Environ Monit Assess (2009) 158:307–314
DOI 10.1007/s10661-008-0584-z

A computer-based program for the assessment of water-induced contamination in irrigated lands

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Received: 14 December 2007 / Accepted: 29 September 2008 / Published online: 30 October 2008

Abstract The non-point characteristic of agrarian contamination hinders its quantification and assignation to a specific territory. The objectives of this work were to unify methodological criteria for agro-environmental evaluation and to propose indices to quantify irrigation-induced contamination. The computer program Irrigation Land Environmental Evaluation Tool (in Spanish, EMR; http://www.jcausape.es/investigacion/EMR.htm) was developed to evaluate the quality of irrigation and the agro-environmental impacts, based on the water, salt, and nitrate balances in the hydrological irrigation basins. The behavior of the proposed indices was analyzed using data registered in various irrigation districts in the Ebro valley (Spain). The Salt and Nitrate Contamination Indices (SCI and NCI, respectively) were based on the unitary mass of exported pollutants, corrected by the "natural and socioeconomic" conditions of the irrigation districts evaluated. SCI and NCI were related to water and nitrogen use, key factors in minimizing contamination. SCI and NCI admit a greater mass of exported pollutants in disadvantaged irrigation districts, which does not allow the exclusion of adequate management in any evaluated irrigation lands. EMR is a user-friendly tool at the service of the agro-environmental surveillance of irrigation lands.

Keywords Agro-environmental evaluation · Water use · Agrarian contamination · Saline Contamination Index · Nitrate Contamination Index

Introduction

The non-point characteristic of agrarian contamination hinders its quantification and assignation to a specific territory, whereby agro-environmental evaluation and irrigation surveillance are not simple tasks. Nevertheless, the loss of water and pollutants in agricultural drainage can be assigned to the hydrological basin of the corresponding drainage and therefore associated to its climatic, geological, and agronomic characteristics, offering an agro-environmental diagnosis of the irrigation area under evaluation.

To ensure that the measured drainage corresponds to the assigned agrarian surface, water balances must be carried out in which the inputs

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and outputs of water should be equal. A correct closure of the water balance, along with the assignment of pollutant concentrations to each of their components, allow the quantification of both irrigation quality and agro-environmental impacts induced by a certain irrigation land.

This methodology has been applied successfully to different irrigation districts of the Ebro basin in the framework of several research projects (Tedeschi et al. 2001; Lasanta et al. 2002; Cavero et al. 2003; Causape et al. 2004a, b; Isidoro et al. 2006a, b).

However, under the same general methodology, several individualized versions emerge for each particular study case. The working scale, the presence of groundwater, the current irrigation systems, and data availability are some of the factors that condition the great methodological variation, making it difficult to contrast the results obtained in the different studied irrigation areas.

The current legislation in the European Union (EU 1991, 1998, 2000, 2006) only refers to the levels of pollutant concentration in waters, although irrigation land studies (Causapé et al. 2006) have demonstrated that the improvement in irrigation efficiency can cause an increase in drainage concentration and a decrease in the mass of exported pollutants.

When protecting the systems that receive irrigation return flows, the most important parameter is the mass of pollutants exported in drainage. Hence, the US Environmental Protection Agency (EPA) defines the Total Maximum Daily Load (TMDL) as the maximum of pollutants that each water body can receive and still meet quality standards without compromising its use (www.epa.gov/, 2007).

Apart from the vulnerability of the systems receiving irrigation returns, legislation should promote adequate irrigation management by complying with environmental indicators based on the mass of exported pollutants, corrected by factors of natural or socioeconomic origin.

In brief, the considerable quantity of data and the complexity of calculations discourage the systematic execution of agro-environmental studies. Frequently, organizations responsible for water issues do not have the appropriate tools or criteria needed to conduct environmental evaluations on irrigation lands. Correct legislation for irrigation management is thereby prevented and currently no requirements exist for minimum levels of water use or maximum levels of irrigation-induced contamination.

Therefore, the objectives of this study were: (1) to unify methodological approaches for the agro-environmental evaluation of irrigation land by presenting them in a user-friendly computer application called Irrigation Land Environmental Evaluation Tool (in Spanish, EMR); (2) to propose agro-environmental indicators for irrigation-induced salt and nitrate contamination; and (3) to analyze the behavior of the proposed indices.

