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Assessment of irrigation and environmental quality at the hydrological basin level II. Salt and nitrate loads in irrigation return flows

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Abstract

Irrigation return flows may induce salt and nitrate pollution of receiving water bodies. The objectives of this study were to perform a salt and nitrogen mass balance at the hydrological basin level and to quantify the salt and nitrate loads exported in the drainage waters of three basins located in a 15,500 ha irrigation district of the Ebro River Basin (Spain). The main salt and nitrogen inputs and outputs were measured or estimated in these basins along the 2001 hydrological year. Groundwater inflows in the three basins and groundwater outflow in one basin were significant components of the measured mass balances. Thus, the off-site impact ascribed solely to irrigation in these basins was estimated in the soil drainage water. Salt concentrations in soil drainage were low (TDS of around 400–700 mg/l, depending on basins) due to the low TDS of irrigation water and the low presence of salts in the geologic materials, and were inversely related to the drainage fractions (DF = 37–57%). However, due to these high DF, salt loads in soil drainage were relatively high (between 3.4 and 4.7 Mg/ha), although moderate compared to other areas with more saline geological materials. Nitrate concentrations and nitrogen loads in soil drainage were highest (77 mg NO_3^-/l and 195 kg N/ha) in basin III, heavily fertilized (357 kg N/ha), with the highest percentage of corn and with shallow, low water retention flood-irrigated soils. In contrast, the lowest nitrate concentrations and nitrogen loads (21 mg NO_3^-/l and 23 kg N/ha) were found in basin II, fertilized with 203 kg N/ha and preponderant in deep, alluvial valley soils, crops with low N requirements (alfalfa and pasture), the highest non-cropped area (26% of total) and with fertigation practices in the sprinkler-irrigated fields (36% of the irrigated area). Thus, 56% of the N applied by fertilization was lost in soil drainage in

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basin III, as compared to only 16% in basin II. In summary, a low irrigation efficiency coupled to an inadequate management of nitrogen fertilization are responsible for the low-salt, high-nitrate concentrations in soil and surface drainage outflows from the studied basins. In consequence, higher irrigation efficiencies, optimized nitrogen fertilization and the reuse for irrigation of the low-salt, high-nitrate drainage waters are key management strategies for a better control of the off-site pollution from the studied irrigation district.

Keywords: Agriculture; Irrigation; Fertilization; Diffuse pollution; Salinity; Nitrate

1. Introduction

The return flows from arid and semiarid irrigated agriculture may increase salt and nitrate concentrations of the receiving water systems, limiting their agricultural, industrial, urban and ecological uses. The upper limit for salts in drinking waters has been set at EC = 2.5 dS/m (European Union, 1998), so that waters with higher salt concentrations require expensive desalting treatments. High salt concentrations in waters also affect negatively industrial processes and crop yields (Tanji and Hanson, 1990). Likewise, the upper limit for nitrates in drinking waters has been set at 50 mg/l in the EU (European Union, 1998) and at 45 mg/l in the USA (USEPA, 1990) since the intake of excessive doses of nitrates presents dangerous health effects. Also, high concentrations of nitrogen and phosphorus in surface waters are a major concern since they may cause eutrophization and hypoxia problems. Therefore, the control of salts and nitrates in irrigation return flows is of important concern since irrigated agriculture is considered the major diffuse contributor to the pollution of surface and groundwater bodies (Aragüés and Tanji, 2003).

The quantification of salt and nitrate loading in irrigation return flows is necessary to ascertain this ‘‘off-site’’ contamination, since the prediction of the resultant concentrations in a body of water after mixing with the return flows requires knowledge of the salt and nitrate masses (i.e., concentrations and flows) in each contributing body. The degree of this pollution depends on the hydrogeological characteristics of the irrigated land and substrata, the agricultural production technologies used, and the water supply and drainage conveyance systems.

Salt loading may vary widely, from values similar to those of the irrigation water to values one order of magnitude higher. Thus, typical salt loading values in irrigation return flows from arid-land irrigated agriculture vary from 2 to 20 Mg/ha/year (Aragüés and Tanji, 2003). Nitrate loading is also highly variable since it is a function of the irrigation and drainage systems, soil characteristics, crop management system, and climatic conditions. Between 50 and 90% of nitrate loading originates from agricultural activities (EEA, 1999), and typical values found in irrigation return flows may vary from 20 kg/ha year in well-managed to more than 200 kg/ha year in poorly managed irrigated systems (Cavero et al., 2003).

This work analyzes the main inputs and outputs of salts and nitrogen measured during the 2001 hydrological year in three hydrological basins located in the Bardenas no. V irrigation district (CR-V) (Aragón, Spain). The input–output water balance and the quality of irrigation in these basins were analyzed in a previous work (Causapé et al., 2004).

The aim of the present work is to relate the quantity and quality (salts and nitrates) of the irrigation return flows of these basins with their physical characteristics and the agronomic management (mainly irrigation and fertilization). The specific objectives are to (i) quantify salt and nitrate loadings, (ii) identify the principal inefficiencies in the management of the production inputs (water and nitrogen), and (iii) develop recommendations aimed at decreasing the ‘‘off-site’’ contamination from these irrigated areas.

