AGRICULTURAL WATER MANAGEMENT 96 (2009) 188–194

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/agwat

Agro-environmental evaluation of irrigation land II. Pollution induced by Bardenas Irrigation District (Spain)

Jesús Causapé Valenzuela *

Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), Avda. Montañana 930, C.P. 50.059 Zaragoza, Spain

ARTICLE INFO

Article history:
Received 21 February 2008
Accepted 5 September 2008
Published on line 11 October 2008

Keywords:
Irrigation district
Irrigation return flows
Water use index
Saline contamination index
Nitrate contamination index

ABSTRACT

It is difficult to quantify non-point contamination caused by irrigated agriculture. As continuation to the evaluation of water use on the scale of large irrigation districts, this second part seeks: (i) to quantify the mass of salt and nitrate exported by Bardenas Irrigation District included in the Arba basin (BID-Arba; 54,438 ha); (ii) to analyze the most influential factors; (iii) to propose agro-environmental contamination indices which can be incorporated into legislation.

For this, salt and nitrate balances were carried out, assigning concentration values to each of the components of the water balance between 1 April 2004 and 30 September 2006. Saline and Nitrate Contamination Indices were also quantified which correct the mass of pollutants exported from irrigation return flows by geological and agronomic factors of the irrigation area studied.

For the whole period of the study the exported mass of salt was 15 kg/(ha day), of which 65% came from geological materials in the area, 34% from irrigation water and only 1% from precipitation. As for exported nitrate, it was 76 g NO_3^-–N/(ha day), only 25% of the quantities measured in other small basins (≈100 ha) of Bardenas district without re-use of drainage water for irrigation, but double the nitrate exported in other modern irrigation districts.

Water and saline agro-environmental indices of BID-Arba resemble those of well-managed modern irrigation districts indicating little margin for improvement in water use and saline contamination. But, the nitrate-contamination-index was 1.5 times higher than well-managed modern irrigation districts indicating the necessity to change nitrogenous fertilization practices to minimize nitrate contamination.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

During recent years, diverse European directives have advocated the attainment and maintenance of the existing ecological state of water bodies in countries which, like Spain, belong to European Union (EU, 2000, 2006). In particular, these directives seek to protect waters from contamination by nitrates of agrarian origin (EU, 1991), which at both national and regional levels have resulted in the declaration of vulnerable areas, the establishment of instructions of good agrarian practices and obligatory measures (BOA, 1997, 2001).

Nevertheless, there is a legal loophole which prevents sound irrigation water management and minimization of the environmental impact on aquatic ecosystems which receive irrigation return flows. Therefore, current European legislation only makes reference to contamination levels based on the concentration of pollutants in waters (EU, 1998), but not to the mass exported through irrigation return flows,

* Tel.: +34 976716324; fax: +34 976716335.
E-mail address: jcausape@jcausape.es.
URL: http://www.jcausape.es/

0378-3774/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.agwat.2008.09.004

the parameter which really should be monitored in order to minimize negative environmental effects on aquatic ecosystems.

This legal loophole is partly justified by the special nature of the non-point source of irrigation-induced contamination, because of the difficulty involved in quantifying it and attributing it to a specific territory. However, once adequate closure of the water balance of a hydrological irrigation basin has been carried out, loss of agrarian pollutants through drainage can be assigned to the irrigation area in this basin. Therefore, legislation based on permissible maximums of pollutant masses exported can be established in connection with the specific characteristics of each irrigation district such as climate, geology and agronomy.

The study of hydrological irrigation basins has been carried out successfully in several small basins in the Ebro valley, where the main problems of agrarian contamination are derived from salinization and concentration of nitrates in waters (Causapé et al., 2006a). Salt masses exported by irrigation lands are widely variable: they oscillating between 4 Mg/(ha year) for non-saline soils in areas of Bardenas-I (Causapé et al., 2004) to 20 Mg/(ha year) for gypsiferous soils that are flood irrigated in Monegros-I (Isidoro et al., 2006a). As to nitrate, masses exported by Ebro irrigation lands oscillate between 30 kg NO_3^-–N/(ha year) (Cavero et al., 2003) in areas with high irrigation and nitrogenous fertilizer efficiency to almost 200 kg NO_3^-–N/(ha year) (Causapé et al., 2004) where half of the nitrogenous fertilizer application is wasted.

