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Irrigation agriculture and groundwater. The case of Miralbueno aquifer (Spain)

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Abstract

A great number of flood irrigation districts which have low irrigation efficiency due to the high permeability of their soils cannot undertake a generalised changeover to pressurized irrigation systems in the short term. This work seeks to study the effects which the changeover of the irrigation system in the Irrigation District Nº V of Bardenas (Spain) would have on the hydric regime of the Miralbueno aquifer; also to evaluate different alternatives to improve water management based on the use of groundwater. For this, a model of the aquifer was made with the help of the Modflow 2000 software and different scenarios were simulated. The results indicate that generalised conversion to pressurized irrigation systems will cause a decrease in the average phreatic level (1.20 m) and in the volume of water drained by the ditches (49% less). Until this measure is taken, the irrigation efficiency of the agrarian system could be increased notably by intensifying the reuse of groundwater by means of: a) the construction of intercepting drainages to reuse groundwater in flood irrigation again, and b) the construction of appropriately distributed wells for drip irrigation of the current area of vegetables.

Additional key words: alternative water supply, irrigation efficiency, Modflow.

Resumen

Agricultura de regadío y aguas subterráneas. El caso del acuífero de Miralbueno (España)

Un gran número de regadíos por inundación que presentan bajas eficiencias de riego por la elevada permeabilidad de sus suelos se ven incapaces de afrontar a corto plazo un cambio generalizado a riego presurizado. Este trabajo pretende estudiar los efectos que tendría el cambio de sistema de riego en la Comunidad de Regantes nº V de Bardenas (Zaragoza) sobre el régimen hídrico del acuífero de Miralbueno, así como valorar distintas alternativas de mejora de la gestión hídrica basadas en el aprovechamiento de las aguas subterráneas. Para ello, se modelizó el acuífero con la ayuda del programa informático Modflow 2000 y se simularon diferentes escenarios. La transformación generalizada a riego presurizado provocará un descenso del nivel freático (1,20 m) y del volumen de agua drenada por los desagües (49% menor). Mientras esta medida no sea posible se podría incrementar sensiblemente la eficiencia del sistema agrario intensificando la reutilización del agua subterránea mediante: a) la construcción de un dren interceptor perpendicular a la dirección del flujo y b) la construcción de captaciones adecuadamente distribuidas para el riego por goteo de la superficie actual de hortalizas.

Palabras clave adicionales: alternativas de suministro de agua, eficiencia de riego, Modflow.

Introduction[1]

With the passing of time and the development of civilization, water use increases (FAO, 2003). Water is a limited natural resource and there are restrictions of use both as to quantity and quality (Aragüés and Tanji, 2003; FAO, 2003). This demonstrates the necessity to exercise appropriate use of water resources, especially in countries such as Spain which may be classified as dry.

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[1] Abbreviations used: CR-V (Irrigation District Nº. V of the Bardenas Canal), CV (coefficient of variation), e (thickness of the materials at the bottom of the drain), ITGE (Instituto Tecnológico y Geominero de España), K (permeability), L (longitude of the drain inside the cell of the model), masl (meters above sea level), W (width of the drain inside the cell of the model).

Irrigated agriculture is frequently accused of excessive water consumption, especially agrarian systems with soils and infrastructures unsuitable for flood irrigation, causing low irrigation efficiencies (Isidoro *et al*., 2004; Causapé *et al*., 2006).

Many irrigation areas converted to flood irrigation on very permeable soils find it impossible to diminish their water consumption (Playán and Mateos, 2006). This is because the only alternative offered is a general changeover to pressurized irrigation systems, and yet the high cost of this measure makes it unviable in the short term (Playán *et al*., 2000). Therefore, in those agrarian systems with low irrigation efficiency, where a general changeover to pressurized irrigation is still not possible, it is necessary to study other alternatives which enable improvement in the use of water for irrigation.

The combined use of surface and groundwater may be a valid alternative in agrarian systems whose irrigation drainage recharges superficial aquifers (Shondi *et al.*, 1989; Sahuquillo, 1993; Khare *et al*., 2006). The reuse of drainage water once it has passed through the aquifer can considerably elevate the global irrigation efficiency of the irrigation districts (Zapata *et al*., 2000; Cots *et al*., 2007).

