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Implementing irrigation: Salt and nitrate exported from the Lerma basin (Spain)

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ABSTRACT

The creation of a new irrigated area influences the pollutants exported from the zone and, consequently, the quality of receiving water bodies. The aim of this study was to analyze the masses of the main pollutants exported by an area before and during its gradual transformation into irrigated land. To this end, salinity balances were carried out and the nitrate exported from the Lerma basin (752 ha, Spain) was quantified during 2004–2008. The agroenvironmental impact was evaluated through the use of pollution indices. The results revealed that the transformation of the area into irrigated land decreased salinity and increased nitrate concentration in drainage. The increase in the volume of drainage increased the masses of salt and nitrate exported, which in turn increased pollution indices during the transition. However, these indices were still lower than those quantified in other irrigated lands and therefore can still be considered to be of low contamination level. This study demonstrates the important environmental influence of introducing irrigation to an area, as pollution levels change and become mainly dependent on the management of irrigation and nitrogenous fertilization. For this reason, it is highly desirable to promote the optimization of agricultural management in a way that minimizes its impact.

1. Introduction

Transformation of dryland agricultural area into an irrigated area modifies the water regime of the area (Baldock et al., 2000; Cai et al., 2003) and can negatively influence water quality. The most important negative influences are water and soil salinization (Tanji and Kielen, 2002) and nitrate pollution (Klocke et al., 1999; Ribbe et al., 2008), which affect the agricultural, industrial, urban and ecological uses of water.

While current European Union legislation imposes limits on the chemical concentration of pollutants in water (DOUE, 2006, 2008), the main risk of environmental pollution induced by irrigation is derived from the combination of quality and quantity of irrigation return flows. Consequently, the masses of pollutants exported are key parameters that need to be controlled to prevent a negative impact on receiving water resources.

An adequate closure of the water balance and the monitoring of water quality in a hydrological basin allows for an accurate accounting of the pollutants in agricultural drainage. The correct measurement of components permits the association of such loss with physical and agronomic characteristics of the studied irrigated land (Tedeschi et al., 2001; Causapé et al., 2004a,b; Isidoro et al., 2006a,b; Ribbe et al., 2008).

In terms of physical characteristics, the natural salinity of the land where irrigation is being implemented can contribute significantly to the mass of salt exported and consequently affect water resources downstream (Christen et al., 2001; Tanji and Kielen, 2002). Moreover, heavy rainfall (and irrigation) can cause lateral and vertical mobility of native salts in the soil, significantly increasing the masses exported (Thayalakumaran et al., 2007). In terms of agronomic factors, García-Garizábal et al. (2009) verified that adequate management of irrigation water can cause significant reductions in the masses of salt and nitrate exported from an agricultural basin. Gheysari et al. (2009) indicate that it is possible to control the levels of nitrate leaching from the root zone with an appropriate joint management of irrigation and fertilization. It has also been shown that a reduction in nitrogenous fertilization can significantly decrease the levels of leaching nitrate without causing a decrease in production (Moreno et al., 1996; Cui et al., 2010), which supports the possibility of a sensitive balance between acceptable environmental impact and high agricultural production.

This article continues the development of water balances and assessment of irrigation quality carried out by Abrahao et al. (2011) for the new irrigated area located in the Lerma basin (Spain). The objective of this study was to quantify the masses of salt and nitrate exported from the basin before and during the gradual implementation of irrigation (2004–2008), to determine the salt an nitrate loads in receiving waters attributable to irrigated agriculture and to relate them to the factors involved in contamination.

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2. Description of study area

The complete geographical, geological, agronomical and climatic description of the study area can be found in Abrahao et al. (2011). This section provides additional information about soil salinity and nitrogen fertilization, specific to the aim of this article.

2.1. Soil salinity

In order to deepen knowledge on the spatial variability of the soil salinity in the basin, maps of the apparent electrical conductivity (EC_a) were generated by a Mobile Geo-referenced Electromagnetic Sensing System (MGESS) (Urdanoz et al., 2008). Specifically, 43,433 measurements were taken in horizontal configuration (EC_{ah}: integrated readings up to 1 m in depth) and in vertical configuration (EC_{av}: integrated readings of the first 2 m of soil).

Field data was collected after the rain events of October 2005 in unirrigated conditions, leading to soil moisture values equivalent to field capacity. Therefore, EC_a differences were due to individual differences of water holding capacity and salinity in each soil. These differences could be related to water holding capacity and salinity depending on the calibration technique used. More information about these methods was presented in Urdanoz et al. (2008). The generated map shows that the average EC_{ah} of the Lerma basin soils was low (0.27 dS/m), although depressed areas at the bottom of the valley presented EC_{ah} values above 6 dS/m (Fig. 1, based on Urdanoz et al., 2008).