Irrigation land environmental evaluation tool (in Spanish, EMR)

Software description

EMR is programmed in JAVA 5 (www.sun.com, 2007) and, although the installer is prepared for the Microsoft Windows environment, it is a cross-platform application, and can be used in Linux or in any other operating system where virtual JAVA can exist. The minimum technical requirements to use the program are: (a) Intel Processor Pentium IV or superior, (b) RAM, 256 MB, and (c) hard disk, 25 MB. EMR installation file “InstalarEMR.exe” and its user manual (Causapé and Pérez 2007) can be downloaded free of charge from the webpage http://www.jcausape.es/investigacion/EMR.htm.

EMR executes daily water balances and quantifies the mass of pollutants exported in drainage (salt and nitrate). Based on this, it presents temporal groupings of the balances (daily, monthly, trimonthly, semiannually, annually or for any other period selected by the user) and calculates a series of indicators of irrigation quality and environmental impact on irrigation land.

To simplify usage, the program input and output files are provided in Excel format, including templates to guide the user. Once the data input files have been created, the user assigns them to his EMR project and selects the output data to be used.

Data management

The first step towards environmental evaluation of irrigation lands is to define precisely the irrigation land to be evaluated and provide the necessary data accordingly. The irrigation land under evaluation can be subdivided into several "subareas", whose definition is quite variable since a "subarea" may correspond to an entire irrigation district, an irrigation sector, or a plot. For each "subarea", EMR requests geographical (coordinates) and agronomic (crop) information, crop coefficients (Kc) to estimate the potential evapotranspiration (ET_C), water holding capacity of the soils (WHC), and irrigation volumes applied, both total (I) and for sprinkler irrigation only.

The program also requests information about the geographical coordinates of the meteorological stations involved in the project, as well as data concerning precipitation (P), reference evapotranspiration (ET_0), wind speed 2 m above ground level (WS) and relative humidity 1.5 m above ground level (RH).

The geographical coordinates of the meteorological stations and subareas involved in the project are used by EMR to interpolate the climatic variables for each "subarea", by using the inverse-square distance technique (Isaaks and Srivastava 1989) where the climatic data for a specific "subarea" (X_Z) obtained from n meteorological stations is equal to the sum of the climatic variable (X_i) divided by the square distances (d_i) of each meteorological station to the geographical center of the subarea, divided by the sum of the inverses of the same square distances.

$$X_Z = \frac{\sum\limits_{i=0}^{i=n} \frac{X_i}{d_i^2}}{\sum\limits_{i=0}^{i=n} \frac{1_i}{d_i^2}} \quad ; d_i^2 \; being = (x_i = x_z)^2 + (y_i - y_z)^2$$

Precipitation will be a direct input to the water balance while ET_0 will be used to estimate potential evapotranspiration (ET_C) as $ET_C = ET_O \cdot K_C$ (Allen et al. 1998). Wind speed 2 m above the surface (WS, m/s) and relative humidity 1.5 m above ground level (RH, %) are used to calculate the percentage of losses due to evaporation and wind drift of sprinkler irrigation (EWDL, %), according to the relationship established by Salvador (2003):

$$\mathrm{EWDL} = 20.34 + 0.214 \cdot \mathrm{WS}^2 - 2.29 \cdot 10^{-3} \cdot \mathrm{RH}^2$$

With this information EMR can accomplish the soil water balance (SWB) for each "subarea", estimating daily: (1) the available water for plants in the soil (AW), (2) the actual evapotranspiration (ET_a), and (3) drainage (D_{SWB}).

Therefore, the daily irrigation inputs ($I-$ EWDL) and precipitation (P) are added to the initial AW (estimated as half of WHC), and ET_C is subtracted only if there is sufficient AW in the soil. It is considered that $ET_a = ET_C$ if $AW_{initial} + P + I - EWDL > ET_C$ and otherwise $ET_a = AW_{initial} + P + I -$ EWDL hence the soil has a wilting point (AW = 0) level of humidity at the end of the day. On the other hand, if $AW_{initial} + P + I - EWDL - ET_a > WHC$, the program interprets that the field soil capacity has been surpassed, obtaining drainage (D_{SWB}) equal to $D_{SWB} = AW_{initial} + P + I - EWDL - ET_a - WHC$, leaving the soil at the termination of each 24 h with field capacity (AW = WHC). In this way, EMR accomplishes the SWB successively each day until the period indicated by the user is completed.

