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IRRIGATION EFFICIENCY AND QUALITY OF IRRIGATION RETURN FLOWS IN THE EBRO RIVER BASIN: AN OVERVIEW

J. CAUSAPÉ*, D. QUÍLEZ and R. ARAGÜÉS
Unidad de Suelos y Riegos, Centro de Investigación y Tecnología Agroalimentaria de Aragón (Diputación General de Aragón), y Laboratorio de Agronomía y Medio Ambiente (DGA-CSIC), Apdo. 727, 50.080-Zaragoza, Spain
*(*author for correspondence, email: jcausape@aragon.es)*

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Abstract. The review analysis of twenty two irrigation efficiency (IE) studies carried out in the Ebro River Basin shows that IE is low (average $IE_{avg} = 53\%$) in surface-irrigated areas with high-permeable and shallow soils inadequate for this irrigation system, high ($IE_{avg} = 79\%$) in surface-irrigated areas with appropriate soils for this system, and very high ($IE_{avg} = 94\%$) in modern, automated and well managed sprinkler-irrigated areas. The unitary salt (total dissolved solids) and nitrate loads exported in the irrigation return flows (IRF) of seven districts vary, depending on soil salinity and on irrigation and *N* fertilization management, between 3–16 Mg salt/ha·year and 23–195 kg NO_3^--N/ha·year, respectively. The lower nitrate loads exported from high IE districts show that a proper irrigation design and management is a key factor to reduce off-site nitrogen pollution. Although high IE's also reduce off-site salt pollution, the presence of salts in the soil or subsoil may induce relatively high salt loads (≥14 Mg/ha·year) even in high IE districts. Two important constrains identified in our revision were the short duration of most surveys and the lack of standards for conducting irrigation efficiency and mass balance studies at the irrigation district level. These limitations emphasize the need for the establishment of a permanent and standardized network of drainage monitoring stations for the appropriate off-site pollution diagnosis and control of irrigated agriculture.

Keywords: concentration, irrigation water, load, nitrate, off-site pollution, salinity

1. Introduction and Objectives

Irrigated agriculture is the main user of water in the Ebro River Basin with almost 0.7 million irrigated hectares (Figure 1) and a total water demand of 6,310 Hm^3/year (CHE, 1996). Surface waters, mainly derived from the Pyrenees, irrigate 91% of the land, and the rest is irrigated with groundwaters. Surface irrigation is the main irrigation system (69% of total), followed by sprinkler (19%) and drip (11%) systems (INE, 2003).

The efficiency of irrigation and the quality of the irrigation return flows (IRF) are important factors controlling water availability for downstream users. The volume of water scheduled by the Ebro Basin Authority (Confederacion Hidrográfica del Ebro, CHE) to the different irrigation districts is based on their net crop water needs corrected by some coefficients which depend on rain probability and the global irrigation efficiency (IE: the percentage of applied water consumed by crops) of