From the EC_{ah} data, Urdanoz et al. (2008) correlated EC_{ah} and electrical conductivity of the soil saturation extract (EC_e) (until 1 m soil depth) and verified that 92% of the study area soils up to this depth presented EC_e below 4 dS/m, which represents a soil salinity that does not affect the performance of most crops in the area. The glacis, where the irrigation activities were mainly carried out, presented low EC_{ah} (0.16 dS/m) and the valleys (with tertiary surfaces) presented EC_{ah} values three times superior (0.44 dS/m). The average EC_{av} for the Lerma basin (0.48 dS/m) was nearly twice that of EC_{ah} (0.27 dS/m), indicating the presence of normal profiles in which soil salinity increases in depth with the proximity to tertiary saline substrate.

2.2. Nitrogen fertilization

During the irrigation years (2006–2008) a survey was conducted (by telephone and face-to-face enquiries) with all farmers included in Lerma basin. Fertilization of maize (main crop in the area) represented an average of 380 kg N/ha year, which slightly exceeded the maximum allowed nitrogen application in areas designated as vulnerable to nitrate pollution in Spain (30 kg N/Mg of expected grain production, BOA, 2009). The general agronomic management consisted of sowing fertilization with compound fertilizers (mainly 8-15-15 and 15-15-15), followed by urea (46% N) and/or multiple applications of liquid fertilizers (32% N: 16% urea and 16% nitrate) by fertigation.

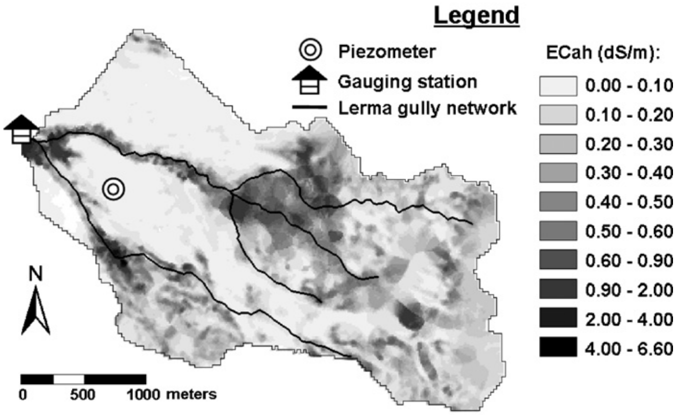

Fig. 1. Apparent electrical conductivity map from an electromagnetic sensor in horizontal configuration (EC_{ah}) in the Lerma basin in October 2005 (Urdanoz et al., 2008).

The application of nitrogenous fertilization on winter cereals (wheat and barley; 164 kg N/ha year) was distributed between the first application in compound fertilizers a few days before sowing and the remainder in the form of urea and/or liquid fertilizers in early spring. Fertilization of tomato was characterized by frequent applications of small rates throughout the cycle, with the aim of overcoming the different nutritional requirements of each vegetative stage. In the Lerma basin, compound fertilizers and liquid fertilizers (fertigation through drip irrigation systems) were mainly used, with an average annual contribution of 182 kg N/ha.

The remaining crops (broccoli, peas, sunflower, onion and sorghum) constituted the minority of crops in the Lerma basin, mainly associated with double cropping of a plot in the same year (Abrahao et al., 2011). Double cropping was more common with the gradual implementation of irrigation, reaching 24% of the irrigated area in 2008. The main associations were peas–maize, broccoli–maize, winter cereal–sorghum, winter cereal–sunflower and peas–sunflower. The development of double cropping increased the use of fertilizers, with most significant increases noted when the associated crop was maize (410 kg N/ha year). During the study period, the ratio of nitrogen fertilization per irrigated area in Lerma basin remained nearly constant, thus the increase in total nitrogen fertilizer applied can be justified by the increase in irrigated area.

It is important to note that the study area was designated as an area vulnerable to nitrate pollution in 2008 (BOA, 2008), which may trigger a reconsideration of nitrogenous fertilization practices that take the water system quality into consideration.

3. Methodology

3.1. Salt balance and exported nitrate

Salt balances were carried out and the nitrate exported from the irrigable area of Lerma basin was quantified during the period of 2004–2008. General salt concentrations were assigned to the water balance components, with a specific consideration for nitrate concentration (Abrahao et al., 2011). However, contaminant concentrations were not assigned to evapotranspiration, wind drift and evaporation losses from sprinkler irrigation, and storage in the soil, either because these components are salt-free or represent insignificant contribution to balances.

The product of concentrations and water volumes is the mass of salt and nitrate for each component. The difference between inputs (P: precipitation, I: irrigation, IWF: incoming water flows from the unirrigable area included in the basin), outputs (LG: Lerma gully) and storage (ΔA: aquifer) of the salinity balance corresponds mainly to the end result of the set of dissolution-precipitation processes.

