Nitrate Exported in Drainage Waters of Two Sprinkler-Irrigated Watersheds

J. Cavero,* A. Beltrán, and R. Aragüés

ABSTRACT

Nitrate contamination of surface waters has been linked to irrigated agriculture across the world. We determined the NO_3–N loads in the drainage waters of two sprinkler-irrigated watersheds located in the Ebro River basin (Spain) and their relationship to irrigation and N management. Crop water requirements, irrigation, N fertilization, and the volume and NO_3–N concentration of drainage waters were measured or estimated during two-year (Watershed A; 494 irrigated ha) and one-year (Watershed B; 470 irrigated ha) study periods. Maize (*Zea mays* L.) and alfalfa (*Medicago sativa* L.) were grown in 40 to 60% and 15 to 33% of the irrigated areas, respectively. The seasonal irrigation performance index (IPI) ranged from 92 to 100%, indicating high-quality management of irrigation. However, the IPI varied among fields and overirrigation occurred in 17 to 44% of the area. Soil and maize stalk nitrate contents measured at harvest indicated that N fertilizer rates could be decreased. Drainage flows were 68 mm yr^{-1} in Watershed A and 194 mm yr^{-1} in Watershed B. Drainage NO_3–N concentrations were independent of drainage flows and similar in the irrigated and nonirrigated periods (average: 23–29 mg L^{-1}). Drainage flows determined the exported mass of NO_3–N, which varied from 18 (Watershed A) to 49 (Watershed B) kg ha^{-1} yr^{-1}, representing 8 (Watershed A) and 22% (Watershed B) of the applied fertilizer plus manure N. High-quality irrigation management coupled to the split application of N through the sprinkler systems allowed a reasonable compromise between profitability and reduced N pollution in irrigation return flows.

The increasing concern of society about the negative environmental effects of intensive agriculture threatens the expansion of irrigation in many areas of the world, including the semiarid south of Europe. However, the high solar irradiation and extended frost-free periods make these areas capable of high yields of field crops without deleterious environmental effects, provided proper management of irrigation and fertilization are used.

Nitrogen is the nutrient that requires better management because it can be lost from the soil–crop system through runoff, leaching, denitrification, and volatilization. Since nitrate leaching is frequently the most important loss process in irrigated agriculture (Hubbard and Sheridan, 1983), adequate management of irrigation water is required for efficient use of nitrogen (Martin et al., 1994; Pang et al., 1997; Schepers et al., 1995; Diez et al., 2000). The amount of nitrate leached from a field is highly variable, being influenced by the irrigation system (Ritter and Manger, 1985), soil characteristics (Sogbedji et al., 2000), and climatic conditions (Klocke et al., 1999). Since nitrate leaching imposes a cost on both the farmer and the environment, it is essential to quantify these losses and establish best management practices aimed at its reduction.

Surface irrigation is the main irrigation system worldwide. Water and nitrate losses below a crop's root zone are almost unavoidable in the conventional management of surface irrigation due to low efficiency and nonuniformity of application (Bouwer et al., 1990; Pang et al., 1997). This is one of the reasons why crops are overfertilized by farmers. Thus, nitrate losses greater than 100 kg N ha^{-1} yr^{-1} have been measured in semiarid irrigated areas in Spain (Cartagena et al., 1995; Causapé et al., 2002; Moreno et al., 1996) and USA (Devitt et al., 1976; Pratt, 1984).

On the other hand, properly designed and managed sprinkler irrigation systems allow for uniform and efficient application of irrigation water, which minimizes water and nitrate losses through deep percolation (Pang et al., 1997; Power et al., 2000; Sexton et al., 1996; Smika et al., 1977). In addition, the split and timely application of fertilizer N through the sprinkler systems makes unnecessary high application rates of N at planting and reduces the risk of nitrate leaching during the early growing stages of crops (Moreno et al., 1996; Normand et al., 1997; Schroder et al., 2000).

The aim of this work was to quantify the concentration and mass of nitrate exported in the drainage waters of two sprinkler-irrigated watersheds and to analyze their relationship to irrigation and nitrogen management in these semiarid areas.

MATERIALS AND METHODS

Description of the Study Areas

The study was conducted in the irrigated areas of Watershed A (from April 1997 to March 1999) and Watershed B (from October 1997 to September 1998), located in Hydrological Sector II of the Monegros II irrigated area (Ebro River Basin, Aragón, Spain). Both watersheds drain into the Ebro River through the Valcuerna Gully. The proper name of Watershed A is "D-IX", while that for Watershed B is "D-XI." The terms

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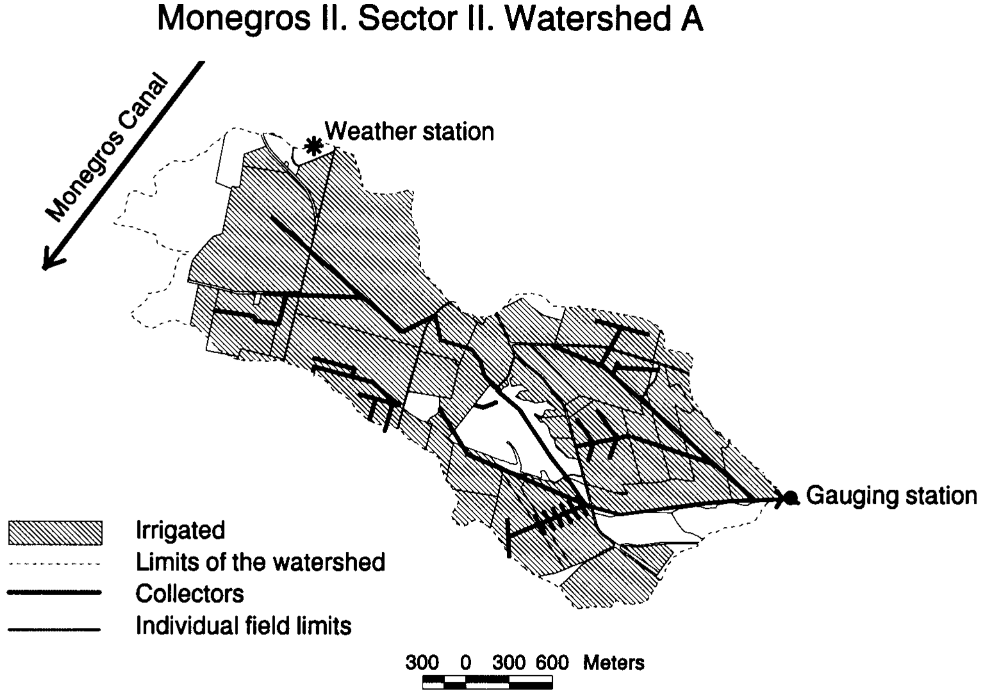
Abbreviations: IPI, irrigation performance index; NIR, net irrigation requirement; PET_c, crop potential evapotranspiration; V_{iw}, volume of irrigation water.

