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Groundwater quality in CR-V irrigation district (Bardenas I, Spain): Alternative scenarios to reduce off-site salt and nitrate contamination

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ABSTRACT

Irrigated agriculture may negatively affect groundwater quality and increase off-site salt and nitrate contamination. Management alternatives aimed at reducing these potential problems were analysed in the 15498 ha CR-V Irrigation District (Spain) by monitoring 49 wells and modelling the hydrological regime in a representative well of the Miralbueno Aquifer. Groundwaters presented low to moderate electrical conductivity (EC) (mean = 0.89 dS/m) and high [NO_3^-] (mean = 94 mg/L). The groundwater depth (GWD) during the 2001 hydrological year responded to the annual cycles of precipitation and irrigation as well as to the secondary cycles derived from irrigation scheduling. GWD were consistently simulated by the groundwater BAS-A model. Model results indicate that an increase in irrigation efficiency and the pumping of groundwater for irrigation will decrease GWD and aquifer's discharge by 56–70%, depending on scenarios. These recommendations will save good-quality water in the reservoir, will be beneficially economical to farmers, and will minimize off-site salt and nitrogen contamination.

1. Introduction

Irrigated agriculture affects the quality of surface and ground waters. In a previous work, Causapé et al. (2004) analysed during the hydrological year October 1999–September 2000 the spatial and temporal variability of salinity (electrical conductivity, EC) and nitrate concentration ([NO_3^-]) in the surface waters (i.e., drainage and river waters) of the Bardenas Irrigation District no. V (CR-V) (Spain) (Fig. 1). These waters were moderate in salinity (average EC = 0.87 dS/m) and high in nitrate (average [NO_3^-] = 55 mg/L), particularly during the October–March non-irrigated season and in areas with highly permeable soils.

The majority of the CR-V district is occupied by quaternary materials (glacis and alluvials), which form aquifers recharged by deep percolation originating for the most part from irrigation. Consequently, the behaviour and quality of the CR-V groundwaters must also be studied to get a comprehensive understanding of the water quality impact of irrigation in this district.

The diffuse (non-point) contamination of aquifers by nitrates originating from intensive irrigated agriculture is recognized as an important and increasing environmental problem in many developed areas around the world. In France, for example, where 60% of the renewable underground water is used for human consumption, nitrate concentrations have increased in the last 30 years, reaching in some areas values higher than 50 mg/L (Roux, 1995), which is the drinking water limit set by the European Union (EU, 1998). Tester and Carey (1985) extrapolated the historic nitrate concentrations in the

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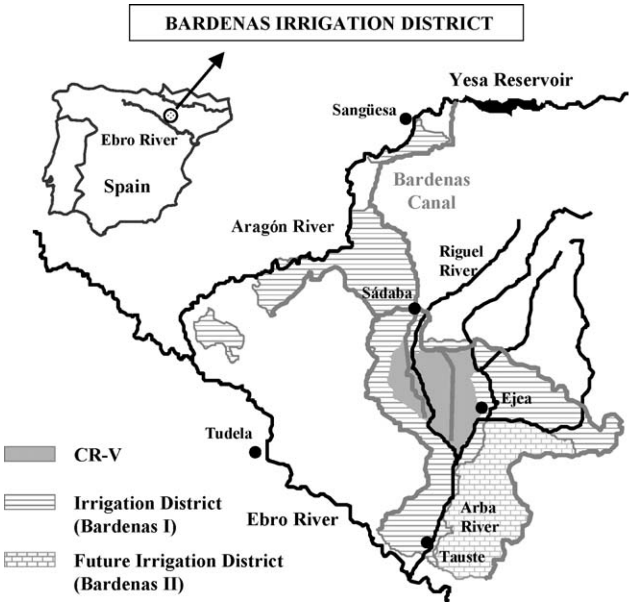

Fig. 1 – Location of the Bardenas Irrigation District no. V (CR-V) study area in the Bardenas irrigation district (Spain). The main villages, rivers and the Yesa Reservoir and Bardenas Canal are also shown.

Great Ouse Chalk Aquifer (USA) and concluded that, with the present tendency, the existing wells in agricultural areas would reach unacceptable [NO_3^-] levels, in contrast to the wells located in non-agricultural areas or in thick-surface deposits.

Groundwater nitrate contamination in developing countries, with 76% of world population, has been less important in the past, but the problem is rising due to increased nitrogen fertilizer applications in new irrigable areas being developed in favourable climatic and edaphic regions. High permeable soils in these new areas or in regions with high rainfall will have the highest nitrate pollution risks (Singh et al., 1995).

