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Salt and nitrate concentrations in the surface waters of the CR-V irrigation district (Bardenas I, Spain): diagnosis and prescriptions for reducing off-site contamination

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Abstract

The return flows from irrigated agriculture may increase the salt and nitrate concentrations of the receiving water bodies, limiting their agricultural, industrial, urban and ecological uses. The objectives of this study are (i) to analyze the sources and levels of salt and nitrate concentrations in the surface waters of the irrigation district n° V of Bardenas I (CR-V), and (ii) to prescribe management practices aimed at protecting the quality of water resources. The electrical conductivity (EC) and nitrate concentration ($[NO_3^-]$) were measured in water samples collected in 28 drainage ditches of CR-V and in eight points along the Riguel River (the main drainage outlet for CR-V) in 14 dates of the 1999–2000 hydrological year. Drainage waters were moderate in salts (year-average EC = 0.87 dS/m) and high in nitrates (year-average $[NO_3^-] = 55$ mg/l), and both of them increased during the non-irrigation season. The lowest EC and $[NO_3^-]$ in the Riguel River were measured at the entrance of CR-V and during the April–September irrigation season (season-average = 0.45 dS/m and 2 mg/l, respectively), and attained the highest values at the river outlet (end of CR-V) and during the October–March non-irrigation season (season-average = 1.55 dS/m and 50 mg/l, respectively). Salt loadings at the river outlet were correlated with river flows ($P < 0.001$), but nitrate loadings were independent of flows ($P > 0.05$) due to the higher nitrate variability in drainage waters. The unitary annual upper limit load emissions from CR-V were 7.2 t total dissolved salts/ha and 59 kg NO_3^--N/ha. The optimization of nitrogen fertilization, the improvement of irrigation efficiency and the internal reuse for irrigation of the low EC-high NO_3^- drainage waters are the key management strategies for decreasing salt and nitrogen load emissions from CR-V and protecting the quality of the receiving water bodies.

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

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1. Introduction

Irrigated agriculture in semiarid areas significantly contributes to crops productivity, stability and diversification. Thus, the irrigated area in Spain amounts only to 15% of the total arable land, but yields 60% of

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the final agricultural production (Fereres and Ceña, 1997). However, the return flows from irrigated agriculture are considered a major diffuse contributor to the contamination of surface and groundwater bodies. The degree of this irrigation-induced 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 (Aragüés and Tanji, 2003).

Along with the social and environmental aspects derived from the need to store and convey the water for irrigation, other important environmental impacts are the salinization and the nitrate contamination of drainage waters and their potential effects on the receiving water bodies that may restrict its agricultural, industrial, urban and ecological uses. As a consequence of this increasing 'off-site' environmental problem, water pollution standards and emerging policies regulating the discharge of irrigation return flows (IRF) are being implemented in developed countries (Tanji and Keyes, 2002). The key policies for mitigating the negative environmental impacts of irrigation are incorporated in the Water Pollution Control Act in USA (National Research Council, 1993), and the Nitrates, Habitats and Environmental Impact Assessment (Institute for European Environmental Policy, 2000), and the Water Framework directives (European Union, 2000) in EU.

The desirable upper limit for dissolved salts in drinking waters as electrical conductivity (EC) is 2.5 dS/m (European Union, 1998). Saline waters also have a negative impact on industrial processes, and crop yields are as well negatively affected due to the reduction in the osmotic potential of the soil solution, the chloride and sodium specific ion-toxicity and the interference of dissolved salts with essential plant nutrients (Ayers and Westcot, 1985). The maximum allowable concentration of nitrate ($[NO_3^-]$) in drinking waters has been set by the USEPA (1990) at 45 mg/l and by the European Community (European Union, 1998) at 50 mg/l, since intake of excessive amounts of nitrate has harmful effects on health, causing the metahemoglobinemia disease (Vigil et al., 1965). In environmental terms, the enrichment of waters with nutrients (nitrogen and phosphorus) stimulates the growth of aquatic vegetation which, when it decomposes, depletes the oxygen dissolved in the water causing eutrophication of the water bodies (Vitousek et al., 1997).

The Ebro River Basin has an irrigated area close to 800.000 ha, and more than 80% is flood irrigated. Due to the low irrigation efficiencies found in many surface irrigated districts of the Ebro Basin and elsewhere (Bouwer et al., 1990; Pang et al., 1997; Faci et al., 2000), water, salts and nitrates are lost below the crops root zone polluting the receiving water bodies. Thus, nitrate losses greater than 100 kg N/ha/year have been measured in semiarid surface irrigated areas in Spain (Cartagena et al., 1995; Moreno et al., 1996) and USA (Devitt et al., 1976; Pratt, 1984). Likewise, salt losses greater than 10 Mg/ha/year have been measured in various surface irrigated Districts of the Ebro Basin (Basso, 1994; Isidoro, 1999).

The major task concerning the viability and the long-term sustainability of irrigated agriculture is the attainment of a proper balance between agricultural productivity and protection of the environment. The objectives of this study are (i) to characterize the levels, the spatial and temporal variability and the sources of salts and nitrates in the drainage waters of an irrigation district (ii) to determine the impact of these drainage waters on the receiving river, and (iii) to identify potential management strategies aimed at protecting the quality of water resources.

2. Materials and methods

2.1. Study area

The study was conducted in the 'Comunidad de Regantes n° V' (CR-V) of the Bardenas irrigation district, representative of the flood irrigated areas of the middle Ebro River (Spain) (Fig. 1). Its climate is characterized by a low precipitation (1965–1994 annual mean = 419 mm), two humid (spring and autumn) and dry (summer and winter) seasons, and a high reference evapotranspiration (1965–1994 annual mean = 1084 mm). During the period October 1999–September 2000 (1999–2000 hydrological year) the precipitation recorded in a weather station located within the study area was 325 mm, and irrigation was 1113 mm (Fig. 2).