Watershed A and Watershed B are used in this manuscript for simplicity and clarity.

The hydrological limits of Watershed A are clearly defined (Fig. 1), and cover an area of 558 ha, which is drained through the 4.4-km-long Watershed A collector. The northwest hydrological limits of Watershed B are open and not well defined (Fig. 1). We selected a study area delimited in the northwest by the concrete-lined Monegros Canal, except for two irrigated fields that were located on the west bank of the canal. The 1007-ha study area was drained by the 5.9-km-long Watershed B collector (Fig. 1). The rest of Watershed B is dryland dedicated to winter cereals and fallow.

Three types of soils can be distinguished based on topographical position in the watersheds. The soils in the lowest areas are Typic Torrifluvents, generally deeper than 2 m, with alternating fine and coarse horizons, but mainly with clay texture. The soils of the hillsides (Typic Haplogypsids and Typic Torriorthens) are relatively shallow (<1.0 m), while the soils



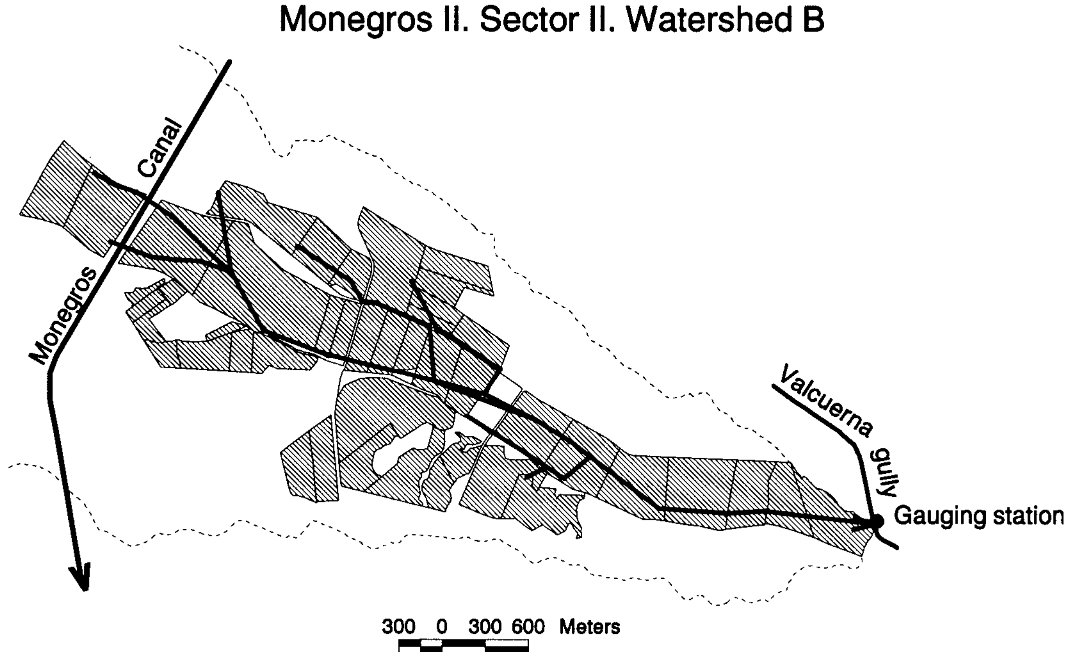


Fig. 1. Schematic layout of Watersheds A and B with indication of the hydrological limits, the main and secondary drainage collectors, the irrigated fields, and the location of the weather station and the gauging stations.

of the platforms (Typic Torriorthens) are very shallow (<0.5 m) with a clay-loam texture in both cases. The watersheds are underlain by continuous geologic substrata of impervious continental lutites. These lutites are present at relatively shallow depths (<2 m) in the hillsides of the valleys, and may temporarily create high water tables and drainage problems (Tedeschi et al., 2001).

Climate and Crop Water Requirements

The climate of the area is Mediterranean semiarid with mean annual maximum and minimum daily air temperatures of 19.8 and 8.9°C, respectively, mean annual precipitation of 296 mm, and mean annual reference evapotranspiration of 1200 mm (Martínez-Cob et al., 1998).

Daily climatic data (maximum, minimum, and mean temperature; precipitation; mean wind speed; maximum, minimum, and mean relative humidity; mean solar radiation) were collected with an automated weather station (Model CR21x; Campbell Scientific, Logan, UT) installed in the area (Fig. 1). The daily reference evapotranspiration was calculated from these climatic data using the Penman–Monteith equation. The potential evapotranspiration of each crop (PET_c) was calculated from the reference evapotranspiration and the crop coefficients derived from FAO guidelines (Doorenbos and Pruitt, 1977) and local agronomic information about the duration of the different phases of crop growth. The net irrigation requirement (NIR) during the irrigation period was computed as the difference between PET_c and the effective precipitation, which was estimated to be 75% of precipitation (Cuenca, 1989).

Water samples from three rainfall events distributed throughout the study period were collected and nitrate concentrations were determined by ion chromatography (Model 2000i/SP; Dionex, Sunnyvale, CA) (Dick and Tabatabai, 1979).

Irrigation

Irrigation development in Watersheds A and B started in 1992 and was completed by 1996. Before the transformation to irrigated land the area was dryland dedicated to a winter cereals–fallow rotation. The high-quality water (electrical conductivity [EC] < 0.4 dS m^{-1}, sodium adsorption ratio [SAR] $<$ 2) from the Monegros Canal was pumped at night to elevated reservoirs and supplied by gravity to each turnout at the demand of farmers. Watershed A had 45 irrigated fields served by 35 irrigation turnouts, which delivered water to automated solid-set sprinklers and center pivots covering 73 and 16% of the 494-ha irrigated land, respectively. The rest of the area is irrigated by means of big guns (3%), hand-moved sprinklers (7%), and linear-move systems (1%). Watershed B had 33 irrigated fields served by 27 irrigation turnouts, which delivered water to automated solid-set sprinklers and pivots covering 43 and 57%, respectively, of the 470 ha of irrigated land (Table 1).

The volumes of irrigation water diverted by each turnout were recorded weekly by reading their corresponding water meters. From these values and the areas irrigated by each turnout, the depths (mm) of irrigation water were calculated. The nitrate concentration in the irrigation water was determined by ion chromatography monthly during the irrigation season because historical data indicated that nitrate concentration was very low (<1 mg L^{-1} NO_3–N) with low variability.