2. Description of the study areas

The 15,500 ha CR-V irrigation district is located in the middle Ebro River Basin (Bardenas I, Aragón, Spain). The survey performed by Causapé (2002) in the CR-V district during year 2000 shows that N fertilizers were generally applied in excessive amounts. Sixty two percent of the total applied N was given to corn, which covered 29% of the district's area. Corn received on the average 43% more N than the recommended amounts; one-third was given at sowing and the rest in a single sidedress given in mid-June. Even though alfalfa fixes the atmospheric N and does not require significant amounts of nitrogen fertilizers, 11% of the total applied N was given to this crop, which covered 30% of the area. N applications in CR-V presented an absolute maximum in the first fortnight of June (50 kg/ha day in 2000) corresponding to corn sidedress, and a relative maximum in April (20 kg/ha day in 2000) corresponding to sowing of corn, sunflower, vegetables, and rice.

Three hydrological basins (I, II, and III) were selected representing the physical characteristics and agronomic management of the CR-V district. The basins are isolated from external surface runoff, but collect groundwaters flowing in the north–south direction. Due to its hydrogeological characteristics, the outlets of basins I and II collect and export all the groundwater fluxes, whereas a significant fraction of this fluxes is not intercepted and exported by the outlet of basin III. Table 1 summarizes the soils, crops and irrigation system characteristics of the three basins. A detailed description of the three studied hydrological basins was given in Causapé et al. (2004).

3. Materials and methods

3.1. Salt and nitrogen balances

The balances were performed for the 2001 hydrological year (from 1 October 2000 to 30 September 2001) considering the most important inputs and outputs of salts and nitrogen in each of the three studied basins.

The simplified salt balance was defined by:

$$\Delta SB = [SI + SP + SGI] - [SGO + SSO] \tag{1}$$

where the inputs are the mass of salts (S) in irrigation (SI), precipitation (SP), and groundwater inflows (SGI), and the outputs are the mass of salts in groundwater outflows (SGO) and surface drainage outflows (SSO). The variation of salt mass in the basin (ΔSB)

Table 1
Soils, crops, and irrigation system characteristics of the three hydrological basins studied in the 2001 hydrological year

	Basin I	Basin II	Basin III
Total area (ha)	95	149	216
Soil (% of total area)[a]	Alluvial (33); saso (67)	Alluvial (60); saso (40)	Saso (100)
Crops (% of total area)	Corn (47); alfalfa (46); other crops (2); non-cropped (5)	Corn (32); alfalfa (16); pasture (13); other crops (13); non-cropped (26)	Corn (55); alfalfa (26); winter cereals (8); other crops (9); non-cropped (2)
Irrigation system (% of irrigated area)	Flood-irrigated (100)	Flood-irrigated (61); sprinkler-irrigated (39%)	Flood-irrigated (100)

[a] Alluvial soils: relatively deep, fine-textured soils, with an average water holding capacity of 176 mm; saso soils: relatively shallow, stony soils, with an average water holding capacity of 85 mm.

during the study period was attributed to salt dissolution or precipitation since the change in the initial and final volumes of water was insignificant (Causapé et al., 2004).

The simplified nitrogen balance was defined by:

$$\Delta NB = [NI + NP + NGI + NF + NSF] - [NGO + NSO + NH] \quad (2)$$

where the inputs are the mass of nitrogen (N) in irrigation (NI), precipitation (NP), groundwater inflows (NGI), fertilizers (NF), and symbiotic fixation (NSF); and the outputs are the mass of nitrogen in groundwater outflows (NGO), surface drainage outflows (NSO), and harvested biomass (NH). Only the nitrate was considered as the soluble form of nitrogen in water. Other forms of nitrogen were not determined because they are generally negligible compared with nitrate (Prunty and Montgomery, 1991; Kengni et al., 1994). The variation of the nitrogen mass in the basin (ΔNB) during the study period include atmospheric losses (volatilization and denitrification), the N variation in the basins (soils and aquifers), and the contribution of N forms in water different than nitrate.

The salt and nitrogen loads in soil drainage were estimated as the difference between the loads in the surface drainage plus groundwater outflows minus the groundwater inflows. Salt and nitrate concentration were estimated by dividing the salt and nitrate loads by the soil drainage given by the BAS program (Causapé et al., 2004).

3.2. Inputs

3.2.1. Irrigation (I) and precipitation (P)

Twelve irrigation and 12 precipitation water samples were taken along the study period and analyzed for salt concentration (EC at 25 °C measured with an Orion-1200 conductimeter) and nitrate concentration ([NO_3^-] measured with a Dionex 2000-isp ion chromatograph). The TDS (mg/l) was obtained from the EC (dS/m) using the equation TDS = 640 EC (USSL, 1954). Given the low variability of these concentrations, the corresponding loads were calculated as the product of the average TDS times the volumes of irrigation or precipitation measured in each basin during the 2001 hydrological year.

3.2.2. Groundwater inflows (GI)

EC and [NO_3^-] in groundwater inflows (GI) of basins II and III were estimated from the corresponding contour maps of the Miralbueno Aquifer delineated from the average salt and nitrate concentrations measured every 21 days in 11 wells during the 2001 hydrological year. EC and [NO_3^-] in GI of basin I were the average values of two samples taken in a well located in the Northern border of this basin (Causapé, 2002).

Since the chemical characteristics of groundwater inflows and surface drainage waters were similar, the EC (dS/m) was converted into TDS (mg/l) using the TDS-EC equations shown later for the surface drainage waters. The salt and nitrogen loads were estimated as the product of the annual volume of groundwater inputs obtained from the water balance of the basins (Causapé et al., 2004) and the annual average salt (TDS) and nitrate ([NO_3^-]) concentrations.

3.2.3. Nitrogen fertilization (NF) and symbiotic fixation (NSF)

The N applied in the three basins during the 2001 hydrological year was obtained through farmer's surveys: doses and type of fertilizers were computed individually for each field, converted to N mass and aggregated to give the N applied in each basin. Since the N fixed symbiotically by alfalfa is quite variable, it was assumed to be similar to the amount extracted in harvesting (27.5 kg N/Mg of harvested biomass; Domínguez, 1997).