In the case of nitrate, the objective was not necessarily to close a balance but to quantify the masses exported and the contribution from irrigation and rainfall. The difference between inputs, outputs and storage can be attributed to the combination of nitrogen cycle components not taken into account (e.g. fertilization, crop exports and volatilization).

$$\text{Inputs} - \text{Outputs} - \text{Storage} = (\text{P} + \text{I} + \text{IWF}) - (\text{LG}) - (\Delta A) \tag{1}$$

A great sampling effort was made to determine the concentration of salt and nitrate in the water exported from the Lerma gully. This gully at the exit of the Lerma basin was initially sampled on a monthly basis until construction of the gauging station in 2005 (Fig. 1), when an automatic sampler equipment (ISCO Model 3600) allowed for daily sampling. Water samples (collected by the automatic sampler equipment) were transported to the laboratory, where the electrical conductivity of water corrected to 25 °C (EC) and nitrate concentration ($[NO_3^-]$) were determined. An Orion-5 Star conductivimeter was utilized for the conductivity measurements, and an AutoAnalyzer 3 equipment was used to determine $[NO_3^-]$ by colorimetry.

Seventeen water samples were selected within the range of variation of EC in the Lerma gully, for which the concentration of bicarbonate ($[HCO_3^-]$) and dry residue (DR) were determined. From these concentrations, the total dissolved solids (TDS) were calculated from Eq. (2) (Custodio and Llamas, 1983):

$$\mathrm{TDS} = \mathrm{DR} + 1/2\,\mathrm{HCO_3}^- \tag{2}$$

EC (dS/m) was converted into TDS (mg/l) for each collected sample through Eq. (3):

$$\mathrm{TDS} = 712.22 \cdot \mathrm{EC} - 104.83; \quad R^2 = 0.99;\ n = 17;\ p < 0.01 \tag{3}$$

Eq. (3) was also used to estimate the total dissolved solids in the incoming water flows and water storage in the aquifer. The concentration of salt and nitrate of incoming water flows was obtained from monthly water samples collected at the gully before entrance into the irrigable area. Due to an absence of data on specific dates, the content of salt and nitrate in the aquifer had to be estimated from the concentrations in the gully water on the same dates, which is acceptable since there were no recent heavy rain events generating runoff.

The salt and nitrate concentration of rainwater was determined from the average of three samples collected in the study area by a pluviometer with an applied sheet of liquid paraffin, which prevented evapoconcentration until the water sample was collected and transported to the laboratory. Finally, salt and nitrate concentration of irrigation water was determined from the average of nine samples taken from the irrigation canal, which presented a low variability (coefficient of variation: $CV_{TDS} = 9\%$). The procedures utilized to determine water volumes of all components were presented in Abrahao et al. (2011).

3.2. Irrigation quality indices

The unit masses of exported salt and nitrate from the irrigable area (D_S and D_N) were obtained after discounting the contaminants introduced by the incoming water flows to the irrigable area. Two indices proposed by Causapé (2009) were applied to further analyze the agroenvironmental impact produced: salt contamination index (SCI) and nitrate contamination index (NCI):

$$\mathrm{SCI} = \left[\frac{D_S\ [\mathrm{Mg/ha}]}{\mathrm{EC_{NR}}\,[\mathrm{dS/m}]}\right] \tag{4}$$

$$\mathrm{NCI} = \left[\frac{D_N\,[\mathrm{kg/ha}]}{\mathrm{FN}\,[\mathrm{kg/ha}]}\right] \tag{5}$$

where EC_{NR} is the average electrical conductivity of the drainage during the unirrigated period and represents the salinity of the geological materials of a particular irrigated land. EC_{NR} was obtained by monitoring the drainage water quality at the gauging station before the implementation of irrigation. FN represents the annual fertilization necessities, which were estimated, annually, from the surfaces occupied by crops, harvest production, and the nitrogen extractions by the crops (Orús and Sin, 2006).

These two indices allow for the comparison of the temporal and geographical impacts generated in different areas by irrigation. Comparison is possible as the indices adjust the exported unit masses by natural factors such as salinity from the local geology in the case of SCI, and climatic and socioeconomic factors (e.g. crops planted and respective nitrogenous fertilization requirements) in the case of NCI. Therefore, these indices are more permissive to unfavourable irrigated areas, representing real limits that well-managed irrigation areas with different characteristics should not exceed. SCI values <2.0 [Mg/(ha year)]/[(dS/m)] and NCI < 0.2 are typical in well managed irrigation zones.

3.3. Statistical procedures

The Mann and Whitney (1947) nonparametric method was utilized to compare EC and $[NO_3^-]$ of the unirrigated period (2004–2005) with those of the irrigated period (2006–2008). Annual comparisons were also carried out to verify the evolution of such water quality parameters with implementation of irrigation. It was considered that the groups were significantly different for a probability of less than a 5% error ($p < 0.05$).