Irrigation efficiency was characterized by the irrigation performance index (IPI), defined as the NIR expressed as a percentage of the volume of irrigation water (V_{iw}) delivered to the crops ($IPI = NIR/V_{iw} \times 100$) (Faci et al., 2000). Irrigation performance index values less than 100% indicate overirrigation and below this threshold the IPI index is similar to the irrigation efficiency index (Clemmens and Burt, 1997). Values greater than 100% indicate deficit irrigation and then the IPI index is not equivalent to the irrigation efficiency. Irrigation performance index values between 85 and 115% indicate high-quality irrigation management.

Nitrogen Fertilization

The crops grown in each field were recorded during the study period. A survey was conducted to determine the main characteristics of the N management by producers in 1997 for Watershed A and in 1998 for Watershed B. Farmers were asked about their methods of N application (i.e., through the irrigation water or directly to the soil) as well as the types, timing, and amount of fertilizers and manures applied. Farmers were also asked for planting and harvesting dates, irrigation management, and the crop yields obtained. The surveyed area covered 73% (maize), 45% (alfalfa), and 100% (sunflower [*Helianthus annuus* L.] and winter cereals) of the total irrigated area in Watershed A, and 52% (maize), 83% (alfalfa), 38% (winter cereals), and 100% (sunflower, pea [*Pisum sativum* L.], and bean [*Phaseolus vulgaris* L.]) of the total irrigated area in Watershed B. Table 1 shows the mean yields and the standard deviations of the surveyed crops.

The nitrogen applied as fertilizer or manure was calculated from the survey data. The N content of the manures was taken from the literature (Domínguez-Vivancos, 1997), and we assumed that 50% of the N in the manure was available to the crop during the first growing season (Smith and Peterson, 1982). We did not consider the N available from the manure applied in previous years. The N applied in the nonsurveyed fields was estimated from the mean N application rates obtained in the corresponding surveyed crops.

In October 1998, 10 maize fields, which represented 67% of the total maize area in Watershed A, were sampled in four

Table 1. Irrigated acreage and mean yield of crops grown in Watersheds A and B during the April 1997 through September 1997 and October 1997 through September 1998 study periods. Values in parentheses are standard deviations.

	Watershed A				Watershed B	
Crop	April 1997–September 1997		October 1997–September 1998		October 1997–September 1998	
	ha	Mg ha^{-1}	ha	Mg ha^{-1}	ha	Mg ha^{-1}
Maize†	269	11.2 (1.7)	208	14.0 (1.7)	267	10.7 (2.2)
Alfalfa‡	72	18.2 (1.8)	97		156	14.8 (0.4)
Sunflower§	19	2.0	61		21	1.9 (0.6)
Winter cereals† (barley and wheat)	70	5.0 (0.5)	110		10	3.5
Peas and beans	0		0		16	
Noncropped	64		18		0	

† Yield at 14% moisture content.
‡ Yield at 12% moisture content.
§ Yield at 9% moisture content.

Table 2. Potential evapotranspiration (PET_c), net irrigation requirement (NIR), mean irrigation depth (V_{iw}), and irrigation performance index (IPI) values for the crops grown in Watersheds A and B during the 1997 and 1998 irrigated periods.

	April 1997–September 1997				April 1998–September 1998					
			Watershed A				Watershed A		Watershed B	
Crop	PET_c	NIR†	V_{iw}	IPI‡	PET_c	NIR	V_{iw}	IPI	V_{iw}	IPI
	mm	mm	mm	%	mm	mm	mm	%	mm	%
Maize	624	441	414	106	769	645	728	89	726	89
Alfalfa	710	475	546	87	827	680	731	93	704	97
Sunflower	536	373	405	92	665	560	404	139	320	175
Winter cereals (barley and wheat)	272	188	154	122	293	209	179	117		
Peas and beans					801	654			532	123

† NIR = PET_c − effective precipitation.
‡ IPI = $(NIR/V_{iw}) \times 100$.

random locations per field, two weeks after the black-layer stage. The samples consisted of the ear and the stalk portion between 0.15 and 0.35 m above the soil surface of the maize plants present in two adjacent, 1-m-long rows. The ears and the stalks were oven-dried at 60°C, and the grain yield and Kjeldhal N were determined. A sample of 2 g of dry stalk was extracted with 10 mL of deionized water (Mills, 1980) and the NO_3–N was determined colorimetrically with a continuous flow autoanalyzer (Anasol; International Controlled Atmosphere, Instrument Division, Tonbridge, UK) (Keeney and Nelson, 1982). Four 2.5-cm-diameter soil cores were collected in each of the four locations at depths of 0 to 0.3, 0.3 to 0.6, and 0.6 to 0.9 m. A composite sample of the four soil cores at each depth was obtained. The NO_3–N content was determined by ion chromatography after extraction of the air-dry soil samples with a saturated $CaSO_4$ solution. A bulk density of 1.4 Mg m^{-3} was used to estimate the soil NO_3–N content in kg ha^{-1}.

Additional specific details about the N and crop management in these maize fields were obtained from the farmers. For the rest of crops of Watershed A (i.e., alfalfa, sunflower, and winter cereals) the mean N rates obtained in the 1997 survey were used in 1998.

Drainage

A mechanical water-level recorder (Model OSK 15200-MV; Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) was used to monitor flow rate through a calibrated broad-crested weir at the Watershed A gauging station (Fig. 1), whereas an electronic water level recorder (Oche, Zaragoza, Spain) monitored flow through a calibrated Parshall flume at the Watershed B gauging station (Fig. 1). The average daily heights of water were computed from the recorded instantaneous values and converted into average daily flow rates with the appropriate calibration curves.

Instantaneous drainage water samples (0.25 L in volume) were taken every two days with automatic water samplers (Model 2900; Isco, Lincoln, NE) installed in the Watershed A and B gauging stations and the NO_3–N concentrations were determined by ion chromatography. The daily and weekly masses of NO_3–N exported from each watershed were calculated from the volumes of drainage and the NO_3–N concentrations.

RESULTS AND DISCUSSION

Irrigation

The PET_c of crops and the NIR were substantially lower in 1997 than in 1998 (Table 2). In both years, alfalfa had the highest PET_c, followed by maize, sunflower, and winter cereals. The precipitation depths were 314 mm (well above the average value in the area) in the 1997 irrigation period and 196 mm (average value in the area) in the 1998 irrigation period (Table 2). The irrigation depths (V_{iw}) applied in 1998 to maize and alfalfa were similar in Watersheds A and B and much higher than those in Watershed A during 1997 (Table 2).

The seasonal IPI values for maize and alfalfa were within 100 ± 15% in both irrigation periods and watersheds, whereas the rest of crops, except sunflower in 1997, were deficit-irrigated (Table 2). When all the crops were computed together, the seasonal mean IPI values varied between 100 and 92% (Fig. 2), indicating that the average irrigation management in both watersheds was excellent.