Additionally, and taking advantage of the information generated by the SWB, EMR estimates the effective daily precipitation (P_{ef}) in each "subarea", considering that if $P < WHC + ET_a - AW$ then $P_{ef} = P$, and otherwise $P_{ef} = WHC + ET_a - AW$. This estimate does not consider the existence of preferential soil flows or the superficial runoff that could be generated. Nevertheless, it is considered to be a quite valid estimate, due to the fact that agricultural plots are usually terraced and intense rain is needed to generate superficial runoff.

EMR also estimates the drainage volume proceeding from irrigation (D_I), by considering for the days and "subareas" with drainage that if $AW + P - ET_a \geq WHC$ then $D_I = I - EWDL$ and otherwise $D_I = [I - EWDL] - [WHC - (AW + P - ET_a)]$. 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.

Once the water inputs from I and P are obtained, along with an estimate of the $\mathrm{ET_a}$ and losses due to EWDL, EMR requests hydrological information about the basin where the evaluated irrigation land is located. This information encompasses the superficial and ground water from the incoming hydric flows (IHF) and outgoing hydric flows (OHF), and the water content in the evaluated system at the beginning and at the end of the balance period, both in soils and in aquifers. The final data are necessary to calculate the water storage in the system for the evaluated period (S).

In this way, EMR accomplishes the water balance of the studied irrigation land, in which the inputs ($\mathrm{IN} = I + P + \mathrm{IHF}$) minus the outputs ($\mathrm{OU} = \mathrm{ET_a} + \mathrm{EWDL} + \mathrm{OHF}$) minus storage ($S$) should be nil. EMR checks the quality of the water balance by means of calculating the error balance as $200 \cdot [(\mathrm{IN} - \mathrm{OU} - S)/(\mathrm{IN} + \mathrm{OU} - S)]$, where error balances of less than 10% can be considered appropriate for this type of study. Likewise, the drainage associated to the evaluated irrigation land, calculated as $D = \mathrm{IFH} - \mathrm{OFH}$, should be similar to the drainage estimated by the soil water balance (D_{SWB}), particularly during extensive periods when water storage in the system becomes less important compared to other components.

Once the water balance is considered satisfactory, the user assigns salt and nitrate concentrations to each of the water balance components. For salts, the result of $\mathrm{IN} - \mathrm{OU} - S$ is not only associated to the balance errors but also to the quantity of dissolved or precipitated salts in the system.

For nitrates, $\mathrm{IN} - \mathrm{OU} - S$ also includes the components of the nitrogen balance not accounted for, such as the nitrate contribution through fertilization, volatility, and nitrogen extraction by the crops. In any case, EMR does not seek to close salt and nitrate balances but mainly to quantify the pollutants exported in drainage as the difference between the pollutants exported and imported through hydric flows.

It is necessary to emphasize that EMR is designed to adapt as much as possible to the availability of data and different work scales. For example, if in a particular irrigation land there is no available data at plot level, subareas can be defined at an irrigation district level, and if for instance there is no data concerning daily irrigation, monthly data can be entered. This allows the evaluation of any irrigation system with such minimum information, although it is evident that a certain loss of precision occurs.

Results

Evaluation of irrigation quality

Working with the information generated in the soil water balance, the results provided by EMR are the net hydric needs and four indices that seek to evaluate the irrigation quality for each "subarea" and for the entire evaluated irrigation land in any period of time defined by the user.

1) Net hydric needs (HNn, mm) are calculated as the difference between potential evapotranspiration ($\mathrm{ET_C}$) plus available water contained in the soil at the end of the balance ($\mathrm{AW_e}$) and effective precipitation (P_{ef}) plus available water contained in the soil at the beginning ($\mathrm{AW_i}$).

$$\mathrm{HNn} = (\mathrm{ET_C} + \mathrm{AW_e}) - (\mathrm{AW_i} + P_{\mathrm{ef}})$$

The HNn estimate the volume of irrigation water necessary to avoid crops from suffering hydric stress and for the soil to contain the same initial humidity conditions.