Nevertheless, as previous studies were carried out on a small scale (between 100 and 3000 ha), processes such as re-use of water for irrigation were not considered. Also, hydrological planning of an entire hydrological basin such as that of Ebro (with more than 800,000 ha irrigated) should be based on sub-basin studies on a larger scale (≈50,000 ha). In this way, the largest irrigation area is monitored by studying the smallest possible number of sub-basins.

This article forms the second part of the agro-environmental study of Bardenas Irrigation District included in Arba basin (BID-Arba) whose study area was described in the first part of this work (Causapé, 2009). As continuation to the evaluation of water use in large irrigation districts, this second part seeks: (i) to quantify the mass of agrarian pollutants (salts and nitrates) exported by BID-Arba (54,438 ha); (ii) to analyze the factors which have most influence on the exported mass of salt and nitrate; (iii) to propose agro-environmental contamination indices for irrigation land which can be incorporated into legislation.

2. Methodology

2.1. Salt and nitrate balances

Balances were made assigning salt and nitrate concentration values to each of the components of the water balance (Causapé, 2009) except for evapotranspiration and losses due to evaporation and wind drift in sprinkler irrigation systems, which were considered pollutant free. The multiplication of concentrations and water volumes gave salt and nitrate masses for each component of water balance.

Inputs in Eq. (1). included precipitation (P), irrigation (I), water used to generate electricity and later discharged into the Arba without being used for irrigation (E), supply to small villages without a wastewater treatment plant (V), water discharged from the Ejea wastewater treatment plant (TP), water discharged from the Bardenas Canal into the Arba when there is too much water (BC), the input via the rivers Riguel (RI), Arba de Luesia (AL) and Arba de Biel (AB) which basins are not irrigated, and lastly, the estimated drainage from the remaining non-irrigated land in the Arba basin (RNI); outputs included drainage via the River Arba in Tauste (AT), outputs via two small Canals of the River Arba (C) and the groundwater outflow through the Arba alluvial (GO). The difference between inputs, outputs and storage (Δ) was attributed to the result of components not considered and to errors associated with the balances.

$$(P + I + E + V + TP + BC + RI + AL + AB + RNI) - (AT + C + GO) - (\Delta) = [\text{inputs} - \text{outputs} - \Delta)] \quad (1)$$

The mass of salts and nitrates exported through drainage associated to irrigation land evaluated (*D*) was calculated as:

$$D = (AT + C + GO) - (E + V + TP + BC + RI + AL + AB + RNI) \quad (2)$$

2.1.1. *Inputs*

Electric conductivity at 25° (EC) and nitrate concentration ($[NO_3^-]$) of rain water was estimated monthly from average values registered in the period 1988–2000 at the EMEP station in Logroño (European Monitoring and Evaluation Program; http://www.nilu.no/projects/ccc/), that is located near the study area. Total Dissolved Solids (TDS) for this component was estimated indirectly through the generally accepted relationship: TDS (mg/l) = 640 EC (dS/m) (Bower and Wilcox, 1965).

Water concentration in the Bardenas canal was applied to I, E, V and to BC. For this, nine samples were taken, in which the EC and $[NO_3^-]$ were measured. Also, dry residue (DR, mg/l) and bicarbonate concentration ($[HCO_3^-]$) mg/l) necessary to estimate TDS (Eq. (3)) were measured (Custodio and Llamas, 1983):

$$TDS = DR + (1/2)HCO_3^- \quad (3)$$

As the concentration of water from the Bardenas Canal was very constant (CV_{TDS} = 9%), it was decided to introduce average values of the nine analyzed samples for the whole period of the balance (TDS = 275 mg/l, $[NO_3^-]$ = 2 mg/l). On the other hand, for RI, AL, and AB with more temporal TDS variability (CV_{RI} = 47%, CV_{AL} = 21%, CV_{AB} = 21%), the relationships EC (dS/m) vs. TDS (mg/l) (Eqs. (4a)–(4c) were established from 10 samples and they were applied to quarterly samples where only EC and $[NO_3^-]$ were measured:

$$TDS_{RI} = 769 \cdot EC_{RI} - 1; \quad n = 10; \quad R^2 = 0.99 \quad (4a)$$

$$TDS_{AL} = 639 \cdot EC_{AL} + 74; \quad n = 10; \quad R^2 = 0.93 \quad (4b)$$

$$TDS_{AB} = 819 \cdot EC_{AB} - 31; \quad n = 10; \quad R^2 = 0.92 \quad (4c)$$

The mass of salt and nitrate for RNI was extrapolated from the composition of RI, AL, and AB drainage. Concentration of water discharged into the Arba from TP as reported by the Aragonese Institute of Water (www.aragon.es).