The correlation coefficient (r) of Spearman was applied to analyze the relationships between the following variables and indicators: irrigation, precipitation, mass of exported salt, mass of exported nitrate, electrical conductivity of water, nitrate concentration, water use index, salt contamination index, and nitrate contamination index.

The r coefficient ranges between −1 and 1, establishing whether relationships are negative, positive, or non-existent ($r = 0$) (Spearman, 1904). Monthly values were used for the irrigated period ($n = 36$) and, in the case of precipitation, the unirrigated period was also utilized ($n = 24$) with the intention of verifying possible changes in the existing relationships. All statistical procedures were carried out with the Statgraphics 15 software.

4. Results and discussion

4.1. Salt

The average mass of salt involved in the salt balances was 4.0 Mg/ha year, with the highest mass in the rainy year of 2004 (5.8 Mg/ha) and lowest mass in the dry year of 2005 (1.3 Mg/ha). With the progressive introduction of irrigation, the mass of salt involved in balances increased at a rate of 0.33 Mg/ha year, from 3.5 Mg/ha year in unirrigated conditions (2004–2005) to 4.5 Mg/ha year in 2008.

The main entrance of salt into the system corresponded to water flows from the unirrigable zone, representing 55% of total inputs over the studied period (Table 1). However, the input of salt through irrigation water surpassed the incoming water flows contribution in 2007, accounting for 61% of inputs in 2008. Thus, despite the low salinity of irrigation water (EC = 0.3 dS/m), this component proved to be important because of the high volumes applied. On the other hand, precipitation presented the lowest salinity (EC = 0.1 dS/m) among all the components considered, contributing with 15% of the salt inputs.

The only output of salt considered was the output drained by the Lerma gully, with an average of 3.1 Mg/ha year. The unirrigated years presented the highest and lowest masses of salt exported by the Lerma basin (5.8 Mg/ha in 2004 and 1.3 Mg/ha in 2005), which was mainly due to differences in the volume of drainage (because 2005 was a dry year, $P = 212$ mm (Abrahao et al., 2011)) as the salinity of water was not significantly different ($EC_{2004} = 5.0$ dS/m and $EC_{2005} = 4.9$ dS/m, $p < 0.05$).

Table 1
Salt masses. In: inputs [precipitation (P), irrigation (I), incoming water flows (IWF) from the unirrigable area]; O: outputs [water drained through the Lerma gully (LG)]; S: storage [in the aquifer (ΔA)] and In–O–S for the years 2004–2008.

Year	Inputs				Outputs	Storage	In–O–S
	P	I	IWF	Σ In	LG	ΔA	
	Mg/ha year						
2004	0.5	0.0	2.5	3.0	5.8	–	−2.8
2005	0.2	0.0	0.5	0.7	1.3	–	−0.6
2006	0.4	0.4	1.8	2.5	2.8	1.2	−1.5
2007	0.3	1.1	0.8	2.2	2.3	2.0	−2.1
2008	0.3	1.4	0.6	2.3	3.2	1.3	−2.2
04–08	0.3	0.6	1.2	2.2	3.1	0.9	−1.8

Significant differences ($p < 0.05$) were verified when comparing the salinity of the gully before and after irrigation was introduced ($EC_{2004–2005} = 5.0$ dS/m; $EC_{2006} = 3.9$ dS/m; $EC_{2007} = 4.2$ dS/m; $EC_{2008} = 4.2$ dS/m). This decrease in salinity with the introduction of irrigation reflects dilution by irrigation water of good quality – despite its evapoconcentration. Across irrigated years, no significant differences were observed in the salinity of water ($p < 0.05$), noting that a greater mass of salt flowed through the gully in 2008 (3.2 Mg/ha year) even with lower values of precipitation (361 mm in 2008 versus 411 mm in 2007 and 426 mm in 2006; Abrahao et al., 2011) and lower incoming flows from the unirrigable zone (27 mm in 2008 versus 31 mm in 2007 and 56 mm in 2006; Abrahao et al., 2011).

The salt content of the water stored in the aquifer was an amount to be considered in the balance, regulating the salt exports from the basin. In the same way for the water balances previously performed in Lerma (Abrahao et al., 2011), in the three years that estimation could be carried out, there was a continuous increase in storage, demonstrating that after the gradual introduction of irrigation the system had not yet reached equilibrium.

The final result of the salinity balance (negative value) revealed a predominance of salt dissolution processes over salt precipitation (In–O–S = −1.8 Mg/ha year, Table 1). In addition, it was verified that dissolution also prevailed over precipitation in every year, resulting in extreme values under unirrigated conditions with high and low rainfall. These values may have been affected by the lack of consideration of aquifer storage for these years.