Nitrate concentrations above the drinking water limits have been found in the supplies of more than one thousand Spanish municipalities with over two million inhabitants (mainly in the Mediterranean area). Moreover, half of the 88 aquifer systems registered in the 1992 Spanish National Atlas have localized areas with [NO_3^-] $>$ 50 mg/L, and only 25% of them have progressed favourably in the last years. According to the 91/676/CE Directive (EU, 1991) concerning the protection of waters against pollution caused by nitrates from agricultural sources, over 40 areas have been declared vulnerable in 2002 and a further increase is foreseen. This problem commonly occurs throughout the world's aquifer.

The growing contamination problem of an aquifer is in most cases an irreversible process. For this reason, it is essential to avoid those processes leading to pollution by minimizing the recharge induced by irrigation and the salt and agrochemical loading in the aquifers (Keeney, 1989). From this perspective, simulation models are useful tools for predicting future scenarios and evaluating alternative management options aimed at minimizing these contamination problems (García, 1996; Baker, 1999).

The objectives of this work are to (i) quantify the salt and nitrate concentrations in the groundwaters of the Bardenas Irrigation District no. V, (ii) identify the most problematic areas and time periods, and (iii) evaluate management alternatives producing more efficient and environmental-friendly irrigated systems.

2. Materials and methods

2.1. Study area: the Bardenas Irrigation District no. V (CR-V)

The CR-V pertains to the Bardenas Irrigation District located in the middle Ebro River (Spain) (Fig. 1), and its 15498 ha are irrigated with the good-quality Bardenas Canal waters (EC = 0.32 dS/m, [NO_3^-] $<$ 2 mg/L). Its climate is characterized by a low precipitation (historical annual mean $P = 419$ mm) and a high reference evapotranspiration (historical annual mean ETo = 1084 mm). The main crops grown in CR-V are alfalfa and corn (each about 30% of the irrigated area), and winter cereals (13%), all of them are flood-irrigated about every 13 days, and the plots are delimited by dikes to prevent surface runoff. Water consumption is high (average of 1114 mm in 2000) and irrigation efficiency is low (IE = 58%), particularly in the highly permeable "saso" soils (IE = 44%). The applied fertilizer nitrogen is excessive, especially in corn (43% higher than the recommended application rate), where one third is applied at preplanting in April and the remaining is applied as sidedress in June (Causapé et al., 2004).

Two soil types are predominant in CR-V: soils associated with glacis ("saso"), very stony, permeable and with a depth-limiting petrocalcic horizon that cover 70% of the irrigated area, and stoneless and deeper soils associated to alluvial valleys which cover almost completely the remaining area. The aquifers in CR-V are associated with the Miralbueno (120 km^2) and Miraflores (50 km^2) glacis, and to the Riguel and Arba alluvial valleys (Fig. 2). These quaternary aquifers lie on impermeable tertiary lutites. The Miralbueno Aquifer is the main aquifer of the CR-V, and is made up of limestones and quartzite boulders included in a clayey matrix, with a thickness decreasing from North (30 m) to South (3 m) (ITGE, 1985). It is a permeable aquifer due to its single-layer intergranular porosity, of unconfined and perched nature, and without hydraulic connections with other aquifers. The recharge of these aquifers originates from irrigation and rainfall, whereas the discharge is through drainage ditches with outfall to the rivers Riguel, Arba and, finally, the Ebro. A more detailed information of the area is given in Causapé (2002).

2.2. Groundwater inventory and monitoring

Forty-nine wells were monitored in spring 2000 (Fig. 2). At times of higher (July 2000) and lower (February 2001) irrigation applications the following data were recorded in each well: groundwater depth (GWD), electrical conductivity at 25 °C measured with an ORION 1230 conductimeter, and nitrate concentration ([NO_3^-]) measured with a DIONEX 2000-isp ion chromatograph.