3.3. Outputs

3.3.1. Surface drainage outflows (SO)

An ISCO autosampler was installed in the gauging stations located at the outlet drainage ditches of each hydrological basin. Daily water samples were taken and analyzed for EC and $[NO_3^-]$. The TDS was measured in 44 samples by filtration and evaporation at 105 °C in order to obtain the TDS (mg/l)-EC (dS/m) equations for each basin:

$$\text{Basin I}: \quad \text{TDS} = 734\text{EC} - 102; \quad R^2 = 0.98 \quad n = 14 \tag{3}$$

$$\text{Basin II}: \quad \text{TDS} = 707\text{EC} - 53; \quad R^2 = 0.99 \quad n = 13 \tag{4}$$

$$\text{Basin III}: \quad \text{TDS} = 856\text{EC} - 118; \quad R^2 = 0.92 \quad n = 17 \tag{5}$$

The EC of all the surface drainage waters was converted into TDS using the above equations. The daily salt and nitrate loads in the surface drainage waters of each basin were calculated as the product of the average daily flow (Causapé et al., 2004) and the salt (TDS) or nitrate ($[NO_3^-]$) concentrations measured on the same day. These daily loads were integrated over the 2001 hydrological year to obtain the annual loads.

3.3.2. Groundwater outflows (GO)

As previously indicated, groundwater outflows (GO) were only relevant in basin III. The average irrigation and non-irrigation season EC and $[NO_3^-]$ of GO in basin III were estimated from the corresponding contour maps delineated for the Miralbueno Aquifer using the irrigated and non-irrigated seasons average salt and nitrate concentrations from samples collected every 21 days in 11 wells. EC was converted into TDS using the previously shown equation for basin III.

Salt and nitrogen loads in GO were obtained for the irrigated and non-irrigated seasons as the product of the corresponding volumes of GO (Causapé et al., 2004) times TDS or $[NO_3^-]$. These values were added to give the annual values for the 2001 hydrological year.

3.3.3. Nitrogen extracted in harvested biomass (NH)

The annual mass of N extracted in the harvested biomass was estimated for each crop from the corresponding yields obtained from the farmer's surveys and the unitary extractions quoted by Domínguez (1997). In those plots with pasture eaten by sheep, no N export outside the catchments was considered. Stubbles were buried and were, therefore, not considered.

4. Results and discussion

4.1. Salts

4.1.1. Inputs

4.1.1.1. Irrigation and precipitation. The average TDS was 190 mg/l (standard deviation, S.D. = 13 mg/l) in the irrigation water. Salt loadings in irrigation were similar in basins I and II and three times lower than that of basin III, due to the much higher volume of irrigation applied in this basin (Table 2). In terms of mass of salts per irrigated area, the salt loads imported into the basins with the irrigation waters were 2.6 Mg/ha (basin III), 2.1 Mg/ha (basin I), and 1.3 Mg/ha (basin II). The lowest value found in basin II was due to the higher irrigation efficiency derived from the presence of alluvial soils (60% of the total area, as compared to 33% in basin I and 0% in basin III) and the existence of sprinkler irrigation (39% of the irrigated area, as compared to 0% in basins I and III). These differential salt loads were also due to differences among basins in crop distribution and non-cropped surfaces (Table 1).

The average TDS in the precipitation water was 48 mg/l (S.D. = 32 mg/l). Due to the lower volumes and salt concentrations, salt loadings in precipitation were depending on basins, between 5 and 10 times lower then the corresponding loadings in irrigation (Table 2).

4.1.1.2. Groundwater inflows. Table 2 shows the volumes of groundwater inflows, the TDS and the corresponding salt loads imported into the three basins during the 2001 hydrological year. Seepage waters from the Bardenas Canal are likely responsible for the four times higher volumes and the almost two times lower salt concentrations of groundwater inflows in basins II and III (TDS = 343–361 mg/l, S.D. = 24–25.3 mg/l) as compared to basin I (TDS = 632 mg/l, S.D. = 0 mg/l; only two samples available). However, since these seepage waters were low in salinity, the input salt loads in basins II and III were only 2.5 times higher than the input in basin I.

4.1.2. Outputs

4.1.2.1. Groundwater outflows. As previously indicated, groundwater outflows were negligible in basins I and II. The average annual EC of groundwater outflows in basin III (0.67 dS/m) was almost 20% higher than the average annual EC of groundwater inflows, due to the progressive salt dissolution of the geologic materials (quartz, calcite, ankerite, dolomite, feldspars, and micas), in contact with the Miralbueno Aquifer. However, whereas the EC of groundwater inflows was rather constant along the 2001 hydrological year, the EC of groundwater outflows decreased during the irrigated season due to the dilution effect of the excess irrigation waters recharging the aquifer. Thus, the average irrigated season EC of ground water outflows (EC = 0.52 dS/m, S.D. = 0.15) was 37% lower than that for the non-irrigated season (EC = 0.82 dS/m, S.D. = 0.04). The annual salt load (1006 Mg) was almost two times higher than the annual salt load exported by surface drainage (Table 2).

4.1.2.2. Surface drainage outflows. EC of surface drainage waters was low to moderate, with maximum values below 1.6 dS/m in the three basins. The maximum values occurred in periods with lower flows (Fig. 1) (i.e., absence of irrigation and precipitation). The lower values of around 0.4 dS/m were close to the EC of the irrigation water (0.33 dS/m) since they originated in part from its direct spill-over into the drainage ditches.