Assuming that the aquifer storage in the years with most and least rainfall can balance each other out, the mass of dissolved salt leaving the system under irrigation conditions (1.9 Mg/ha year) was 14% higher than under unirrigated conditions. With gradual introduction of irrigation, a progressive increase of the dissolved salt was observed (1.5 Mg/ha in 2006 to 2.2 Mg/ha in 2008). Geochemical models developed in other irrigated areas of Ebro river basin (Causapé et al., 2004c) already verified the prevalence of dissolution processes of gypsum and halite over the precipitation of calcite. However, García-Garizábal (2010) reported that an increase in irrigation efficiency in areas with lower salinity than Lerma could reverse this situation and the precipitation of calcite would dominate over the dissolution of other salts.

The salt exported from the irrigable area throughout the study period was measured at 1.9 Mg/ha year, with the greatest masses exported occurring during the rainy year of 2004 (3.3 Mg/ha) and the lowest in the dry year of 2005 (0.8 Mg/ha) – both under unirrigated conditions. With the gradual implementation of irrigation, there was a continued increase in the masses exported, reaching an annual rate of over half a ton of salt per hectare – from 1.0 Mg/ha in 2006 to 2.6 Mg/ha in 2008 (Table 2).

Considering the total mass of salt exported from the irrigable area, 51% originated from the dissolution of geological materials (0.9 Mg/ha year), 31% from salt in irrigation water (0.6 Mg/ha year) and 18% from rainwater (0.3 Mg/ha year). However, these percentages varied. Under unirrigated conditions (2004–2005), 83% of salt originated from dissolution processes. In contrast, under irrigated conditions (2006–2008), dissolution contributed only 24% and irrigation water was the main contributor of salt (57% of drained salt).

In 2004 and 2005, the monthly evolution of exported salt from the irrigable area of the basin depended mainly on rainfall and consequent potential dissolution of that salt. Over time, the quantity of salt exported peaked mainly in irrigation months (April–September), although some peaks were observed as a result of heavy rains (Fig. 2).

The average salt contamination index of the study area was 0.49 [Mg/(ha year)]/[(dS/m)]. In unirrigated conditions, the SCI ranged between 0.86 and 0.21 [Mg/(ha year)]/[(dS/m)] depending on whether the year was rainy or dry. With the implementation of irrigation, the increase in the masses of salt exported caused an increase in the SCI, which rose from 0.28 [Mg/(ha year)]/[(dS/m)] in 2006 to 0.70 [Mg/(ha year)]/[(dS/m)] in 2008.

These values are not worrisome, as Causapé (2009) compared SCI values of different irrigated areas of the Ebro basin (similar irrigation water quality) and related them to the use of irrigation, concluding that SCI values < 2.0 [Mg/(ha year)]/[(dS/m)] ensure a high water use and a relatively small mass of exported salt for the natural conditions of irrigation. Thus, irrigation with a water use index of approximately 50% and lower salinity ($EC_{NR} = 1.1$ dS/m) presented salt contamination indices six times higher than those of Lerma in 2008. Additionally, if the irrigated area contains gypsum ($EC_{NR} = 1.8$ dS/m), the SCI can be up to fifteen times higher (Table 3).

Table 2
Percentage of irrigable area irrigated, mass of exported salt from the irrigable zone (D_S), average electrical conductivity of drainage during the unirrigated period (EC_{NR}) and salt contamination index (SCI) during the five study years (2004–2008).

Year	Irrigated area (%)	D_S (Mg/ha year)	EC_{NR} (dS/m)	SCI [Mg/(ha year)]/[(dS/m)]
2004	0	3.3	3.8	0.86
2005	0	0.8	3.8	0.21
2006	31	1.0	3.8	0.28
2007	68	1.5	3.8	0.41
2008	85	2.6	3.8	0.70
04–08	–	1.9	3.8	0.49

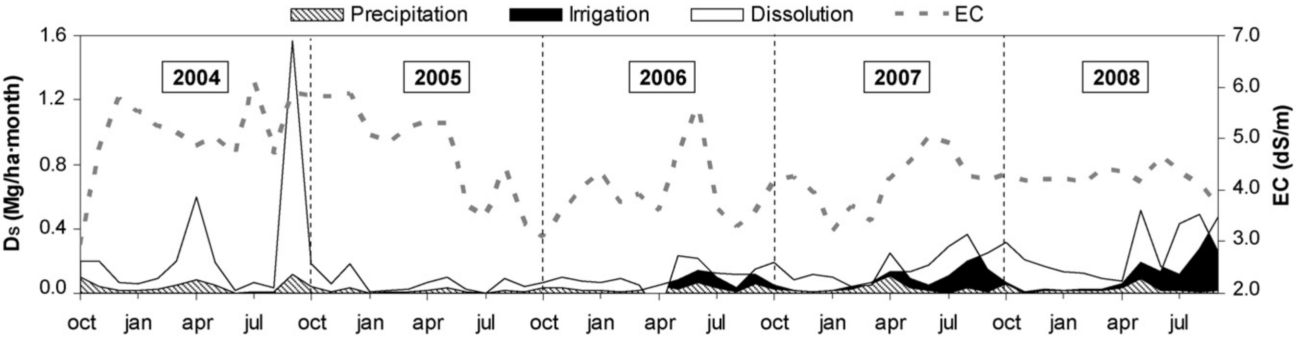

Fig. 2. Monthly evolution of the electrical conductivity of water (EC), salt exported from the irrigable zone of the Lerma basin (D_S), and the contribution of precipitation, irrigation and dissolution of geological materials, during the five study years (2004–2008).