2) Water use efficiency (WUE, %) is calculated as actual evapotranspiration ($\mathrm{ET_a}$) plus available water stored in the soil at the end of the balance period ($\mathrm{AW_e}$) divided by the sum of the available water resources for plants (initial available water contained in the soil ($\mathrm{AW_i}$), effective precipitation (P_{ef}), and irrigation volume (I).

$$\mathrm{WUE} = \left[(\mathrm{ET_a} + \mathrm{AW_e}) \big/ (\mathrm{AW_i} + P_{\mathrm{ef}} + I)\right] \cdot 100$$

This index refers to the level of water use by the crops and it is greatly conditioned by irrigation management. Thus, loss of water due to evaporation and wind drift in sprinkler irrigation or through deep percolation would imply a decrease in the WUE.

3) Water deficit (WD, %) is calculated as the difference between potential evapotranspiration ($\mathrm{ET_C}$) and actual evapotranspiration ($\mathrm{ET_a}$) divided by potential evapotranspiration ($\mathrm{ET_C}$).

$$\mathrm{WD} = \left[(\mathrm{ET_C} - \mathrm{ET_a})\big/\mathrm{ET_C}\right] \cdot 100$$

This index evaluates to what extent irrigation, as a complement to $\mathrm{AW_i}$ and P_{ef}, has been unable to satisfy the hydric needs of crops. The greater the WD, the greater hydric stress the crops will have suffered as a consequence of inadequate irrigation management.

4) Irrigation drainage fraction (IDF, %) is calculated as the percentage of drainage proceeding from irrigation (D_{I}) in respect to the irrigation volume applied (I).

$$\mathrm{IDF} = \left(D_{\mathrm{I}}\big/I\right) \cdot 100$$

This index evaluates the "losses" of irrigation water through deep percolation. It is conditioned by the irrigation dose in relation to the soil humidity at the moment of applying irrigation.

5) Irrigation efficiency (IE, %) is calculated as one minus the relationship between the output volume of irrigation water not used in evapotranspiration by crops (drainage from irrigation—D_{I} plus losses due to evaporation and wind drift from sprinkler irrigation—EWDL) and the volume irrigation applied (I).

$$\mathrm{IE} = \left[1 - \left[\left(D_{\mathrm{I}}+\mathrm{EWDL}\big/I\right)\right]\right] \cdot 100$$

A theoretical IE of 100% would indicate that the total volume of applied irrigation was used to satisfy the hydric needs of the crops or was accumulated in the water reserves of the soil for later use.

This series of indices allows the evaluation of the irrigation quality in each of the "subareas" and for the group of irrigation areas assessed in a specific period of time. High quality irrigation will be experienced when the WD and the IDF are nil and the WUE and IE approach 100%. Techniques of controlled deficit irrigation can be utilized to cause a deliberate WD, and likewise, in certain circumstances, it may be necessary to apply excessive irrigation (IDF > 0) to favor the leaching of salt with the consequent loss of WUE and IE.

Indices of agro-environmental evaluation

Lastly, EMR presents the results of three indices that can quantify water use and also salt and nitrate contamination (major agro-environmental problems) for the irrigation land being assessed. Water Use Index (WUI) is calculated as one minus drainage associated to the irrigation land evaluated (D) plus the losses due to evaporation and wind drift (EWDL) divided by precipitation (P) plus irrigation (I).

$$\mathrm{WUI} = \left[1 - \left[(D+\mathrm{EWDL})\big/(P+I)\right]\right] \cdot 100$$

A high WUI implies highly efficient use of hydric resources (precipitation and irrigation); while a low WUI indicates low irrigation efficiencies and/or scarce hydric regulation in the hydrological basin, also leading to a waste of water within the irrigation land assessed.

The agro-environmental impact is quantified based on the Salt Contamination Index (SCI) and Nitrate Contamination Index (NCI). Both indices correct the unitary masses of pollutants exported (masses exported per surface unit) by factors of a certain "natural and socioeconomic" extent, such as geology and the agronomic possibilities of a specific irrigation land. Thus, SCI, was calculated as the unitary salts exported (D_{S}) divided by the average electrical conductivity of the drainage during the non-irrigation period ($\mathrm{EC_{NI}}$), a representative parameter of the salinity of the geological materials of a particular irrigation land,

The NCI was calculated as the unitary nitrate exported in drainage (D_{N}) divided by the nitrogenous fertilization needs for the system. EMR calculates the annual fertilization necessities (FN) by working from the "subarea" harvest production and the nitrogen extractions by the crops (Orús and Sin 2006), except for leguminous plants, in which the nitrogen extraction is considered null because of their capacity to fix nitrogen symbiotically.

$$\mathrm{SCI} = D_{\mathrm{S}}/\mathrm{EC}_{\mathrm{NI}} \quad ; \quad \mathrm{NCI} = D_{\mathrm{N}}/\mathrm{FN}$$

Fertilization necessities are dictated by the planted crops, and therefore conditioned to the climate and socioeconomic possibilities of the irrigation land which are factors beyond the farmer's control. Along with greater fertilization necessities comes a significant risk of nitrate leaching, which the NCI compensates in the agro-environmental evaluation.