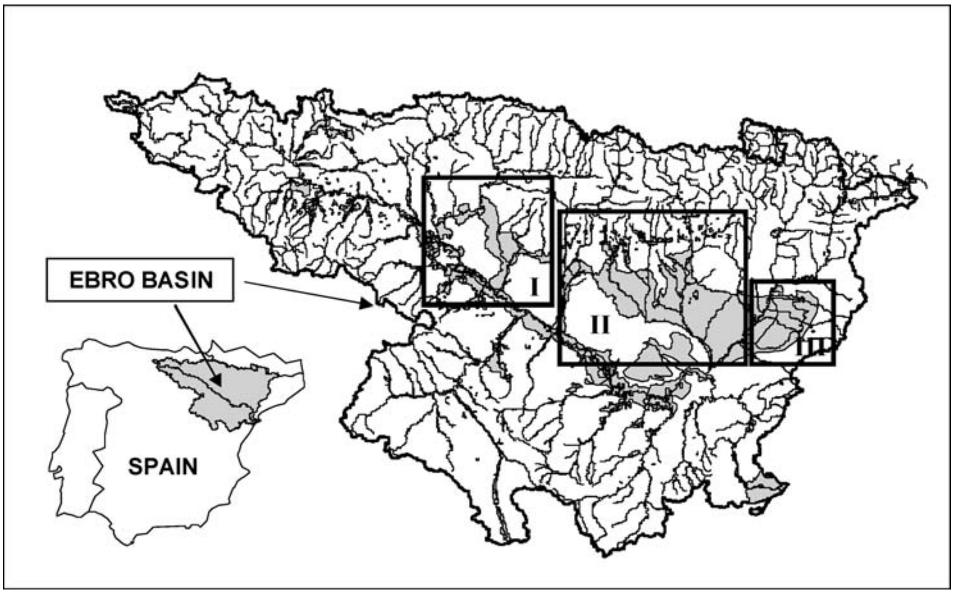

Figure 1. Distribution of the irrigable land in the Ebro River Basin. The total irrigated area in 1999 was 682,359 ha (INE, 2003). The study sites are located in the west (I), central (II) and east (III) zones of the Basin.

the given district. The global IE in the large irrigated perimeters of the Ebro River Basin has been estimated at 60%, but a detailed study analysing its variability as affected by crops, soils and irrigation systems and management is lacking.

The return flows from irrigated agriculture (IRF: irrigation return flows) have long been recognized as the major diffuse or "non-point" contributor to the pollution of surface and groundwater bodies (Aragüés and Tanji, 2003). The water quality in the Ebro River Basin is predominantly affected by dissolved salts and nitrates present in IRF. The increasing salinity trends observed in many rivers of this Basin (Quílez, 1998) and the nitrate concentrations measured in the groundwater monitoring network implemented by CHE demonstrate the increases in environmental pollution induced by IRF.

The highest salt concentrations have been measured in IRF from salt-affected soils, reaching values as high as ten times the maximum allowable salt concentrations for human consumption (2.5 dS/m, European Union, 1998). Salinity of IRF from non-saline areas are much lower (generally electrical conductivity EC < 1.5 dS/m), but they are still two to five times higher than those of the corresponding irrigation waters.

Nitrate concentrations as high as 250 mg/L (i.e., five times the sanitary limit of 50 mg/l set in Europe; European Union, 1998) have been recorded in shallow aquifers located in intensive agricultural areas. Surface waters in irrigated areas are more diluted and rarely reach 50 mg/L, but their nitrate concentrations can be still one order of magnitude higher than those present in uncontaminated waters.

The monitoring of water quality in water courses receiving IRF has shown that the salt and nitrate concentrations tend to increase along the direction of the flow of water and in periods with low flows (winter). However, maximum nitrate concentrations have also been measured at times of nitrogen fertilizer applications, especially in corn (June–July) (Isidoro, 1999; Causapé *et al.*, 2004a).

In compliance with one objective of the European Water Framework Directive (European Union, 2000) (i.e., the attainment of a good ecological status of water bodies), CHE is supporting in recent years studies to characterize the water quality in the Ebro Basin (CHE, 1998, 2001a, b, 2002). However, the impact of IRF on the natural quality of waters has not been evaluated in detail.

The objectives of this study are (1) to synthesize, analyze and relate the available information on the irrigation efficiency (IE) and the volume and quality (salts and nitrates) of irrigation returns flows in selected irrigated areas of the Ebro River Basin, and (2) to establish proposals for off-site pollution control of irrigated agriculture in this Basin.

2. Materials and Methods

A total of 103 studies carried out in irrigated areas of the Ebro River Basin during the last 25 years were reviewed. These studies analyzed the irrigated areas from different perspectives, scales and methodologies depending on objectives and data availability. Since most studies were qualitative and insufficiently documented, only 22 studies with quantitative data applicable to our objectives were finally selected.