In general, EC was lower during the irrigated season due to the dilution effect of irrigation (Fig. 1). Thus, the average values for the irrigated and non-irrigated season were 0.9 and 1.2 dS/m (basin I), 0.7 and 0.9 dS/m (basin II), and 0.5 and 0.6 dS/m (basin III). Even though salinity was lower in the irrigated season, the salt loads were 1.1–3.6 times higher (depending on basins) than in the non-irrigated season because of the increased flows during the irrigated period (Fig. 1).

The highest annual average EC was measured in basin I (1.05 dS/m) due to the dissolution of salts present in the tertiary substratum. The drainage water of basin II were also affected by the tertiary materials but its annual average salinity was lower (EC = 0.78 dS/m) due to its dilution by the Bardenas canal seepage waters. The lowest salinity was found in basin III (mean annual EC = 0.54 dS/m) due to its lower contact with the tertiary materials and the influence of the Bardenas canal seepage waters.

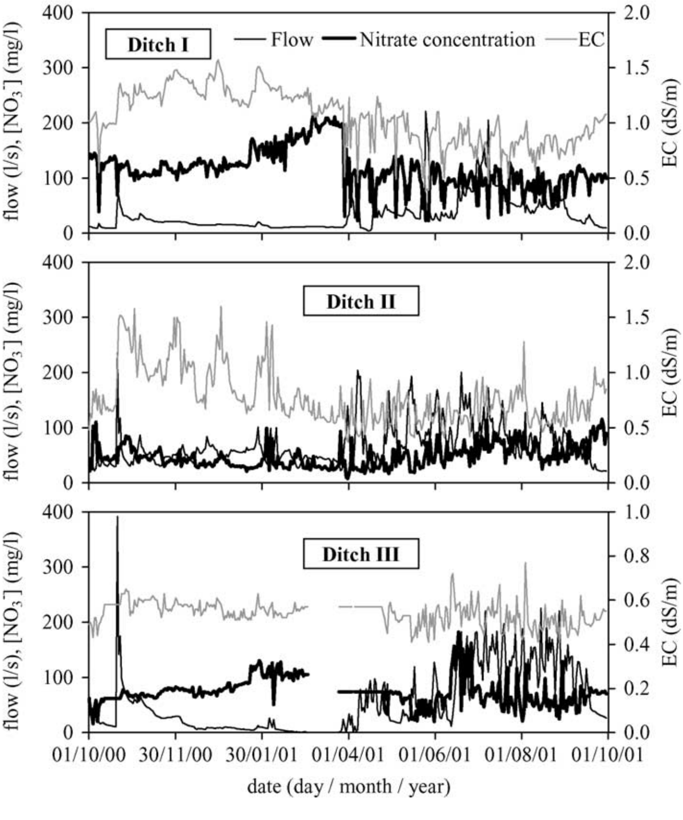

Fig. 1. Daily flow (l/s), nitrate concentration ([NO_3^-], mg/l), and electrical conductivity (EC, dS/m) in the surface drainage outflows from basins I, II, and III during the hydrological year 2001.

The annual unitary salt loads in the surface drainage waters were 6.5 Mg/ha (basin I), 6.8 Mg/ha (basin II), and 2.6 Mg/ha (basin III). The low unitary salt load of basin III was due to its low average TDS (Table 2) as well as to the fact that part of the drainage waters were not collected by the outlet ditch but were exported as groundwaters. Thus, the total annual unitary salt load (i.e., groundwater + surface drainage water) exported from basin III was 7.2 Mg/ha, slightly higher than the salt loads exported from basins I and II. However, these loads of 6.5–7.2 Mg/ha should not be solely attributed to return flows from irrigation within the basins, since a fraction of it originated from the salt loads imported with groundwater inflows.

The daily salt loads were linearly correlated with the corresponding average daily flows (Fig. 2). The high significance ($P < 0.001$) of the regression equations shown in this figure allows its use for estimating salt loads from only the daily flows. The correlations depended on soil characteristics and irrigation management of the basins. Thus, the best correlation ($R^2 = 0.95$) was found in the more homogeneous basin III (all the soils are "sasos" and all of them are flood-irrigated), an intermediate correlation ($R^2 = 0.72$) was found in basin I (flood-irrigated saso and alluvial soils), and the worst correlation ($R^2 = 0.47$) was found in the more heterogeneous basin II (different soils and irrigation systems). The observations in basin I falling below the general salt load-flow relationship were due to the spill-over of