The CR-V has an area of 15,498 ha irrigated with the Bardenas Canal which derives from the Yesa

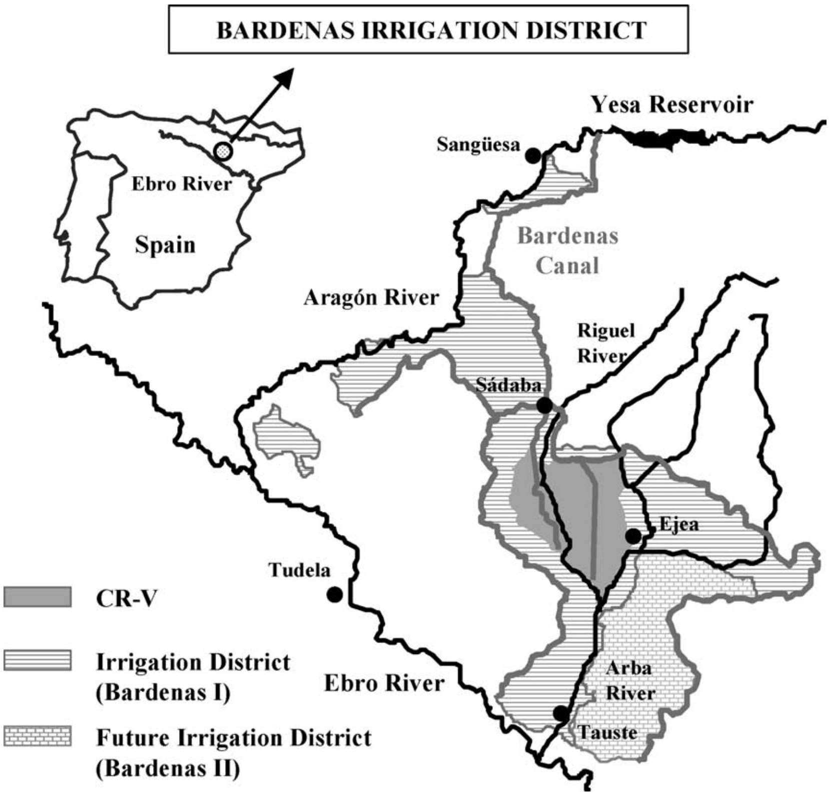

Fig. 1. Location of the CR-V study area in the Bardenas irrigation district (Spain). The main villages, rivers and the Yesa Reservoir and Bardenas Canal are also shown.

Reservoir located in the Aragón River (Fig. 1). The snowmelt irrigation water is of excellent quality ($EC = 0.32$ dS/m and $[NO_3^-] < 2$ mg/l). Seventy per cent of the soils (locally named 'sasos') lie over extensive glacis, are relatively shallow and very permeable, and have a low water retention capacity (60 mm). Several valleys penetrate into these glacis collecting and transporting the IRFs towards the Riguel and Arba rivers, which are the main drainage outlets of CR-V (Fig. 1). The water retention capacity of the relatively deep valleys soils (30% of the soils) is 182 mm.

The main crops are alfalfa (31% of the irrigated area), corn (29%), winter cereals (13%), sunflower (8%) and vegetables (6%). These crops are mainly flood-irrigated on a turn basis (irrigations around every 13 days) with high water consumptions (average of 1114 mm in year 2000) and low irrigation efficiencies (average of 58% for CR-V and 44% for the 'sasos' soils) (Lecina et al., 2001). Fig. 2 shows the daily irrigation (I) applied to CR-V during the 1999–2000 hydrological year. The applied fertilizer N was generally excessive, especially in corn where N doses were 43% higher than those recommended by the local Extension services, and its fractionation was low (one third of the N was applied at pre-planting and the rest as side-dress in June) (Causapé, 2002).

2.2. Sampling

Twenty-eight independent drainage ditches were chosen covering almost completely the CR-V area, and a sampling point was selected at or close to the outlet of each ditch (Fig. 3). Eight equidistant sampling points (P1–P8) were selected along the Riguel River; P1 was located at the entrance of the irrigated area and P8 one km upstream of the Riguel outlet to the Arba River (Fig. 3). Water samples were taken in the 36 points on a monthly basis (fortnightly in June and July, the months of greater N fertilization) during the 1999–2000