Table 3
Exported salt (D_S), average electrical conductivity of drainage during the unirrigated period (EC_{NR}), water use index (WUI) and salt contamination index (SCI) in irrigated areas of Monegros I (Isidoro et al., 2006a,b), Monegros II (Tedeschi et al., 2001), Bardenas I (García-Garizábal, 2010) and Lerma basin (Bardenas II) in 2008.

	D_S (Mg/ha year)	EC_{NR} (dS/m)	WUI (%)	SCI [Mg/(ha year)]/[(dS/m)]
Monegros I	20.0	1.8	48	11.1
Monegros II	14.0	8.4	90	1.7
Bardenas I (low WUI)	4.5	1.1	56	4.1
Bardenas I (high WUI)	1.5	1.1	83	1.4
Bardenas II-Lerma	2.6	3.8	83	0.7

García-Garizábal (2010) demonstrated that the incremental water use in flood irrigation areas (WUI between 50 and 80%) with low salinity (EC_{NR} = 1.1 dS/m) caused a decrease of 70% in the salt contamination index, reaching levels of 1.4 [Mg/(ha year)]/[(dS/m)] that were similar to sprinkler irrigation areas (WUI = 90%) with higher salinity (EC_{NR} = 8.4 dS/m) (Tedeschi et al., 2001).

In 2008, the irrigated areas of Lerma, with moderate-high natural salinity (EC_{NR} = 3.8 dS/m) and water use (WUI = 83%), presented salt contamination indices that were inferior to other studied irrigation areas. This highlights the fact that although an increase was verified in the masses of salt exported during the first years of implementation of irrigation; the values obtained were still low considering the salinity of the area. Further, it is possible that such values will continue to increase until irrigation is completely consolidated in the area.

When analyzing the implementation of irrigation, precipitation had a lower degree of relationship ($p < 0.05$) to the masses of salt exported during the irrigated period, which was the reverse during the unirrigated period, when these were strongly related ($p < 0.001$) (Table 4). Moreover, significantly positive relationships were found between the implementation of irrigation and the masses of salt exported as well as EC of the water of the Lerma gully. This demonstrates the influence of irrigation on increasing salt concentration and masses exported, which ultimately translated into a significant increase in the salt contamination index.

Table 4
Spearman correlation for precipitation under unirrigated conditions ($P_{04–05}$), precipitation under irrigated conditions ($P_{06–08}$), irrigation (I), and water use index (WUI) with the masses of salt exported (D_S), electrical conductivity of the drainage (EC) and salt contamination index (SCI).

	$P_{04–05}$	$P_{06–08}$	I	WUI
D_S	0.993***	0.418*	0.428*	−0.335*
EC	ns	ns	0.418*	ns
SCI	–	ns	0.454**	−0.539**

ns = non significant.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

Finally, WUI, which evaluates efficiency through the wise use of water, presented negative significant relations with the masses of salt exported ($p < 0.05$) and with SCI ($p < 0.01$), indicating the importance of water management in the reduction of irrigation contamination.

4.2. Nitrate

Analyzing data of Table 5, it can be observed that the greatest nitrate input in the Lerma basin during the study period was due to irrigation water (corresponding to 45%), followed by incoming flows from unirrigable areas (41%) and rain water (14%). Annually, these percentages varied depending on the volume of rainfall and irrigation applied, such that the greatest components were rain water and incoming flows in rainy years (2004 and 2006) and the major component was irrigation in the years when irrigation was more developed (2007 and 2008).

In any case, these water balance components presented low concentrations of nitrate (average values of 2 mg/l for irrigation water, 8 mg/l for incoming flows from unirrigable areas and 0.4 mg/l for rain water). However, although these components only accounted for 10% of nitrate exported from the Lerma gully (12.3 kg NO_3-N/ha year) or stored in groundwater (8.9 kg NO_3-N/ha year), their continuous storage throughout the study buffered the amount of nitrate exported by the implementation of irrigation.

The remaining 90% (In–O–S) of nitrate exported was a result of the other components of the nitrogen cycle that were not taken into account but were primarily caused by excesses in the application of nitrogenous fertilization. According to the surveys, the annual average fertilization rate (273 kg N/ha irrigated) was 26% higher than the requirements of crops (217 kg N/ha irrigated).