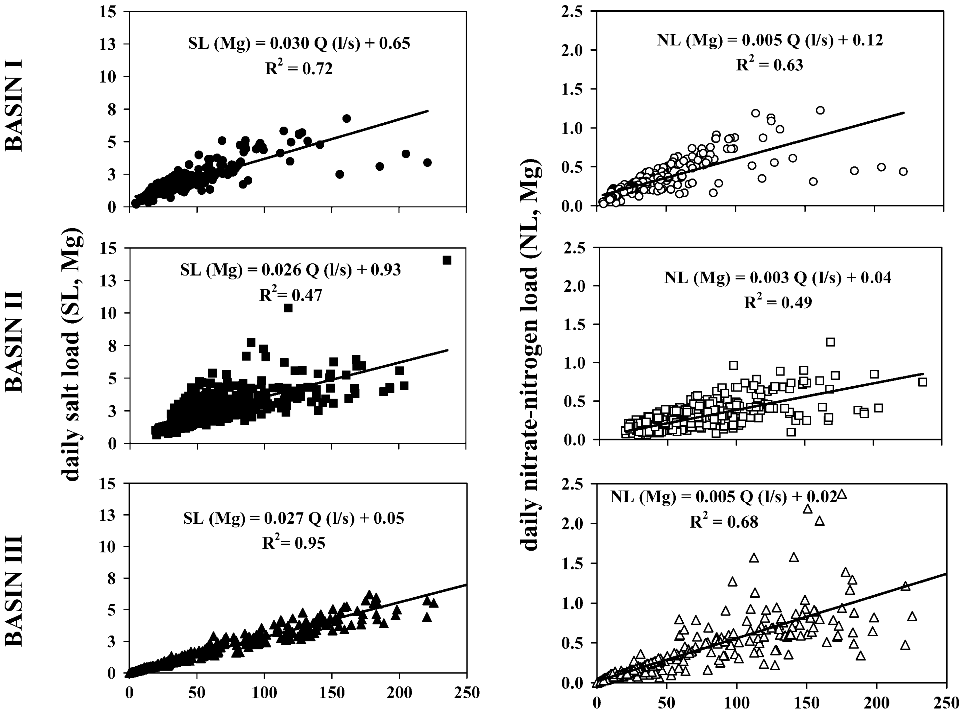

Fig. 2. Relationships and linear regression equations between daily salt (SL) and nitrate (NL) loads and average daily flows (Q) in the surface drainage outflows of basins I, II, and III during the 2001 hydrological year.

irrigation water into the drainage ditches, that increased the flows proportionally more than the salt loads.

4.1.3. Salt balance

The differences between the input and output salt loads were negative in the three basins (ΔSB in Table 2), suggesting that salt dissolution from the tertiary materials predominated over salt precipitation. In terms of mass of salts per hectare, the salt dissolution was slightly higher in basin II (1.7 Mg/ha in basin I, 1.9 Mg/ha in basin II and 1.8 Mg/ha in basin III), which is the area with the lower volume of applied water and with more saline geologic materials (Causapé et al., 2004).

Salt loads in irrigation and groundwater inflows were similar in basins I and III, whereas in basin II the salt load imported with groundwater inflows was 2.6 times higher than the salt load imported with irrigation (Table 2). Salt load in groundwater outflows accounted for 64% of the total mass of salts exported from basin III, whereas it was irrelevant in basins I and II (Table 2). These results emphasize the need for performing hydrogeological studies in order to identify the sources and sinks of water and pollutants at the hydrological basin level because, depending on the hydrogeology of the study areas, the groundwater components may be even more significant than the surface water components of the salt balance.

4.1.4. Salt loading in soil drainage

As previously indicated, salt loads measured in surface drainage waters can not be solely attributed to return flows from irrigation within the study basins. For this reason, we analyzed salt loads in soil drainage waters in order to identify the off-site impact derived exclusively from irrigated agriculture.

The highest salt concentration (TDS) in soil drainage was found in basin II, followed by basins I and III (Table 2). These estimates were consistent with the corresponding drainage fractions (DF), which were 37% (basin II), 45% (basin I), and 57% (basin III) (Causapé et al., 2004). Since the presence of salts in the soils of these basins is minor, the "weathering

Table 2
Volume of water (*V*, dam^3), average salt concentration (TDS, mg/l) and salt load (SL, Mg) in the input and output components of the salt balance and in soil drainage of hydrological basins I, II, and III for the 2001 hydrological year

	Basin I			Basin II			Basin III		
	V (dam^3)	TDS (mg/l)	SL (Mg)	*V* (dam^3)	TDS (mg/l)	SL (Mg)	*V* (dam^3)	TDS (mg/l)	SL (Mg)
Inputs									
Irrigation	1055	190	200	996	190	189	3018	190	573
Precipitation	499	48	24	784	48	38	1138	48	55
Groundwater inflows	353	632	223	1413	343	484	1531	361	553
Outputs									
Groundwater outflows	0	–	0	0	–	0	2235	450	1006
Surface drainage	1070	571	611	2150	463	995	1704	332	566
ΔSB (inputs − outputs)	–	–	−164	–	–	−284	–	–	−391
Soil drainage	717	541	388	738	693	511	2407	423	1018

effect'' was relatively unimportant as compared to the ''evapo-concentration effect'', and the salinity of drainage waters was inversely related to the drainage fraction (equivalent to the leaching fraction) (Aragüés and Tanji, 2003). In contrast, in soils high in salt minerals, TDS of drainage waters tends to be rather constant and almost independent of drainage fractions since it is controlled by mineral's solubility. Thus, in the gypsum-rich soils of La Violada district (Ebro River Basin, Spain), Aragüés et al. (1990) measured salt concentrations close to gypsum saturation that were quite constant and independent of drainage volumes.

The annual salt loads per unit area also depended basically on drainage fractions (Table 4). The highest value of 4.7 Mg/ha was found in basin III (DF = 57%), an intermediate value of 4.1 Mg/ha was found in basin I (DF = 45%) and the lowest value of 3.4 Mg/ha was found in basin II (DF = 37%). Thus, irrigation management is the critical issue for a proper control of off-site salt pollution in the study areas. Basso (1994) found a higher average salt load of 6 Mg/ha year for the Bardenas I district (where the study basins are located), but some areas in this district have higher salt contents than those in our study sites.

Our results indicate that the off-site salt pollution of the three study basins is much lower than that found in other areas with more saline geological materials (i.e., values close to 20 Mg/ha year in the gypsum-rich La Violada district of Monegros I (Aragüés et al., 1990), and 14 Mg/ha year in one hydrological basin of Monegros II, with saline lutites in the subsoil (Tedeschi et al., 2001)).