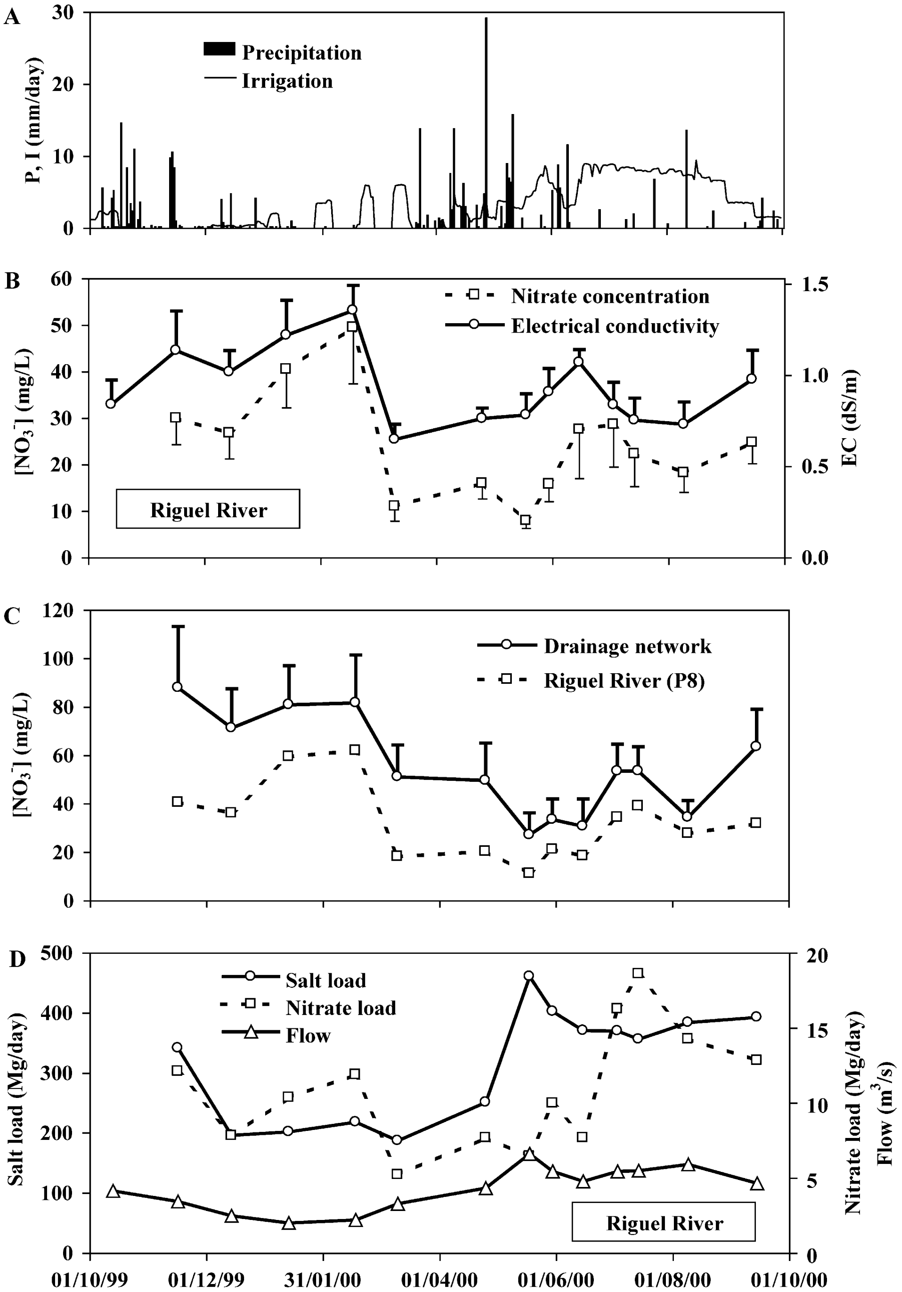

Fig. 2. Seasonal variation of (A) irrigation and precipitation, (B) average EC and nitrate concentration ($[NO_3^-]$) measured at the eight sampling points of the Riguel River, (C) average $[NO_3^-]$ measured in 28 drainage ditches of the CR-V study area and in the Riguel River at the end point (P8) of the study area, and (D) daily flow, salt and nitrate loads measured in 14 dates in the Riguel River at the end point (P8) of the study area, during the 1999–2000 hydrological year. Vertical bars indicate 0.5 standard deviation.

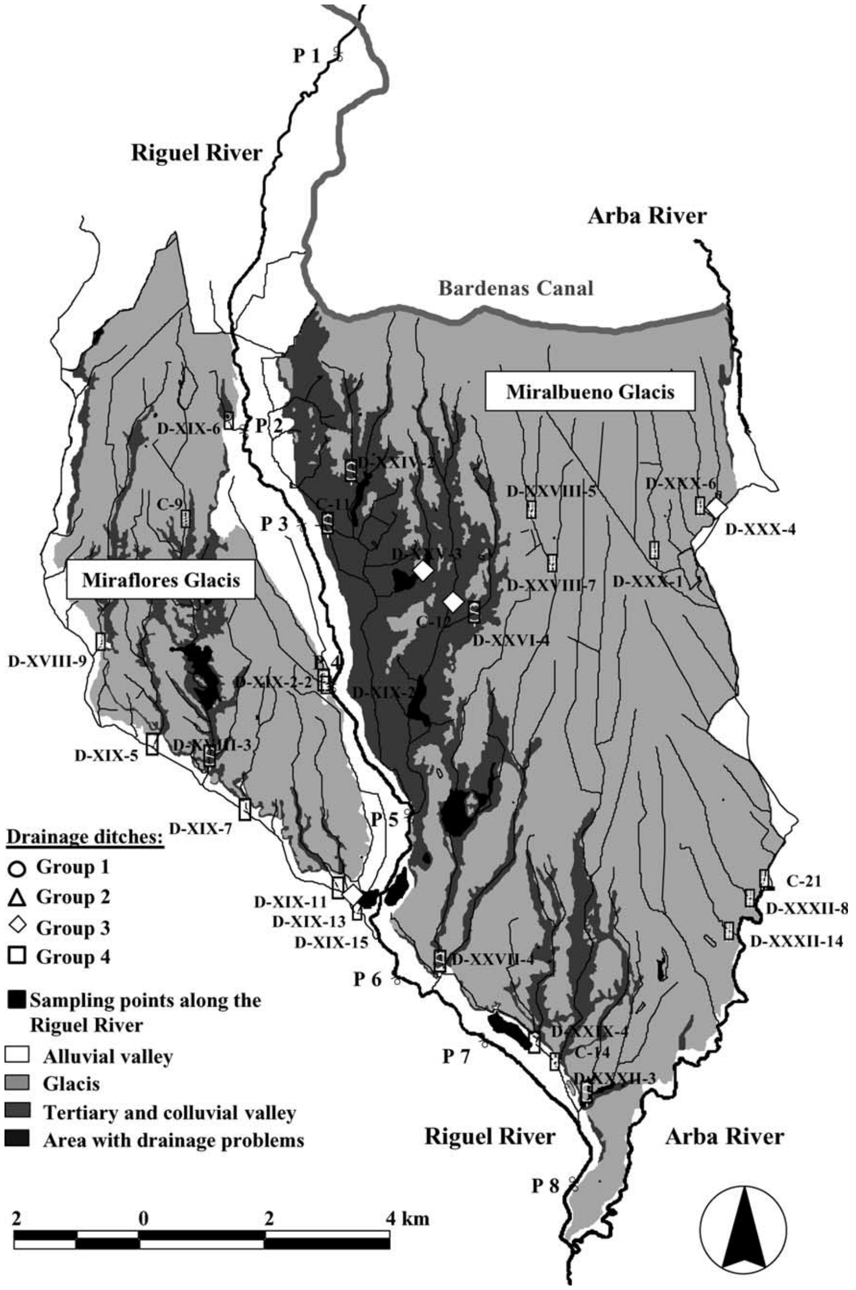

Fig. 3. Location of the eight sampling points along the Riguel River and the 28 sampling points in the drainage ditches of the CR-V study over the geomorphologic map of Basso (1994). The different symbols in the drainage ditches indicate the different groups of the cluster analysis.

hydrological year. EC (Orion-1230 conductimeter) and ([NO_3^-]) (Dionex 2000-isp ion chromatograph) were determined in all water samples except [NO_3^-] in October, which was not measured.

