1. Salt concentrations and loads in water inputs

Table 2 presents for the HY and IS of each decade the flow-weighted mean TDS and the associated salt loads (SL) and yields (L) in the VID input waters (irrigation, I; precipitation, P; other inputs, OI; and canal seepages, CS). TDS_I, TDS_{OI} and TDS_{CS} increased during the study period, whereas TDS_P was low and quite constant in the three decades. In all cases, salinity in these input waters was relatively low and without negative effects on crop yields.

The main input of salts was irrigation (SL_I), representing about 65% of total inputs in the three decades, followed by canal seepages (SL_{CS}, about 18% on total inputs in the 80's and 90's and 14 % in the 00's due to its lower CS volumes), other inputs (SL_{OI}, 9% to 13% of total inputs), and precipitation (SL_P, < 10% in the three decades). Total salt loads were similar in the 80's and 90's and almost halved in the 00's mainly due to their lower I and CS volumes. About 80% of total inputs took place in the irrigated season (Table 2), with mean salt yields in the irrigation water (L_I) of about 2 Mg/ha in the 80's and 90's and 1.2 Mg/ha in the 00's, and values below 0.5 Mg/ha in the other water inputs (Table 2).

3.3.2. Salt concentrations and loads in water outputs

Table 3 presents for the HY and IS of each decade the flow-weighted mean TDS values and the associated salt loads (SL) and yields (L) in the VID outflow waters (Q) and in the VID irrigation return flows (Q*).

3.3.2.1. Outflow waters

The mean monthly TDS_Q values were relatively steady within the 1700-2000 mg/L interval, except in the NIS of the 80's that were higher than in the other two decades (Fig. 2c). The low March and April TDS_Q values in the 80's were due to direct Monegros Canal operational releases into La Violada Gully and the corresponding salt-dilution of the gully waters in these months. The TDS_Q monthly values in the IS were almost constant (Fig. 2c) and approaching gypsum saturation (Table 1), when a high proportion of outflow waters originated from drainage of the gypsum-rich VID soils.

As typical in systems with relatively steady TDS, the monthly salt yields (L_Q) followed the monthly outflow volumes (Q) (Figs. 1b and 1d, respectively), with the highest salt yields taking place in the IS. These IS monthly L_Q values varied between 2 and 3 Mg/ha in the 80's and 90's, and decreased to values close to 1 Mg/ha in the 00's.

The annual mean TDS_Q was highest in the 80's, intermediate in the 00's and lowest in the 90's (Table 3). The 14% higher TDS_Q in the 00's than in the 90's was attributed to (i) reductions in low-EC bypass waters, canal releases and, particularly, canal seepages in the 00's, (ii) higher irrigation efficiencies and lower leaching fractions in the 00's that further evapo-concentrated the applied irrigation water and its dissolved salts, and (iii) intense reuse of drainage waters for irrigation in 2005 and 2006 that increased the salt concentrations of these return flows.

The HY mean salt loads where similar in the 80's and 90's and more than halved in the 00's (Table 3). Similar results were obtained in the IS. The HY mean salt yields were very high and similar in the 80's (19.3 Mg/ha) and 90's (19.8 Mg/ha) and decreased by 48% in the 00's (10.2 Mg/ha) due to a similar 50% Q decrease in this decade. These parallel L_Q and Q reductions were a consequence of the relatively steady and close to gypsum saturation TDS_Q values in the three decades.

3.3.2.2. Irrigation return flows

Since the contribution of the diluted OI (other inputs) flows was discounted from the total outflows (Q) to estimate the volume of the IRF (Q*), TDS in the IRF (TDS_{Q*}) were higher than the corresponding TDS_Q (Table 3). These TDS_{Q*} were still lower than gypsum solubility (2630 mg/L in distilled water; Tanji, 1969) due to preferential flows through the soil that do not equilibrate with gypsum, areas with low soil gypsum content, and the contribution of other low-EC waters not included in OI as tail waters from the flood irrigated plots, canal and secondary ditch operational losses and canal seepages.

Irrigation season TDS_{Q*} values obtained in each study year were related to the irrigation performance indicators ICUC (irrigation consumptive use coefficient) and DRF (drainage fraction). ICUC could not be calculated in the 80's because of the lack of ET_a data in this decade, and year 2008 was deleted from the regressions because it was not representative of normal irrigation practices due to the beginning of the irrigation modernization works in this year. TDS_{Q*} was linearly and positively correlated ($P < 0.01$) with ICUC and linearly and negatively correlated ($P < 0.001$) with DRF (Fig. 3). The slopes of the linear regressions indicate that TDS_{Q*} will increase by 252 mg/L per 10% increase in ICUC (i.e., an increase in ICUC from 50% to 70% will imply a 27% increase in TDS_{Q*}) and by 162 mg/L per 10% decrease in DRF (i.e., a decrease in DRF from 50% to 30% will imply a 15% decrease in TDS_{Q*}), whereas the independent terms indicate that the maximum TDS of La Violada Gully waters for base flows (i.e., ICUC = 100% and DRF = 0%) will be about 3000 mg/L. The lower TDS_{Q*} with lower ICUC were attributed to the higher proportion of low-EC waters to the total flows when irrigation efficiencies become lower, indicating a mismanagement of irrigation water. Higher ICUC and TDS_{Q*} values were achieved in the 00's (Fig. 3a) for reasons given before. The higher DRF and lower TDS_{Q*} values were achieved in the 90's, with high inputs (I, P and CS) and outputs (Q), giving rise to higher diluted-flows.