4.2. Nitrogen

4.2.1. Inputs

4.2.1.1. Irrigation and precipitation. The average [NO_3^-] measured in irrigation (1.22 mg/l, S.D. = 0.92 mg/l) and precipitation (0.55 mg/l, S.D. = 0.56 mg/l) were very low and the corresponding nitrogen loads were also low (Table 3). Thus, N inputs in irrigation and precipitation were negligible, since they supposed less than 1% of total inputs.

4.2.1.2. Groundwater inflows. Nitrate concentrations of groundwater inflows in basins II and III were fairly constant along the 2001 hydrological year (average [NO_3^-] = 60 mg/l, S.D. = 4 mg/l) and lower than in basin I (average [NO_3^-] = 164 mg/l, S.D. = 42 mg/l) (Table 3) because of the dilution arising from the Bardenas canal seepage waters. The high value of 164 mg/l in basin I is, therefore, representative of the significant N pollution of the Miraflores Aquifer derived from intensive N fertilization in the saso soils located in the Northern Miraflores Glacis.

4.2.1.3. Nitrogen fertilization and symbiotic fixation. The farmer's surveys for the 2001 hydrological year indicate that N fertilization per unit cultivated area was similar in basins I and II (average of 233 and 203 kg N/ha, respectively) and much lower than in basin III (357 kg N/ha). These values were the result of the surfaces cropped to corn in each basin (Table 1), which is the most heavily crop fertilized with N, and the different N doses applied to corn (402, 262, and 495 kg N/ha of corn in basins I, II, and III, respectively).

Table 3
Volume of water (V, dam^3), average nitrate concentration ($[NO_3^-]$, mg/l) (when applicable) and nitrate load (NL, Mg of N) in the input and output components of the N balance and in soil drainage of hydrological basins I, II, and III for the 2001 hydrological year

	Basin I			Basin II			Basin III		
	V (dam^3)	$[NO_3^-]$ (mg/l)	NL (Mg)	V (dam^3)	$[NO_3^-]$ (mg/l)	NL (Mg)	V (dam^3)	$[NO_3^-]$ (mg/l)	NL (Mg)
Inputs									
Irrigation	1055	1.22	0.291	996	1.22	0.274	3018	1.22	0.832
Precipitation	499	0.55	0.062	784	0.55	0.097	1138	0.55	0.141
Groundwater inflows	353	164	13.1	1413	60	19.1	1531	60	20.8
Fertilization	–	–	21.1	–	–	21.8	–	–	75.4
Symbiotic fixation	–	–	17.4	–	–	9.94	–	–	21.2
Outputs									
Groundwater outflows	0	–	0	0	–	0	2235	74	37.2
Surface drainage	1070	92	23.3	2150	47	22.6	1704	67	25.7
Harvested biomass	–	–	24.1	–	–	18.8	–	–	44.0
ΔNB (inputs − outputs)	–	–	4.6	–	–	9.8	–	–	11.5
Soil drainage	717	58	9.2	738	21	3.4	2407	77	42.3

Table 4
Values estimated in soil drainage of basins I, II, and III: volume (*D*), drainage fraction (DF), salt concentration (TDS), unitary salt load (USL), nitrate concentration ($[NO_3^-]$), unitary nitrogen load (UNL), UNL in percent of nitrogen fertilization (UNL_{NF}) and UNL per unit of nitrogen and water applied (irrigation + precipitation) (UNL_{NW})

Basin	*D* (mm)	DF (%)	TDS (mg/l)	USL (Mg/ha)	$[NO_3^-]$ (mg/l)	UNL (Kg/ha)	UNL_{NF} (% of NF)	UNL_{NW} (kg N/kg N mm)
I	755	45	541	4.1	58	98	44	2.6×10^{-4}
II	495	37	693	3.4	21	23	16	0.9×10^{-4}
III	1113	57	423	4.7	77	195	56	2.9×10^{-4}

The main reasons for the different N doses applied to corn were the different irrigation systems in each basin (61% flood irrigation in basin II as compared to 100% in basins I and III) and the differential percentages of the saso soils in each basin (67% in basin I, 40% in basin II, and 100% in basin III). Due to the lower irrigation efficiencies in the saso than in the alluvial soils (Causapé et al., 2004), nitrogen doses applied in the saso soils are higher to compensate for their high leaching fractions.

The end result of this differential management, coupled to the larger surface area of basin III (Table 1), is that the mass of N imported with fertilization was similar in basin I (233 kg N/cultivated ha) and basin II (203 kg N/cultivated ha) and much lower than that in basin III (347 kg N/cultivated ha) (Table 3).

N inputs by symbiotic fixation (Table 3) were estimated considering the surfaces cropped to alfalfa in each basin (43, 23, and 56 ha in basins I, II, and III, respectively) and the yields obtained in the farmer's surveys (around 14 Mg/ha).

4.2.2. Outputs

4.2.2.1. Groundwater outflows. Nitrate concentrations in groundwater outflows of basin III were almost three times lower in the irrigated (average $[NO_3^-] = 40$ mg/l) than in the non-irrigated season (average $[NO_3^-] = 110$ mg/l), mainly due to the dilution effect of the excess irrigation waters recharging the Miralbueno Aquifer.

The mass of N exported in groundwater outflows of basin III was close to 37 Mg (Table 3), almost 45% higher than the load exported with the surface drainage outflows. This result highlights the need for performing N balances at the hydrological basin scale in order to determine the different N components. Thus, Tanji et al. (1975) emphasized from a study performed in the Sacramento Valley (USA) that in areas with significant groundwater contributions, the conclusions on the quality and quantity of irrigation return flows based solely on surface flows could lead to significant misinterpretations.