2.1.2. Outputs and storage

The importance and variability of concentration of the AT (CV_{TDS} = 42%) led to the installation of an automatic sampler (ISCO 3700C) which facilitated a daily sampling frequency and later laboratory analysis of EC and [NO_3^-]. The EC vs. TDS relationship was established from 27 samples:

$$TDS_{AT} = 711 \cdot EC_{AT} - 20; \quad n = 27; \quad R^2 = 0.99 \tag{5}$$

For other output components sampling was carried out with less precision. Thus, the average concentration of three samples taken in the canals was assigned to C (TDS = 850 mg/l; [NO_3^-] = 25 mg/l); the average concentration of three samples taken in a spring near the Arba in Tauste gauging station was assigned to GO (TDS = 1758 mg/l; [NO_3^-] = 61 mg/l); and finally, for salt and nitrate content in the aquifer the average concentration of five samples taken in well P-XXX-1 (TDS = 482 mg/l; NO_3^-] = 75 mg/l) was considered representative of the BID-Arba's aquifers (Causapé et al., 2006b).

2.2. Agro-environmental indices

Agro-environmental impact from salt and nitrate was quantified based on the Indices of contamination by salt and by nitrate. Salt Contamination Index (SCI, Eq. (6a)) was calculated as exported salt mass per surface unit (D_S) divided by average EC of drainage water during the non-irrigation period (EC_{NI}), a parameter representative of the salinity of geological materials in the area.

On the other hand, Nitrate Contamination Index (NCI;) was calculated as the relation between nitrate exported in drainage per surface unit (D_N) and the nitrogenous fertilization needs (Eq. (6b)). Fertilization Needs (FN) were calculated annually from individual areas of crops that were grown, the average production of the area (Agrarian statistic. www.aragon.es) and unitary nitrogen extractions by individual crops (Orús and Sin, 2006), except for alfalfa, for which NF was considered nil because of its capacity to fix nitrogen symbiotically.

$$SCI = \frac{D_S}{EC_{NI}} \tag{6a}$$

$$NCI = \frac{D_N}{FN} \tag{6b}$$

Both indices correct unitary masses (mass per surface unit) of pollutants exported by factors of ''natural'' influence to a certain extent, such as geology and agronomic possibilities of a particular irrigation area. Thus, these indices are more permissive with irrigation districts with more ''natural'' risks to leach salt (geologically more saline) and nitrate (with crops with greater fertilization needs).

3. Results and discussion

3.1. Salt balance

Sixty seven percent of salt was introduced into the basin through irrigation water (Table 1), despite the fact that water from Bardenas canal is non-saline (EC = 0.36 dS/m). Salt

Table 1 – Salt balance (inputs—P: precipitation, I: irrigation, RI: Riguel, AL: Arba de Luesia, AB: Arba de Biel, RNI: remaining non-irrigation, E: electricity, V: village, BC: Bardenas Canal and TP: treatment plant; outputs: AT: Arba in Tauste, C: canals and GO: groundwater outflow; ΔS: increment of salt in the system) and salt load exported in the drainage associated to Bardenas Irrigation District included in the Arba basin (D_S) during complete period of study (April 2004/September 2006) and by semesters (April–September and October–March)