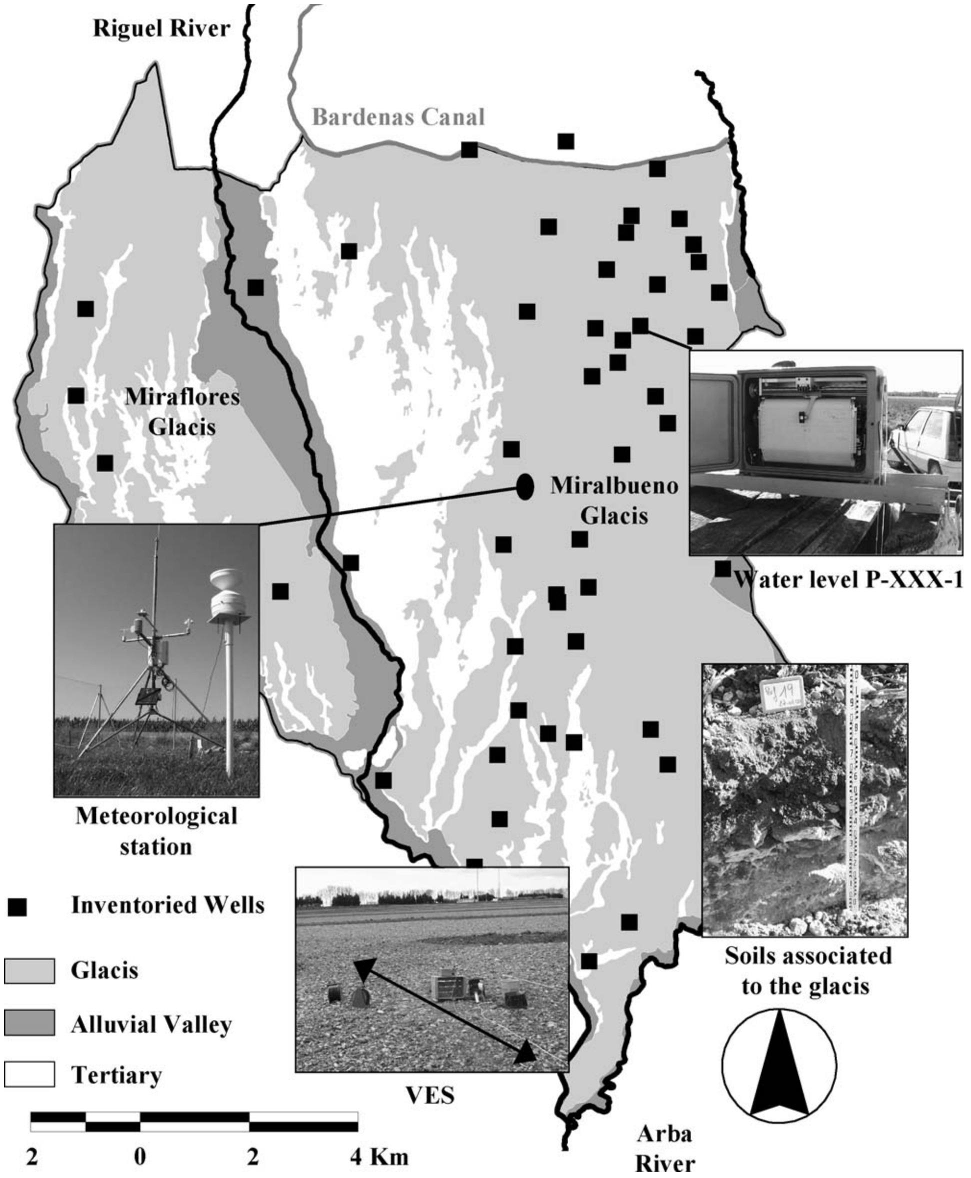

Fig. 2 – Location over the geomorphologic map of Basso (1994) of the 49 monitored wells, the meteorological station and the well P-XXX-1 installed with a continuous water level recorder. Pictures of the water level recorder, the soils associated to the glacis and the vertical electrical sounding (VES) method are also shown.

In addition, a continuous water level recorder was installed in the well P-XXX-1, located in the Miralbueno Aquifer (Fig. 2). These data were used for the validation of the BAS-A model described below.

2.3. *Modelling the hydrological regime of the Miralbueno Aquifer*

The daily groundwater depth of the Miralbueno Aquifer was estimated by quantifying the daily water inputs (recharge) and outputs (discharge). The aquifer recharge is the volume of water that percolates below the crop's root zone (i.e., the drainage, *D*), and was calculated on a daily basis through the following soil water balance:

$$\Delta W = (I + P) - (\mathrm{ETa} + D)\pi$$

where ΔW is the change in soil water content (SWC), I the irrigation, P the precipitation, and ETa is the actual evapotranspiration of crops.

To facilitate these calculations, the BAS model was developed that incorporates daily climatic data (precipitation, air temperature, and reference evapotranspiration), soil parameters (water content at field capacity (FC) and permanent wilting point (WP), and initial soil moisture), and agronomic data (daily irrigation depth, cropping and sowing dates, base temperature, and degrees-day accumulated to attain the different phenological stages of each crop). BAS calculates the crop potential evapotranspiration ($\mathrm{ETc} = \mathrm{ETo} \times K_c$) from the reference evapotranspiration (ETo) and the crop coefficients (K_c) estimated from sowing dates, base temperatures, and degrees-day accumulated that define the four phases of the crops cycle following FAO (Allen et al., 1998).

The FAO methodology was also applied for estimating soil evaporation in periods without cultivation.