The calculation of these indices from annual data registered in studies of different irrigation areas of the Ebro valley (Tedeschi et al. 2001; Lasanta et al. 2002; Cavero et al. 2003; Causapé et al. 2004a, b; Isidoro et al. 2006a, b) detects a relationship between the WUI and the SCI and NCI (Fig. 1) demonstrating that adequate water use is the key factor to minimize irrigation-induced contamination.

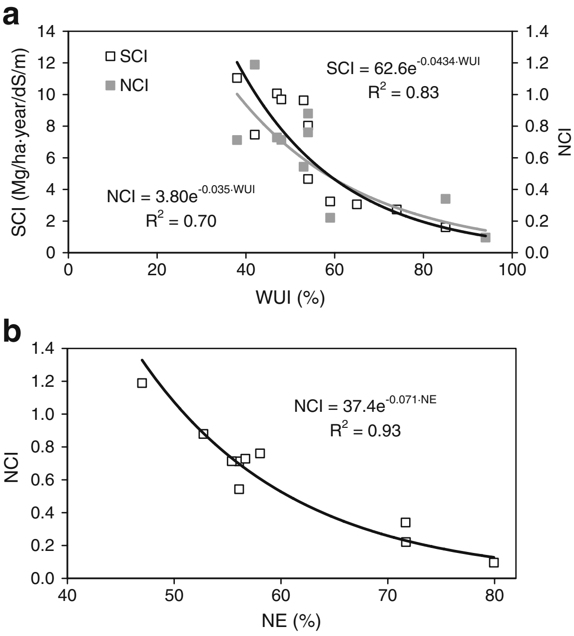

Fig. 1 **a** Relationship between Water Use Index (WUI) and Salt and Nitrate Contamination Indices (SCI and NCI). **b** Relationship between nitrogen efficiency (NE) and the Nitrate Contamination Index (NCI)

Nevertheless, the relationship between WUI and SCI ($R^2 = 0.83$) is considerably better than the relationship between WUI and NCI ($R^2 = 0.70$), demonstrating that in the case of nitrate it is not only necessary to use water correctly, but appropriate nitrogenous fertilization management is also required, proven by the good relationship verified between the nitrogen efficiency (NE = fertilization necessities between applied nitrogen) and NCI ($R^2 = 0.93$).

Based on the previous relationships (Fig. 1), if an objective value of SCI < 2 Mg/ha·year/dS/m and NCI < 0.2 was given for irrigation, this would assure a value of water and nitrogen in fertilization use higher than 80%.

Table 1 shows a synthesis of the average annual results of irrigation studies in the Ebro basin (Tedeschi et al. 2001; Lasanta et al. 2002; Cavero et al. 2003; Causapé et al. 2004a, b; Isidoro et al. 2006a, b), grouped in three large irrigation districts (Bardenas I, Monegros I, and Monegros II).

Monegros II has proven to be an outstanding example of a modern, well-managed irrigation district ($\mathrm{WUI}_{\mathrm{Monegros\ II}} = 90\%$) with abundant salts in the subsoil ($\mathrm{EC}_{\mathrm{NI}} = 8.4$ dS/m), and a SCI 67% lower than inadequately managed non-saline irrigation districts ($\mathrm{WUI}_{\mathrm{Bardenas\ I}} = 52\%$), despite the fact that it exports 71% more salt. Thus, SCI allows irrigation lands which are naturally more saline to have a greater mass of exported salt.

In the case of the irrigation lands studied in Bardenas I, where the exported salt comes almost exclusively from irrigation water, by significantly improving irrigation efficiency (WUI from 52% to 90%) it would be possible to almost double $\mathrm{EC}_{\mathrm{NI}}$ (from 0.85 to 1.7 dS/m) and to halve the mass of exported salts (from 4 to 2 Mg/ha·year) and therefore minimize SCI (from 4.8 to 1.2 Mg/ha·year/dS/m) to attain values in the same order of those obtained in well-managed modern irrigation districts with a high content of salts in the subsoil, such as Monegros II.