Farmers were surveyed for their nitrogen fertilization practices (dates and rates) during the hydrological year 2000–2001 in three hydrological basins belonging to three of the four groups identified in the Cluster analysis of drainage waters (D-XXX-1 in group 1, D-XXV-3 in group 3 and D-XIX-6 in group 4).

2.3. Data analysis

The 28 drainage ditches were classified by Cluster multivariate statistical analysis taking as variables the mean EC and [NO_3^-] measured in the water samples taken during the 1999–2000 hydrological year.

The effect of irrigation on the salt and nitrate concentrations of drainage waters were discriminated by Cluster analysis taking as variables the mean EC and [NO_3^-] of the 28 ditches measured in each sampling date and the cumulative volumes of irrigation applied in CR-V during the five-days period prior to each sampling date. This time period was considered representative of the sampling date. The irrigation volumes were provided by the Ebro River Authority (CHE). The Cluster analyses were made with the standardized data, the squared Euclid distance, and the Ward method for obtaining hierarchical conglomerates (Hair et al., 1999).

Total dissolved solids (TDS, mg/l) were estimated from the measured EC values (dS/m) using the regression equation:

$$\mathrm{TDS} = 89 + 682\mathrm{EC};\ R^2 = 0.98$$

obtained from eight samples collected in the Riguel River.

The daily salt and nitrate loads exported by the Riguel River at P8 in each sampling date were calculated, respectively, as the products of TDS and [NO_3^-] times the corresponding daily mean flows estimated at P8 (Q_{P8}). These Q_{P8} estimates were obtained from the flows measured by CHE at the Arba–Tauste gauging station (Q_{Tauste}) and the $Q_{P8}-Q_{\mathrm{Tauste}}$ regression equations developed for the irrigation (April–September) and the non-irrigation (October–March) seasons in a 3-years period (1994–1997) in which a gauging station existed at P8. These equations, significant at $P < 0.05$, are

$$\text{October–March}: Q_{P8} = 1.38 + 0.34Q_{\mathrm{Tauste}};$$

$$R^2 = 0.67$$

$$\text{April–September}: Q_{P8} = 3.30 + 0.31Q_{\mathrm{Tauste}};$$

$$R^2 = 0.59$$

where Q are daily mean flows (m^3/s).

3. Results and discussion

3.1. Fertilization practices

The monthly amounts of N applied in each of the three surveyed basins during the hydrological year 2000–2001 show that most of the N was applied in the June sidedress given to corn (Fig. 4). Nitrogen fertilization was maximum in D-XXX-1 (349 kg N/ha), largely exceeding the doses in D-XIX-6 (222 kg N/ha) and D-XXV-3 (146 kg N/ha). The highest rates of N in the three basins were given to corn, amounting to 402 kg N/ha (D-XIX-6), 262 kg N/ha (D-XXV-3), and 495 kg N/ha (D-XXX-1). The lowest amount applied in basin D-XXV-3 was split in three times by fertigation, whereas only one sidedress N was given in June in the other basins.

3.2. EC and [NO_3^-] in drainage waters

The frequency histograms of EC and [NO_3^-] measured in the 392 drainage water samples (28 sites

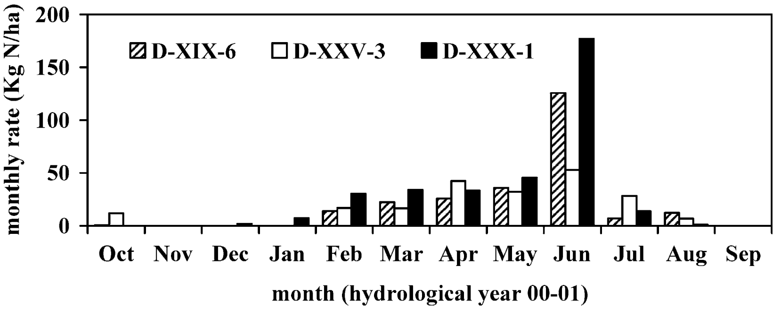

Fig. 4. Monthly rates of N applied to the crops in the three surveyed basins during the hydrological year 00–01.

and 14 dates) biased towards low EC and [NO_3^-] values due to the low salt and nitrate concentrations in the irrigation water, the predominance of highly-permeable 'saso' soils, and the sampling intensification in the irrigation season (June and July). EC and [NO_3^-] in some water samples were close to those of the Bardenas Canal, indicating that in some occasions the irrigation water was directly diverted to the drains (i.e. bypass or operational losses).

The average EC of drainage waters was moderate (0.87 dS/m) and only 25% of the samples had EC >1 dS/m (quartile-75 = 1.03 dS/m). In contrast, the average [NO_3^-] was high (55 mg/l), and 50% of the samples had [NO_3^-] >50 mg/l (median = 49 mg/l).

Nitrate concentration variability (CV = 63%) was much higher than EC variability (CV = 38%), suggesting that [NO_3^-] in drainage waters were affected by those processes affecting EC variability (as irrigation), plus other man-made processes such as the amount and timing of N fertilization (Fig. 4) and the type of crops planted (i.e. differential N uptake).

The low irrigation water EC, the low irrigation efficiencies (i.e. low evapo-concentration effect) and the prevailing non-saline 'saso' soils (i.e. low weathering effect) explain the low EC of drainage waters, as compared to other gypsiferous or salt-affected irrigated areas of the middle Ebro Basin. Thus, Isidoro (1999) found values of around 2.4 dS/m in La Violada irrigation district, characterized by its low irrigation efficiency and the presence of gypsum in the soil, and Tedeschi et al. (2001) found values higher than 10 dS/m in two hydrological Basins of Monegros II, characterized by its high irrigation efficiency and by the presence of saline lutites in the subsoil. The high drainage [NO_3^-] measured in CR-V are similar or somewhat greater than typical values found in corn-intensive irrigated areas (i.e. annual means of 38–49 mg/l, Jaynes et al., 1999; 41–70 mg/l, Bouraoui et al., 1999; 39 mg/l, Isidoro, 1999).