The calculation method is based on the storage of precipitation and irrigation in the soil and the subsequent soil moisture increase. The plant's available soil water content (AW) is estimated as the difference between soil water content and WP. If $\text{ETc} \leq \text{AW}$, then $\text{ETa} = \text{ETc}$; if $\text{ETc} > \text{AW}$, then $\text{ETa} = \text{AW}$. In both cases, soil water content decreases by ETa. The drainage value (*D*) depends on the actual soil water content. If $\text{SWC} \leq \text{FC}$, then $D = 0$; if $\text{SWC} > \text{FC}$, then $D = \text{SWC} - \text{FC}$. The BAS model assumes the absence of preferential flows in the soil profile and that all the precipitation and irrigation infiltrate into the soil. These simplifications may provoke some errors because the drainage may be affected by the existence of bypass flows (Larsson and Jarvis, 1999; Thomas and Phillips, 1979), irrigation uniformity, surface runoff in the plots, and evaporation and drift losses in sprinkler irrigation (Faci and Bercero, 1991).

The soil water BAS model was coupled to the BAS-A module that simulates the aquifer discharge and estimates the daily groundwater depths. The additional input variables needed by BAS-A are the initial groundwater depth, the effective porosity, and the relationship between groundwater depth and the rate of fall of the groundwater as a result of the discharge towards the drainage ditches. Given the high permeability of the aquifer (around 400 m/day, Causapé, 2002) and its relatively shallow depths (generally less than 5 m), it was assumed that the drainage water (*D*) reached the saturated zone in a relatively short time, increasing the saturated thickness (ΔST) according to the equation:

$$\Delta\text{ST} = \frac{D}{\Phi_e},$$

where Φ_e is the effective porosity of the aquifer. This one-dimensional equation does not consider lateral flows.

After knowing on a daily basis the initial groundwater depth, the recharge (*D*), and the relation between the rate of fall of the groundwater and the groundwater depth, BAS-A calculates the daily evolution of the groundwater depth and the corresponding discharge towards the drainage ditches.

2.3.1. Model validation

The validation of BAS-A was performed by comparing the groundwater depth estimates with those measured in well P-XXX-1 during the 2001 hydrological year (October 2000–September 2001). Groundwater depths in well P-XXX-1 are influenced by a "regional recharge effect" and a "local-recharge effect". The regional recharge effect was simulated by computing the recharge arising from a fictitious 190 ha-plot (57% corn, 24% alfalfa, 13% winter cereal, and 6% vegetables) that represents all the plots irrigated by the ditch where well P-XXX-1 is included. The local effect was simulated by computing the recharge arising from the 8.25 ha alfalfa plot where the well is located. The total recharge in well P-XXX-1 was the sum of the regional and local recharges.

The daily climatic data inputted to the BAS-A model were obtained from a Campbell weather station located in the Miralbueno Glacis (Fig. 2), whereas the daily irrigation volumes were provided by CR-V from the gauging devices installed in the irrigation ditches. The maximum rooting depths of the crops were measured in open pits, where soil samples were also taken in the different horizons for laboratory analysis of stone content, bulk density, and water retention at 0.03 MPa (field capacity) and 1.5 MPa (permanent wilting point), and water holding capacity (WHC) (Soil Survey Laboratory, 1996).

The relationship between groundwater depth (GWD, m) and the rate of fall of the groundwater (ΔGWD, m/day) in P-XXX-1 was obtained from the decomposition of its discharge curve (ΔGWD versus GWD) in two cells associated to the regional and the local aquifer's drainage, respectively. The equation, fitted by least squares, was:

$$\Delta\text{GWD} = 0.070\,e^{-2.940\text{GWD}} + 0.023\,e^{-0.286\text{GWD}};\ R^2 = 0.85(P < 0.05)$$

The aquifer's effective porosity was determined from a vertical electrical sounding (VES) (Fig. 2) performed in the proximity of well P-XXX-1 and the resistivity of the groundwater measured with an ORION-1230 conductimeter (Custodio and Llamas, 1983). The groundwater depth estimated from the VES was 4.85 m, similar to the value measured in P-XXX-1 at the time of sounding. The estimated effective porosity was 25%, similar to the average value proposed by Custodio and Llamas (1983) for loose gravels.

2.4. Model application

The impact of irrigation management (irrigation efficiency and groundwater pumping for irrigation) on the groundwater depth of the Miralbueno Aquifer at well P-XXX-1 was simulated with BAS-A under three hypothetical scenarios:

- Scenario I: simulates the improvement of irrigation management in the 8.25 ha alfalfa plot. The simulation considers an allowable soil water depletion = 75% of WHC, and an irrigation depth = ETc of the previous day. The rest of the BAS-A inputs are those used in the validation analysis. The irrigation efficiency, defined as ETa/(I + P), is higher than 90%.
- Scenario II: similar to scenario I with improved irrigation efficiencies, but applied to the fictitious 190 ha-plot representative of all the plots irrigated by the ditch where P-XXX-1 is located.
- Scenario III: simulates the pumping of groundwater from well P-XXX-1 to irrigate the 8.25 ha alfalfa plot. The rest of conditions are similar to those in scenario I.