		April/ September 2004 (kg/(ha day))	October 2004/ March 2005 (kg/(ha day))	April/ September 2005 (kg/(ha day))	October 2005/ March 2006 (kg/(ha day))	April/ September 2006 (kg/(ha day))	April 2004/ September 2006 (kg/(ha day))
I—inputs	P	0.06	0.02	0.02	0.04	0.05	0.22
	I	7.76	1.46	6.30	0.55	8.98	5.03
	RI	0.59	0.06	0.05	0.06	0.09	0.17
	AL	0.42	0.07	0.01	0.21	0.08	0.16
	AB	0.64	0.18	0.08	0.32	0.17	0.28
	RNI	2.73	0.49	0.23	1.14	0.57	1.04
	E	1.18	0.00	0.00	0.00	0.00	0.24
	V	0.10	0.60	0.07	0.40	0.00	0.23
	BC	0.05	0.02	0.00	0.00	0.00	0.01
	TP	0.09	0.08	0.07	0.07	0.07	0.08
O—outputs	AT	21.96	24.68	8.54	10.51	17.39	16.66
	C	0.26	0.26	0.26	0.26	0.26	0.27
	GO	0.16	0.16	0.16	0.16	0.16	0.16
I	ΣInputs	13.89	3.09	6.94	2.98	10.26	7.45
O	ΣOutputs	22.38	25.10	8.96	10.93	17.81	17.08
ΔS	ΔSalt	5.50	−4.98	−2.24	0.40	1.34	0.01
I − O − ΔS		−13.99	−17.03	0.22	−8.34	−8.89	−9.63
D_S[a]		16.57	23.61	8.44	8.71	16.82	14.87

[a] D = (AT + C + GO) − (E + V + TP + BC + RI + AL + AB + RNI).

introduced through irrigation was in consonance with irrigation volumes applied, oscillating between 8.98 kg/(ha day) during April 2006/September 2006 and 0.55 kg/(ha day) during October 2005/March 2006. Salt contributed from the exterior of the BID-Arba (RI, AL, AB, RNI) accounted for 22% of input, with other components being considerably smaller (E = V = P = 3%, TP = 1%, and BC = 0.2%).

As for the outputs, 98% occurred through the AT. The EC of samples collected in the Arba river oscillated between 7.5 dS/m (9 July 2006) and 0.9 dS/m (1 April 2004), with an average of 3.45 dS/m (CV = 38%). The remaining salt exported from BID-Arba was far inferior (C = 2%, GO = 1%), thus justifying less precision in their calculation.

Storage of salt oscillated between 5.5 kg/(ha day) during April 2004/September 2004 and −4.98 kg/(ha day) during the following semester (October 2004/March 2005). The very seasonality of irrigation and rain meant that annual storage was inferior to six-monthly storage. Thus, storage between April 2004 and March 2005 was only 0.52 kg/(ha day) and in the following year (April 2005 through March 2006) it was −1.84 kg/(ha day). When the balance period is longer, storage is less important compared to other components. Storage for the whole study period was only 0.01 kg/(ha day), which was 0.06% of total salt evacuated.

The difference between inputs and outputs plus storage, corresponds to the result of the dissolution/precipitation processes plus the errors of the hydrosaline balance. Since the closure of water balances was acceptable (Causapé, 2009), the values obtained should correspond, for the most part, to the processes of dissolution/precipitation. Thus, in four of the five semesters and for the whole period of the study negative values were registered, indicating a prevalence of dissolution over precipitation processes. Values oscillated between −17 kg/(ha day) from October 2004 through March 2005 and 0.22 kg/(ha day) from April 2005 through September 2005, with an average for the whole of the study period of −9.63 kg/(ha day).

The positive value for April 2005 through September 2005 would indicate a precipitation of minerals (calcite) superior to the dissolution of gypsum and halite, present in the southern half of the Arba basin (Causapé, 2009). This circumstance was coherent with high irrigation efficiency in this semester (97%; Causapé, 2009), the resulting water evapoconcentration, and calcite precipitation observed in the petrocalcics of the soils.

The mass of salt exported through drainage associated with BID-Arba oscillated between 23.61 kg/(ha day) from October 2004 through March 2005 and 8.44 kg/(ha day) from April 2005 through September 2005. For the total period of study the exported mass of salt was 14.87 kg/(ha day), of which 65% came from the geological materials in the area, 34% from irrigation water and only 1% from rain.

Seasonal variability of the results obtained is related to rainfall and its influence on irrigation management. Thus, the rainiest year (April 2004/March 2005) had the greatest mass of dissolved salt (15.55 kg/(ha day)) and exported salt (20.09 kg/(ha day)) as a consequence of the greater volume of water introduced into the system (P = 426 mm and I = 614 mm; Causapé, 2009) and lower water use index (WUI = 82%; Causapé, 2009). On the other hand, the driest year (April 2005/March 2006) had the smallest mass of dissolved salt (4.07 kg/(ha day)) and exported salt (8.58 kg/(ha day)) as consequence of the lower volume of water introduced into the system (P = 312 mm and I = 456 mm; Causapé, 2009) and greater water use (WUI = 92%; Causapé, 2009).