3.3. Cluster analysis of EC and [NO_3^-] in drainage waters

The Cluster analysis classified the 28 ditches in four EC-[NO_3^-] groups (Fig. 5). Twenty nine percent of the ditches were in group 1, characterized by low EC and high [NO_3^-] values (centroid = 0.67 dS/m and 62 mg/l) and 39% in group 2, characterized by intermediate EC and [NO_3^-] values (centroid = 0.90 dS/m and 43 mg/l). Groups 3 (14% of ditches) and 4 (18% of ditches) had opposite characteristics: lowest EC and [NO_3^-] in group 3 (centroid = 0.63 dS/m and 29 mg/l), and highest EC and [NO_3^-] in group 4 (centroid = 1.14 dS/m and 67 mg/l).

The overlapping of these groups with the geomorphologic map of Basso (1994) shows that all the ditches in group 1 (low EC, high [NO_3^-]) were located in the Miralbueno Glacis (between the Riguel and the Arba rivers; Fig. 3). Two unexpected results were the exclusion of ditch D-XXX-4 (probably due to its dilution by waters of the Ejea treatment plant) and the inclusion of ditch C-14 which in its final section drains soils developed on the tertiary substrate. The ditches in group 3 (low EC and [NO_3^-]) drain soils developed on valleys and slopes, dominated by alfalfa and pasture crops (low in nitrogen fertilization) and rice (high in surface run-off waters of low EC). Group 4 (high EC and [NO_3^-]) includes those ditches located in the Miraflores Glacis (west side of the Riguel River). Even though the soils and agronomical practices are similar in Miralbueno and Miraflores glacis, the ditches in group 1 (Miralbueno Glacis) had lower EC and [NO_3^-] than the ditches in group 4 (Miraflores Glacis). The main reason for this different behavior is that the seepage of water from the Bardenas Canal dilutes the groundwaters in the Miralbueno Glacis but not those in the Miraflores Glacis since the Riguel River acts as an interceptor drain (Fig. 6). Finally, the ditches in group 2 (intermediate EC and [NO_3^-]) drain areas with mixed characteristics.

The ditches with the highest [NO_3^-] drain the more permeable 'saso' soils cropped to corn and high in N fertilization inputs, 349 kg N/ha in D-XXX-1 (group 1) and 222 kg N/ha in D-XIX-6 (group 4). In contrast, the ditches with the lowest EC and [NO_3^-] drain the high water-retention valley soils with lower N inputs by fertilization, 146 kg N/ha in D-XXV-3 (group 3). The differences in the amount of fertilizer N applied in the three basins were directly related to the surfaces devoted to corn and the different doses applied to this crop (402 kg/ha in D-XIX-6, 262 kg/ha D-XXV-3, and 495 kg/ha in D-XXX-1). Corn N rates were directly related to the proportion of 'saso' soils in each area because farmers over-fertilize these soils trying

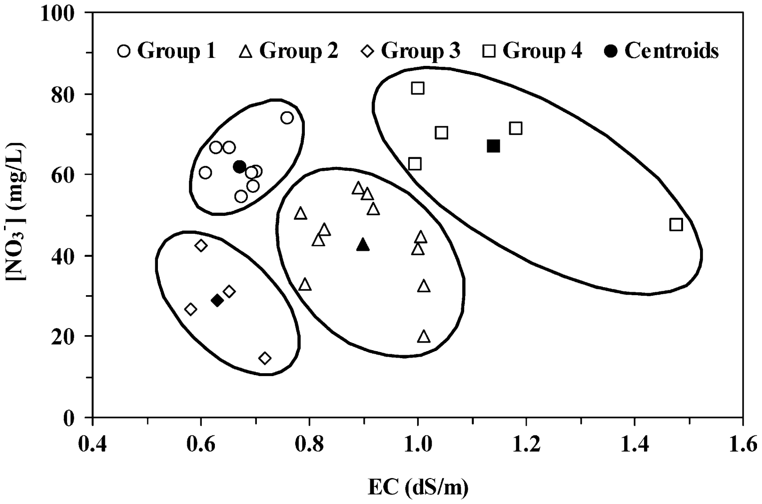

Fig. 5. Electrical conductivity (EC)-nitrate concentration ($[NO_3^-]$) binary diagram: Cluster analysis discrimination of the 28 drainage ditches sampled in CR-V. EC and ($[NO_3^-]$ are mean values of the sampling dates performed during the 1999–2000 hydrological year.

to counteract the high leaching of nitrates occurring in these low irrigation efficiency (IE = 44%) fields.

3.4. Influence of irrigation on EC and $[NO_3^-]$ of drainage waters

The two Cluster analyses performed on 'EC-volume of irrigation' and '$[NO_3^-]$-volume of irrigation' classified the sampling dates in three groups with a remarkable seasonality (Fig. 7).

The 'High-irrigation' or Summer group was characterized by high irrigation volumes, relatively low EC and moderate $[NO_3^-]$ (centroids = 40.9 mm, 0.77 dS/m and 43 mg/l), and comprised four sampling dates (30 May, 3 and 14 July and 9 August). The 15 June sampling does not belongs to this group because the volume of irrigation applied decreased due to large precipitations before this date (Fig. 2). The 'Low-irrigation' or Spring–Autumn group had similar EC and $[NO_3^-]$ than the Summer group, but much lower volumes of irrigation (centroids = 14.3 mm, 0.80 dS/m and 44 mg/l). The sampling dates of 10 March, 25 April, 18 May, 15 June, 14 September and 13 October belong to this group. Finally, the 'non-irrigation' or Winter group was characterized by the lack of irrigation and the highest EC and $[NO_3^-]$ (centroids = 0.6 mm, 1.07 dS/m and 79 mg/l), and includes the 16 November, 14 December, 13 January and 17 February sampling dates (Fig. 7).