For each of these studies the following information was recorded (Table I): name of irrigated area, geographical location, surface area, scale of work, bibliographical reference, irrigation system (IS), land suitability (LS) for the given IS, and irrigation efficiency (IE). IS was characterized by the percentage of the area with sprinkler-irrigated systems. LS was ranked from classes 5 (suitable) to 1 (unsuitable) on the basis of average soil physical characteristics such as depth, texture, water holding capacity (WHC), infiltration rate and land levelling. All the sprinkler-irrigated soils were ranked as suitable (class 5) because IE depends on irrigation management (doses and irrigation intervals) rather than on soils characteristics. Although the definition of IE varied among the studies, it basically designates the percentage of the applied irrigation water evapotranspired by the crops grown in the studied area. Thus, IE depends on the climatic characteristics of the area, irrigation management and soil's water holding capacity.

Based on IS, LS and IE, the 22 areas were classified through a multivariant statistical cluster analysis (Hair *et al.*, 1999). The analysis was carried over the standardized variables, taking as similarity measurement the squared Euclidian distance and using the Ward method for obtaining hierarchical conglomerates.

Finally, seven studies with consistent and adequate information on the volume and quality (salts and nitrates) of irrigation return flows (IRF) were selected. Besides

TABLE I

Characteristics of the selected irrigated areas with irrigation efficiency data: name of irrigated area, geographical location (zones I, II and III in Figure 1), irrigated area, scale of the study, author(s) and year, irrigation system (IS: percentage of irrigated land with sprinkler-irrigated systems), land suitability for irrigation (LS: 1 = unsuitable; 5 = suitable), irrigation efficiency (IE), and irrigated areas grouped by a cluster analysis based on their IS, LS and IE values. The average IE (IE_{avg}) and its coefficient of variation (CV) are presented for each group

Irrigated area	Zone (Figure 1)	Area (ha)	Scale	Authors (year)	IS(%)	LS (1–5)	IE (%)	Group
Alto Aragón (A)	II	120,000	District	Nadal and Lacas (1998)	0	2	65	Group 1
Arbeca (Canal de Urgell)	III	430	Plot	Cots *et al*. (1993)	0	1	30	$IE_{avg} = 53\%$
CR-V (A) (Bardenas)	I	15,500	Plot	Lecina *et al*. (2001)	0	2	53	CV = 21%
C-XIX-6 (Bardenas)	I	94	Basin	Causapé *et al*. (2004b)	0	2	56	
C-XXV-3 (Bardenas)	I	149	Basin	Causapé *et al*. (2004b)	39	3	62	
C-XXVII (Bardenas)	I	409	Basin	Basso (1994)	0	2	65	
C-XXX-3 (Bardenas)	I	217	Basin	Causapé *et al*. (2004b)	0	1	45	
D-XIV (Monegros)	II	3,863	Basin	Isidoro *et al*. (2004)	0	1	47	
Linyola (A) (Urgell)	III	–	Plot	Canela *et al*. (1991)	0	2	66	
Rufas (A) (Monegros)	II	445	Plot	Lecina *et al*. (2000a, b)	0	1	47	
Tarazona (A)	I	4,000	Plot	Zapata (2002)	0	1	50	
Bayunga (Caparroso)	I	1,152	Plot	Zapata and Ederra (2002)	0	3	75	Group 2
CR-V (B) (Bardenas)	I	15,500	Plot	Lecina *et al*. (2001)	0	4	80	$IE_{avg} = 79\%$
La Melusa (Canal Aragón y Cataluña)	II	0.55	Plot	Maté *et al*. (1997)	0	4	80	CV = 8%
La Torrasa (Canal Aragón y Cataluña)	II	330	Plot	Maté *et al*. (1994)	0	4	70	
Linyola (B) (Urgell)	III	–	Plot	Canela *et al*. (1991)	0	4	90	
Rufas (B) (Monegros)	II	445	Plot	Lecina *et al*. (2000a, b)	0	4	78	
Tarazona (B)	I	4,000	Plot	Zapata (2002)	0	4	85	
Torrerribera (Urgell)	III	107	Basin	Barragán *et al*. (2001)	0	3	77	
Alto Aragón (B)	II	120,000	District	Nadal and Lacas (1998)	100	5	96	Group 3
D-IX (Monegros)	II	494	Basin	Cavero *et al*. (2003)	100	5	94	$IE_{avg} = 94\%$
D-XI (Monegros)	II	470	Basin	Tedeschi *et al*. (2001)	100	5	92	CV = 2%

the pertinent information given in Table I, we also recorded the soil salinity status, the annual (hydrological year basis) volume of IRF, the total dissolved solids and nitrate concentrations in IRF, and the annual salt and nitrate loads in IRF (Table II).

