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# Watershed Monitoring for the Assessment of Irrigation Water Use and Irrigation Contamination

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## 1. Introduction

One of the main current questions on the sustainability of life in our planet is if in the next years there will be sufficient water to satisfy the necessities of agriculture and of the other users of this important resource (urban, industrial, touristic and ecological uses).

Irrigation activities allow for the increase of agrarian yields, also allowing for a greater stability in food supply, mainly in those regions where the development of crops is limited by rain. In this way, agriculture consumes 70% of all water extracted from natural courses, being considered the main responsible factor for global fresh water shortage (FAO, 2002).

Nevertheless, although the volumes employed by the agrarian sector are high, at a global level it is estimated that only 50% of the water extracted is finally utilized by plants; the remaining share ends up in drainage and irrigation return flows in rivers and aquifers (FAO, 2003).

These volumes returned to water systems could contribute to a reduction in the impact generated by the extraction of resources if the water quality was not very distant from that of the original water extracted, due to the transport of salts and agrochemicals from the soil profile.

Regarding the presence of agrochemicals, nitrate is a very important issue for water quality, and above all, is associated with notable changes implemented in agriculture in the last decades (OMS, 2004). The problem of nitrate with respect to other agrochemicals is its effect on human health by the simple fact of being present in high concentrations in potable water. The consumption of water with high concentrations of nitrate causes the development of methemoglobinemia in the blood, making the blood stream incapable of transporting enough oxygen through the organism and leading to death of the individual (OMS, 2004).

On the other hand, the occurrence of high concentrations of nitrate in rivers and oceans is causing serious environmental effects on aquatic plants and animals, leading to the occurrence of anoxic zones and eutrophication of water resources (Diaz, 2001), as is evidenced on the coast of the United States (Scavia and Bricker, 2006) and China (Wang, 2006).

The impacts generated by irrigation can be aggravated by physical (geology and climate) and agronomic (management of irrigation and fertilization) factors. For example, the natural salinity of the area in which irrigation is implemented can contribute significantly to the

export of salts from the irrigated area, affecting water resources downstream (Christen et al., 2001; Tanji and Kielen, 2002). Strong rain events, on the other side, cause lateral and vertical mobility of the exported masses of contaminants (Thayalakumaran et al., 2007). Intense rain can also contribute to the erosion of soil and leaching of fertilizers and other agrochemicals (Carter, 2000).

Regarding agronomic factors, García-Garizábal et al. (2009) verified that an adequate management of irrigation water can reduce significantly the masses of salts and nitrates exported from an agrarian watershed. 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. Also, it has been demonstrated that a decrease in nitrogenous fertilization can considerably decrease nitrate leaching levels without causing a drop in productivity (Moreno et al., 1996; Cui et al., 2010). It is therefore possible to achieve equilibrium between acceptable environmental impacts and high agrarian yields.

The main objective of this chapter is to compare and relate water use and contamination generated by salts and nitrates in two irrigated areas with different agronomic characteristics (flood vs. pressurized irrigation). This was carried out through the monitoring of the irrigated hydrological watersheds, analyzing the water use index and salt and nitrate contamination indices calculated for each watershed.

## 2. Description of study zones

### 2.1 Location

The study zones correspond to two irrigated watersheds, which are representative of the Bardenas Irrigation District (Spain; Figure 1). The first watershed presents flood irrigation while the second watershed presents pressurized irrigation systems. Both zones are supplied with good quality water (EC = 0.3 dS/m; $NO_3^-$= 2 mg/l) from the Yesa reservoir, transported to the watersheds through the Bardenas channel (Figure 1).
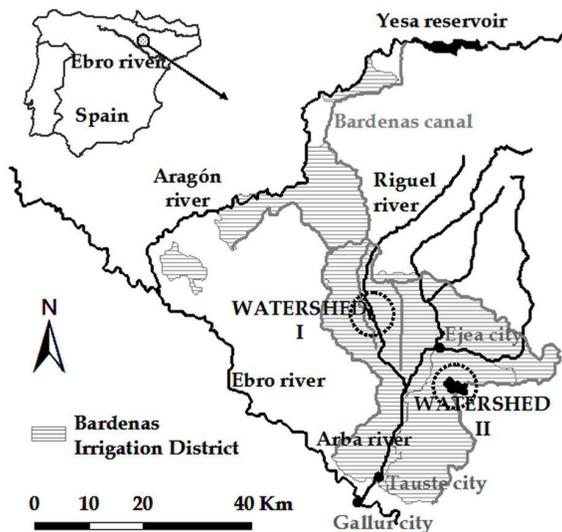


Fig. 1. Location of the Bardenas Irrigation District and the irrigated watersheds, object of this study.

The irrigation ditch network surrounding the flood-irrigated watershed constitutes the superficial water divide, delimiting a 95 ha hydrological watershed of which 96% corresponds to soils destined to irrigation. The remaining surface is occupied by access trails and superficial drainage network, which evacuates the irrigation surplus. The watershed is located at 367 masl

In the case of the pressurized-irrigated area, the watershed was delimited from the terrain digital model (CHE, 2010) and a point situated at the end of the gully, which is a natural drain and evacuates the agrarian drainage waters of the watershed. This watershed presents an extension of 405 ha of irrigated area and is located at an average altitude of 350 masl