Nevertheless, the IPI values computed at the irrigation turnout level were rather variable with coefficients of variation of the seasonal mean IPI values of 25 and 36% for Watershed A in 1997 and 1998, respectively, and 29% for Watershed B in 1998, suggesting that water management differed among farmers. Thus, overirrigation (IPI < 85%) was attained in 17 and 27% for Watershed A in 1997 and 1998, respectively, and 44% for Watershed B in 1998 of the total irrigated areas.

A trend in IPI during the irrigation period was also evident (Fig. 2), so that the IPI values tended to increase as the irrigation season progressed. Overirrigation was most common in April, mainly due to the maize post-planting irrigations given to promote maize emergence

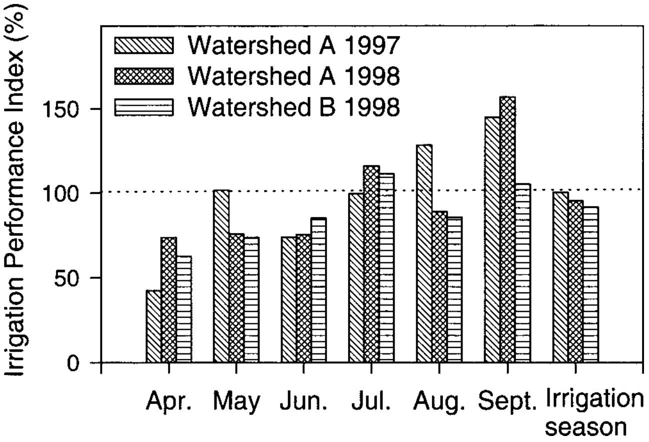


Fig. 2. Irrigation performance index [IPI = $(NIR/V_{iw}) \times 100$, where NIR is net irrigation requirement and V_{iw} is the volume of irrigation water] for the 1997 and 1998 irrigated months and the 1997 and 1998 irrigated seasons in Watersheds A and B.

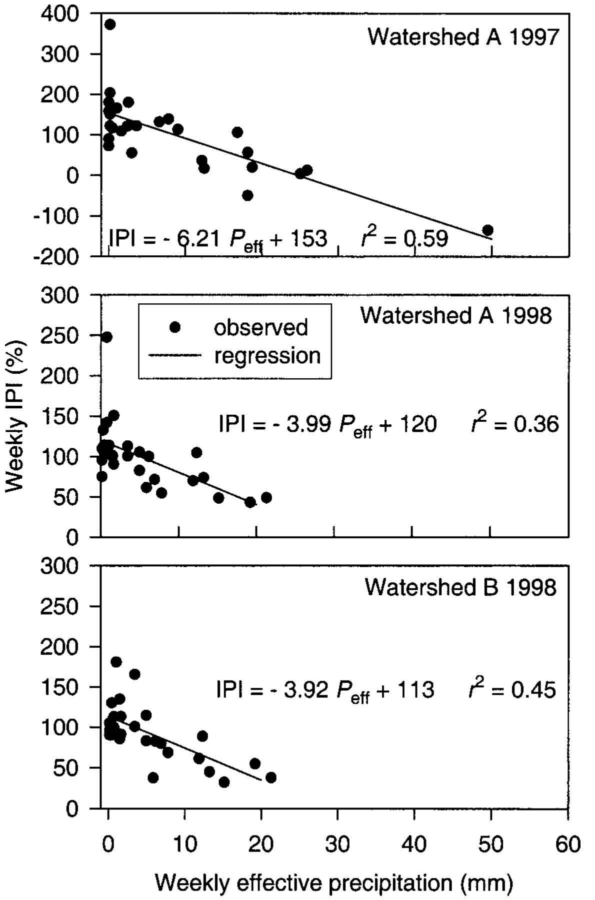


Fig. 3. Relationships and linear regression equations between the weekly irrigation performance index (IPI) values and the weekly volumes of effective precipitation (P_{eff}) in Watershed A (1997 and 1998 irrigation season) and Watershed B (1998 irrigation season).

in these crusting-susceptible soils. Thus, the survey of farmer practices revealed that they irrigated maize three to five times postplanting, with an average depth of 22 mm per irrigation. High frequency irrigation is effective against soil crusting, but taking into account that the irrigation systems allow for smaller irrigations, the irrigation depths should be minimized during this period to prevent deep percolation of water.

The analysis of the relationships between the weekly IPI and the weekly PET_c, effective precipitation, and V_{iw}, the three variables included in its calculation, indicated that the only significant ($P < 0.001$) correlation in Watersheds A and B were the negative correlations between IPI and effective precipitation (Fig. 3), suggesting that precipitation was not adequately accounted for in the scheduling of irrigation. Presumably, the farmers hesitated to modify their computerized irrigation programming on the basis of the precipitation events.

These results show that the overall irrigation management performance in Watersheds A and B was within acceptable limits, although precipitation depths should be properly incorporated in the irrigation scheduling, the volumes of irrigation given to maize in April to promote its emergence should be minimized, and the irrigation depths given to sunflower, winter cereals, peas, and beans should be increased to match their net irrigation requirements.

Nitrogen Fertilization

Maize was the most widely grown crop in the study areas, followed by alfalfa. As compared with long-term average values in nearby areas, the mean yields of maize (11–14 Mg ha^{-1}) and alfalfa (15–18 Mg ha^{-1}) were in the high range, while those for sunflower (2 Mg ha^{-1}) and winter cereals (3.5–5 Mg ha^{-1}) were in the low range (Table 1). As previously indicated, the low yields of winter cereals and sunflower were probably a consequence of the insufficient irrigation, which did not meet the NIR of these crops.

Maize received 318 to 320 kg ha^{-1} of fertilizer N, similarly in both watersheds and years (Table 3). These rates were moderate compared with those applied in other Spanish irrigated areas (Moreno et al., 1996; Román et al., 1996). The average available N for the crop, estimated as the fertilizer N plus 50% of the manure N, was 350 kg ha^{-1}, and the average maize yield was 12 Mg ha^{-1}. Thus, the average N application rate per unit maize grain yield was 29 kg N Mg^{-1}, similar to the recommended value of 28 to 30 kg N Mg^{-1} (Betrán and Pérez-Bergés, 1994). However, this recommended rate was determined in flood-irrigated experiments, where irrigation efficiency is usually lower.

The preplant fertilizer N applied to maize ranged between 47 and 32% of the total fertilizer N, and the manure applied at preplanting covered 53 to 60% (Watershed A) and 27% (Watershed B) of the maize growing area, with mean N rates of approximately 50 kg ha^{-1} (Watershed A) and 74 kg ha^{-1} (Watershed B) (Table 3).