It is important to note that the nitrate concentrations in the Lerma gully were already high before the implementation of irrigation, especially in dry years like 2005, when low precipitation concentrated waters. In fact, the statistical comparison between unirrigated (67 mg/l) and irrigated (54 mg/l) periods showed a lower $[NO_3^-]$ during the irrigation period ($p < 0.05$). However, when considering the period of irrigation expansion in isolation, $[NO_3^-]$ increased significantly (from 24 mg/l in 2006 to 56 mg/l in

Table 5
Nitrate masses. In: inputs [precipitation (P), irrigation (I), incoming water flows from unirrigable areas (IWF)]; O: output [water evacuated by the Lerma gully (LG)]; S: storage [in the aquifer (ΔA)] and In–O–S for the years 2004–2008.

Year	Inputs				Output	Storage	In–O–S
	P	I	IWF	Σ In	LG	ΔA	
	kg NO_3-N/ha year						
2004	0.5	0	2.6	3.1	19.3	–	−16.2
2005	0.2	0	0.3	0.5	6.3	–	−5.8
2006	0.4	0.7	0.4	1.4	6.0	3.9	−8.5
2007	0.3	1.8	0.6	2.8	10.4	25.8	−33.4
2008	0.3	2.3	0.4	3.1	19.5	14.5	−30.9
04–08	0.3	1.0	0.9	2.2	12.3	8.9	−19.0

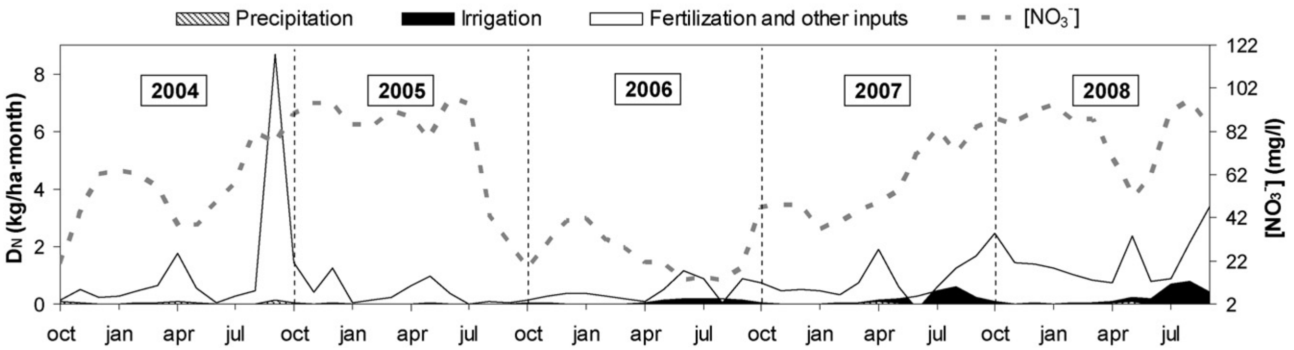

Fig. 3. Monthly evolution of nitrate concentration ($[NO_3^-]$) and nitrate exports in the irrigable area of the Lerma basin (D_N) and the contribution of precipitation, irrigation and nitrogenous fertilization and other inputs, during the five study years (2004–2008).

2007, and to 82 mg/l in 2008, $p < 0.05$), which together with the increased water flow caused a progressive increase in the nitrate circulating through the Lerma gully mainly during the summer months (Fig. 3).

It was observed that in 2004, the irrigable area exported 16.7 kg NO_3-N/ha year even without irrigation probably because heavy rains leached residual nitrate present in the soil of unirrigated agriculture of previous years (Table 6). The absence of leachable nitrate in the soil coupled with the lack of rain caused a considerable decrease in the nitrate exported in 2005 (6.0 kg NO_3-N/ha year), which lasted until 2006 (5.6 kg NO_3-N/ha year). The gradual implementation of irrigation, which began in 2006, led to a progressive increase in the fertilizer requirements of the area, thus increasing the nitrogen applied, and the mass of exported nitrate in the drainage. The greatest mass of nitrate was exported from the irrigable area in 2008 (19.1 kg NO_3-N/ha year), which was the year of highest irrigation volume applied and nitrogen fertilizer necessities.

Reports on the mass of nitrate exported in other established irrigated areas with conditions similar to those of Lerma (Cavero et al., 2003) have found concentrations that were similar as well as much higher (14 kg NO_3-N/ha year and 49 kg NO_3-N/ha year, respectively) than the maximum values exported in Lerma (19.1 kg NO_3-N/ha in 2008).

In a study conducted in unirrigated basins with twice the precipitation values of Lerma (Casalí et al., 2008), similar and even higher nitrate concentration values were obtained (16 kg NO_3-N/ha year and 37 kg NO_3-N/ha year, respectively). This demonstrates the importance of nitrogenous fertilization management, especially in areas of elevated pluviometry or under irrigation. Gheysari et al. (2009) studied the leaching of nitrate in maize areas and assessed the influence of different levels of irrigation and nitrogenous fertilization, finding maximum leachate values of 8.4 kg NO_3-N/ha year. These values are lower than those found in the Lerma basin during the years of greatest transformation (2007 and 2008), which is attributable to reduced application of fertilizers (142 kg N/ha) and greater control of irrigation (applied in function of the decline in the availability of soil water).