## 2.2 Climate

The climate is Mediterranean warm (ITGE, 1985), presenting a historical reference evapotranspiration ($ET_o$) of 1068 mm/year and precipitation (P) of 460 mm/year (Figure 2; GA, 2009), with high annual variability. During the three years comprehending this study, there was an average climate year (2006) and two medium-dry years (2007 and 2008).
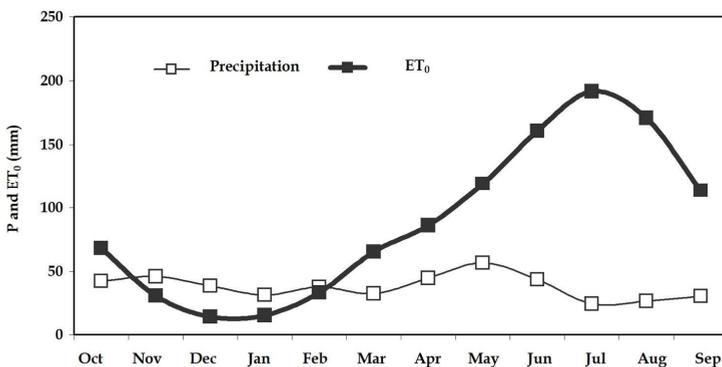


Fig. 2. Historical monthly dynamics of precipitation (P) and reference evapotranspiration ($ET_o$) in the zone of the two studied watersheds (GA, 2009a).

The dry months correspond to winter and summer seasons, while the wettest months are registered during spring and fall. Regarding $ET_0$, minimum values are registered in winter and maximum values in summer, which widely exceed precipitation (Figure 2), making irrigation necessary to satisfy the water demands of the crops.

## 2.3 Geology

The watersheds are located on a glacis of gravel with loamy matrix, constituting a free aquifer. A network of drainage ditches and drains affects the aquifer by forming a valley where tertiary substratum surfaces, constituting the local impermeable limit and acting also as a source of salts (Causapé et al., 2004a).

A sampling network transformed into piezometers determined a gravel thickness of up to 5.5 meters in the flood-irrigation watershed and of up to 10 meters in the pressurized-irrigation watershed. The thicknesses decreased progressively from the topographically higher zones until the lower part of the watershed, where it almost disappeared and the impermeable substratum surfaced.

Regarding the hydraulic characteristics of the aquifer, ITGE (1995) and SIAS (2009) estimate permeabilities of up to 90 m/day and transmissivities of up to 600 m²/day, with an effective porosity of approximately 10-15%.

## 2.4 Soils

The soils of the study zones were characterized through the elaboration of apparent electric conductivity (ECa) maps in homogeneous humidity conditions close to field capacity (after intense rain). To this end, ECa readings were obtained with a georeferenced mobile electromagnetic sensor (SEMG; Amezketa, 2007) model IS of Dualem, in horizontal configuration (ECah), integrating a depth of one meter, and in vertical configuration (ECav), which integrates a depth of 2 meters.

Data revealed low soil salinity ($CEah_{Flood}$= 0.16 dS/m; $CEav_{Flood}$= 0.25 dS/m; $CEah_{Press}$= 0.27 dS/m; $CEav_{Press}$= 0.48 dS/m), although slightly higher values were found in the soil of the pressurized-irrigation zone due to the natural salinity of the subsoil. The highest ECa recorded in the flood-irrigation watershed was 1.28 dS/m on tertiary lutites compared to almost 6 dS/m (Urdanoz et al., 2008) registered on the tertiary of the pressurized-irrigation zone.

Regarding the texture of the soils, Lecina et al. (2005) have already made a first characterization in the zone, classifying the soils in two groups. The first group corresponds to the soil developed on the glacis, with loamy texture, stone content between 11 and 13% and a moderate water holding capacity (WHC), classified as Calcixerollic Xerochrept with Petrocalcic Xerochrept inclusions (Soil Survey Staff, 1992). Conversely, the second group included the soil developed on the tertiary with loamy texture, much lower stone content, between 4 and 18%, and a higher water holding capacity, and classified as Typic Xerofluvent (Soil Survey Staff, 1992).

## 2.5 Agronomy: Irrigation and fertilization

Irrigation is the main component differentiating the two watersheds (Figure 3). Therefore, although both watersheds present on-demand irrigation, in which the farmers chose the time and amount of water to be applied (maximum annual water allowances established at the beginning of the season in function of the available reserves in the reservoir supplying the system), one of the watersheds was submitted to flood irrigation while the other watershed presented pressurized irrigation systems, with 86% of the surface occupied by sprinkler systems and the remaining 14% occupied by drip irrigation systems.
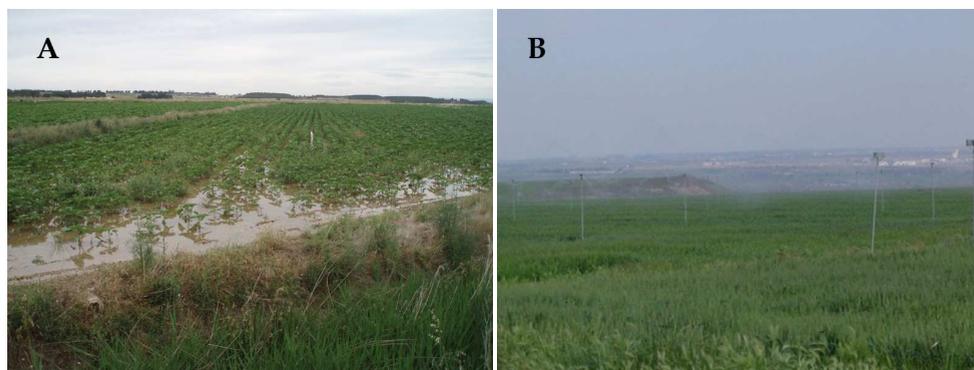


Fig. 3. Pictures of the flood irrigation system (A) and pressurized irrigation system (B).