4.2.2.2. Surface drainage outflows. Daily nitrate concentrations in surface drainage waters were high in general, with maximum values of 215 mg/l (basin I), 116 mg/l (basin II) and 182 mg/l (basin III) (Fig. 1). The lowest daily $[NO_3^-]$, induced by direct spill-over of irrigation or heavy precipitations, were 8 mg/l (basin II), 16 mg/l (basin III) and 23 mg/l (basin I).

The ratios between the maximum and minimum $[NO_3^-]$ were much higher than the corresponding EC ratios indicating that, besides irrigation, fertilization management played a critical role in the fate of exported nitrates by surface drainage waters. Thus, the daily [NO_3^-] behaviour was determined by irrigation, precipitation, and the available soil nitrate content. Although [NO_3^-] in surface drainage waters tended to decrease during the irrigation season due to the dilution effect of the low-nitrate irrigation waters, the first irrigations after a given application of N fertilizers provoked the partial leaching of soil nitrates and produced instantaneous nitrate's peaks in the drainage waters. Thereafter, soil nitrate contents decreased progressively due to crop's extraction and leaching induced by the successive irrigations, therefore producing a progressive decrease of drainage water [NO_3^-] until the end of the summer crops cycle. These trends are clearly shown in basin III, where corn was heavily fertilized in June. The subsequent mid-June irrigations sharply increased drainage water nitrate concentrations in that period, decreasing thereafter until the end of the irrigated season (Fig. 1).

Nitrate concentrations during the irrigated season were lower than during the non-irrigated season in basins I and III, whereas the opposite trend occurred in basin II (Fig. 1). Thus, the average [NO_3^-] in the irrigated and non-irrigated seasons were 94 and 138 mg/l (basin I), 68 and 80 mg/l (basin III), and 55 and 42 mg/l in basin II (i.e, the irrigation/non-irrigation [NO_3^-] ratios were 0.7–0.8 in basins I and III, but increased to 1.3 in basin II). This differential behaviour could be ascribed to the lower irrigation efficiencies of the flood-irrigated saso soils preponderant in basins I and III, which produced high drainage volumes of low [NO_3^-] during the irrigation season. In contrast, the alluvial soils were preponderant in basin II, and 39% of the surface was sprinkler-irrigated, so that the higher irrigation efficiencies produced lower drainage volumes of higher [NO_3^-] during the irrigation season. In the low-efficient, flood-irrigated La Violada district, nitrate concentrations were also lower in the irrigation season (Isidoro, 1999), whereas in the high-efficient, sprinkler-irrigated Monegros II district, Cavero et al. (2003) found similar nitrate concentrations in the two seasons.

The highest annual mean [NO_3^-] (92 mg/l) was measured in basin I, where only 16 days of the 2001 hydrological year had [NO_3^-] below the sanitary EU limit of 50 mg/l. The annual mean [NO_3^-] in basin III was 67 mg/l, and only 46 days had values below sanitary EU level. The lowest annual mean [NO_3^-] (47 mg/l) was measured in basin II, where 225 days had [NO_3^-] below the sanitary EU level. As for salt concentrations, the lower [NO_3^-] in basins II and III were mainly due to the dilution effect of the seepage waters from the Bardenas Canal. The higher annual mean [NO_3^-] in basin III than in basin II was attributed to higher N applications in basin III (357 kg N/ha, as compared to 203 kg N/ha in basin II).

The annual nitrate–nitrogen loads exported in the surface drainage waters were quite similar in the three basins (around 23–26 Mg N; Table 3). However, taking into account the groundwater outflows in basin III, this basin exported a total N load of 63 Mg N, which was almost three times higher than the N exported from basins I and II. The daily nitrogen loads were linearly correlated ($P < 0.001$) with the corresponding average daily flows (Fig. 2). As for salts, the dilution effect of spill-over of irrigation water on some observations of basin I is also evident in this figure. Salt loads were better correlated with flows than nitrate loads in basins I and, specially, III. The reason is that salt loads mainly depend on drainage fractions (i.e., irrigation efficiency), whereas nitrate loads also depend on the cycle of crops and on N fertilization. In contrast to the similar slopes of the regression equations found for salts, the slopes for nitrates were statistically different ($P = 0.05$) among basins (III = I > II)

(Fig. 2). The order of decreasing slopes corresponded with the order of decreasing percentages of saso soils in each basin (III > I > II; Table 1) because of the lower irrigation efficiencies and higher nitrate leaching in these shallow and low water retention soils. Thus, the improvement of irrigation and fertilization management in the saso soils is a critical issue for decreasing the off-site nitrogen pollution of the study basins.

4.2.3. Nitrogen balance

The differences between the input and output nitrogen loads were positive in the three basins (ΔNB in Table 3), indicating that the unmeasured inputs were larger than the unmeasured outputs. ΔNB represented less than 10% of the total inputs or outputs in basins I and III, whereas ΔNB in basin II represent around 22% of the total inputs or outputs.

The largest N input in the three basins was N fertilization, but N inputs in groundwater inflows and symbiotic fixation were also relevant. N outputs were similarly important in surface outflows and harvested biomass (basins I and II), whereas N exported in groundwater outflows of basin III were as important as the other N outputs (Table 3).