3. Results and discussion

3.1. Piezometry and quality of groundwaters

The exploitation of groundwaters in CR-V is low to moderate, mainly for livestock and agricultural purposes. Most wells were drilled in the eighties when water restrictions in the Bardenas Irrigation District started. Eighty-six percent of the inventoried wells are located in the Miralbueno Aquifer. Most wells are lined and some of them include an underground gallery perpendicular to the direction of flow that increases the collection of water. The direction of groundwater flows in

CR-V follows a principal component towards the South. The Miralbueno Aquifer has a saturated thickness which varies between 15 m in the North and 2 m in the South, and the average hydraulic gradient is 0.85%.

The CR-V groundwaters have a low to moderate salinity (mean EC = 0.89 dS/m) and a high nitrate content (mean $[NO_3^-]$ = 94 mg/L). The wells located in the Miralbueno Aquifer have lower mean values (0.80 dS/m and 91 mg/L) than those located in the Riguel and Miraflores aquifers (1.44 dS/m and 116 mg/L) due to its dilution from seepage waters from the Bardenas Canal (0.32 dS/m and <2 mg/L) (Fig. 2). The higher EC of the Miraflores Aquifer could also result from its lower thickness (ITGE, 1985) and the higher salt content of its tertiary substrate, as indicated by the higher salinity of the gully waters that limits the Aquifer westwards (Causapé, 2002).

Nitrate concentrations in CR-V groundwaters are similar to those found in other shallow aquifers draining irrigated areas. Hudak (2000) monitored 7793 wells in Texas (USA) and found that more than half of the Northeast wells had $[NO_3^-]$ >50 mg/L. He associated the highest levels of nitrate contamination to shallow aquifers in agricultural areas. Arrate (1994) studied the Vitoria quaternary Aquifer (Spain) and found that $[NO_3^-]$ was negligible in the 1960s, when the area was rain fed, but increased to values of 50–100 mg/L in 1986, after the introduction of irrigation and the intensive use of nitrogen fertilizers. This increasing contamination tendency continues, reaching $[NO_3^-]$ of 200 mg/L and up to 500 mg/L in some occasions in 1993.

The EC and $[NO_3^-]$ contour maps of the Miralbueno Aquifer (Fig. 3) show that the lowest values were found in the North (EC < 0.6 dS/m and $[NO_3^-]$ < 50 mg/L), due to the seepage of the Bardenas Canal, and that there was a general tendency to increase towards the South. This trend was also observed in the Vitoria Aquifer being recharged by the Apodaka karst Aquifer (Arrate, 1994).

In the absence of irrigation and the typical low precipitations in CR-V, the drainage recharging the aquifers was low in volume, but relatively high in salts and nitrate. In contrast, during the irrigation season the volume of drainage was high, but the EC and $[NO_3^-]$ were lower (Causapé et al., 2004) and diluted the more concentrated groundwaters. Thus, in February 2001 (no irrigation) 30% of the Miralbueno wells had EC values lower than 0.8 dS/m, against 46% in July (irrigation). Similarly, 27% of the wells had $[NO_3^-]$ <100 mg/L in February, against 90% in July. Likewise, 97% (February) and 74% (July) of the wells had $[NO_3^-]$ above the 50 mg/L drinking water limit. Pauwels et al. (2001) also measured maximum $[NO_3^-]$ (200 mg/L) in winter and minimum $[NO_3^-]$ (100 mg/L) in summer in the schist aquifer of a small basin with 87% of its surface devoted to intensive agriculture.

3.2. *Validation of BAS-A in well P-XXX-1 of the Miralbueno Aquifer*

The groundwater depth measured in well P-XXX-1 responded to the annual cycle of the precipitation and irrigation regimes along the 2001 hydrological year, as well as to the secondary cycles derived from the seasonal irrigation scheduling in the area of influence (Fig. 4). Thus, GWD increased at the beginning of the hydrological year, until the relatively heavy autumn precipitations induced a fast decrease at the end of October 2000. Thereafter, precipitations were scarce and GWD increased progressively (i.e., discharge > recharge) reaching a maximum value of around 5 m by the end of March. The start of the alfalfa and pre-sowing corn irrigations in April produced a GWD decrease that levelled-off in May (corn is not irrigated in this month), further decreasing in June and thereafter due primarily to the heavy irrigations given to corn. The lowest GWD were attained in July and August, with pronounced peaks every 13 days in coincidence with the interval of the irrigation events. GWD increased again by the end of the hydrological year because irrigation stopped in September 21st due to lack of water in the Yesa Reservoir.