Regarding the crops, distribution varied significantly in the watersheds as a consequence of the irrigation system in use. In the flood-irrigation watershed, winter cereal (46%) and alfalfa (31%) were the main crops, at the expense of minority crops such as maize and sunflower, with extensions no greater than 15% of the annual surface (Table 1). In the pressurized-irrigation watershed, maize was always the major crop (55%), followed by winter cereal (24%) and tomatoes (9%), with minor contributions of broccoli, sunflower or peas. Alfalfa was not found in the second watershed, even though it is a very common crop in this Irrigation District.

| % | 2006 | | 2007 | | 2008 | |
|---|---|---|---|---|---|---|
| Crop | Flood | Pressurized | Flood | Pressurized | Flood | Pressurized |
| Winter cereal | 33 | -- | 51 | 25 | 55 | 23 |
| Alfalfa | 39 | -- | 31 | -- | 24 | -- |
| Maize | 8 | 61 | 3 | 63 | -- | 40 |
| Tomato | -- | 10 | -- | 4 | -- | 14 |
| Others | 20 | 29 | 15 | 8 | 21 | 23 |

Table 1. Distribution of the main crops in the flood-irrigation watershed and in the pressurized-irrigation watershed, for the three hydrological study years (2006-2008).

Irrigation volumes present variations among crops. In the flood-irrigation watershed, winter cereal presented 2-3 irrigation doses per year, each one of 128 mm. It must be noted that, very punctually, some farmers did not irrigate because rain was sufficient to satisfy the water demands. Alfalfa and maize, with higher water demands, presented 8-10 irrigation doses of 122 mm and 8 irrigation doses of 136 mm, respectively.

| Crop | Flood | | | Pressurized | | |
|---|---|---|---|---|---|---|
| | Irrigation | N Fert. | Yield | Irrigation | N Fert. | Yield |
| | mm | kg N/ha | kg/ha | mm | kg N/ha | kg/ha |
| Winter cereal | 235 | 162 | 5000 | 157 | 164 | 4600 |
| Alfalfa | 1057 | 61 | 11700 | -- | -- | -- |
| Maize | 1088 | 420 | 10600 | 740 | 380 | 12000 |
| Tomato | -- | -- | -- | 552 | 182 | 80000 |

Table 2. Irrigation doses, nitrogenous fertilization and average yield for the crops in the flood- and pressurized-irrigation watersheds, for the three hydrological study years (2006-2008).

In the pressurized system, irrigation was characterized by a high number of applications, but with small volumes. Therefore, low doses were applied to winter cereal (10 doses of 15.7mm) while corn (40 doses of 18.5 mm) reached a total volume of 740 mm per year. Both were irrigated with sprinkler systems. Tomatoes were irrigated via drip irrigation, with very

frequent applications of small doses of water throughout the entire cycle, resulting in a total annual volume of 552 mm.

Regarding fertilization, the average annual doses were 156 kg N/ha in the flood-irrigation watershed and 273 kg N/ha in the pressurized-irrigation watershed, without significant variations in doses for the same crop. Therefore, the doses were sensibly high for corn, 420 kg N/ha in flood systems, compared to 380 kg N/ha in sprinkler systems. Winter cereal received an average fertilization of 163 kg N/ha, while tomatoes received 182 kg N/ha. For alfalfa, the average annual doses of nitrogen reached 61 kg N/ha although this fertilizer was not needed because alfalfa is a leguminous. In this sense, the good agrarian practice code (BOE 1996; BOA 1997), derived from the European directive 91/676 (EU 1991), establishes that nitrogenous fertilization of alfalfa is null with an exception for the year of implementation of the crop, with a limit of 30 kg N/ha. Nitrogenous fertilization was applied mainly in the form of complex NPK fertilizers (8-15-15 and 15-15-15), urea (46% N), nitrogenous solution N-32 (32% N) and, to a smaller extent, ammonia nitrate (33.5% N).

## 3. Methodology

Water use management was evaluated along with the contamination generated by both irrigated zones during three hydrological years (2006-2008). To this end, annual water balances were executed and the contaminant exports (masses of salts and nitrates) were quantified in each watershed. Subsequently, a series of indices was calculated to evaluate irrigation management and relate the contaminants to the salinity characteristics and nitrogenous fertilization (agronomic) of each irrigated zone. The Irrigation Land Environmental Evaluation Tool (in Spanish EMR; Causape, 2009) was used, which automates the calculations for the execution of the water balances and calculations of water use management indices (net hydric needs-HN; water use index-WUI; irrigation efficiency IE) and contamination indices (salt contamination index-SCI; nitrate contamination index-NCI).

### 3.1 Water balances

Annual water balances were executed from measurements or estimations of the main inputs, outputs and water storage in each irrigated watershed (Figure 4). The equation used in the balances was:

$$Inputs – Outputs - Storage = Error\ balance$$

$$(P + I + IWF) – (ET + Q + EWDL) – (Ss + Sa) = Error \qquad (1)$$

were the inputs through precipitation (P), irrigation (I) and incoming water flows (IWF), minus the outputs through evapotranspiration (ET), drainage (Q) and losses due to evaporation and wind drift and evaporation losses from sprinkler irrigation (EWDL), minus water storage in the soil (Ss) and aquifers (Sa), constitute the balance error.