Hydrological year mean salt yields (L_{Q*}) were about 98% of total salt loads (L_Q) indicating that irrigated agriculture in VID was the main source of salts in La Violada Gully. Irrigation season mean salt yields [12.8 Mg/ha (80's), 14.2 Mg/ha (90's) and 6.9 Mg/ha (00's)] were equivalent to about 70% of salt yields in the hydrological year. The lower seasonal L_{Q*} values in the 00's than in the 80's and 90's (Fig. 5) were the result of lower I and Q* volumes due to changes in cropping patterns, severe drought and reuse of drainage waters in 2005 and 2006, construction of secondary reservoirs that resulted in higher irrigation efficiencies (ICUC), and entrance in service of the new elevated La Violada Canal in 2003 that reduced canal seepages.

The irrigation season salt yields were high and relatively constant (L_{Q*} = 14.1 Mg/ha) for ICUC values below 51%, and decreased for ICUC values above this threshold (Fig. 4a). Similarly, L_{Q*} remained constant at 14.1 Mg/ha for DRF values above 66% and decreased for DRF values below this threshold (Fig. 4b). Based on these relationships, a regression model was fitted to estimate L_{Q*} from ICUC that yielded a constant L_{Q*} for a model-estimated ICUC below 51%, and a L_{Q*} that decreased exponentially above this threshold. Similarly, a regression model was fitted to estimate L_{Q*} from DRF that yielded a constant L_{Q*} for the model-estimated DRF above 66%, and a L_{Q*} that decreased potentially below this threshold. The fitted models shown in Fig. 4, significant at $P < 0.001$, could be used to estimate seasonal salt yields in the IRF of VID (or other irrigation districts with similar characteristics) on the basis of these seasonal irrigation performance indices. Hence, target ICUC or DRF values could be set with these models on the basis of maximum salt yields compatible with the TMDL or salt load licensing approaches (Quinn, 2011).

The high salt yields found in the IRF of VID in the 80's and 90's were attributed to the combination of a poor irrigation management (average on-farm irrigation efficiency = 53%, Barros et al., 2011b) and the presence of gypsum in the soils. Hence, the best strategy to reduce VID salt loads is to decrease drainage volumes (DRF) by improving irrigation efficiency (ICUC). The irrigation modernization works taking place in VID, where irrigation systems are being changed from low-efficiency gravity to high-efficiency sprinkler systems, should reduce significantly these salt loads.

This conclusion has been supported in a flood-irrigation district of the Ebro River basin where increases in irrigation efficiencies from 53% to 73% decreased salt yields from 4.5 Mg/ha to 1.2 Mg/ha (García-Garizábal et al. 2009), and in simulation studies using the CIRFLE (Bardenas I irrigation district in the Ebro River Basin; Quílez et al., 2012) and SWAP (Voshmgir irrigation district in Northern Iran; Noory et al., 2011) models where salt loads were reduced, respectively, by 46% for drainage reductions of 60%, and by 30-49% for drainage reductions of 22-48%. High salt yields similar to those in VID during the 80's and 90's were found in the D-XI sprinkler irrigation system in the Ebro River Basin (Tedeschi et al., 2001), but unlike VID (very high IRF of about 900 mm with relatively low EC of about 2 dS/m), the high salt yields in D-XI resulted from low IRF (194 mm) with very high EC (7.5 dS/m) due to irrigation efficiencies of 85% and the presence of saline lutites in the substrate. The comparison between the VID and D-XI irrigation districts highlights the importance of irrigation management for a sound control of salt export loads from irrigated agriculture.

3.4. Salt balance (SB), salt balance index (SBI) and irrigation concentration factor (CF)

Salt balances (SB) were similar in the 80’s and 90’s, much lower (in absolute terms) in the 00’s (Table 3), and quite similar among years of a given decade (i.e., low standard deviations in Table 3). The negative SB indicate that salt outputs were much higher than salt inputs due to gypsum dissolution and leaching of dissolved salts with the VID drainage waters. Hence, between 84 and 79 % of the annual salt yields came from this geologic material. Most of the HY unbalances took place during the IS (65 % in the 80’s, 70 % in the 90’s and 67 % in the 00’s) pointing to irrigation as the mobilizing agent for salts.