Also, water quality permitting, irrigation using drainage waters can contribute a considerable mass of nitrates to crops thereby favouring: a) reduction in the use of fertilizers, b) better nitrogen application according to the needs of the crops, and c) a decrease in the mass of pollutants exported outside the agrarian system (Causapé *et al*., 2004a; Toze, 2006).

The objective of this work is to evaluate different alternatives to improve the use of water resources of the Miralbueno aquifer (Zaragoza, Spain) for irrigation purposes, as well as to study its performance considering possible widespread change to pressurized irrigation systems in the Irrigation District Nº V of the Bardenas Canal (CR-V).

Methodology

Study area

The Miralbueno aquifer (120 km^2) is situated on the left bank of the river Ebro in the province of Zaragoza (Spain, Fig. 1). It is associated to quaternary deposits belonging to a system of glacis-terraces which has its source area in the conglomerates of Santo Domingo Sierra (Pre-Pyrenees). Lithologically, it is formed by homometric and partly rounded pebbles (Mesozoic and Eocene limestone, and quartzite) within clay matrix, with occasional tracts of clay and silt interspersed in the gravel. The waterproof substratum consists of clay, silt and sand of the tertiary formations whose irregular geometry determines the thickness of the glacis (from 30 m to the north up to 3 m to the south; ITGE, 1985).

Miralbueno is a permeable aquifer by inter-granular porosity, with a single layer, unconfined and perched aquifer, not connected to any other aquifers. It is recharged by irrigation drainage and precipitations (450 mm, of which 60% occur in spring and autumn; ITGE, 1985) while the water is discharged via a great number of drainage ditches which converge toward the rivers Riguel and Arba (Ebro tributaries). The groundwater flows toward the south (coinciding with the topographical slope) with a hydraulic gradient of 0.85% (Causapé, 2003).

Above 80% of the aquifer there is irrigated agriculture (8,250 irrigated ha mainly dedicated to alfalfa and corn) which, because of its physical (very permeable soils) and agronomic (flood irrigation in a rotation system) characteristics receive excessive doses of irrigation (average 1999-2003: 13,000 m^3 ha^{-1}; CR-V authority) and fertilizers (the corn crop of 2000: 412 kg N ha^{-1} for average productions about 9,000 kg ha^{-1}; Causapé, 2003). This causes frequent water restrictions and excessive duration of interval of time between irrigation applications, causing water stress in crops with the consequent economic loss. Vegetables like peppers and tomatoes (more profitable crops which occupy 10% of the surface) are especially sensitive because of their reduced root depth, and their potential productivity can be cut by half (Causapé, 2003).

Also, low irrigation efficiency causes inadequate nitrogenous fertilization management, high leached nitrate and therefore: a) decrease in the net yield due to the excessive purchase of fertilizers and b) a high nitrate concentration in groundwater (frequently > 100 mg L^{-1}; Causapé, 2003).

Simulation of the current scenario

The mathematical model of the Miralbueno aquifer was created with the help of Modflow 2000 software (Harbaugh *et al*., 2000), to carry out flow simulations in a saturated porous environment. For this, a model of a single layer containing an unconfined aquifer was created. The geometry of the model is described by a