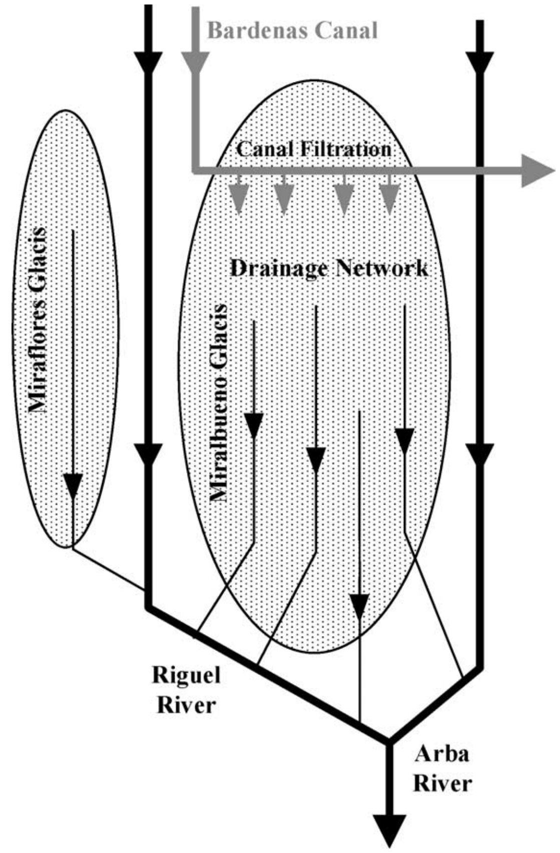

Fig. 6. Conceptual summarization of the inflow/outflow fluxes in CR-V.

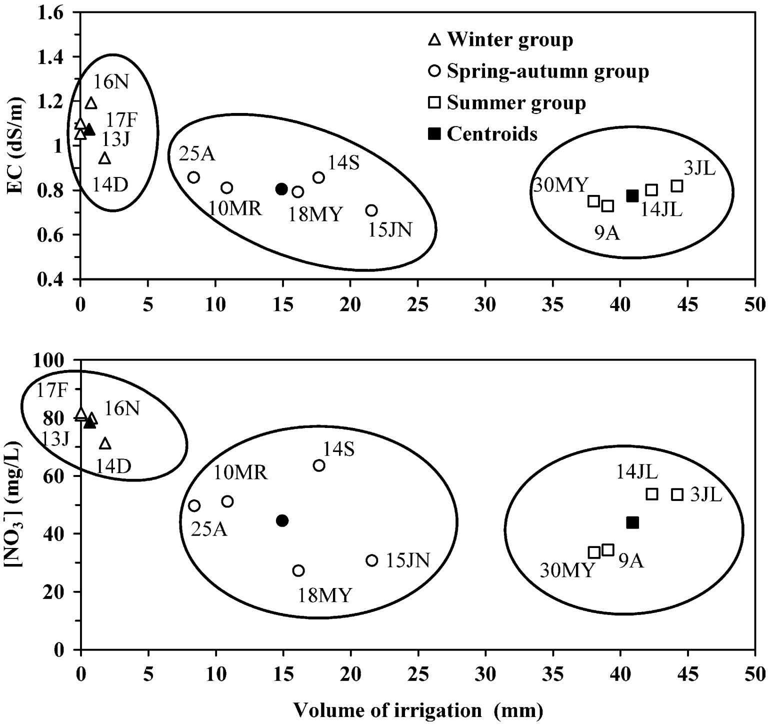

Fig. 7. Average electrical conductivity (EC) and nitrate concentration ($[NO_3^-]$) of the 28 drainage ditches sampled in 13 dates during the 1999–2000 hydrological year against the cumulative volume of irrigation diverted to the CR-V study area in the five days prior to each sampling date. Discrimination of groups by Cluster analysis and position of their centroids.

The low-irrigation group has the lowest similarity (distance > 4) due to the variability in rainfall, irrigation, and nitrogen fertilization. In contrast, the non-irrigation group has the highest $[NO_3^-]$ similarity (distance < 0.5) because of the lower rainfall variability and the absence of irrigation and nitrogen fertilization. Finally, the high-irrigation group has a higher similarity in EC (distance $= 1$) than in $[NO_3^-]$ (distance $= 2$) due to decreased soil nitrate contents as the season progressed as a result of the leaching of nitrates and N-uptake by crops.

Irrigation is a key factor in determining the level and temporal variability (seasonality) of EC and $[NO_3^-]$ in the CR-V drainage waters. The highest EC and $[NO_3^-]$ values were measured in winter (no irrigation), and the lowest in summer (period of maximum irrigation volumes) as a result of the inefficient flood-irrigation management that generates high return flows with relatively low salt and nitrate contents. This seasonality has been found also in the surface-irrigated district of La Violada in Monegros I (middle Ebro Basin, Spain) (Isidoro, 1999). In contrast, $[NO_3^-]$ were much higher (around 120 mg/l) and similar in the irrigated and non-irrigated seasons of a Monegros II sprinkler-irrigated district characterized by its high irrigation efficiency (average of 90%) (Cavero et al., 2003).

3.5. EC and $[NO_3^-]$ in the Riguel River: spatial and temporal variability

The average EC of the 112 water samples taken along the Riguel River at eight sites in 14 dates of the 1999–2000 hydrological year was relatively low (0.94 dS/m), and 64% of the samples were lower than 1 dS/m. The average $[NO_3^-]$ was 25 mg/l, its variability (CV $= 69\%$) doubled that of EC (CV $= 35\%$), and 92% of the samples were lower than 50 mg/l.

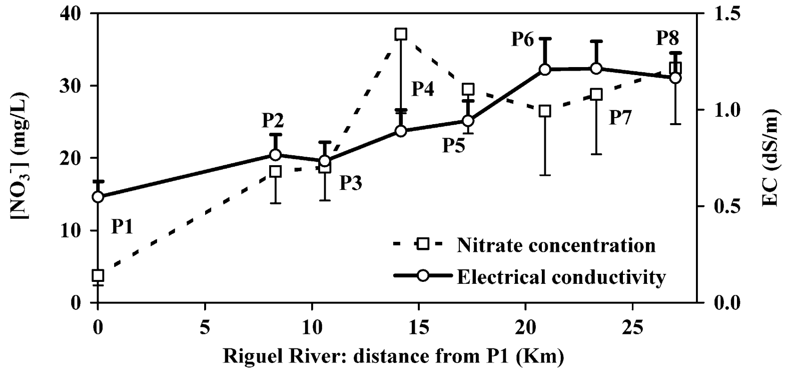

Fig. 8. Average electrical conductivity (EC) and nitrate concentration ($[NO_3^-]$) measured in 14 dates during the 1999–2000 hydrological year at the eight sampling points (P1–P8) of the Riguel River. Vertical bars indicate 0.5 standard deviation.