In general, groundwater depths simulated by BAS-A corresponded well with those measured at well P-XXX-1 (Fig. 4), although the irrigation-induced peaks were somewhat underestimated because only the 8.25 ha-plot was included in BAS-A to simulate the "local-recharge" effect. The pronounced peak experienced in mid-July (GWD = 1.2 m) was due to a direct spillover of irrigation water into the well and for this reason it was not simulated by the model. In summary, the results presented in Fig. 4 indicate that the model assumptions and approximations were appropriate. Therefore, BAS-A is a suitable model for predicting the hydrodynamic regime of the Miralbueno Aquifer under different scenarios.

3.3. *Application of BAS-A to three irrigation management scenarios*

The actual CR-V flood-irrigation management, with irrigation intervals of about 13 days, induced large variations in the available soil water (Fig. 5). The high irrigation depths (125–192 mm; Fig. 5) were above FC in all irrigation events, producing the deep percolation of water and the recharge of the aquifer. As the soil water holding capacity is limited (WHC = 85 mm), the longer irrigation intervals lead to the full consumption of the available water and, thus, to water stress and decreased crop yields.

The BAS simulation results indicate that the improvements in irrigation management proposed in scenarios I–III will maintain soil water content at higher and more constant values (Fig. 5), therefore preventing the actual crop's water stress. Furthermore, the high irrigation efficiencies (>90%) attainable under the proposed scenarios and the low precipitation during the irrigation season (P total = 104 mm) will prevent almost completely the deep percolation of water and the aquifer's recharge.

In scenario I (improved irrigation management in the 8.25 ha-plot of well P-XXX-1), the present water consumption of 1700 mm/year will decrease by 59%, the present drainage of 1297 mm/year will decrease by 82%, and the elevation of the groundwater during the irrigation season will be smaller due to the lower aquifer's recharge (Fig. 6). In scenario II (improved irrigation management in the fictitious 190 ha-plot representative of a complete irrigation turn), the irrigation-induced recharge will be practically eliminated, and the increase in GWD will follow the natural hydrological regime of the