The results obtained in the revised studies are representative of the irrigated areas in the Ebro River Basin, although they usually originated from research projects carried out in areas of special interest.

3. Results and Discussion

3.1. Irrigation efficiency

The cluster analysis classifies the 22 areas into three groups (Table I). The first group comprises eleven areas with surface irrigation systems (except C-XXV-3, with 39% of the area sprinkler irrigated) and soils generally unsuitable for this irrigation system (i.e., shallow soils with limited water holding capacity, WHC = 50 to 80 mm). The average IE of this group is low (53%) and the crops grown in these areas are subject to water stress and reduced crop yields (the actual evapotranspiration may be up to 30% lower than the potential evapotranspiration). This water stress is frequently associated to excessive irrigation intervals (more than 12 days) for these low WHC soils. The coefficient of variation of the average IE is relatively high (21%) because IE mainly depends on soils variability rather than on irrigation management variability.

The second group comprises eight areas with surface irrigation systems and more suitable soils (deep soils with WHC > 120 mm). Moreover, laser levelling is generally practised in theses areas. The average irrigation efficiency (79%) is 49% higher than in the first group, and its coefficient of variation is lower (8%), because these soils hold most of the infiltrated water and IE depends more on irrigation management than on soils variability.

The third group comprises three sprinkler-irrigated areas and features the greatest average IE (94%) with the lowest variability (CV = 2%). These areas have modern, automated and well managed sprinkler-systems (generally, solid sets and pivots).

It should be clarified that the IE values given in Group 2 (areas with suitable soils for surface irrigation systems) were obtained at the plot scale (except in Torrerribera), where the reuse of drainage water for irrigation is not considered. Thus, the global IE at the irrigation district level will be greater in cases of drainage water reuse by farmers. In addition, the IE values given in Group 3 (sprinkler-irrigated areas) do not take into account wind drift and evaporation losses of the applied irrigation water which could decrease significantly the real IE in these areas with relatively high wind speeds. Thus, Salvador (2003) indicated that 15 to 20% of the applied water could evaporate before infiltrating the soil even at wind speeds <3 m/s. The conclusion is that the differences in IE among Groups 3 and 2

TABLE II

Characteristics of the selected irrigation districts with irrigation return flow data: Name of irrigation district, geographical location (zones I, II and III in Figure 1), irrigated area, author(s) and year, irrigation system (IS: percentage of irrigated land with sprinkler-irrigated systems), irrigation efficiency (IE), soil salinity, annual volume of IRF, total dissolved solids (TDS) and nitrate concentrations (NO_3^-) in IRF, and annual salt and nitrate loads in IRF

							Irrigation return flows				
Irrigation district	Zone (Figure 1)	Area (ha)	Authors (year)	IS (%)	IE (%)	Soil salinity	Volume (mm/year)	TDS (mg/l)	NO_3^- (mg/l)	Salt load (Mg/ha·year)	Nitrate load (kg NO_3^--N/ha·year)
C-XIX-6	I	95	Causapé *et al*. (2004b, c)	0	56	Negligible[1]	755	541	58	4	98
C-XXV-3	I	149	Causapé *et al*. (2004b, c)	39	62	Negligible	495	693	21	3	23
C-XXX-3	I	216	Causapé *et al*. (2004b, c)	0	45	Negligible	1113	423	77	5	195
C-XXVII	I	409	Basso (1994)	0	65	Moderate[2]	635	2170	–	14	–
D-XIV	II	3863	Isidoro (1999)	0	47	Gypsum[3]	989	1678	28	16	68
D-IX	II	494	Cavero *et al*. (2003)	100	94	Moderate	48	–	125	–	14
D-XI	II	470	Tedeschi *et al*. (2001)	100	92	Moderate	194	6983	112	14	49