Table 3. Mean rates of nitrogen (N) applied as fertilizer or manure, and percentage of N fertilizer applied at preplanting to the crops grown in Watersheds A and B. Values in parentheses are standard deviations.

	Watershed A						Watershed B		
	April 1997–September 1997			October 1997–September 1998			October 1997–September 1998		
	Fertilizer	Manure	Preplant	Fertilizer	Manure	Preplant	Fertilizer	Manure	Preplant
	—— kg N ha^{-1} ——		%	—— kg N ha^{-1} ——		%	—— kg N ha^{-1} ——		%
Maize	**318 (60)**	**53 (64)**	**47 (25)**	**320 (63)**	**48 (56)**	**32 (17)**	**318 (36)**	**74 (143)**	**36 (27)**
Alfalfa	**55 (27)**		**†**				**34 (24)**		**†**
Sunflower	**62 (0)**		**54 (0)**				**100 (85)**		**70 (42)**
Winter cereals (barley and wheat)	**145 (38)‡**		**34 (6)**				**155 (0)**		**26 (0)**
Peas							**50 (0)**		**100 (0)**

† Fifty percent of the alfalfa fields received all the N before the start of growth in February; in the rest of fields the N was split between February and July.
‡ Includes the preplanting application before the irrigation period considered.

In Watershed A, approximately 70% of the total postplant N applied to maize was supplied through the irrigation systems in one to three applications (from the six-leaf to the tassel-emergence stage) of a 32% N urea–nitrate–ammonium (50–25–25) solution, and the rest was supplied as urea (46% N) mechanically broadcasted over the soil at the maize six-leaf stage. In contrast, only 40% of the total postplant N applied to maize in Watershed B was supplied through the irrigation systems.

The rates of N fertilizer applied to alfalfa, peas, and beans were low (50–55 kg ha^{-1}). Sunflower received moderate N rates (62–100 kg ha^{-1}) with 54 to 70% applied at preplanting and the rest in a postplant application through the irrigation systems. Winter cereals received approximately 150 kg N ha^{-1} with 26 to 34% applied at preplanting and the rest as ammonium nitrate (33.5% N) or urea applied mechanically (Table 3).

The results of the surveyed (Watershed A in 1997 and Watershed B in 1998) and measured (Watershed A in 1998) maize fields indicate that grain yields increased with increases in the available N up to approximately 400 kg ha^{-1}, and then they tended to decrease. However, only 6 out of the 31 maize fields surveyed had available N values higher than 400 kg ha^{-1} (Fig. 4A). Maize grain yield was independent of the proportion of the total N applied at preplanting, although yields higher than approximately 12 Mg ha^{-1} were only found when less than about 45% of the N was applied before planting (Fig. 4B). Higher proportions of preplant N were ineffective in promoting maize yields and could lead to potential losses of N below the root zone.

The results of the 10 maize fields sampled in October 1998 in Watershed A suggest that, within the measured ranges, grain N was independent of total and postplant fertilizer N (Fig. 5A,E). The stalk N and the stalk NO_3–N tended to increase as the N applied increased just above thresholds for total and postplant N of 350 kg ha^{-1} (Fig. 5B,C) and 300 kg ha^{-1} (Fig. 5F,G), respectively. Stalk NO_3–N contents measured in 70% of the maize fields were above the 0.07 to 0.2% range proposed by Binford et al. (1992) as indicative of N overfertilization, and the stalk N contents measured in all the maize fields were higher than the value of 0.43% proposed by Binford et al. (1990) as indicative of excess N. However, these threshold values were obtained under more humid climatic conditions and without irrigation. According to Villar (1999), a stalk N threshold value of 0.5% would be more appropriate for the climatic and cropping conditions of this study. Thus, considering the stalk N and stalk NO_3–N found and the thresholds established by Villar (1999) and Binford et al. (1992), respectively, 60 to 70% of the sampled fields were overfertilized (Fig. 5B,C).

The NO_3–N content of the soils sampled at maize harvest ranged between 42 and 284 kg ha^{-1}, with a mean value of 117 kg ha^{-1}. With some exceptions, soil NO_3–N tended to increase with increasing applications of total and postplant N (Fig. 5D,H). However, the soil NO_3–N content at maize harvest is not only determined by the balance of N inputs and N uptake, but also by the N losses during the growing season (Schroder et al., 2000) that are mostly related to irrigation management. Thus, the field that received the highest rate of fertilizer N

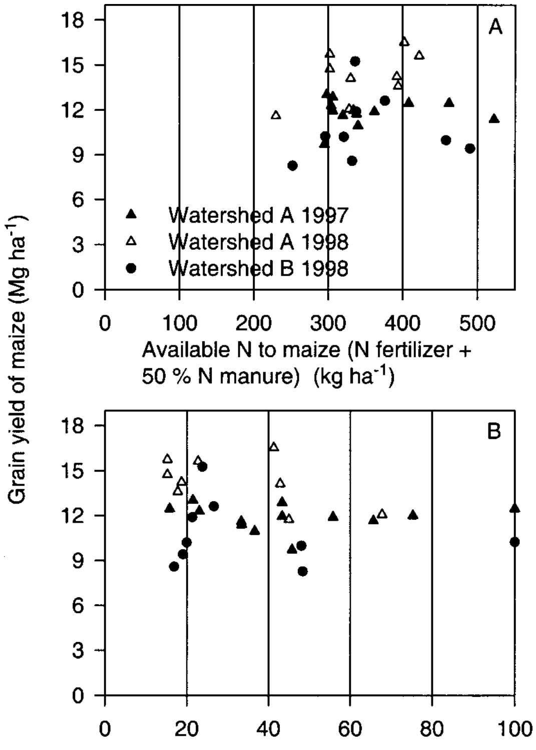


Fig. 4. Relationships between maize grain yield and (*A*) available N and (*B*) percent of total N applied at maize preplanting.