Climate data regarding precipitation and reference evapotranspiration ($ET_o$; Penman-Monteith) necessary for the execution of balances were obtained from agro-climatic stations that the Integral Counseling Service to Irrigation (in Spanish SIAR; GA, 2009a) installed in the proximity of the watersheds.
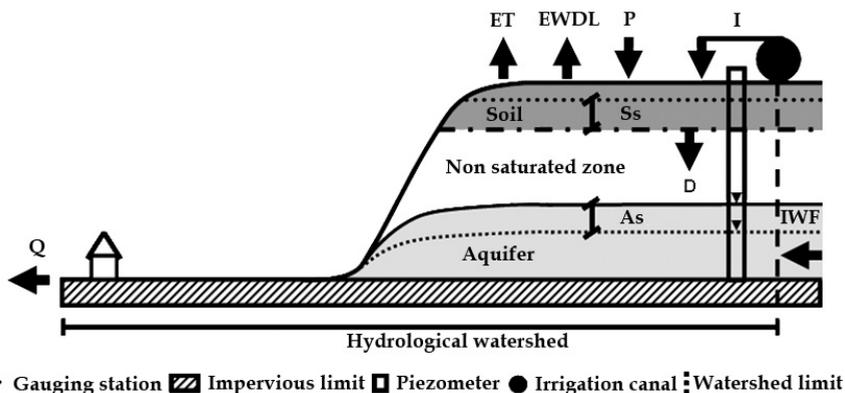
Fig. 4. Hydrogeological conceptual model in which the main hydric components are represented in the irrigated watersheds: irrigation (I), precipitation (P), losses due to evaporation and wind drift of sprinkler irrigation systems (EWDL), evapotranspiration (ET), soil drainage (D), incoming water flows (IWF), flow measured at the gauging station (Q), water stored in the soil (Ss) and in aquifers (Sa).

The daily irrigation volumes were facilitated by the Irrigation district. In the case of pressurized-irrigation, the losses via evaporation and wind drift in sprinkler systems were quantified through the equation proposed by Playán et al. (2005):

$$\text{EWDL (\%)} = 20.34 + 0.214 \cdot \text{ws [m/s]}^2 - 2.29 \cdot 10^{-3} \cdot \text{HR [\%]}^2 \tag{2}$$

where data on wind speed 2 m above the surface (WS, m/s) and relative humidity 1.5 m above ground level (HR, %) were needed.

The annual contribution of incoming water flows to the balance in the flood-irrigation watershed was quantified through the piezometer network. To this end, the saturated water thickness (SWT) measured once every 21 days in a piezometer installed northwest of the watershed was related to the water volume flowing through the drainage at the gauging station. The gauging station presented a rectangular flow meter and electronic limnigraph that registered water height every 15 minutes (h), transformed into flow according the equation ($Q_{Flood}$ (m$^3$/s) = 0.0002 h$^2$ – 0.0020 h – 0.0179; n= 9; R$^2$ = 0.99; p< 0.001), yielding the calculation of IWF$_{Flood}$:

$$\text{IWF}_{Flood} \text{ (m}^3\text{/day)} = 186.39 \cdot \exp^{1.82 \, SWT}; \text{ n = 11; R}^2 = 0.79; \text{ p< 0.001} \tag{3}$$

The incoming water flows in the pressurized-irrigation watershed from the unirrigable area included in the watershed were estimated from precipitation data and based on a runoff coefficient of 0.087. This coefficient was obtained from the relationship precipitation-flow. Based on the entire dataset available from the gauging station, it was verified that heavy rains yielded a higher runoff coefficient (0.313), which was then applied to daily rainfall events exceeding 25 mm.

In the pressurized-irrigation watershed, the equation utilized was provided by software Winflume (Wahl, 2000):

$$Q_{Press} \text{ (m}^3\text{/s)} = 1.73 \cdot (h + 0.00347)^{1.624} \text{ for h} \leq 0.5 \text{ m} \tag{4}$$

$$Q_{Press} \ (m^3/s) = 10.28 \cdot (h + 0.01125)^{1.725} \ \text{for } h > 0.5 \ m \qquad (5)$$

Regarding crop evapotranspiration ($ET_C$), it was calculated on a daily basis from the crop coefficients ($K_C$) determined for the study zone by Martínez-Cob (2004) and by $ET_o$ according to the equation $ET_C = ET_o \cdot K_C$ (Allen et al., 1998). In this sense, $ET_C$ was corrected daily by the real evapotranspiration ($ET_R$) from calculations developed by the EMR software. Therefore, daily data of irrigation, precipitation, evapotranspiration, along with hypothetic initial useful water available for the plants (AWinitial), constituted the inputs for the execution of the water balance in the soil of each plot, resulting in the daily estimations of real evapotranspiration, useful water stored in the soil (AU) and soil drainage.

Therefore, starting from an initial volume of available water for plants in the soil (AW), EMR adds the daily inputs by irrigation (I - EWDL) and precipitation (P), and $ET_C$ is subtracted only if there is sufficient AW in the soil. EMR considers that ETa = $ET_C$ if AWinitial + P + I - EWDL > $ET_C$, but otherwise ETa= AWinitial + P + I - EWDL – hence, the soil has a wilting point level of humidity at the end of each day (AW = 0). On the other hand, if AWinitial + P + I - EWDL - ETa > WHC, the program interprets that the field soil capacity has been surpassed, obtaining drainage (DSWB) equal to DSWB = AWinitial + P + I - EWDL - ETa - WHC, leaving the soil at the termination of each day at field capacity (maximum AW = WHC).

In order to obtain an approximate value of the water content in the soil in the beginning of the study, the execution of balances started one year before. With the information generated by the soil water balance, EMR estimates the direct components of the water balance in the watershed: real evapotranspiration, water storage and soil drainage. The drainage volume proceeding from irrigation (DI) was estimated by considering for the days and plots with drainage that if AW + P – ETa ≥ WHC then DI = I - EWDL and otherwise DI = [I - EWDL] - [WHC - (AW + P - ETa)]. The interpretation of this calculation is that, on any given day, rainfall will always occur before irrigation and thereby irrigation drainage takes priority over rainfall drainage. It is assumed in this study that a farmer takes rainfall into account when deciding whether to irrigate, although evidently weather forecasting is by no means infallible.

Regarding water storage, from the balance equation it was obtained that soil storage resulted from the difference between water volume at the beginning and end of each hydrological year for each balance estimated by EMR. For water storage in the aquifer, this was calculated from the water height variation in the aquifer, measured by the piezometer network at the beginning and end of each hydrological year, applying an effective porosity between 15-20% according to the lithology of the materials extracted during sampling and to values registered during other local studies (Custodio & Llamas, 1983; ITGE, 1995).