[1]Average ECe < 2 dS/m.
[2]2 dS/m < average ECe < 6 dS/m.
[3]ECe = 2.2 dS/m.

could be substantially lower or almost similar when the beneficial reuse practices in Group 2 and the detrimental wind effect in Group 3 are taken into account. Thus, as pointed out by Playán *et al.* (2000), properly managed surface irrigation systems in suitable soils may have IE's comparable to those of sprinkler-irrigated systems at significant lower costs. In contrast, pressurized systems are required to attain high IE's in shallow and low WHC soils or in soils susceptible to crusting that are generally unsuitable even in well managed surface irrigation systems.

In spite of the different methodologies and concepts used in the reviewed studies for determining IE, the values given in Table I may be representative for the Ebro River Basin. The extrapolation of these values to plots or basins on the basis of their soils and irrigation systems may give a broad picture of the IE in other areas of the Basin. However, studies assessing the global IE at the irrigation district scale are scarce and require further attention.

3.2. Off-site irrigated pollution: Salts and nitrates in irrigation return flows (IRF)

Salt concentrations in IRF tend to increase with increasing IE's (Figure 2) because of the higher evapo-concentration of the irrigation water in the crop's root zone. Although nitrate concentrations also increase with evapo-concentration, high

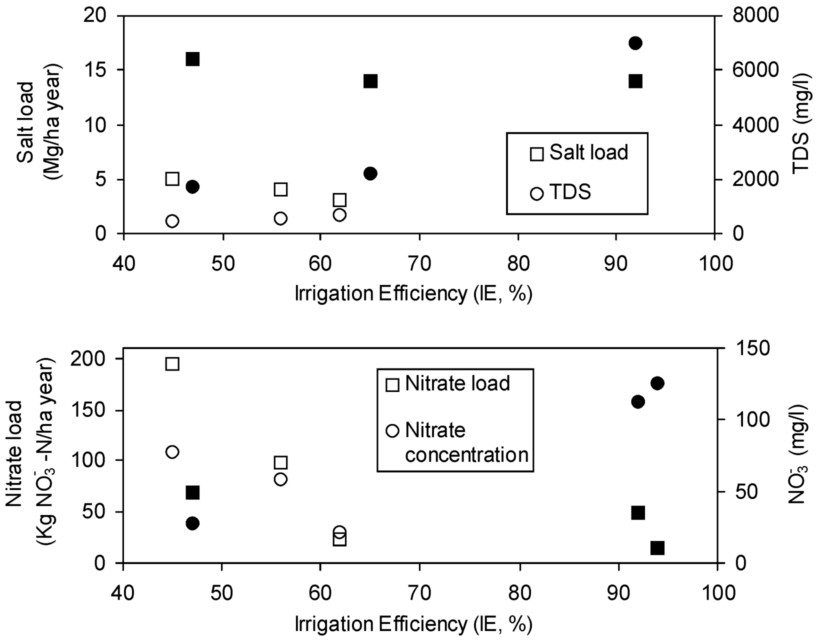

Figure 2. Relationships between irrigation efficiency and salt and nitrate concentrations and loads in the irrigation return flows of seven areas in the Ebro River Basin. The solid symbols correspond to saline or gypsiferous areas.

concentrations are also found in low IE areas (as in C-XXX-3; Table II) because farmers apply high doses of N fertilizers to compensate for the high nitrate leaching typical of these areas (Causapé, 2002).

The annual salt loads exported from saline (C-XXVII), gypsiferous (D-XIV) and other salt mineral (as lutites in D-IX and D-XI) areas are three to five times higher than those exported from non saline areas (C-XIX-6, C-XXV-3 and C-XXX-3) (Table II). Among the salt-affected areas, the exported salt loads decrease with increasing IE (Figure 2) because of the decreased drainage and deep percolation volumes and the corresponding decreases in mineral dissolution. Among the non-saline areas, the exported loads also decrease with increasing IE because of the lower amounts of applied irrigation water and salts. As an example, for irrigation waters typical of the large irrigation perimeters located in the left bank of the Ebro River (EC irrigation water <0.4 dS/m) salt loads applied with the irrigation water may be 1 Mg/ha·year in high IE areas against more than 2 Mg/ha in low IE areas.