The mass of salt exported globally by the BID-Arba (15 kg/(ha day)) is between 11 kg/(ha day) obtained in three small sub-basins (between 97 and 216 ha) in the northern portion of the Bardenas-I irrigation district, which is located in the glacis with little salt content (Causapé et al., 2004), and 42 kg/(ha day) of another sub-basin (433 ha) with more saline soils in the southern portion of the Bardenas-I irrigation district (Lasanta et al., 2002). Another small basin in Monegros-II (470 ha), with very saline subsoil and recently transformed to sprinkler irrigation, had 2.5 times more exported salt in irrigation return flows (37 kg/(ha day), Tedeschi et al., 2001) although this quantity could be overestimated because external flows to the basin were not discounted. Finally, another basin in Monegros-I (3863 ha) with gypsum in flood-irrigated soils exported four times more than BID-Arba (56 kg/(ha day); Isidoro et al., 2006a).

In accordance with these comparative results, the quantity of salt exported in BID-Arba drainage was less than expected, favoured by intense re-use of water in BID-Arba on the scale of the whole irrigation district.

3.2. *Nitrate balance*

Irrigation water and precipitation made up 82% of the nitrate input studied (Table 2), although most of it was used by crops. The other input components, which were 60 and 13%, respectively of water and salt circulating in the Arba river, were only 4% of nitrate exported by this river (76.8 g NO_3^-–N/(ha day)), with notably little contribution from the non-irrigated land areas (RI + Al + AB + RNI = 2.3 g NO_3^-–N/(ha day)) and from treated wastewaters (TP = 0.2 g NO_3^-–N/(ha day)).

AT accounted for 96% of the nitrate outputs registering daily values of nitrate concentration between 1 mg/l (10 September 2005) and 94 mg/l (18 November 2004) with an average of 44 mg/l (CV = 32%). Nitrate exported by the lateral canals (25 mg/l) and through the Arba alluvial (61 mg/l) only accounted for 4% of the nitrate outputs.

Nitrate storage for the whole period of study was practically nil, although it oscillated in six-monthly periods between 194 g NO_3^-–N/(ha day) from April 2004 through September 2004 and −175 g NO_3^-–N/(ha day) in the following semester. Intense re-use of water during the drought year October 2004/September 2005, caused nitrate exported into the Arba was only 65% of water discharged from the aquifers. As a result excessive N fertilization of leaching/immobilization processes, the rate of N leached, 62 g NO_3^-N/(ha day), exceeds the 18 g NO_3^-N/(ha day) introduced by the NO_3^-N contained in P and I.

These quantities only accounted for 23% of outputs, proving the existence of other components, such as nitrate introduced with fertilizers, not taken into account in the balance. It should be noted that during the drought year October 2004/September 2005 immobilization of 53 g NO_3^-–N/(ha day) occurred because most of the nitrate contributed in

Table 2 – Nitrate balance (inputs—P: precipitation, I: irrigation, RI: Riguel, AL: Arba de Luesia, AB: Arba de Biel, RNI: remaining non-irrigation, E: electricity, V: village, BC: Bardenas Canal and TP: treatment plant; outputs: AT: Arba in Tauste, C: canals and GO: groundwater outflow; ΔN: increment of nitrate in the system) and nitrate load exported in the drainage associated to Bardenas Irrigation District included in the Arba basin (D_N) during complete period of study (April 2004/September 2006) and by semesters (April–September and October–March)