Finally, the adequate closure of the water balances was quantified through the calculation of percentage errors:

$$\text{Error (\%)} = [(\text{Inputs} – \text{Outputs} – \text{Storage}) / (\text{Inputs} + \text{Outputs} + \text{Storage})] \cdot 200 \qquad (6)$$

## 3.2 Evaluation of water use and irrigation quality

In order to calculate the irrigation quality during the three study years (2006-2008), the net hydric needs (HN) of the crops were calculated along with water use and irrigation efficiency indices, calculated by EMR once acceptable and satisfactory errors were achieved, which highlight the goodness of the water balances.

The hydric needs estimates the volume of irrigation water necessary to avoid crops from suffering water stress and for the soil to contain the same initial moisture conditions. The potential evapotranspiration and final useful water in the soil are added, to which effective precipitation and initial useful water in the soil are subtracted.

$$HN \text{ (mm)} = (ET_C + AWfinal) - (AWinitial + Pef) \tag{7}$$

The water use index quantifies the percentage of water resources (irrigation and precipitation) that have been used for evapotranspiration:

$$WUI \text{ (\%)} = [1 - (D + EWDL) / (I + P)] \cdot 100 \tag{8}$$

Finally, irrigation efficiency evaluates the percentage of irrigation volume that has not left the system, being used to satisfy the hydric needs of the crops or stored in the water storage in the soil.

$$IE \text{ (\%)} = [1 - (DI + EWDL) / (I)] \cdot 100 \tag{9}$$

### 3.3 Irrigation contamination: Masses of salts and nitrates exported

In order to quantify the masses of contaminants exported through the drainage associated with the watershed, salt and nitrate concentrations were assigned to the superficial drainage, to the subterranean flow, and to water storage in the aquifer.

$$D = Q - IWF + Sa \tag{10}$$

To this end, drainage stations were equipped with automatic water sampling equipment, programmed to collect daily samples. Subsequently the water samples were taken to the laboratory where the electrical conductivity at 25 °C was determined with an Orion 5-star conductivimeter equipped with a DuraProbe probe, and nitrate concentration was determined via colorimetry (AutoAnalyzer 3).

In order to determine the salt concentration in each water sample, electrical conductivity was transformed into total dissolved solids with the equation:

$$TDS \text{ (mg/l)} = DR \text{ (mg/l)} + \tfrac{1}{2} HCO_3^- \text{ (mg/l)}; \text{ (Custodio y Llamas, 1983)} \tag{11}$$

being DR the dry residue, and $HCO_3^-$ the concentration of bicarbonate measured in 31 and 17 samples of the flood- and pressurized-irrigation watersheds, respectively. The values calculated were related to the measured EC for each water sample analyzed and were used to calculate the total dissolved solids in the drainage waters of both irrigated areas:

$$TDS_{Flood} \text{ (mg/l)} = 704 \cdot EC \text{ (dS/m)} + 90; n = 31; R^2 = 0.97; p < 0.001 \tag{12}$$

$$TDS_{Press} \text{ (mg/l)} = 712 \cdot EC \text{ (dS/m)} - 105; n = 17; R^2 = 0.99; p < 0.001 \tag{13}$$

For the incoming water flows, the electrical conductivity and nitrate concentration were determined from monthly values of water samples collected at subterranean or superficial entry points. Finally, the masses of salts and nitrates stored in the aquifer were obtained from the analyses of manually-obtained samples taken October 1 of the corresponding year for each piezometer.

### 3.4 Salt and nitrate contamination indices

Habitually, water contamination is evaluated by the contaminant concentration, although it is the load of exported salts in irrigation return flows that modifies the salinity of the hydric systems receiving such return flows, in function of the mixture proportions. Nevertheless, when considering only the masses of salts exported, ''natural'' salinity can mask the salinity induced by the management of each irrigation zone. The salt contamination index was calculated (SCI; Causapé, 2009) to determine the environmental impact of irrigation, and compare it to other zones with different natural conditions. This index corrects the exported mass by the electrical conductivity of drainage water under nonirrigated conditions ($EC_{NR}$), which is an indicator that represents the ''natural'' salinity of each irrigated zone.

$$SCI = D_{Salts} / EC_{NR} \tag{14}$$

In the case of nitrate, the exported mass is conditioned by the crops, hindering the comparison of the agroenvironmental impact induced by different irrigated zones or different years of the same irrigated area. The nitrate contamination index (NCI; Causapé, 2009) allows for such comparisons, differentiating the crop pattern with respect to other variables such as climate or agronomic management (irrigation and fertilization). This index analyzes the impact of agrarian activities and fertilization practices through a relationship between the nitrate exported through the drainage of the watershed and the theoretical nitrogenous fertilization needs (FN = Average yield (GA, 2009b) · Nitrogen extractions (Orús and Sin, 2009)) of the area to evaluate.

$$NCI = D_N / FN \tag{15}$$

## 4. Results and discussion

### 4.1 Water balances

Water balances resulted satisfactory due to annual errors between -4.4% and 0.3% (Table 3), which remark the goodness of the balances and an adequate measurement and/or estimation of the components. In this way, it was possible to carry out the calculation of the management indices from the different components that constitute the balance equation.

Irrigation constituted the main contribution of water to the watersheds (45% of inputs), except in 2006 and 2007 for the pressurized-irrigation zone, where the installation of the irrigation systems was still being carried out and a part of the irrigable plots was under fallow conditions and did not present water supply. In 2008, after total implementation of irrigation systems, the water doses applied by the farmers increased until the same magnitude order was achieved for both watersheds (Table 3).