The greatest nitrate loads in IRF correspond to irrigation districts with the lower irrigation and nitrogen use efficiencies (C-XXX-3, C-XIX-6 and D-XIV), whereas the smallest loads occur in districts with high IE and the use of fertigation (D-IX and D-XI), and in areas such as C-XXV-3 with prevalence of pasture crops and low N fertilization applications (Causapé, 2002).

The average annual unitary salt (0.76 Mg/ha·year) and nitrate (3 kg NO_3^--N /ha·year) loads exported from the Ebro River to the Mediterranean Sea were calculated from the flow and concentrations recorded by CHE over the last 20 years in the Tortosa monitoring station. These loads are one order of magnitude lower then those measured in IRF (Table II). These contrasting loads demonstrate the magnitude of salt and nitrate pollution provoked by irrigated agriculture against the base line quality of the Ebro Basin waters as well as the negative impact of IRF on the quality of the Ebro River.

These results demonstrate that irrigation and nitrogen fertilization management, in addition to the geology and salinity of the soils, are the key factors controlling the export of salt and nitrate loads from irrigated agriculture. Differences in the salt and nitrate loads exported from irrigated areas with similar physical characteristics indicate the importance of input's management (in particular, irrigation and N fertilization) in minimizing the pollution induced by irrigated agriculture.

4. Conclusions

Irrigation efficiency in the Ebro River Basin is low to moderate (average IE = 53%) in surface irrigated areas with soils unsuitable for this system, moderate to high (IE = 79%) in surface irrigated areas with suitable soils, and very high (IE = 94%) in areas with automated and well managed sprinkler irrigation systems.

Most studies analyze salinity and nitrate concentrations in irrigation return flows (IRF) but few quantify salt and nitrate loads and their relationships with the physical characteristics and the agronomic management in the study areas. The environmental impact of salt-affected areas with low IE (exporting up to 16 Mg/ha·year of salts) and areas with low irrigation and nitrogen fertilization efficiencies (exporting up to 200 Kg NO_3^--N/ha·year) are of great concern. In contrast, the low salt (3 Mg/ha·year) and nitrogen (14 Kg NO_3^--N/ha·year) loads exported respectively from areas of low salinity and high irrigation and nitrogen fertilization efficiencies demonstrate the prospects for minimizing off-site pollution through the appropriate management of irrigation water and nitrogen fertilization.

The salinity of most irrigation waters in the Ebro River Basin are low (EC < 0.4 dS/m), so that the leaching requirements for most crops are negligible. Therefore, most irrigated districts may attain high irrigation efficiencies without compromising yields due to increasing root zone salinity. High-quality irrigation and nitrogen fertilization management would allow to control both the internal (soil salinization) and external (salt and nitrate emissions) negative effects in the irrigated areas of the Ebro River Basin.

Water, salt, and nitrogen balance studies at the hydrological basin scale are reliable approaches to quantify off-site pollution provoked by irrigated agriculture, to identify the main input's inefficiencies and pollutant sources, and to establish best management practices aimed at its control. However, the lack of continuity of research projects and the variability of concepts and methodologies used are serious obstacles to delineate appropriate irrigation planning and management.

Therefore, there is an urgent need for the implementation of a permanent and standardized network of IRF monitoring stations for the control of IRF in the Ebro River Basin. This network should consist of a series of stations for the continuous measurement of flows and dissolved solids concentrations at the exit of the hydrographical basins draining the large irrigated areas of the Basin. This permanent network should be preceded by the experience gained in an experimental irrigated area in order to test, improve and validate the methodologies to be developed (i.e., design, installation and maintenance of reliable gauging stations and automatic water samplers, frequency of sampling, bias estimations in cyclic systems, etc.).

The information on global irrigation efficiencies and loads of exported pollutants gathered in this IRF network, coupled to the existing CHE network of 240 monitoring stations installed in most rivers of the Basin, will allow to determine the maximum daily allowable loads that will comply with the attainment of good ecological status of water bodies dictated by the European Water Framework Directive.