Irrigation season salt balance indices (SBI) (Fig. 5) show that IRF salt yields were 3.4 (in 2005) to 6.3 (in 1984) times higher than the imported salt yields in irrigation, precipitation and canal seepages. These SBI are in the range found in other irrigation districts (6.4 in Spain, Tedeschi et al., 2001; 9.3 in Australia and 3.1 in USA, Duncan et al., 2008). Higher SBI corresponded with lower ICUC (correlation significant at $P<0.05$). In contrast, SBI and DFR were not significantly correlated ($P>0.05$), although the lowest SBI were found in years 2005 and 2006 (Fig. 5) with important reuse of drainage waters and lower DRF.

Irrigation water concentration factors (CF) varied by season. Irrigation return flows contained between 7.3 (in 1998) and 12.4 (in 1982) times more salts than the irrigation water (Fig. 5). The lower CF values were found in the 90’s (mean CF = 7.5 vs. 9.0 in the 00’s and 11.7 in the 80’s) showing the already indicated higher contribution of diluted flows (tail waters, operational losses in irrigation ditches and canal seepages) in this decade. The mean CF’s in the three decades were significantly different ($P < 0.01$). The lower CF’s in the 00’s and 90’s than in the 80’s could suggest that gypsum content is decreasing in some VID soils after almost eighty years of irrigation. If this conclusion is validated in future studies, it will be anticipated that VID off-site salt pollution will be significantly reduced in the coming years do to decreased salt sources (gypsum) coupled to higher irrigation efficiencies and lower drainage fractions in the new sprinkler-irrigated VID.

4. Conclusions

Salt yields in VID irrigation return flows were high and similar in the 80's and 90's and halved in the 00's due to relatively steady salt concentrations coupled to concomitant decreases in irrigation and outflow volumes derived from the combination of (i) a shift from high to low water-demanding crops, (ii) water shortages and intensification of drainage water reuse in 2005 and 2006, (iii) decreased canal seepages after the entrance in service of the new elevated La Violada canal in 2003, (iv) better control of tail-waters from irrigation ditches, and (v) construction of five internal reservoirs that allowed for a better irrigation performance (Barros et al., 2011a,b). The salt balances revealed that 82% of the exported salts originated from soil gypsum dissolution. In this situation, salt discharge to downstream areas mainly depends on the quantity of water used and thus on the water requirement of crops and the irrigation efficiency. Therefore, the key management strategy to minimize VID off-site salt pollution is to increase irrigation performance. The ongoing irrigation modernization in VID from low-efficient gravity to high-efficient sprinkler systems should further reduce the off-site negative salinity impacts on the receiving water bodies.

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Table 1. Chemical characterization (mean ± standard deviation) of irrigation and outflow waters in VID for the 1980's (1982-1984), 1990's (1995-1998) and 2000's (2005-2008) study periods: electrical conductivity (EC), main ions, sodium adsorption ratio (SAR) and gypsum and calcite saturation indices (SI); *n* = number of samples selected in each period.

Sample	EC	Ca^{2+}	Mg^{2+}	Na^{+}	Cl^{-}	SO_4^{2-}	HCO_3^{-}	SAR	Gypsum	Calcite	n^{c}
	dS/m				*meq/l*			*(mmol/l)*$^{0.5}$	*SI*		
Irrigation water measured in Monegros Canal (CMO)											
1980's[a]	0.32 ± 0.02	2.3 ± 0.2	0.67 ± 0.30	0.40 ± 0.04	0.48 ± 0.06	0.65 ± 0.22	2.3 ± 0.2	0.33 ± 0.21	-2.15	0.23	6
1990's[b]	0.37 ± 0.01	2.1 ± 0.3	0.73 ± 0.18	0.45 ± 0.35	0.50 ± 0.03	0.83 ± 0.06	1.9 ± 0.4	0.39 ± 0.44	-2.09	0.12	5
2000's	0.42 ± 0.04	2.5 ± 0.6	0.59 ± 0.30	0.56 ± 0.26	0.67 ± 0.02	0.83 ± 0.13	2.3 ± 0.6	0.46 ± 0.59	-2.02	0.27	16
Outflow water measured in La Violada Gully D-14 monitoring station											
1980's[a]	2.32 ± 0.44[c]	17.6 ± 3.4	9.4 ± 2.0	3.7 ± 0.8	1.8 ± 0.4	28.8 ± 6.3	1.9 ± 1.1	1.02 ± 0.16	-0.22	0.64	16
1990's[b]	1.86 ± 0.23[c]	15.4 ± 3.1	6.6 ± 1.5	1.8 ± 0.6	1.3 ± 0.4	20.2 ± 4.6	2.5 ± 1.7	0.53 ± 0.16	-0.35	0.76	67
2000's	2.25 ± 0.19[c]	16.9 ± 2.6	7.9 ± 1.6	2.4 ± 0.4	1.8 ± 0.3	22.6 ± 3.0	4.2 ± 1.1	0.67 ± 0.11	-0.30	1.00	18

[a]Data from Quílez, 1985

[b]Data from Isidoro et al, 2006

[c]EC in drainage water: n = 49 in 1980's; n = 1461 in 1990's and n = 2699 in 2000's.