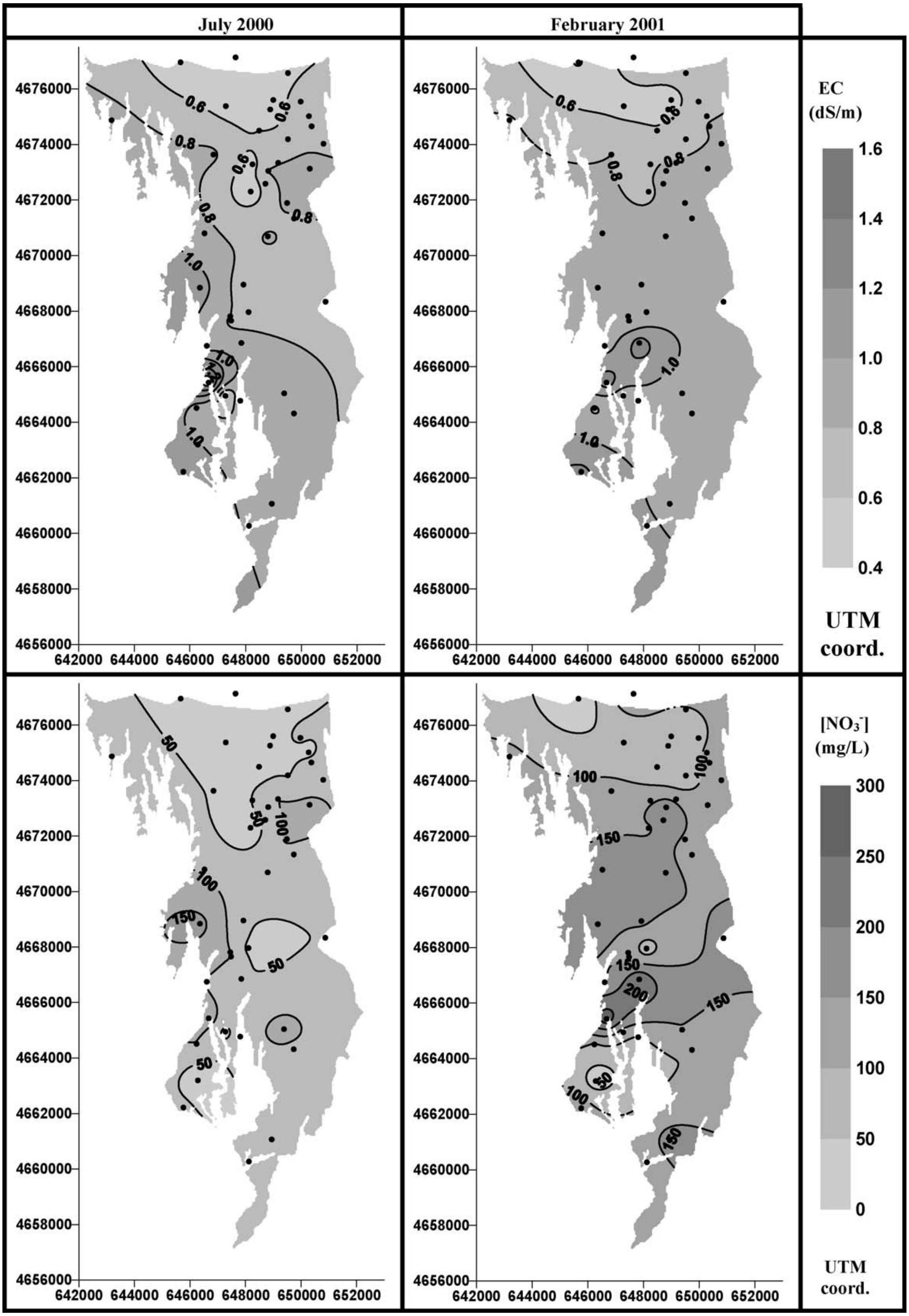

Fig. 3 – July 2000 and February 2001 EC and [NO_3^-] contour maps of the Miralbueno Aquifer.

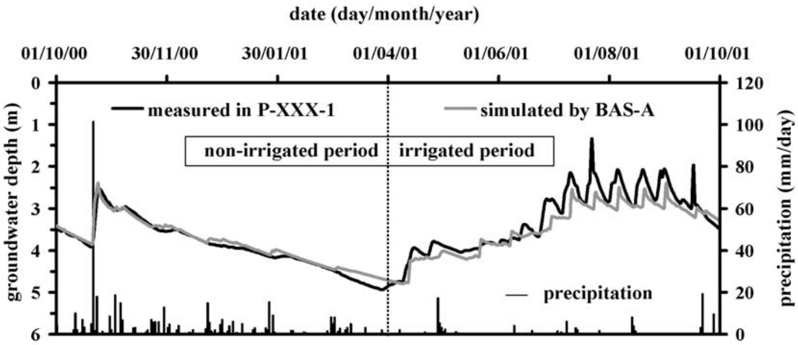

Fig. 4 – Daily groundwater depths measured in well P-XXX-1 and simulated by BAS-A during the 2001 hydrological year. The irrigated and non-irrigated periods and the daily precipitation are also shown.

Miralbueno Aquifer, so that it will be depleted by the middle of the summer season (Fig. 6).

Obviously, these GWD increases imply decreased water stored in the aquifer and decreased aquifer's discharge towards the drainage ditches and, ultimately, towards the Riguel, Arba, and Ebro rivers. Thus, the aquifer's discharge during the irrigation season will decrease by 56% (scenario I) and 70% (scenario II) with respect to the actual discharge.

In scenario III (pumping of well P-XXX-1 for irrigation of the 8.25 ha-plot), canal water demand will be zero and GWD during the irrigation season will increase due to groundwater extraction as well as to decreased recharge derived from the higher irrigation efficiency (Fig. 6). However, the aquifer would not become exhausted, suggesting that this scenario will be viable in practical terms.

Obviously, the improved irrigation management accomplished in the three scenarios will produce lower volumes of drainage with higher salt and nitrate concentrations due to an increase in the ET concentration factor. Salt loading in drainage waters will be reduced due to a decrease in the mass of salts applied with the irrigation water and the lower weathering and higher precipitation of minerals (Aragüés and Tanji, 2003). In addition, it is anticipated that the improved irrigation management will promote the decrease in the amount of fertilizer N applied to crops, thus reducing nitrate leaching (Prunty and Montgomery, 1991 and Saad, 1999) and nitrate loading in drainage waters.

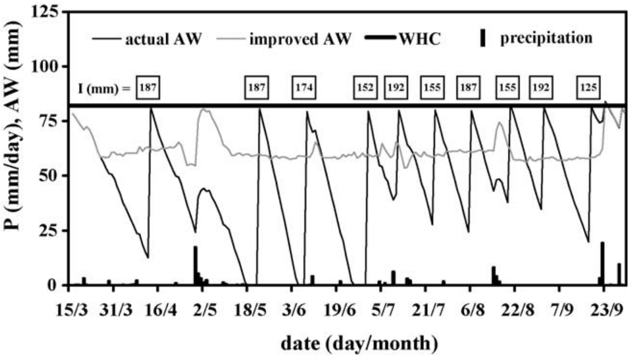

Fig. 5 – Variation along the 2001 irrigation season of the available soil water content (AW) in the alfalfa plot of well P-XXX-1 simulated by BAS under the actual and the improved irrigation management scenarios. The daily precipitation (*P*) and irrigation depths (*I*) are also presented. The soil water holding capacity (WHC) is 85 mm.