Regarding precipitation, it is considered to be the second most important water input in the balances (41%), oscillating between 426-450 mm in the rainiest year (2006) and 305-361 mm in the driest year (2008). Finally, subterranean water flows constituted up to 24% of the water inputs involved in the balances.

Regarding the outputs, evapotranspiration was the main component, resulting in 63-78% of outputs. The water volume measured in the drainage stations varied significantly, constituting 37% of outputs in the watershed with flood irrigation, and 16% in the watershed irrigated by pressurized systems. Nevertheless, subterranean flows presented a greater contribution in the flood-irrigation watershed (Table 3). When discounting the

contributions of subterranean water to the volume of water flowing through the gauging station, the drainage of the watershed was always greater in the flood-irrigation system. The water outputs counted as evaporation and drift losses increased to 6%.

| | Inputs | | | Outputs | | | Storage | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | P | I | IWF | ET | Q | EWDL | Sa | Ss | Unb. | Error |
| | mm | mm | mm | mm | mm | mm | mm | mm | mm | % |
| Flood | | | | | | | | | | |
| 2006 | 450 | 567 | 285 | 830 | 417 | 0 | 42 | 65 | -52 | -4.4 |
| 2007 | 372 | 512 | 307 | 753 | 469 | 0 | 4 | -39 | 4 | 0.3 |
| 2008 | 305 | 559 | 271 | 686 | 451 | 0 | -16 | 13 | 1 | 0.1 |
| Total | 1127 | 1638 | 862 | 2269 | 1337 | 0 | 30 | 39 | -48 | -1.5 |
| Pressurized | | | | | | | | | | |
| 2006 | 426 | 144 | 56 | 425 | 123 | 20 | 9 | 48 | 1 | 0.2 |
| 2007 | 411 | 397 | 31 | 643 | 106 | 57 | 68 | -36 | 1 | 0.1 |
| 2008 | 361 | 519 | 27 | 656 | 118 | 59 | 69 | 7 | -2 | -0.2 |
| Total | 1198 | 1060 | 114 | 1724 | 347 | 136 | 146 | 19 | 0 | 0.0 |

Table 3. Water balance in the flood- and pressurized-irrigation watersheds. Inputs [precipitation (P), irrigation (I), incoming water flows (IWF)], outputs [evapotranspiration (ET), gauging station (Q) and evaporation and wind drift losses in sprinkler irrigation systems (EWDL)] and storage [in soil (Ss) and aquifers (Sa)] of water during the study period 2006-2008). Balance error (inputs-outputs-storage and unbalance).

Water storage was only 5-10% of the water volume involved in the balances, although its consideration resulted important in this type of studies as in the case of soil, WHC (maximum water volume that can be stored/evacuated from soil) itself can be in the order of precipitations during the driest years. The flood-irrigation watershed presented small annual variations in aquifer storage, while the pressurized-irrigation watershed presented water storage in the aquifer for all years, possibly associated with the fact that the pressurized watershed had newly-implement systems and did not reach equilibrium conditions at phreatic levels. In this sense, it is predicted that in the next years the variations in storage will decrease until equilibrium conditions are achieved in the system, and in the future both zones will probably present similar storage variations.

## 4.2 Evaluation of water use and irrigation quality

Evapotranspiration evolved differently in the two watersheds during the study period. In the flood-irrigation watershed, evapotranspiration suffered a decrease of 17% due to a change in crop pattern, with an expansion of winter cereal at the expense of maize and alfalfa. In the pressurized-irrigation watershed, evapotranspiration increased by 54%, due to the progressive increase of cultivated surface once the installation of irrigations systems was completed. Crop variations in the watersheds are reflected also on the hydric needs of the system, although unit volumes were similar, the greater cultivated surface in the pressurized-irrigation watershed conditioned higher water demands (Table 4).

| Flood/Pressurized | HN | I | IE | | | | WUI |
|---|---|---|---|---|---|---|---|
| | | | Winter cereal | Maize | Alfalfa | Tomatoe | |
| Year | hm³/year | hm³/year | % | % | % | % | % |
| 2006 | 0.54 / 0.54 | 0.55 / 0.58 | 82 / -- | 74 / 75 | 78 / -- | -- / 90 | 87 / 85 |
| 2007 | 0.40 / 1.33 | 0.48 / 1.61 | 88 / 62 | 56 / 74 | 77 / -- | -- / 90 | 82 / 84 |
| 2008 | 0.55/ 1.90 | 0.53/ 2.10 | 82 / 86 | -- / 71 | 72 / -- | -- / 86 | 79 / 83 |
| Average | 0.50 / 1.26 | 0.52 / 1.43 | 84 / 74 | 65 / 73 | 76 / -- | -- / 89 | 83 / 84 |

Table 4. Hydric needs (HN) of the crops, irrigation volume (I), irrigation efficiency (IE) of the main crops, and water use index (WUI) in the two irrigated watersheds during hydrological years 2006-2008.

The water use index was moderate-high, reaching 83% in the flood-irrigation watershed and 84% in the pressurized-irrigation watershed (90% could have been reached if evaporation and wind drift losses in the sprinkler system were nil). Evaporation and wind drift losses accounted for 13% of total irrigation in the watershed (15% of sprinkler irrigation). This value is slightly inferior to that calculated by Dechmi et al. (2003) and Playán et al. (2005) in other sprinkler-irrigation zones in the proximities, where evaporation and wind drift losses accounted for 15-20% of the applied irrigation.

Tomatoes presented the best irrigation applications, achieving plot irrigation efficiencies of 89%, followed by winter cereal (79%) and alfalfa (76%). Maize, which presents a high economic value in this zone, presented the lowest efficiency values (69%), possibly due to the fact that the great volumes of water were applied by the farmers when faced by the possibility of low productivity due to hydric deficit.