Table 2. Main water and salt balance inputs in VID (mean ± standard deviation) for the hydrologic year (HY) and the irrigation season (IS) of the 1980's (1982-1984), 1990's (1995-1998) and 2000's (2005-2008) study periods: total dissolved solids (TDS); mass of salts (SL) and mass of salts per unit irrigated land (salt yield, L). The irrigated area of each period is also presented.

		1980's		1990's		2000's	
		HY	IS	HY	IS	HY[d]	IS
Irrigation	I (mm)	1045±74[a]	916±87[a]	1002±69[b]	939±45[b]	550±36[b]	492±55[b]
	TDS_I (mg/l)	190[a]		234[c]		245	
	SL_I (Mg)	7771±549[a]	6811±650[a]	8746±615	8203±418	4463±1532	3940±1258
	L_I (Mg/ha)	2.0±0.1[a]	1.7±0.2[a]	2.3±0.2	2.2±0.1	1.4±0.1	1.2±0.1
Precipitation	P (mm)	452±44[a]	221±53[a]	473±170[b]	220±100[b]	398±51[b]	223±32[b]
	TDS_P (mg/l)	54[a]		54[a]		46	
	SL_P (Mg)	955±92[a]	467±112[a]	953±345	444±203	598±213	323±70
	L_P (Mg/ha)	0.24±0.02[a]	0.12±0.03[a]	0.26±0.09	0.12±0.05	0.18±0.02	0.10±0.01
Other inputs	OI (mm)	123±81[a]	84±61[a]	89±31[b]	24±16[b]	66±22[b]	40±11[b]
	TDS_{OI} (mg/l)	262±37[a]	361±70[a]	377±63[c]	478±69[c]	418±27	402±25
	SL_{OI} (Mg)	1180±579[a]	1095±601[a]	1197±220	396±251	851±164	499±111
	L_{OI} (Mg/ha)	0.30±0.15[a]	0.28±0.15[a]	0.32±0.06	0.11±0.07	0.27±0.08	0.16±0.03
Canal seepages (CS)	CS (mm)	290±11	204±13	275±11[b]	201±9[b]	125±36[b]	77±19[b]
	TDS_{CS} (mg/l)	190[a]		234[c]		245	
	SL_{CS} (Mg)	2153±82	1513±97	2402±78	1755±70	942±54	577±14
	L_{CS} (Mg/ha)	0.55±0.02	0.39±0.02	0.64±0.03	0.47±0.02	0.31±0.09	0.18±0.05
Irrigated Area (ha)		3913[a]		3731±29[b]		3213±754[b]	

[a]Data from Quílez, 1985

[b]Data from Barros et al., 2011a

[c]Data from Isidoro et al., 2006

[d]Hydrological years 2006, 2007 and 2008

Table 3. Main water and salt balance outputs in VID (mean ± standard deviation) for the hydrologic year (HY) and the irrigation season (IS) of the 1980's (1982-1984), 1990's (1995-1998) and 2000's (2005-2008) study periods: total dissolved solids (TDS); mass of salts (SL) and mass of salts per unit irrigated land (salt yield, L). The irrigated area of each period is also presented. Salt balance (SB) = inputs-outputs.

		1980's		1990's		2000's	
		HY	IS	HY	IS	HY[e]	IS
Actual crop's evapotranspiration	ETa (mm)	670±58[a]	512±31[a]	750±24[b]	633±14[b]	601±35[b]	486±25[b]
Outflow (Q)	Q (mm)	942±139[a]	658±107[a]	1160±58[b]	828±22[b]	520±56[b]	357±86[b]
	TDS_Q (mg/l)	2055±217[a]	2003±172[a]	1708±75[c]	1723±61[c]	1953±43	2001±94
	SL_Q (Mg)	75350±3777[a]	51151±4857[a]	74030±6937	53216±299	32667±8305	22762±7611
	L_Q (Mg/ha)	19.3±0.8[a]	13.1±1.2[a]	19.8±1.8	14.3±0.2	10.2±1.1	7.1±1.5
Irrigation return flows (Q*)	Q* (mm)	819±77[a]	574±47[a]	1071±74[b]	805±14[b]	453±38[b]	317±81[b]
	TDS_{Q*} (mg/l)	2312±153[a]	2232±136[a]	1820±45	1760±40	2177±104	2213±159
	SL_{Q*} (Mg)	74170±3259	50056±4302	72833±6994	52820±364	31816±8180	22263±7522
	L_{Q*} (Mg/ha)	19.0±0.8	12.8±1.1	19.5±1.8	14.2±0.1	9.9±1.1	6.9±1.5
Salt balance ($SB = L_I + L_P + L_{OI} + L_{CS} – L_Q$)	(Mg/ha)	-16.2±0.8	-10.6±1.2	-16.3±1.9	-11.4±0.2	-8.0±1.1	-5.4±1.5
Irrigated Area (ha)		3913 [a]		3731 ± 29[b]		3213 ± 754[b]	