The average EC and $[NO_3^-]$ of the 14 sampling dates generally increased along the river, with minimum values at the entrance of CR-V (P1: 0.55 dS/m and 4 mg/l) and maximum values at the lower reaches (P8: 1.17 dS/m and 32 mg/l) (Fig. 8). The highest relative increase in $[NO_3^-]$ occurred between P1 (4 mg/l) and P2 (18 mg/l), the first sampling point within the irrigated area. The maximum $[NO_3^-]$ along the river was measured at P4 (37 mg/l). The groundwater component, high in $[NO_3^-]$, is predominant at this point because of its location behind a dam that diverts most of the river flows. Thereafter (sampling point P5), these high $[NO_3^-]$ waters were diluted by the return flows from the irrigated sasos, low in nitrates.

The highest increase in EC occurred between P5 and P6 (0.27 dS/m), and was due to the entrance among these points of the Valareña Creek. This creek has relatively high flows and salts and relatively low nitrates because it drains soils developed on tertiary materials (high in salts) and the crops planted in its watershed (rice, winter cereals, alfalfa and festuca) are low in N requirements. For this reason, $[NO_3^-]$ was slightly lower in P6 than in P5.

The average EC and $[NO_3^-]$ of the P1–P8 water samples along the 1999–2000 hydrological year tended to increase during October–February, reached their maximum values (1.36 dS/m and 50 mg/l) in 17 February, and sharply decreased in the next sampling date of 10 March due to the start of irrigation in CR-V (Fig. 2). Although, in general, the average EC and $[NO_3^-]$ of the P1–P8 water samples were parallel along the 1999–2000 hydrological year, there are two clear exceptions, evident in Fig. 2: (i) the 18 May sampling, where EC was similar to that in 25 April, whereas $[NO_3^-]$ decreased by half due to the high spring precipitation events which leached most of the nitrates present in the soil in April, and (ii) the 3 July sampling, where EC was substantially lower than the EC measured in the previous sampling (15 June) due to the start of heavy irrigations given to corn (Fig. 2), whereas $[NO_3^-]$ did not decrease due to the counter effect of sidedress N applications given to corn in the middle of June. Thus, in addition to irrigation that affects to both EC and $[NO_3^-]$, there are additional factors (N sources-sinks) that affect only to $[NO_3^-]$.

The variability of the P1–P8 average EC values measured in the different sampling dates was lower than the $[NO_3^-]$ variability (Fig. 2). The lowest EC variability was obtained in samples taken after the occurrence of some precipitation events (i.e. CV = 15% and 13% in 25 April and 15 June), reflecting the smoothing effect of precipitation on the EC variability along the river. In contrast, the highest $[NO_3^-]$ variability along the river was obtained in months of highest N fertilization (i.e. CV = 63–77% between 15 June and 14 July) due to the cumulative drainage flows, high in nitrates, reaching the river.

As expected, $[NO_3^-]$ of the Riguel waters at the exit point (P8) paralleled the average $[NO_3^-]$ of the 28 drainage ditches of CR-V along the 1999–2000 hydrological year (Fig. 2). In both systems, the maximum $[NO_3^-]$ values were measured in winter, decreasing afterwards due to the diluting effects of irrigation and spring precipitations. In the middle of June, $[NO_3^-]$ increased again due to the coupling effects of irrigation and sidedress N fertilization given to corn. Nitrate concentration in Riguel-P8 was lower than ditch-average [NO_3^-] in all sampling dates due to the diluting effect of the low-nitrate flows entering the Riguel River at P1. The differences between Riguel-P8 and ditch-average [NO_3^-] decreased considerably in the June–August irrigated months (Fig. 2), when the IRFs from CR-V are the main component of the Riguel flows.

3.6. Salt and nitrate loads exported by the Riguel River

The Riguel flow at P8 was lowest in winter and increased after March and in summer due to the IRFs from CR-V (Fig. 2). In consequence, the maximum salt and nitrate loads exported by the Riguel at P8 occurred in summer, even though the higher salt and nitrate concentrations were recorded in winter. Although water quality standards are based in maximum allowable concentrations, it should be highlighted that the quantification of salt and nitrate loads is critical to ascertain the ‘off-site’ contamination of irrigated agriculture and its final effect on the receiving water bodies (Jaynes et al., 1999; Stites and Kraft, 2001; Cavero et al., 2003; Aragüés and Tanji, 2003).

While the salt loads paralleled in general the river flows, the nitrate loads were more variable (Fig. 2) as they were also affected by N fertilization and crops N uptake (i.e. nitrate content in soils). Thus, even though the Riguel flow at P8 slightly increased in March, the nitrate load sharply decreased because most of the soil nitrates were already leached by the preceding precipitation events. In contrast, although the Riguel flows were quite constant in July, nitrate loads sharply increased due to the June sidedress N fertilization given to corn (Fig. 4).

This differential behavior of the salt and nitrate loads is illustrated by the linear regressions obtained between the P8 average daily flows and the P8 daily salt and nitrate loads, which show that flows and salt loads were significantly correlated ($P < 0.001$), whereas flows and nitrate loads were not correlated ($P > 0.05$) (Fig. 9). This lack of correlation between flow and nitrate loads is the result of the high nitrate variability in the drainage waters due to both natural (mineralization of organic matter, precipitation-induced leaching, N uptake by crops) and anthropogenic (N fertilization, irrigation-induced leaching) effects. For instance, the sample taken on 18 May had the highest flow (6.6 m^3/s) but a relatively low nitrate load (6.5 Mg/day) and concentration (11 mg/l) due to soil nitrate leaching by previous precipitation events. Even if this observation is deleted from the regression, nitrate loads and flows will be only slightly correlated ($R^2 = 0.23$, significant at $P < 0.06$), corroborating that nitrate loads were mainly related to the previously indicated source-sink N effects. This could indicate a limited stock of nitrate in soils as compared to an unlimited stock of salt minerals.