4. Groundwater use, irrigation efficiency, and nitrogen fertilizer management

As previously indicated, the improvements in irrigation efficiency defined in the hypothetical scenarios I–III will potentially allow for a better adjustment of the nitrogen fertilization. Hence, Causapé (2002) observed that farmers in CR-V link fertilizer and water applications (i.e., the lower the irrigation efficiency, the higher the N doses). Spalding et al. (2001) concluded that nitrate leaching could be reduced while maintaining crop yields by combining appropriate irrigation and N fertilization management, and Baker (1990) quoted the case of an irrigated area in Minnesota (USA) where N split applications in four times reduced nitrate leaching by 79% with respect to a single application. Thus, the practice of fertigation will provide for larger splitting of N applications and a reduction in nitrogen fertilizer quantities (especially at pre-sowing), thus minimizing nitrate leaching towards the aquifer.

The use of groundwaters for irrigation in CR-V is a wise practice due to its low salinity and high nitrate concentrations. This practice will supply crops with additional N and will reduce the volume of groundwaters reaching the drainage network. However, groundwater depths of the Miralbueno Aquifer will increase (Fig. 6, scenario III) and the aquifer could be exhausted depending of the pumped volumes of water.

As an example of this recommended practice, Sahuquillo (1993) reported economical and environmental benefits in the Mijares-Plana system in Castellón (Spain) by the conjunctive use of surface and groundwaters for irrigation. Nevertheless, irrigating with high [NO_3^-] groundwaters could increase aquifer's nitrate contamination if farmers do not take into account the N applied with irrigation. Thus, Arrate (1994) found in the eastern sector of the Vitoria Aquifer (Spain) that irrigating with groundwaters produced annual [NO_3^-] increases of about 20 mg/L/year during the 1986–1993 period because farmers hesitated to modify their traditional fertilizer practices.

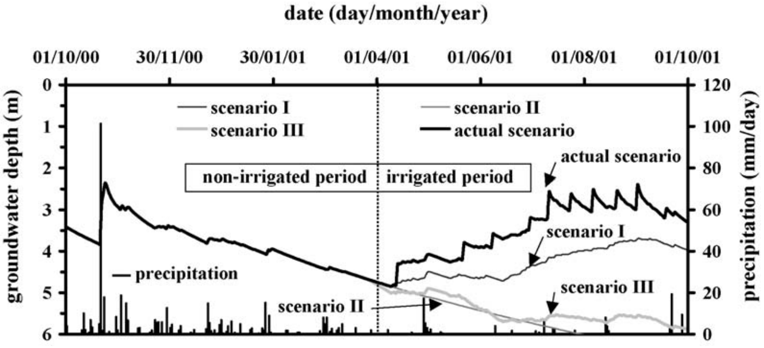

Fig. 6 – Daily groundwater depths in well P-XXX-1 simulated by BAS-A for the actual and the proposed scenarios I–III during the 2001 hydrological year. The irrigated and non-irrigated periods and the daily precipitation are also shown.

Groundwater irrigation of vegetables crops in CR-V could be viable since they cover only 6% of the Miralbueno Glacis (i.e., around 500 ha). The actual yield of vegetables crops is only 50% of its potential due to water stress derived from the large irrigation intervals and the reduced root system in these shallow soils. Consequently, high-frequency irrigation with groundwaters will eliminate water stress, increase the nitrogen use efficiency, allow decreasing the applied fertilizer N and reduce nitrate loading in the irrigation return flows. Assuming a decrease in applied fertilizer N from the actual 400 kg N/ha (Causapé, 2002) to 200 kg N/ha and based on an average annual irrigation depth of 700 mm and an average nitrate concentration of 60 mg/L in groundwaters, the amount of N in the pumped groundwaters will be some 100 kg N/ha, so that about one half of the vegetable N needs will be satisfied through groundwater irrigation. We estimated that the implementation of this strategy could decrease the amount of N in the aquifer by 150,000 kg, which corresponds roughly to a 10% decrease in the off-site N contamination.

5. Conclusions

The conjunctive use of surface and groundwaters for irrigation in CR-V, coupled to the proposed improvements in irrigation and N fertilizer management will (i) save water of good quality in the Yesa Reservoir, whose present capacity is insufficient to fully satisfy the crop water requirements in dry years, (ii) reduce the actual water stress in crops (especially in drip-irrigated vegetables), (iii) minimize off-site contamination by salts and nitrates, and (iv) be economical for farmers due to a saving in N fertilizers. However, soil and water monitoring programs should be implemented in CR-V since this strategy could increase root-zone soil salinity and will reduce the volume of water stored in the aquifers and, thus, the volume of water in drainage ditches that are partly reused for downstream irrigation.

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