[a]Data from Quílez, 1985

[b]Data from Barros et al., 2011a

[c]Data from Isidoro et al., 2006

[e]Hydrological years 2006, 2007 and 2008

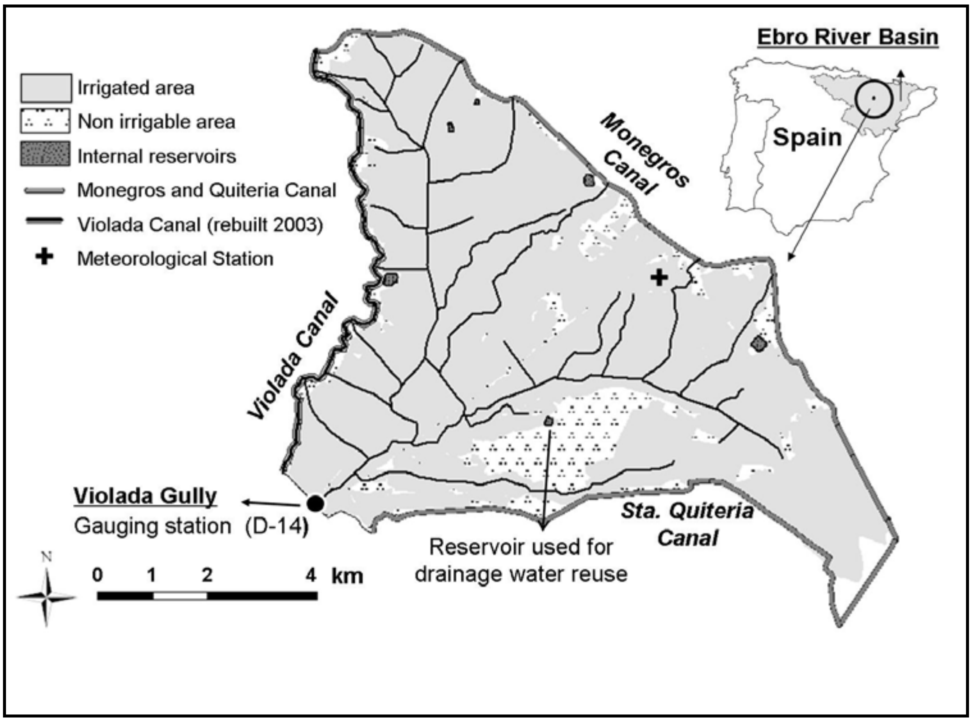

Fig. 1 – Location of La Violada Irrigation District (VID) in the middle Ebro River Basin (Spain): Violada, Monegros and Sta. Quiteria canals, drainage network, Violada Gully with the location of the D-14 gauging station, irrigated and non irrigable areas and location of the meteorological station and the reservoir used for drainage water reuse.