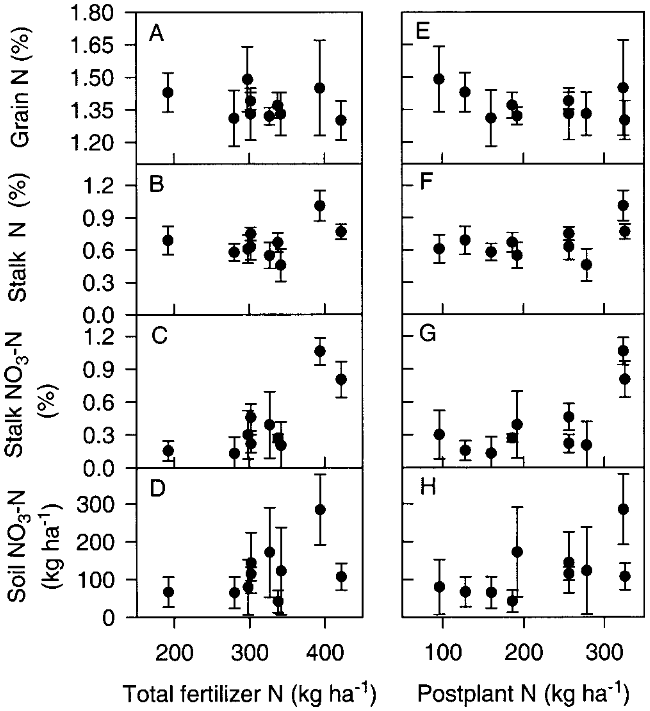


Fig. 5. Relationships between maize grain N (*A* and *E*), stalk N (*B* and *F*), stalk NO_3–N (*C* and *G*), and soil NO_3–N (*D* and *H*), and total and postplant applied fertilizer N measured in 1998 at 10 maize fields of Watershed A at harvest. Each point is the mean ± standard deviation of four sampling locations within each field.

(422 kg ha^{-1}; Fig. 5D) had a low value of 105 kg soil NO_3–N ha^{-1} due to nitrate leaching derived from the shallow-depth (<0.35 m) soil in this field and the high volume of irrigation water applied, which was 33% above the maize NIR.

The N and NO_3–N content in the basal portion of the maize stalk and the residual soil NO_3–N content at maize harvesting found in our work indicate that the N rates applied to maize could be reduced, thereby decreasing the potential for nitrate losses in drainage waters (Schepers et al., 1991). In central Spain, Diez et al. (2000) found similar yields when applying 150 kg N ha^{-1}. Our results also show that the timing of applications could be improved by decreasing the proportion of total N applied at preplanting (high maize yields were only obtained when preplant N was less than 45% of total N), which could be easily accomplished by increasing the N applications through the irrigation system.

Drainage

In general, drainage flow rates measured at the Watershed A and B gauging stations were lowest during the winter months and immediately before the commencement of the irrigation period in March. Drainage increased during the irrigation season and decreased again at the end of the irrigation period in September (Fig. 6A). Obviously, this trend was due to the irrigation

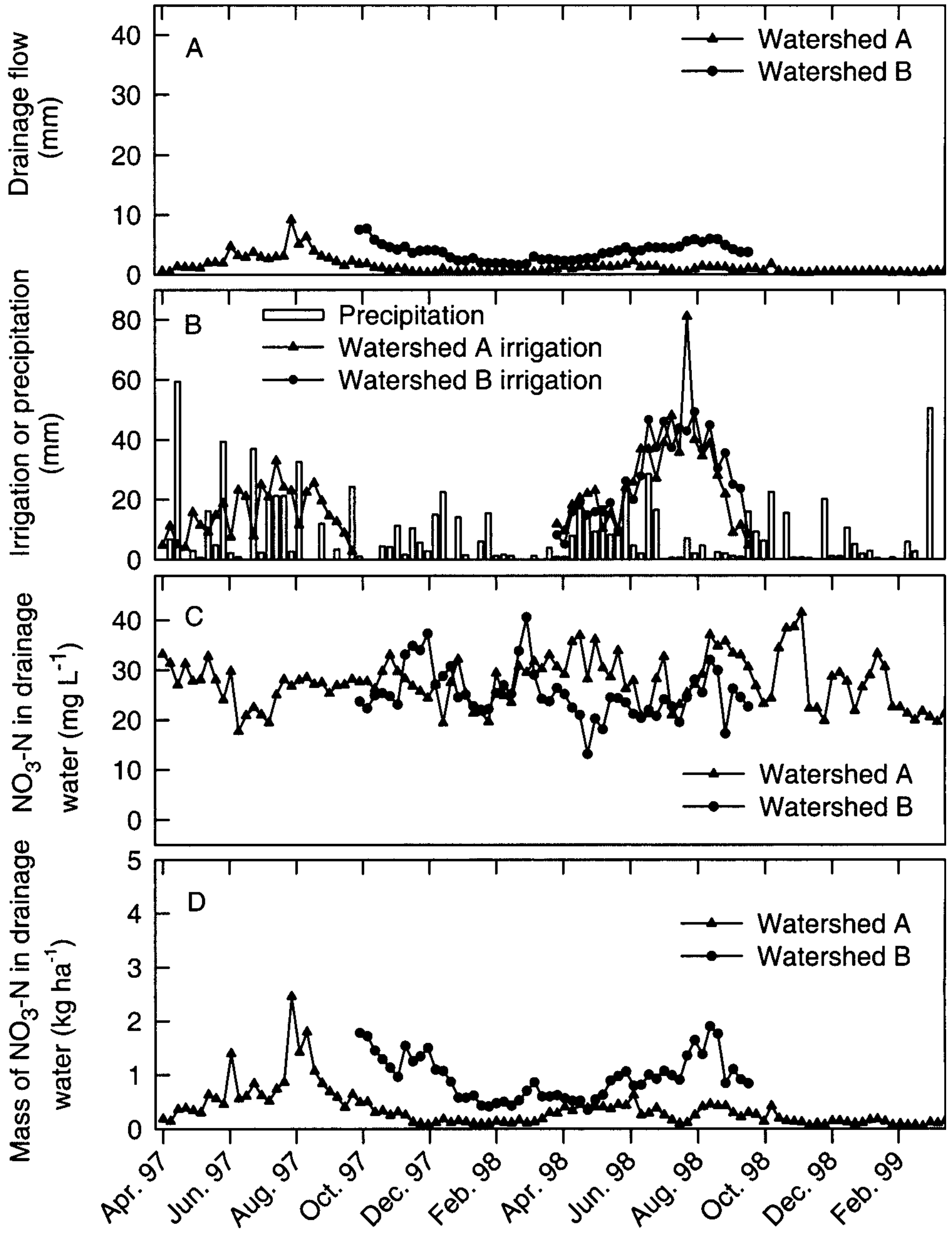


Fig. 6. Weekly values of drainage flow (*A*), irrigation and precipitation (*B*), NO_3–N concentration in drainage water (*C*), and NO_3–N load in drainage water (*D*) in the study periods April 1997 through March 1999 (Watershed A) and October 1997 through September 1998 (Watershed B). The scale for drainage flow is double the scales for irrigation and precipitation.

Table 4. Volume of drainage water per unit irrigated area (D) and mean NO_3–N concentration of the drainage water at the Watershed A and B gauging stations during the given irrigated and nonirrigated periods. Values in parentheses are standard deviations.