		April/September 2004 (g $N–NO_3^-$/ha day)	October 2004/ March 2005 (g $N–NO_3^-$/ ha day)	April/ September 2005 (g $N–NO_3^-$/ ha day)	October 2005/ March 2006 (g $N–NO_3^-$/ ha day)	April/ September 2006 (g $N–NO_3^-$/ ha day)	April 2004/ September 2006 (g $N–NO_3^-$/ ha day)
Inputs	P	9.8	4.2	3.7	6.5	9.1	6.7
	I	12.8	2.4	10.4	0.9	14.8	8.3
	RI	1.6	0.2	0.1	0.3	0.3	0.5
	AL	1.5	0.2	0.0	0.6	0.3	0.5
	AB	1.6	0.7	0.2	1.1	0.2	0.7
	RNI	1.5	0.2	0.1	0.4	0.3	0.5
	E	1.9	0.0	0.0	0.0	0.0	0.4
	V	0.2	1.0	0.1	0.7	0.0	0.4
	BC	0.1	0.0	0.0	0.0	0.0	0.0
	TP	0.1	0.1	0.3	0.2	0.4	0.2
Output	AT	108.7	137.0	29.0	41.7	67.6	76.8
	C	1.8	1.8	1.8	1.8	1.8	1.8
	GO	1.2	1.2	1.2	1.2	1.2	1.2
I	ΣInputs	31	9	15	11	25	18
O	ΣOutputs	112	140	32	45	71	80
ΔN	ΔNitrate	194	−175	−79	14	47	0
I − O − ΔN		−275	44	62	−48	−93	−62
D_N[a]		103	138	31	41	69	76

[a] $D = (AT + C + GO) − (E + V + TP + BC + RI + AL + AB + RNI)$.

the input components and stored in the aquifers was used by crops with re-use of water for irrigation.

Capacity for regulation and re-use of water in the system had the effect that, in contrast to what was detected in other works on a smaller scale (Causapé et al., 2004; Isidoro et al., 2006b), a non-irrigation semester (October 2004/March 2005) presents the greatest exported nitrate mass (138 g NO_3^-–N/(ha day)) while the irrigation semester (April 2005/September 2005) presents the smallest (31 g NO_3^-–N/(ha day)).

Nitrate exported in BID-Arba for the whole period of study was 76 g NO_3^-–N/(ha day), much less than 300 g NO_3^-–N/(ha day) in small flood-irrigated basins (Causapé et al., 2004; Isidoro et al., 2006b) where the percentage of cultivated maize was higher (50% vs. 14%) and irrigation return flows were not re-used. However, the mass exported by another sprinkler-irrigated basin with 42% maize, was half (38 g NO_3^-–N/(ha day), Cavero et al., 2003) that of the BID-Arba, verifying that nitrogenous fertilization management in BID-Arba can be improved.

3.3. *Agro-environmental evaluation*

The semester balances showed that the hydric regulation capacity masks the existent relationship between drainage and the climatic, geological and agronomic factors which condition it in the short term. Nevertheless, the existent parallelism between accumulated WUI (Causapé, 2009) and the semester accumulated SCI and NCI (Fig. 1) reflects that the agro-environmental impact of irrigation is highly conditional on water use.

The storage in aquifers overestimated water use and underestimated saline and nitrate contamination indices in first semester. Nevertheless, the output of the following semester reflected a more real situation in the first year of the study, when the smallest WUI (82%; Causapé, 2009) and bigger SCI (5.5 kg/(ha day)/dS/m) and NCI (0.5) were achieved. The drought meant better irrigation management and escalation of re-use of drainage water, which resulted in the increase in WUI and continuous descent of SCI until the beginning of the last semester when the end of the drought

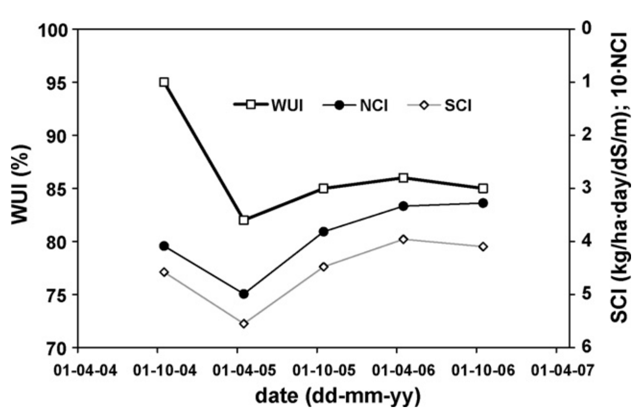

Fig. 1 – Evolution of semester cumulative Use Water Use Index (WUI; Causapé, 2009), Salt Contamination Index (SCI) and Nitrate Contamination Index (NCI) in Bardenas Irrigation District included in Arba basin between 1 April 2004 and 30 September 2006.