4.2.4. Nitrate loading in soil drainage

The off-site N pollution derived exclusively from irrigation in the basins was estimated from nitrate loads in soil drainage. The differences in the average nitrate concentrations in soil drainage among the basins were attributed to the different soils, crops and management practices in each basin (Table 1). Thus, the highest soil drainage [NO_3^-] of 77 mg/l was found in basin III, which has the highest percentage of corn and saso soils that are heavily fertilized to compensate for nitrate leaching losses. In contrast, the lowest soil drainage [NO_3^-] of 21 mg/l was found in basin II, predominant in crops (alfalfa and pasture) with low N requirements, with the highest non-cropped area and with fertigation practices in the sprinkler-irrigated fields.

The annual mean [NO_3^-] in soil drainage halved the corresponding values in the surface drainage waters of basins I and II, whereas they were similar in basin III (Table 3). Annual nitrogen loads per unit nitrogen and water applied (irrigation + precipitation) were similar in basins I and III (2.6–2.9 $\times$ 10^{-4} kg N/kg N mm) and three times higher than the value of 0.9 $\times$ 10^{-4} found in basin II (Table 4). Thus, N load in soil drainage per unit of water and fertilizer applied was considerably lower in basin II, preponderant in deep alluvial soils and with 39% of the area fertigated through sprinkling irrigation.

The annual nitrogen loads per unit total area of each basin are given in Table 4. As indicated in the introduction section, these values cover the typical interval (20–200 kg N/ha) found in properly to poorly managed irrigated agriculture. The annual unitary N load measured by Basso (1994) for the whole Bardenas I district (where the study basins are located) was 36 kg N/ha. This value is significantly lower than the drainage volume and surface weighted average value for our three basins (120 kg N/ha) because of the different soils and crops and, specially, because a considerable proportion of farmers reuse the drainage waters for irrigation, therefore, increasing the N efficiency at the irrigation district level. Isidoro (1999) measured an average [NO_3^-] of 33 mg/l and an N load of 70 kg N/ha year in the drainage outlet of La Violada district, predominant in corn and flood-irrigated with an average drainage fraction of 50%. The lower N load in La Violada than in basins I and III is explained by its lower proportion of saso soils. Finally, Cavero et al. (2003) found in the drainage outlets of two experimental basins of Monegros II (predominant in corn, 100% sprinkler-irrigated and with fertigation management) nitrate concentrations higher than 100 mg/l but low annual N loads of 18 kg N/ha (basin D-XI) and 49 kg N/ha (basin D-XI).

Since most of the N leached in soil drainage comes from fertilization, the above N loads indicate that 44% (basin I), 16% (basin II) and 56% (basin III) of the N applied by fertilization was lost in soil drainage (Table 4). These differential losses are in agreement with the proportions of saso soils that, as shown by Causapé et al. (2004) determine the drainage fractions and the applied fertilizer N in each basin (45% and 233 kg N/ha in basin I, 37% and 203 kg N/ha in basin II, and 57% and 357 kg N/ha in basin III). These results emphasize the need for improving irrigation and fertilization management in the flood-irrigated saso soils (basins I and III), where the high nitrate losses in soil drainage are unacceptable from an economic and environmental point of view.

5. Conclusions and recommendations

Salt concentrations in surface drainage waters of the three studied basins were low due to the relatively small presence of salt minerals and the low efficiency of irrigation (i.e., high drainage fraction). In contrast, the high drainage fractions provoked relatively high total annual salt loads (around 7 Mg/ha). However, since groundwater inflows were important in the three basins, the off-site salt pollution exclusively derived from irrigated agriculture within the basins was estimated from an analysis of soil drainage. Annual salt loads in soil drainage were relatively small (between 4.7 and 3.4 Mg/ha, depending on basins) and directly related to their drainage fractions, indicating that irrigation management is the critical issue for the control of salt loading in the irrigation return flows of the studied basins.

Nitrate concentrations in surface drainage waters were high (annual mean $[NO_3^-]$ of 92 to 47 mg/l, depending on basins). The lowest values were found in the two basins with diluting inflows arising from water seepage of the Bardenas Canal. The total annual nitrogen loads in soil drainage were around 200 kg/ha in basin III and 100 kg/ha in basin I, but only around 25 kg/ha in basin II. (i.e., 56 and 44% of the N applied by fertilization in basins III and I, as compared to only 16% in basin II). These differential losses were due to the different proportions of the shallow, low water retention, flood-irrigated saso soils present in each basin. Due to the high drainage fractions of these soils, farmers apply very high doses of N fertilizers to compensate for the high nitrate leaching, so that these soils are the main source for the elevated off-site N pollution of basins I and III. In contrast, the low value of basin II was attributed to the relatively low proportion of saso soils and the use of fertigation with sprinkler irrigation in 36% of the irrigated area.

Based on these conclusions, the following recommendations should be followed in the CR-V district: (1) reduce bypass losses in irrigation ditches and prevent seepage losses in the Bardenas Canal, (2) improve the management of the present flood irrigation system and increase the flexibility in water delivery with internal regulation reservoirs, (3) change to pressurized systems in the saso soils were drainage losses are unavoidable in flood irrigation due to their low water retention capacity, (4) improve N fertilization practices, especially in the saso soils, by reducing the doses, using slow release fertilizers, and in particular, implementing fertigation practices in conjunction with pressurized systems, and (5) since drainage waters are low in salts and high in nitrates, promote the reuse of drainage waters for irrigation by establishing appropriate water charges and penalties.

These recommended practices will contribute to the establishment of a more efficient and profitable agricultural system (i.e., saving of irrigation water and fertilizers) while reducing the off-site water quality impacts from irrigated agriculture and, ultimately, the load of contaminants to the Ebro River.

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