In this sense, although the higher efficiency and better use of water is demonstrated in pressurized-irrigation systems under adequate agronomic management (Clemmens & Dedrick, 1994; Zalidis et al., 1997; Tedeschi et al., 2001; Al-Jamal et al., 2001; Caballero et al., 2001; Cavero et al., 2003; Causapé et al., 2006;) in comparison to nonpressurized- or flood-irrigation systems (Clemmens & Dedrick, 1994; Isidoro et al., 2004; Causapé et al., 2004b; Causapé et al., 2006), an adequate flood irrigation management has allowed for water resource use values similar to those of an adequately managed modern pressurized system (Table 4). García-Garizábal & Causapé (2010) verified that the implementation of simple improvements in flood irrigation management on the part of the irrigation management organisms (from rotation to on-demand flood irrigation with maximum water allowances, and creation of water consumption accounts) increased by 26% the water use at the Irrigation District (Table 5).

| | Water flow | Irrigation efficiency |
|---|---|---|
| Year | hm³ | % |
| 2000 | 133 | 67 |
| 2007 | 116 | 93 |

Table 5. Water volume circulating through the drainage network of Bardenas District nº V and irrigation efficiency in 2000 (traditional flood irrigation) and 2007 (improved flood irrigation). Taken from García-Garizábal & Causapé (2010).

Therefore, an adequate management of flood irrigation and the implementation of pressurized systems allowed for good water use indices to be obtained by the farmers (79-87%), although water management still has to be sequentially adjusted to achieve continuous and uniform high values at the plots, which could be up to 95% (Tanji & Kielen, 2002). Superior efficiency recordings are not recommended, as the good conservation state of the agrarian soils would be at risk due to the insufficient leaching of evapoconcentrated salts accumulated in the soil profile (Abrol et al., 1988).

Therefore, in accordance to the previous results, the water use indices in the flood-irrigation watershed have a scarce margin for improvement, and the farmers' labour should be focused on maintaining such indices. Nevertheless, Lecina et al. (2005) affirm that it could be possible to increase water use in this zone with the implementation of pressurized-irrigation systems. On the other hand, the farmers of the watershed that already presents pressurized irrigation systems must concentrate efforts on improving irrigation application, mainly reducing the losses through evaporation and wind drift in sprinkler systems by applying water during the night or in low-wind periods (Playán et al., 2005; Zapata et al., 2007; Zapata et al., 2009).

### 4.3 Irrigation contamination: Exported masses and contamination indices

The salt masses accounted at the gauging stations of both watersheds were similar, although the pressurized-irrigation watershed presented a greater annual variability due to the increase in drainage volumes (irrigation system under implementation) and to the higher salinity of its return flows. The salts exported by each watershed (own drainage of the system) were significantly different, with 1.7 t/year in the flood-irrigation watershed and 3.2 t/year in the pressurized-irrigation watershed, due to less salt masses incorporated in subterranean flows and higher storage of salts in the aquifer in the latter (Table 6).

In relation to other zones, the masses exported by both watersheds were lower than those measured in irrigation zones with low-moderate water use index (around 50%), presenting annual exports between 3.4 and 4.7 t/year (Causapé et al., 2004c; Duncan et al., 2008), and similar to values encountered in irrigation zones with moderate-high irrigation efficiencies, between 73% (5.2 t/ha year; Roman et al., 1999) and 82% (3.9 t/ha year; Caballero et al., 2001).

| Flood / Pressurized | $Q_{Salts}$ | $IWF_{Salts}$ | $Sa_{Salts}$ | $D_{Salts}$ | $CE_{NR}$ | SCI |
|---|---|---|---|---|---|---|
| Year | t/ha | t/ha | t/ha | t/ha | dS/m | $t \cdot ha^{-1}/dS \cdot m^{-1}$ |
| 2006 | 2.8 / 2.8 | 1.4 / 1.8 | 0.5 / 1.2 | 1.9 / 2.2 | 1.1 / 3.8 | 1.8 / 0.6 |
| 2007 | 3.1 / 2.3 | 1.6 / 0.8 | 0.0 / 2.0 | 1.5 / 3.5 | 1.1 / 3.8 | 1.4 / 0.9 |
| 2008 | 2.9 / 3.2 | 1.2 / 0.6 | -0.1 / 1.3 | 1.6 / 3.9 | 1.1 / 3,8 | 1,5 / 1,0 |
| Average | 2.9 / 2.8 | 1.4 / 1.1 | 0.1 / 1.5 | 1.7 / 3.2 | 1.1 / 3.8 | 1.6 / 0.8 |

Table 6. Mass of salts exported through drainage ($Q_{salts}$), mass of salts introduced in the incoming subterranean water flows ($IWF_{salts}$), mass of salts stored in the aquifer ($Sa_{salts}$), mass of salts associated with the watershed ($D_{salts}$), electrical conductivity under nonirrigated conditions ($EC_{NR}$) and salt contamination index (SCI) in the two studied watersheds (Flood- and pressurized-irrigation).

Regarding the salt contamination index, although the flood-irrigation watershed presented lower natural salinity ($EC_{NR-Flood}$= 1.1 dS/m *vs*. $EC_{NR-Press}$= 3.8 dS/m) the SCI values were higher than those calculated for the pressurized-irrigation watershed. The high natural

salinity of the pressurized-irrigation watershed motivated higher salt exports than those of the flood-irrigation zone, even presenting similar water use values. The higher amount of salts present in the subsoil of the pressurized-irrigation watershed caused the ''evaluation'' of the salinity impact to be lower due to the impossibility to export naturally low salt masses. In this sense, irrigation zones with high use values obtain salt contamination indices of only 0.4 t/ha·year·dS/m, while irrigation zones with lower efficiencies present higher values (1.9 t/ha·year·dS/m), reaching up to 11.4 t/ha·year·dS/m in agrarian systems with high natural salinity values.