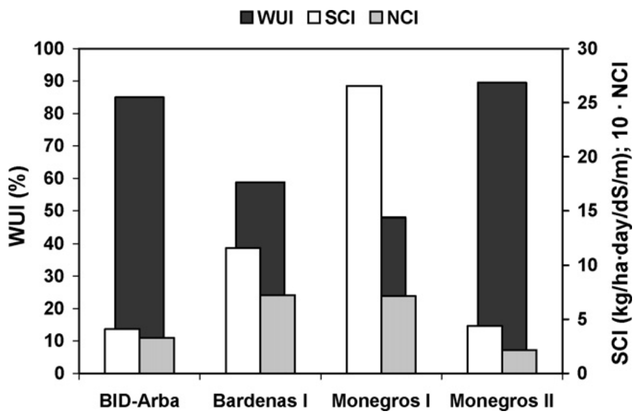

Fig. 2 – Water Use Index (WUI), Salt Contamination Index (SCI) and Nitrate Contamination Index (NCI) in Bardenas Irrigation District included in Arba basin (BID-Arba), average of four small basins in Bardenas I Irrigation District, another small basin in Monegros I irrigation district and average of two small basins in Monegros II Irrigation District.

reversed the tendency. On the other hand, NCI continued to fall from the second semester, which indicated a descent of exported nitrate lower than the fertilization needs descent. Fertilization needs, conditional on the drought first and on the new common agricultural policy conditions later, were 93, 84, and 83 kg NO_3^-–N/(ha year) for 2004, 2005 and 2006 years, respectively.

By comparing the indices obtained for BID-Arba with those obtained from data from other studies made in small flood irrigated basins in Bardenas-I (Lasanta et al., 2002; Causapé et al., 2004) and Monegros-I (Isidoro et al., 2006a,b), it can be deduced that water use in BID-Arba was far superior (Fig. 2) as a consequence of intense re-use of drainage water carried out on a global scale. It also caused some smaller indices of saline contamination (SCI: 4.1 kg/(ha day) dS/m) and nitrate contamination (NCI: 0.3) which situates them, particularly SCI, at almost the same level as modern irrigation districts in Monegros-II (Fig. 2), with sprinkler irrigation systems and use of ferti-irrigation.

Water use is the key factor to the minimization of environmental impact, since it does not only diminish water and salt exported in the drainage, but it also favours appropriate nitrogenous fertilization management and thereby a reduction in exported masses of nitrate.

According to the comparative results, it seems that water use in global BID-Arba and saline contamination induced by irrigation have little margin for improvement. However, minimizing nitrate contamination is possible if nitrogen fertilization is improved by means of adjustment and division of the doses applied. Thereby, ICN of BID-Arba will be as low as well managed modern irrigation districts.

4. Conclusions

Sixty seven percent of salt and 46% of nitrate were introduced into the basin through irrigation, while 98 and 96%, respectively of salt and nitrate were discharged to the Arba River. The other input components which made up 60 and 13%, respectively of water and salt circulating in the Arba, only accounted for 4% of nitrate exported by this river (76.8 g NO_3^-–N/(ha day)), with notably low contribution from non-irrigated land (RI + Al + AB + RNI = 2.3 g NO_3^-–N/(ha day)) and from treated wastewater (TP = 0.2 g NO_3^-–N/(ha day)).

For the whole period of study, the exported mass of salt was 15 kg/(ha day) of which 65% came from geological materials in the area, 34% from irrigation water and only 1% from precipitation. The mass of dissolved salt in BID-Arba was 9.6 kg/(ha day), although drought and high irrigation efficiency between April and September 2005 led to a slight prevalence of precipitation over dissolution of salt in this semester. As for exported nitrate, it was 76 g NO_3^-–N/(ha day), only 25% of values measured in small basins of the same irrigation district (300 g NO_3^-–N/(ha day)) but double that of well managed modern irrigation districts (38 g NO_3^-–N/(ha day)).

Capacity for regulation and storage of water in BID-Arba masked the existing relationship between climate and agronomic management during semester and annual periods and its drainage. Nevertheless the parallelism between accumulated WUI, SCI and NCI showed that the agro-environmental impact of irrigation is highly conditional on water use.

BID-Arba on a global scale makes a case for intense re-use of water, smaller agro-environmental impact than irrigation of this and other flood-irrigated areas studied on a smaller scale. WUI and SCI resemble those of well-managed modern irrigation district indicating little margin of improvement in water use and saline contamination. However, it is necessary to adapt nitrogen fertilization to decrease NCI and to minimize nitrate contamination.