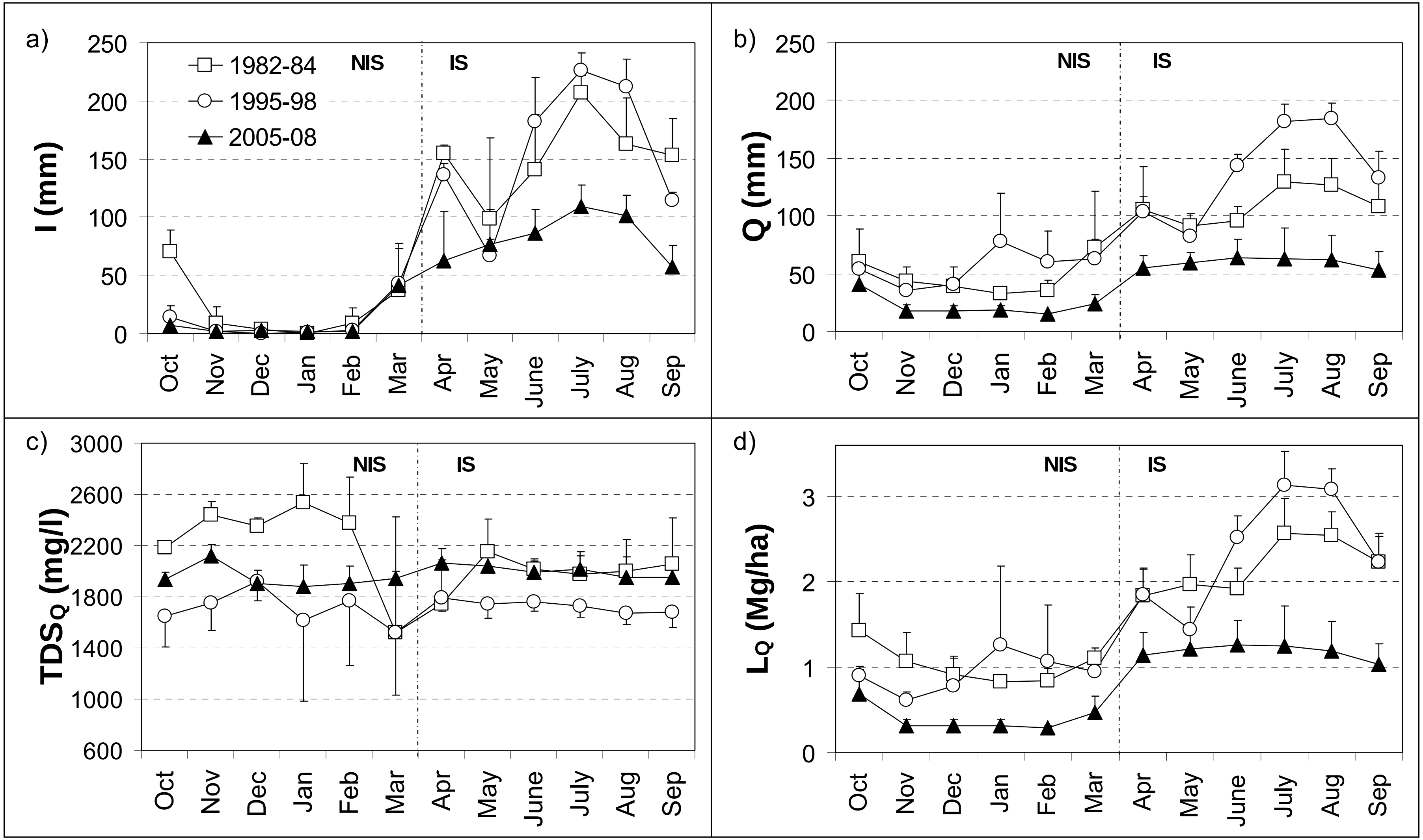

Fig. 2– Monthly averages of a) irrigation volume (I) applied in VID, and b) outflow (Q), c) flow-weighted total dissolved solids (TDS_Q), and d) salt yield (L_Q) measured at La Violada Gully D-14 monitoring station during the 1980's (1982-1984; data from Quílez, 1985), 1990's (1995-1998; I and Q data from Barros et al., 2011a; TDS_Q data from Isidoro et al., 2006) and 2000's (2005-2008; I and Q data from Barros et al., 2011a) study periods. Vertical bars represent one standard deviation of the monthly averages. NIS and IS are the non irrigation and irrigation seasons, respectively.