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References

Aragüés, R. and Tanji, K. K.: 2003, 'Water quality of irrigation return flows', in: *Encyclopaedia of Water Science*, Marcel Dekker, pp. 502–506.

Barragán, J., Cots, L. and Pla, I.: 2001, "Estudio de los aspectos cuantitativos y cualitativos de los retornos de las aguas de excedentes de riego y calidad ambiental de las mismas". Oficina de Planificación Hidrológica. Confederación Hidrográfica del Ebro. Unpublished.

Basso, L.: 1994, "Los retornos salinos del polígono de riego Bardenas I y su contribución a la salinización de los ríos Arba y Riguel". *Tesis doctoral*, Universidad de Zaragoza, Facultad de Filosofía y Letras. Departamento de Geografía y Ordenación del Territorio. 224 pp.

Canela, Ll., Barragán, J. and Montserrat, J.: 1991, 'Evaluación del riego por tablares en la colectividad de Linyola Canal de Urgell (Lleida)', *Riegos y Drenajes* **50**, 24–28.

Causapé, J.: 2002, "Repercusiones medioambientales de la agricultura sobre los recursos hídricos de la comunidad de regantes no V de Bardenas (Zaragoza)". *Tesis Doctoral*. Departamento de Ciencias de la Tierra de la Universidad de Zaragoza. 153 pp. Available in http://www.cervantesvirtual.com.

Causapé, J., Quílez, D. and Aragüés, R.: 2004a, 'Salt and nitrate concentrations in the surface waters of the CR-V irrigation district (Bardenas I, Spain): Diagnosis and prescriptions for reducing off-site contamination', *J. Hydrol.* **295**, 87–100.

Causapé, J., Quílez, D. and Aragüés, R.: 2004b, 'Assessment of irrigation and environmental quality at the hydrological basin level. I: Irrigation quality', *Agricult. Water Manage.* (in press).

Causapé, J., Quílez, D., Aragüés, R.: 2004c, 'Assessment of irrigation and environmental quality at the hydrological basin level. II: Salt and nitrate loads in irrigation return flows', *Agricult. Water Manage.* (in press).

Cavero, J., Beltrán, A. and Aragüés, R.: 2003, 'Nitrate exported in the drainage water of two sprinkler irrigated watershed', *J. Environ. Qual.* **32**, 916–926.

Cots, Ll., Montserrat, J., Borrás, E. and Barragán, J.: 1993, Evaluación del uso del agua en la zona de "Les Planes" (430 ha) del término municipal de Arbeca (Colectividad no 13 de los Canales de Urgell, Lleida). XI Jornadas Técnicas sobre Riegos. Asociación Española de Riegos y Drenajes. Valladolidm, pp. 178–185.

CHE: 1996, 'Plan Hidrológico de la cuenca del Ebro', available in http://oph.chebro.es/PlanHidrologico/inicio.htm.

CHE: 1998, Red de control de calidad de aguas subterráneas. Consultor: Carmen Costa Alandí. Unpublished.

CHE: 2001a, Asistencia técnica para la red de control de calidad de aguas subterráneas. Estudio hidrogeoquímico y estadístico de los datos analíticos, propuesta de mejora. Consultor: Zamaltea. Unpublished.

CHE: 2001b, Hidrogeoquímica de las aguas subterráneas de la Cuenca del Ebro: descripción de los principales procesos químicos. Consultor: Isabel Morer Camo. Unpublished.

CHE: 2002, Caracterización hidroquímica de las aguas de la cuenca del Ebro: Marco General y Dominio Central Ibérico. Consultor: Isabel Morer Camo. Unpublished.

European Union: 1998, 'Council Directive 98/83/CE of 3 November 1998 imposed to the surface waters devoted to the production of water for human consumption', *Official Journal L 330*, 5/12/1998, 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*, 22/12/2000, 1–72.