Indices of water use, saline and nitrate contamination can be incorporated into legislation because they facilitate the evaluation of the agro-environmental impact of irrigation districts with different sizes, geology, and agronomy.

Acknowledgements

The work has been financed by the Ebro Basin Authority, which, together with the Bardenas Irrigation District authority and the Water Institute of Aragon have facilitated the basic data for the execution of this study.

REFERENCES

Boletín Oficial de Aragón, 1997. Zonas vulnerables y código de buenas prácticas agrarias de Aragón (BOA del 11 de junio de 1997).

Boletín Oficial de Aragón, 2001. Programas de actuación de obligado cumplimiento en zonas vulnerables de Aragón (BOA del 3 de enero de 2001).

Bower C.A. Wilcox, L.V. 1965. Soluble salt. In: Methods of soil analysis. Chemical and Microbiological Agronomy No. 9. American society of agronomy. Part 2. pp. 933–951.

Causapé, J., Quílez, D., Aragüés, R., 2004. Assessment of irrigation and environmental quality at the hydrological basin level. II. Salt and nitrate loads in irrigation return flows. Agricultural Water Management 70, 211–218.

Causapé, J., Quílez, D., Aragüés, R., 2006a. Irrigation efficiency and quality of irrigation return flows in the Ebro River Basin: an overview. Environmental Monitoring and Assessment 117, 451–461.

Causapé, J., Quílez, D., Aragüés, R., 2006b. Groundwater quality in CR-V irrigation district (Bardenas I, Spain): alternative scenarios to reduce off-site salt and nitrate contamination. Agricultural Water Management 84, 281–289.

Causapé, J., 2009. Agro-environmental evaluation of irrigation land. I. Water use in Bardenas Irrigation District (Spain). Agricultural Water Management 96, 179–187.

Cavero, J., Beltrán, A., Aragües, R., 2003. Nitrate exported in the drainage water of two sprinkler irrigated watershed. Journal Environmental Quality 32, 916–926.

Custodio, E., Llamas, M., 1983. Hidrología Subterránea. Ediciones Omega. 2.290 pp.

European Union, 1991. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused bay nitrates from agricultural sources. Official Journal L 375, December 31, 1991: 1–8.

European Union, 1998. Council Directive 98/83/CE of November 3, 1998 imposed to the surface waters devoted to the production of water for human consumption. Official Journal L 330, December 5, 1998: 32–54.

European Union, 2000. Directive 2000/60 of the European Parliament and of the Council establishing a framework for community action in the field of water pollution. Official Journal L327, December 22, 2000: 1–72.

European Union, 2006. Directive 2006/118/EC of the European Parliament and of the Council of 12 December 2006 on the protection of groundwater against pollution and deterioration. Official Journal L372/19, December 27, 2006: 19–31.

Isidoro, D., Quílez, D., Aragüés, R., 2006a. Environmental impact of irrigation in La Violada District (Spain): I. Salt export patterns. Journal of Environmental Quality 35, 766–775.

Isidoro, D., Quílez, D., Aragüés, R., 2006b. Environmental impact of irrigation in La Violada District (Spain). II. Nitrogen fertilization and nitrate export patterns in drainage water. Journal of Environmental Quality 35, 776–785.

Lasanta T., Mosch W., Pérez-Rontomé M.C., Navas A.,Machín J., Maestro M., 2002. Effects of irrigation on water salinization in semi-arid environments. a case study in Las Bardenas, Central Ebro Depression, Spain. Environmental change and water sustainability. García-Ruíz J.M., Jones A., Arnáez J. Eds. Instituto Pirenaico de Ecología: 198–218.

Orús F., Sin, Elena. 2006. El balance del nitrógeno en la agricultura. Capitulo 1 en Fertilización Nitrogenada. Guía de actualización. Informaciones Técnicas. Centro de Transferencia Agroalimentaria. Ed. Gobierno de Aragón. 196 pp.

Tedeschi, A., Beltrán, A., Aragüés, R., 2001. Irrigation management and hydrosalinity balance in a semi-arid area of the middle Ebro River Basin (Spain). Agricultural Water Management 49, 31–50.