In Lerma, NCI was influenced by the mass of nitrate exported and by fertilizer necessities. NCI gradually increased with the transformation of the basin, from 0.07 in 2006 to 0.11 in 2008, reflecting a greater increase in exported nitrate than in fertilizer necessities.

Causapé (2009) observed that irrigated areas with nitrate contamination indices below 0.2 had reasonable use of water and nitrogen fertilizer. So far, the expansion of irrigation in the Lerma basin is being carried out with an acceptable management of nitrogen fertilizers. In fact, although the fertilization necessities of Lerma in 2008 (166 kg N/ha) were higher than in other irrigated areas studied (Table 7), the mass of nitrate exported was lower, resulting in the lowest nitrate contamination index.

During the unirrigated period, precipitation was strongly related ($p < 0.001$) to the mass of nitrate exported, but it was found to be non-significantly related after the introduction of irrigation. By contrast, a significant negative relationship started to appear between precipitation and nitrate concentration ($p < 0.05$), suggesting the dilution of irrigation return flows (Table 8). Such shifts in

Table 6
Mass of nitrate exported (D_N), fertilization necessities (FN), and nitrate contamination index (NCI) during the five study years (2004–2008).

	D_N (kg NO_3-N/ha year)	FN (kg N/ha year)	NCI (–)
2004	16.7	–	–
2005	6.0	–	–
2006	5.6	78	0.07
2007	9.7	150	0.06
2008	19.1	166	0.11
04–08	11.4	131	0.08

Table 7
Nitrate exported (D_N), fertilization necessities (FN), water use index (WUI), and nitrate contamination index (NCI) in the irrigated areas Monegros I (Isidoro et al., 2006a,b), Monegros II (Cavero et al., 2003), Bardenas I (García-Garizábal, 2010) and for the Lerma basin (Bardenas II) in 2008.

	D_N (kg NO_3-N/ha year)	FN (kg N/ha year)	WUI (%)	NCI
Monegros I	111	155	48	0.71
Monegros II	32	145	90	0.22
Bardenas I (high FN and low WUI)	101	115	56	0.88
Bardenas I (low FN and high WUI)	51	76	83	0.67
Bardenas II-Lerma	19	166	83	0.11

Table 8
Spearman correlation under unirrigated conditions (P_{04-05}), precipitation under irrigation conditions (P_{06-08}), irrigation (I), and water use index (WUI) with the mass of nitrate exported (D_N), nitrate concentration ($[NO_3^-]$) and nitrate contamination index (NCI).

	P_{04-05}	P_{06-08}	I	WUI
D_N	0.953***	ns	0.527**	−0.403*
$[NO_3^-]$	ns	−0.336*	0.358*	ns
NCI	–	ns	0.420*	−0.422*

ns = non significant.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.

relationships showcase the influence of irrigation on contamination behavior.

Additionally, significant relationships were found between irrigation and the masses of nitrate exported, nitrate concentration of drainage water and nitrate contamination index. Gheysari et al. (2009) found significant relationships between the mass of nitrate leached and the application of irrigation and nitrogenous fertilization and, like other authors (Power et al., 2001; Zotarelli et al., 2007), concluded that there is also a joint influence of irrigation and fertilization on the masses of nitrate exported.

In Lerma, the water use index also presented significant relationships with the masses exported and nitrate contamination index. As Causapé (2009) detected in other irrigated areas, in Lerma the water use index was more closely related to the salt contamination index ($p < 0.01$) than to the nitrate contamination index ($p < 0.05$), demonstrating that in the case of nitrate contamination, not only an adequate use of water is necessary, but also an adequate management of nitrogenous fertilization.

5. Conclusions

The influence of irrigation is evident as the contamination levels were mainly influenced by climatic factors during the unirrigated years, becoming strongly dependent on the management of irrigation water and nitrogenous fertilization after the introduction of irrigation. The relationship between the water use index and the salt and nitrate contamination indices indicates that adequate irrigation management, in combination with fertilization (in the case of nitrate), are key factors for sustainable development of this new irrigated area. Therefore, an increase in irrigation efficiency in the basin would contribute towards reductions in fertilizer losses and dissolution of salt, leading to a better use of nitrogen fertilizer and reduction of masses of salt and nitrate exported.

Although the values of salt and nitrate contamination at the end of this study were still low-polluting considering the natural salinity and fertilizer necessity conditions, a better adjustment of the current water and fertilizer rates applied can result in lower agroenvironmental impacts in the future and significant savings for the farmers without reductions in crop yields.

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