Hair, J., Anderson, R., Tatham, R. and Black, W.: 1999, *Análisis Multivariante*. Prentice Hall Iberia, 5th ed., Madrid. 832 pp.

Isidoro, D., 1999, "Impacto del regadío sobre la calidad de las aguas del barranco de La Violada (Huesca): salinidad y nitratos". *Tesis doctoral*, Universidad de Lérida, Escuela Técnica Superior de Ingeniería Agraria. Departamento Medio Ambiente y Ciencias del Suelo. 267 pp.

Isidoro, D., Quílez, D. and Aragüés, R.: 2004, 'Water balance and irrigation performance analysis: La Violada irrigation district (Spain) as a case study', *Agricult. Water Manage.* **64**(2), 123–142.

Instituto Nacional de Estadística (INE): 2003, *Censo Agrario 1999*. [CD-ROM], Madrid.

Lecina, S., Montserrat J. and Cots Ll.: 2000a, 'El uso del agua en el regadío de Flumen (I). Zona noroccidental de la Acequia de Rufas (Huesca)', *Riegos y Drenajes XXI* **111**, 42–44.

Lecina, S., Montserrat, J., Cots, Ll.: 2000b, 'El uso del agua en el regadío de Flumen (II). Zona noroccidental de la Acequia de Rufas (Huesca)', *Riegos y Drenajes XXI* **112**, 54–57.

Lecina, S., Isidoro, D., Dechmi, F., Causapé, J., Playán, E., Faci, J. M., and Laplaza, J. M.: 2001, "Evaluación de los riegos de la Comunidad de Regantes V del Canal de Bardenas". XIX Congreso Nacional de Riegos y Drenajes (AERYD). Zaragoza 2001. Actas del Congreso, pp. 169–170.

Maté, L., Cruz, J. and Cruz, L. M.: 1994, "Evaluación de la eficiencia de un polígono de riego en la zona del Canal de Aragón y Cataluña y estimación del ahorro potencial de agua de riego debido a la aplicación de la técnica de refino láser y al aumento del módulo de agua disponible". Acta Symposium Nacional sobre presente y futuro de los regadíos españoles. Unpublished.

Maté, L., Ruíz, M., San Martín, J. M. and Aguareles, M.: 1997, Determinación de la eficiencia del riego por inundación y de los volúmenes extraídos por el sistema radicular del cultivo de maíz a distintas profundidades, con auxilio de la sonda de neutrones, en una parcela refinada por el método laser. Confederación Hidrográfica del Ebro. 7 pp. Unpublished.

Nadal, E. and Lacas, M.: 1998, Eficiencia de los regadíos en el sistema de riegos del Alto Aragón. Aguas de la cuenca del Ebro S.A. 158 pp. Unpublished.

Playán, E., Slatni, A., Castillo, R. and Faci, J. M.: 2000, 'A case study for irrigation modernisation: II. Scenario Analysis', *Agric. Water Manage.* **42**(2000), 335–354.

Quílez, D., 1998, "La salinidad en las aguas superficiales de la cuenca del Ebro: Análisis del impacto potencial del regadío de Monegros II". *Tesis doctoral*, Universidad de Lérida, Escuela Técnica Superior de Ingeniería Agraria. Departamento de Medio Ambiente y Ciencias del Suelo. 351 pp.

Salvador, R.: 2003, Estudio de las pérdidas por evaporación y arrastre en los sistemas de riego por aspersión: Diferencias entre riegos diurnos y nocturnos. Proyecto fin de carrera de Ingeniería Agrónoma. Universidad de Lérida, Escuela Técnica Superior de Ingeniería Agraria. Departamento de Medio Ambiente y Ciencias del Suelo. 206 pp.

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

Zapata, N.: 2002, Estudio del uso del agua en la Comunidad de Regantes de Tarazona. Propuestas de mejora. Oficina del Regante. DGA. 21 pp. Unpublished.

Zapata, N. and Ederra, I.: 2002. "Estudio del uso del agua en la comunidad de regantes de la acequia Bayunga: Antes y después de la modernización". Actas del XX Congreso Nacional de Riegos. Ciudad Real, pp. 141–144.