In the case of nitrate, the mass exported by the flood-irrigation zone reached 61 kg N/ha·year with a low annual variability, compared to 12 kg N/ha·year of the pressurized-irrigation system, although the latter increased exports in more than 200% during the study period (2006-2008).

This increase in the mass of exported nitrates is associated with the increase in drainage volumes measured in the gauging station, due to the expansion of irrigation in the pressurized-irrigation watershed, and to the consequent higher volumes of irrigation water and nitrogenous fertilization entering the watershed.

The flood-irrigation watershed presented minimum annual variations in the nitrate stored in the aquifer, while the pressurized-irrigation watershed always recorded positive nitrate storage due to water storage suffered by the aquifer at the end of irrigation cycles (Table 7).

When compared to other irrigated zones, the masses of exported nitrates were always lower than those quantified in irrigation areas with efficiencies of approximately 50% (Causapé et al., 2004b; Isidoro et al., 2006b) and were similar to the masses measured in irrigation systems with efficiencies higher than 70% (Cavero et al., 2003; Bustos et al., 2006). Nevertheless, in the last two irrigation zones the fertilization needs were of the same order of those calculated in the pressurized-irrigation watershed and 2-3 times superior to those of the flood-irrigation watershed.

| Flood / Pressurized | $Q_N$ | $IWF_N$ | $Sa_N$ | $D_N$ | FN | NCI |
|---|---|---|---|---|---|---|
| Years | kg N/ha | kg N/ha | kg N/ha | kg N/ha | kg N/ha | -- |
| 2006 | 59 / 6 | 10 / 0.4 | 4 / 4 | 53 / 10 | 75 / 78 | 0.70 / 0.12 |
| 2007 | 67 / 10 | 10 / 0.6 | 2 / 26 | 59 / 36 | 82 / 150 | 0.72 / 0.24 |
| 2008 | 56 / 19 | 6 / 0.4 | -3 / 15 | 47 / 33 | 77 / 166 | 0.61 / 0.20 |
| Average | 61 / 12 | 9 / 0.5 | 1 / 15 | 53 / 26 | 78 / 131 | 0.68 / 0.20 |

Table 7. Nitrate masses exported through drainage ($Q_N$), nitrate mass introduced in the incoming subterranean flows ($IWF_N$), nitrate mass stored in the aquifer ($Sa_N$), mass of exported nitrates associated with the watershed ($D_N$) nitrogenous fertilization needs (FN), nitrate contamination index (NCI) in the two studied watersheds (Flood- and pressurized-irrigation).

The lower nitrogenous fertilization needs of the flood-irrigation watershed ($NF_{Flood}$= 78 kg N/ha *vs*. $NF_{Press}$= 131 kg N/ha) induced NCI values always higher than those of the pressurized-irrigation watershed. Therefore, although the flood-irrigation watershed presented lower nitrogen requirements, the masses of exported nitrates was higher due to greater drainage volumes, even when water use indices were similar for both watersheds.

This fact caused a lower impact, although the amount of nitrogen applied to the pressurized-irrigation watershed was higher. This behaviour is similar to the one obtained when nitrate contamination indices are compared to those of other irrigation areas.

Irrigation areas with high water use (73-90%) and nitrogenous fertilization needs (144-213 kg N/ha) obtain nitrate contamination indices of approximately 0.25, while other zones with application efficiencies around 50% present higher NCI values (1.2), presenting in this case nitrogenous fertilization needs of 164 kg N/ha.

## 5. Conclusions

The proposed methodology for the monitoring of hydrological watersheds and execution of water balances to evaluate irrigation management resulted satisfactory, mainly when calculating annual errors between -4.4% and 0.3%, which remarks the goodness of the balances and allows for the evaluation of irrigation and water resource management from the values provided.

Although there was a clear difference between the irrigation systems present in the evaluated watersheds (flood and sprinkler irrigation), the water use values obtained were similar, approximately 84%. This fact highlights the possibility of reaching adequate water management levels by adapting the irrigation systems, although it is necessary to know the soil, crop, and supply capacity characteristics in order to establish the management strategy and most adequate water management.

Regarding the exports of contaminants, the highest mass of salts was measured in the irrigation zone with the most saline subsoil ($D_{Salts-Flood}$= 1.7 t/ha year *vs.* $D_{Salts-Press}$= 3.2 t/ha year), while the highest nitrate mass was measured at the watershed with the lowest nitrogenous fertilization input ($D_{Nitrate-Flood}$= 53 kg N/ha year *vs.* $D_{Nitrate-Press}$= 26 kg N/ha year) due to the greater drainage volume ($Station_{Flood}$= 446 mm *vs.* $Station_{Press}$= 116 mm). The contamination indices always resulted better for the pressurized-irrigation watershed (SCI= 0.8 t $\cdot$ ha$^{-1}$/dS $\cdot$ m$^{-1}$; NCI= 0.20) than for the flood-irrigation watershed (SCI= 1.6 t $\cdot$ ha$^{-1}$/dS $\cdot$ m$^{-1}$; NCI= 0.68), and therefore it is possible to reduce the degree of contamination if water use is improved, decreasing the irrigation return flow volumes.

## 6. Acknowledgments

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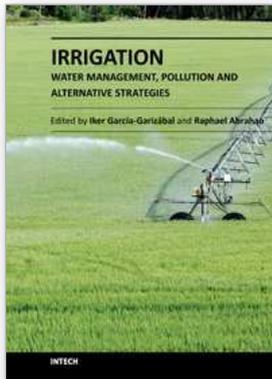
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Edited by Dr Iker Garcia-Garizabal

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