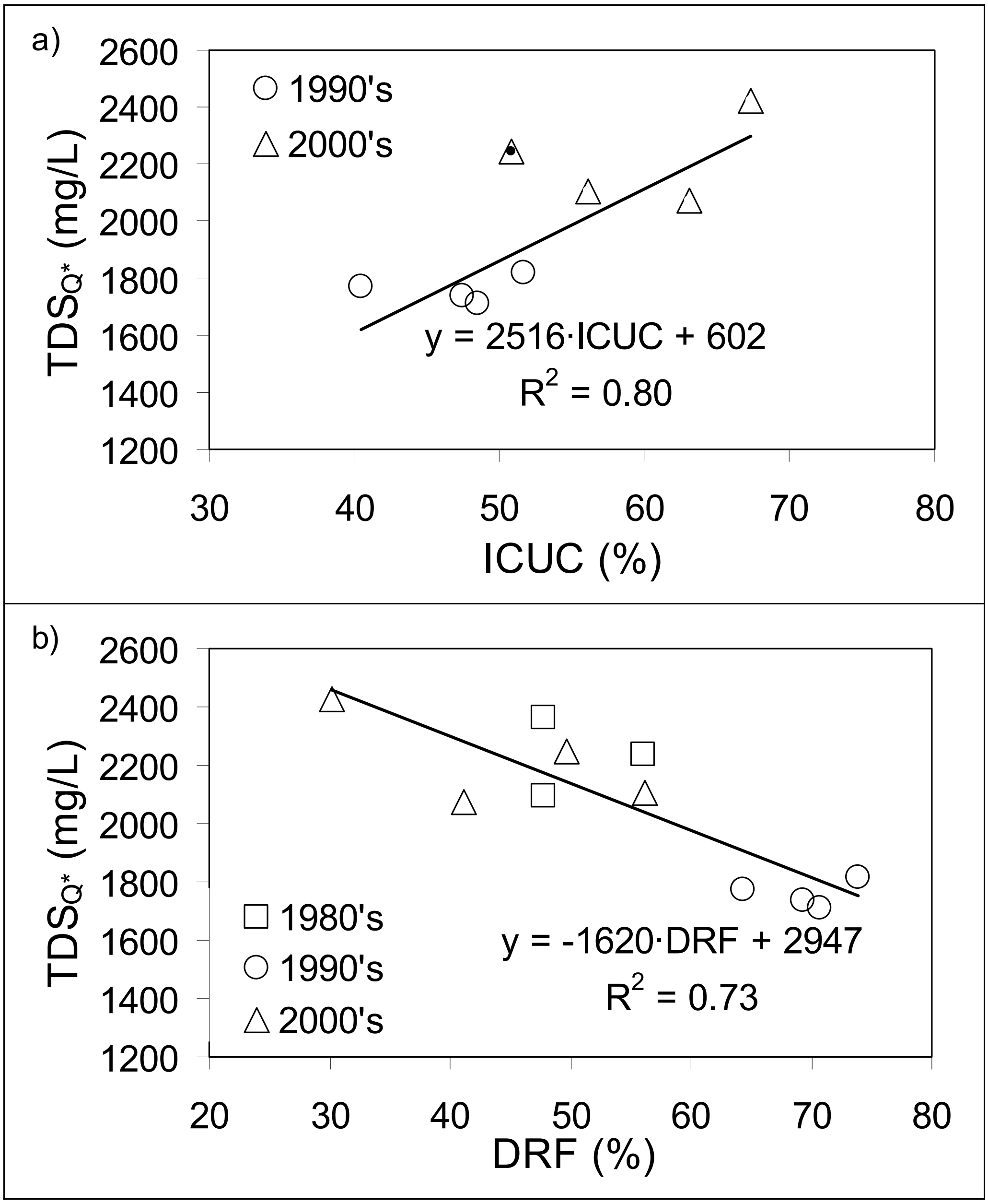

Fig. 3 – Relationships between the irrigation season flow-weighted mean TDS_{Q*} measured in the VID irrigation return flows and the irrigation performance indices a) ICUC (irrigation consumptive use coefficient) and b) DRF (drainage fraction) (data from Barros et al., 2011b) for the 1980's (1982-1984; data from Quílez, 1985), 1990's (1995-1998; data from Isidoro et al., 2006) and 2000's (2005-2008) study periods. The corresponding linear regression equations are also shown (2008 was eliminated in the regression between TDS_{Q*} and ICUC).