In NCI, fertilization necessities play a similar role to that of $\mathrm{EC}_{\mathrm{NI}}$ in SCI, which is demonstrated by the fact that the irrigation district of Bardenas I has a higher NCI (0.74) than Monegros I (0.71)

Table 1 Water Use Index (WUI), Electric conductivity of drainage in non-irrigation period (EC_{NI}), annual mass of salts exported in the drainage (D_S), Salt Contamination Index (SCI), Fertilization Necessities (FN), annual mass of nitrate exported in the drainage (D_N), and Nitrate Contamination Index (NCI) for irrigation districts studied in Bardenas I (Lasanta et al. 2002; Causapé et al. 2004a, b), Monegros I (Isidoro et al. 2006a, b), and Monegros II (Tedeschi et al. 2001; Cavero et al. 2003)

	WUI	EC_{NI}	D_S	SCI	FN	D_N	NCI
	%	dS/m	Mg/ha·year	Mg/ha·year/dS/m	Kg N/ha·year	Kg NO_3^-N/ha·year	–
Bardenas I	52	0.85	4	4.8	146	108	0.74
Monegros I	48	1.78	20	11.4	155	111	0.71
Monegros II	90	8.40	14	1.6	145	31	0.22

despite exporting smaller nitrate masses in drainage (108 compared to 111 Kg NO_3^-N/ha·year).

However, when considering the almost identical fertilization necessities in the three irrigation districts (Fig. 1), it was observed that the NCI of Monegros II is 70% lower than that of Bardenas I and Monegros I, where agro-environmental problems are solved by using more adequate irrigation and nitrogenous fertilization management, thus minimizing the mass of exported nitrate.

The calculation of these indices, based on the mass of pollutants exported per surface unit, allows a comparison between irrigation districts of different sizes. Nevertheless, the study scale can influence the results obtained, since the greater the area, the greater the possibilities of re-using water within the evaluated system, leading to a consequent increase in the WUI and decrease in SCI and NCI.

Summarizing, these indices are more permissive with disadvantaged irrigation lands, *i.e.*, geologically more saline and where crops with greater fertilization necessities are cultivated—therefore with greater "natural" risk of salts and nitrate leaching. Nevertheless, all irrigation lands require good administration which can be achieved through adequate agronomic management at plot level and/or through appropriate water management at irrigation district level.

Conclusions

EMR is a user-friendly tool for agro-environmental evaluation of irrigation, supported by results obtained in research projects based on the same methodology. The methodological unification incorporated in EMR for the agro-environmental evaluation of irrigation land allows the comparison of irrigation quality and agro-environmental impacts in a wide variety of irrigation districts. The possibility of utilizing the program on different scales and with minimum data availability facilitates its systematic use by technicians in charge of water management.

The agro-environmental indicators proposed for salt contamination (SCI) and nitrate contamination (NCI) are related to water and nitrogen use, key factors for the minimization of the environmental impact induced by irrigation land. In this way, if an irrigation land has indices of salt and nitrate contamination lower than 2 Mg/ha·year/dS/m and 0.2 respectively, this indicates that irrigation uses more than 80% of the hydric resources (irrigation and precipitation) and of the nitrogen incorporated by fertilization.

The fact that SCI and NCI are based on the exported unitary mass of pollutants corrected by factors representative of their "natural and socioeconomic" conditions, means that these indices are more permissive with disadvantaged irrigation districts, which does not allow the exclusion of adequate management in any evaluated irrigation lands.

The Irrigation Land Environmental Evaluation tool (in Spanish, EMR), distributed free of charge (http://www.jcausape.es/investigacion/EMR.htm), is an effective tool at the service of the agro-environmental surveillance of irrigation land. The attainment of objective values leading to more efficient agrarian systems with greater respect for the environment can be achieved by imposing the incorporation of the calculated indices into current legislation.

Acknowledgements The author wishes to express his gratitude to the Ebro Basin Authority and to the Education and Science Ministry within the framework of the project AGL2005-07161-C05–01/AGR (Project entitled "Network of agricultural experimental basins for research on non-point pollution induced by irrigation"). Special thanks to Sergio Pérez, the computer specialist responsible for EMR, and to Ignacio Clavería, the agricultural engineer who tested the computer application.

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