	Watershed A gauging station		Watershed B gauging station	
Study period	D	NO_3–N	D	NO_3–N
	mm	mg L^{-1}	mm	mg L^{-1}
Irrigated, April 1997–September 1997	74	26.3 (5.3)		
Nonirrigated, October 1997–March 1998	18	26.9 (7.1)	89	28.1 (5.8)
Irrigated, April 1998–September 1998	30	29.2 (10.1)	105	23.1 (4.9)
Nonirrigated, October 1998–March 1999	13	26.1 (7.8)		

return flows resulting from excess water applied to some fields. However, precipitation also affected drainage flows, as shown by the higher flows measured at the Watershed A gauging station in 1997 (irrigated-season precipitation = 314 mm) than in 1998 (irrigated-season precipitation = 196 mm) (Fig. 6B).

The high-quality irrigation management in both study areas resulted in relatively low drainage flows (Table 4), which represented 5 to 11% of the irrigation + precipitation water entering in Watershed A and 18% of the irrigation + precipitation water entering in Watershed B (Table 5). The patterns of flow measured at the Watershed A and B gauging stations were similar, but higher in the Watershed B gauging station than in the Watershed A gauging station (Fig. 6A). Thus, for the 1998 hydrological year, October 1997 through September 1998, the volumes of drainage per unit irrigated area were 194 mm in Watershed B but only 48 mm in Watershed A (Table 4). The higher drainage in Watershed B was attributed to (i) the seepage of the Monegros Canal, that accounted for 33 mm during the irrigation period (Table 5), (ii) the contribution from precipitation falling on the larger area of nonirrigated land within this watershed (Fig. 1), and (iii) the larger overirrigated area in Watershed B (44% of the total irrigated area in 1998) than in Watershed A (27% of the total irrigated area in 1998).

The NO_3–N concentrations in the drainage waters ranged between 7 and 55 mg L^{-1} (Watershed A gauging station) and between 9 and 42 mg L^{-1} (Watershed B gauging station), and 98% of the water samples had values above 10 mg L^{-1}. In general, the weekly NO_3–N concentrations were higher at the beginning (April–May) and end (August–September) of the irrigation periods, and decreased during June and July (Fig. 6C). The higher concentrations at the beginning of the irrigation periods were attributed to the preplanting applications of N to maize (Bjorneberg et al., 1996) in a period of low irrigation efficiencies (Fig. 2), and to the postplant applications of N to winter cereals (Table 3), whereas the lower concentrations in June and July were related to the period of maximum N uptake by maize, coupled to IPI values higher than 100% in July (Fig. 2).

In contrast, Isidoro (1999) found higher drainage NO_3–N concentrations in June and July than in April and May in La Violada irrigation district. The opposite behavior in these two nearby areas was attributed to differences in nitrogen and irrigation water management. All the maize postplant N was applied to the soil in June in La Violada, as compared with the split applications through the irrigation water in Watersheds A and B. Moreover, in June and July the IPI values in the La Violada level-basin irrigated district were lower than 50%, as compared with values between 70 and 110% in Watersheds A and B.

The mean NO_3–N concentrations during the irrigated and nonirrigated seasons were similar (not significantly different at $P < 0.05$) in both watersheds, ranging between 26 and 29 mg L^{-1} at the Watershed A gauging station and between 23 and 28 mg L^{-1} at the Watershed B gauging station (Table 4). The lower irrigated-season NO_3–N concentration at the Watershed B gauging station (23 mg L^{-1}) than at the Watershed A gauging station (29 mg L^{-1}) may be a result of the low-nitrate Monegros Canal seepage water collected at the Watershed B gauging station. The NO_3–N concentrations of the drainage water were similar to those found in other studies (Kladivko et al., 1991; Klocke et al., 1999) and moderately higher than the 20 mg L^{-1} value suggested by Keeney (1982) as the lowest achievable concentration in the drainage waters of many irrigated fields under good agronomic practices and profitable crop productions. However, these concentrations are double the threshold human consumption NO_3–N concentrations established by the USEPA (10 mg L^{-1}) and the European Union (11.3 mg L^{-1}).

Table 5. Water balance at Watersheds A and B.

	Inputs			Outputs		
Period	Irrigation	Precipitation	Canal seepage	PET_c†	Drainage	Inputs − outputs
	mm					
	Watershed A					
April 1997–March 1998	382	439		734	93	−6
April 1998–March 1999	565	353		845	43	30
October 1997–September 1998	583	321		865	48	−9
	Watershed B					
October 1997–September 1998	740	321	33	1008	194	−109

† Crop potential evapotranspiration.

Water Balance

Deep percolation was not measured, although it may be approximated by the input − output difference if steady state conditions are assumed. This assumption may be acceptable for an annual period, but not for just the irrigated or the nonirrigated periods. The water balance in Watershed A (Table 5) indicated that deep percolation was negligible and that the difference between inputs and outputs was less than 4% of the total input or output water. The negative value obtained in Watershed B suggests that there was not deep percolation and that the outputs were overestimated and/or the inputs were underestimated (Table 5). Thus, in Watershed B the actual evapotranspiration was probably lower than the calculated PET_c, since this was estimated assuming maximum potential crop yields, and the peas–beans and sunflower crops were underirrigated (Table 2). Also, a nonmeasured ground water input to the Watershed B study area could result from precipitation in its large dry-land watershed, which could explain its negative water balance. In any case, the difference between the inputs and outputs in Watershed B was less than 10% of the total input or output water, indicating that the closure of the water balance was satisfactory. The better closure of the water balance in Watershed A than in Watershed B during the study period, but also when comparing the same time period (October 1997–September 1998) (Table 5), suggest that results from Watershed A were more reliable.

Nitrate Nitrogen Loads in Drainage Waters as Affected by Irrigation and Nitrogen Fertilization Management

The estimated mass of N fertilizer and manure applied to Watersheds A and B varied between 166 and 221 kg ha^{-1} in the irrigated seasons and between 3 and 32 kg ha^{-1} in the nonirrigated seasons, representing more than 93% (irrigated season) and 57% (nonirrigated season) of the total imported mass of N (Table 6). This is an expected result due to the low average NO_3–N concentrations measured in the irrigation (1.14 mg L^{-1}) and precipitation (1.94 mg L^{-1}) waters.

The weekly NO_3–N loads (Fig. 6D) paralleled the weekly drainage flow rates (Fig. 6A) in both monitoring stations, and they were linearly correlated ($P < 0.001$) so that each millimeter of drainage produced losses of 0.27 (Watershed A) and 0.25 (Watershed B) kg NO_3–N ha^{-1}. Thus, as found in other studies (Bjorneberg et al., 1996; Ritter et al., 1991), the volume of drainage basically determined the exported mass of nitrates.