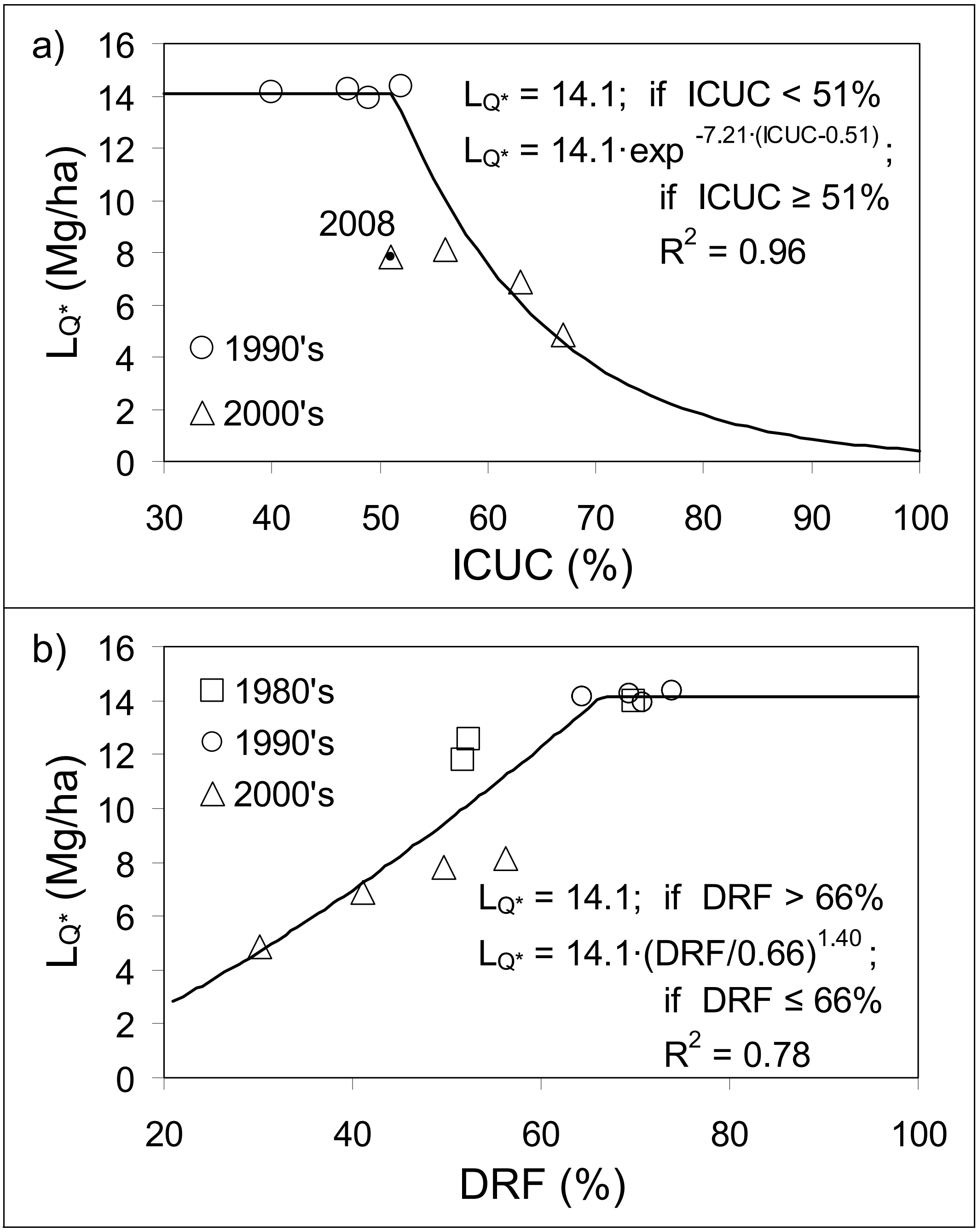

Fig. 4 – Relationships between the irrigation season salt yields (L_{Q^*}) measured in the VID irrigation return flows and the irrigation performance indices a) ICUC (irrigation consumptive use coefficient and b) DRF (drainage fraction) (data from Barros et al., 2011b) for the 1980's (1982-1984; data from Quílez, 1985), 1990's (1995-1998; data from Isidoro et al., 2006) and 2000's (2005-2008) study periods. The corresponding regression equations are also shown (2008 was eliminated in the regression between L_{Q^*} and ICUC).

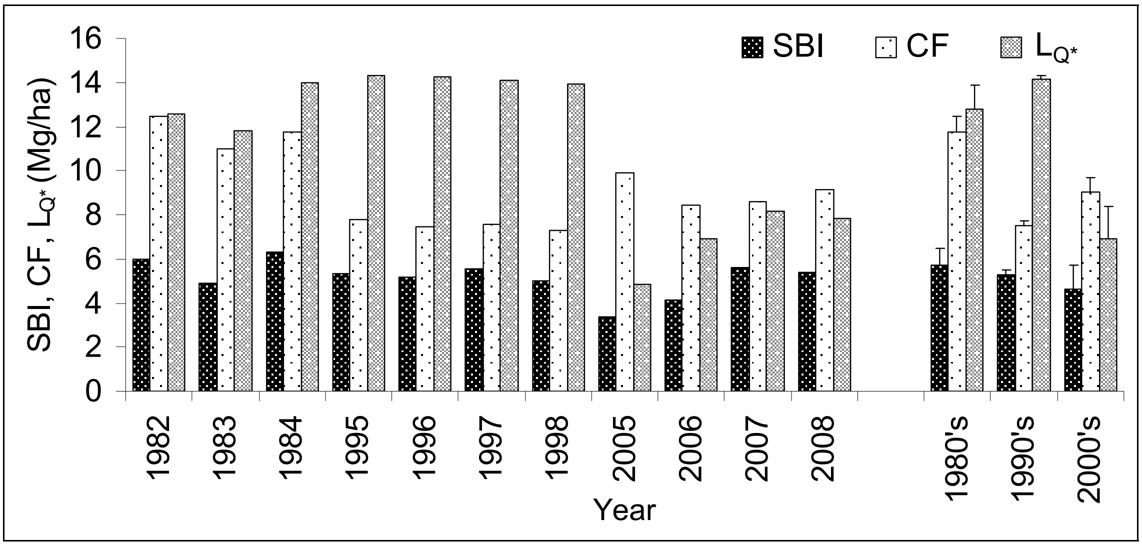

Fig. 5 – Irrigation season salt balance indices (SBI), irrigation water concentration factors (CF) and salt yields measured in the VID irrigation return flows in each study year. The average values for the 1980's (1982-1984), 1990's (1995-1998) and 2000's (2005-2008) study periods are also shown, where vertical bars represent one standard deviation.