Based on the 15,498 irrigated hectares of the CR-V approximately drained by the Riguel River at P8, the annual salt (112,149 Mg) and nitrate (4045 Mg) loads correspond, respectively, to unitary annual emissions of 7.2 t salt/ha and 59 kg NO_3^--N/ha. Sixty percent (salt) and 56% (nitrogen) of the annual loads were exported during the irrigation season. Although these figures should be taken as an upper limit (the Riguel River at P8 collects also some flows from outside CR-V), they give the orders of magnitude of the annual unitary salt and nitrogen mass discharges from the CR-V irrigation district.

The annual mass of N per unit irrigated land exported by the Riguel River at P8 was 59 kg NO_3^--N/ha year, similar to the 54 kg NO_3^--N/ha year obtained by Basso (1994) in the 1991–1992 hydrological year, suggesting that during the last ten years no changes have occurred in the studied area in terms of water, fertilizer management and crops distribution. These unitary exports are similar to those found in La Violada (66 kg NO_3^--N/ha year; Isidoro, 1999) and much higher than those found in the efficient sprinkler-irrigated district of Monegros II (18 kg NO_3^--N/ha year; Cavero et al., 2003).

Whereas the highest nitrate loads exported from CR-V through the Riguel River are obtained in summer as a consequence of sidedress corn N fertilization and the hydrological regime derived from irrigation, in more humid areas nitrate leaching occurs mainly in winter, when water and N uptake by crops are minor and precipitation is high (Burt, 1988; Normand et al., 1997). The opportunity for controlling nitrate leaching and loads is therefore greater in semi-arid irrigated areas of low precipitation than in humid

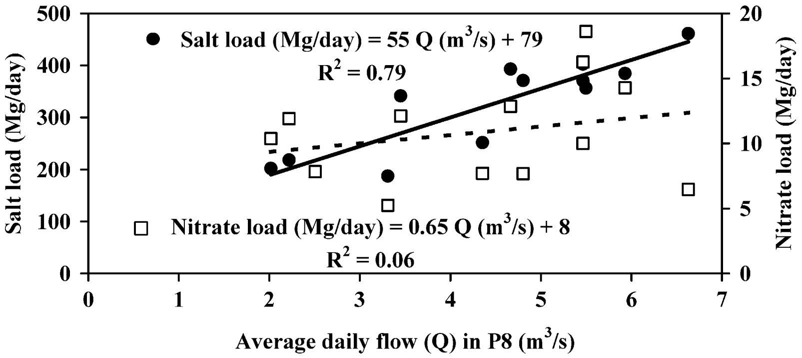

Fig. 9. Relationships and linear regression equations between average daily flow and daily salt and nitrate loads measured in the Riguel River at the end point (P8) of the CR-V study area.

areas where high precipitation is an unavoidable water source for off-site N pollution.

4. Conclusions

4.1. General conclusions

The Cluster analysis performed on the drainage water samples proved to be an appropriate technique to classify the quality (salts and nitrates) of drainage waters and to identify the most problematic areas and time periods for ‘off-site’ pollution.

Salt and nitrate concentrations and loads in the Riguel River, the main outlet for the study area, behaved differently along the 1999–2000 hydrological year. Flows and salt loads were correlated, whereas flows and nitrate loads were not correlated because of the higher nitrate variability impaired by both natural and anthropogenic reasons.

In surface irrigated areas with low irrigation efficiencies, salt and nitrate concentrations in drainage waters are lower in the irrigated than in the non-irrigated season, but salt and nitrate loads are higher in the irrigated season due to the larger drainage fractions and flows. Thus, the critical factor for a proper control of ‘off-site’ diffuse pollution is an efficient management of irrigation, coupled to a better management of N fertilization in the source-contaminating soils. An efficient irrigation and fertilizer management will significantly decrease salt and nitrogen loads in IRFs, which is the key variable for the quantification of the ‘off-site’ contamination of irrigated agriculture.

4.2. Prescriptions in the CR-V

The principal ‘off-site’ pollution problem faced by the CR-V District is nitrate losses in drainage waters that contaminate the Riguel and, ultimately, the Ebro River. A key management strategy for mitigating this pollution is the optimization of N fertilization, coupled to an improvement in irrigation efficiencies and uniformities. The results obtained in three experimental basins show that fertilizer N could be drastically decreased according to corn needs (from values higher than 400 to values of around 260 kg N/ha) without affecting yields. Also, splitting of N applications will help in reducing nitrate losses, especially in the corn-growing ‘saso’ soils, since the single sidedress N fertilization given to corn in June provoked le maximum nitrate loads measured in the Riguel River in July. Thus, Baker (1990) quoted the case of an irrigated area where N fertilization was fractioned in four times, reducing its drainage nitrate losses by 79% with respect to a single application.

Given the low salt and the high nitrate concentrations in the drainage waters of CR-V, its reuse for irrigation is a sensible strategy for reducing off-site pollution effects. Based on a 50% leaching fraction (equivalent to a 50% irrigation efficiency), a threshold tolerance of ECe = 1.7 dS/m for corn (Ayers and Westcot, 1985), and assuming steady-state conditions for salts (i.e. no salt dissolution or precipitation), the CR-V drainage waters (average EC = 0.79 dS/m for the irrigation season) could be reused two times without compromising corn yields due to an increase in root-zone salinity. This reuse strategy will decrease the volume of IRFs and the presently high salt (7.2 Mg/ha) and nitrate (59 kg NO_3^--N/ha) loads exported from CR-V. In addition, taking into account a corn N requirement of 280 kg N/ha for a yield of 10 Mg/ha (Betrán and Pérez-Berges, 1994), an irrigation-season average [NO_3^-] of 43 mg/l in drainage waters, and an average irrigation depth of 1000 mm, this reuse strategy could save up to 97 kg N/ha, equivalent to one third of the N requirements in corn.

In summary, water and N source control and the reuse of drainage waters for irrigation within the CR-V irrigation district are key management prescriptions that will have beneficial effects both in terms of economics and ‘off-site’ contamination of the receiving water bodies.

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