The mass of NO_3–N exported by Watershed A drainage waters varied between 19 and 9 kg ha^{-1} in the irrigated periods and between 5 and 4 kg ha^{-1} in the nonirrigated periods (Table 6). The mass of NO_3–N exported by the Watershed B drainage waters was higher than that in Watershed A and similar (i.e., approximately 25 kg ha^{-1}) in the irrigated and nonirrigated periods. As previously indicated, the higher NO_3–N loads in Watershed B were mainly attributed to the higher drainage flows derived from the precipitation falling in its larger watershed. Other reasons for the higher NO_3–N loads in Watershed B could be its larger relative area cropped with maize (57% and 42–54% of the irrigated areas in Watersheds B and A, respectively), which was the crop with the highest N fertilizer rates, and also the lower postplant application of N to maize through the irrigation system (40 and 70% of the postplant N in Watersheds B and A, respectively). The appropriate splitting of N in the irrigation water has been proposed as an efficient and low-cost practice to reduce nitrate leaching losses in areas of low precipitation (Kessavalou et al., 1996; Power et al., 2000; Schepers et al., 1995).

The higher NO_3–N load in Watershed A during the irrigation period of 1997 compared with the irrigation period of 1998 (Table 6) was attributed to the above-average precipitation of 314 mm in 1997, as compared with the precipitation of 196 mm in 1997, which was similar to the historical average. Since precipitation events are for the most part unpredictable, it should be recognized that some nitrate losses are unavoidable, even under a farmer's best management practices.

The mass of exported N expressed in percent of the applied fertilizer plus manure N was 5 to 9% for irrigation periods and 15 to 25% for nonirrigation periods in Watershed A, and 11% for the irrigation period and 733% for the nonirrigation period in Watershed B (Table 6). Considering the entire study periods for each watershed, NO_3–N loads represented 8.5% of the applied fertilizer plus manure N in Watershed A and 21.8% in Watershed B. Since closure of the water balance (Table 5) was better in Watershed A than in Water-

Table 6. Imported mass of N through irrigation, precipitation, and fertilizer + manure, and exported mass of NO_3–N in the drainage waters of Watersheds A and B. Mass values given per unit irrigated area. The exported N is also given as percent of the fertilizer + manure mass of N.

	Imported N					
Period	Irrigation	Precipitation	Fertilizer + manure	Total	Exported NO_3–N in drainage water	
	kg ha^{-1} irrigated land					% of fertilizer + manure
		Watershed A				
Irrigated, April 1997–September 1997	1.6	6.1	209.6	217.3	19.4	9
Nonirrigated, October 1997–March 1998	0.0	2.4	32.4	34.8	5.0	15
Irrigated, April 1998–September 1998	8.8	3.8	166.3	178.7	8.9	5
Nonirrigated, October 1998–March 1999	0.0	3.1	14.0	17.1	3.5	25
		Watershed B				
Nonirrigated, October 1997–March 1998	0.0	2.4	3.3	5.7	24.2	733
Irrigated, April 1998–September 1998	9.9	3.8	221.4	235.1	24.8	11

shed B and the hydrological limits of Watershed B were not restricted to the studied area, the 8.5% figure found in Watershed A can be considered as more representative of the NO_3–N load losses derived from irrigated agriculture in this area.

The NO_3–N loads measured in the drainage waters were, in general, lower than those reported in other watersheds of the Ebro River basin with similar crops and climatic conditions but surface-irrigated (Basso, 1994; Causapé et al., 2002; Isidoro, 1999). Basso (1994) reported in a three-year study mean annual NO_3–N losses of 35 to 59 kg ha^{-1} in the Bardenas I irrigation district, which represented 16 to 30% of the applied fertilizer N. Causapé et al. (2002) found annual NO_3–N losses of 98 and 195 kg ha^{-1}, representing 44 and 56% of the applied fertilizer N, in two watersheds of the Bardenas I district. Finally, Isidoro (1999) reported in a two-year study in the La Violada irrigation district (Monegros I) mean annual NO_3–N losses of 68 kg ha^{-1} or 23% of the applied fertilizer N.

The drainage NO_3–N losses, particularly those found in Watershed A that can be considered as more representative for our study area, were in the low range of those reported in other studies around the world. In the semiarid conditions of west-central Nebraska (394 mm of precipitation from April to September), Klocke et al. (1999) found under sprinkler irrigation mean annual losses of 52 kg NO_3–N ha^{-1} (27% of applied fertilizer N) for continuous maize and 91 kg NO_3–N ha^{-1} (105% of applied fertilizer N) for a maize–soybean [*Glycine max* (L.) Merr.] rotation. The Management Systems Evaluation Area (MSEA) results from Iowa (nonirrigated maize and soybean) found annual losses of 4 to 66 kg NO_3–N ha^{-1}, representing 6 to 115% of the applied fertilizer N (Jaynes et al., 1999). Pratt (1984) found in various irrigated areas of California annual average losses of 82 kg NO_3–N ha^{-1} (50% of the applied fertilizer N). In summary, despite the relatively high drainage NO_3–N concentrations found in our work, the low drainage discharges derived from high-quality irrigation management resulted in NO_3–N loads that were in the low range of those measured in other irrigated areas.

CONCLUSIONS

Under the semiarid climatic conditions of the Ebro River basin, most water for crops is provided through irrigation. Consequently, irrigation management greatly influences nitrate losses in drainage waters. The high quality of irrigation water in the Monegros irrigation area allows for negligible leaching fractions.

Our work indicates that the high quality of irrigation management (IPI within 100 ± 15) attained with sprinkler irrigation, coupled to the postplanting splitting of fertilizer N through the irrigation systems, resulted in relatively low annual drainage NO_3–N losses (8.5% of the applied N for the more representative and well-managed watershed). Nevertheless, there is room for improvement within the studied watersheds, since (i) a substantial part of the plots (17–44% of the total irrigated area, depending on years and watersheds) was overirrigated, (ii) farmers did not account properly for precipitation on the scheduling of irrigation, (iii) postplanting irrigation depths given to promote maize emergence could be decreased, (iv) a large proportion (60–70%) of the sampled maize fields were overfertilized, and (v) a larger fraction of fertilizer N could be split through its application with the irrigation water rather than applying it as preplant fertilizer. Taking into account these considerations, nitrate leaching losses in the drainage waters of these irrigated watersheds could be further decreased.

Although nitrogen pollution regulations are generally based on maximum allowable concentrations (MAC), the mass of nitrogen exported per unit irrigated area is important for controlling the nitrogen contamination in the receiving water bodies. Thus, even though drainage nitrate concentrations in the study areas are above the MAC, their nitrogen loads can be considered low, allowing for the attainment of a sensible compromise between profitability and N pollution in irrigation return flows.

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