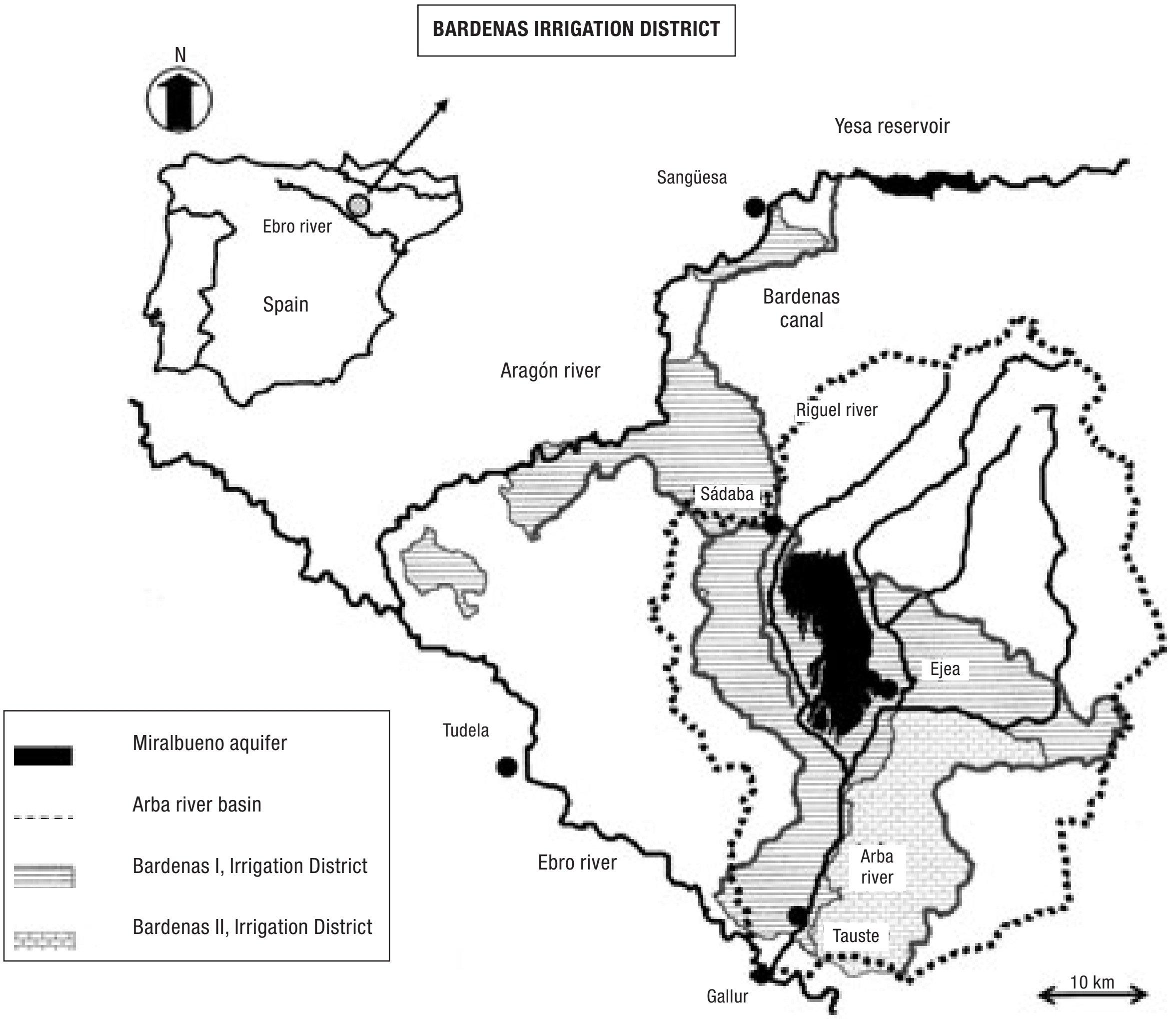

Figure 1. Location of Miralbueno Aquifer.

grid of 40 rows and 20 columns, whose cells have dimensions of 500 by 500 m. The aquifer was defined within the grid by inactive cells, thus reducing its extension to 101.75 km^2 (Fig. 2).

The highest contour of each cell was calculated based on digital cartography with contour lines every 5 m (Government of Aragon Cartographic Service). The lowest contour of each cell was calculated from stratigraphic profiles of the aquifer elaborated by means of electric geophysics (ITGE, 1985). Given the geological materials constituting the aquifer and the information collected in Custodio and Llamas (1983), an effective porosity of 25% and permeability of 150 m d^{-1} were estimated.

The average recharging of each cell was calculated independently for the four seasons of the year (autumn, winter, spring and summer) based on average precipitation data (National Institute of Meteorology, El Bayo: 1961-2000) and of irrigation volumes (CR-V: 1999-2003) corrected by the average irrigation efficiency of the area (50%; Causapé, 2003; Lecina *et al.*, 2005). The model takes into account filtrations from the Bardenas Canal estimating in its cells some additional recharges of 864 m^3 d^{-1} (Ebro Basin Authority).

The drainage network was simulated in each cell to the south of the Bardenas Canal to a depth of 2 m and with a conductance of 10,000 m d^{-1} estimated in the manual calibration taking into account the order of magnitude obtained from the equation:

$$Conductance = \frac{KLW}{e}$$

where K (m d^{-1}) is the permeability of the materials at the bottom of the drain; e (m), their thickness; L (m)

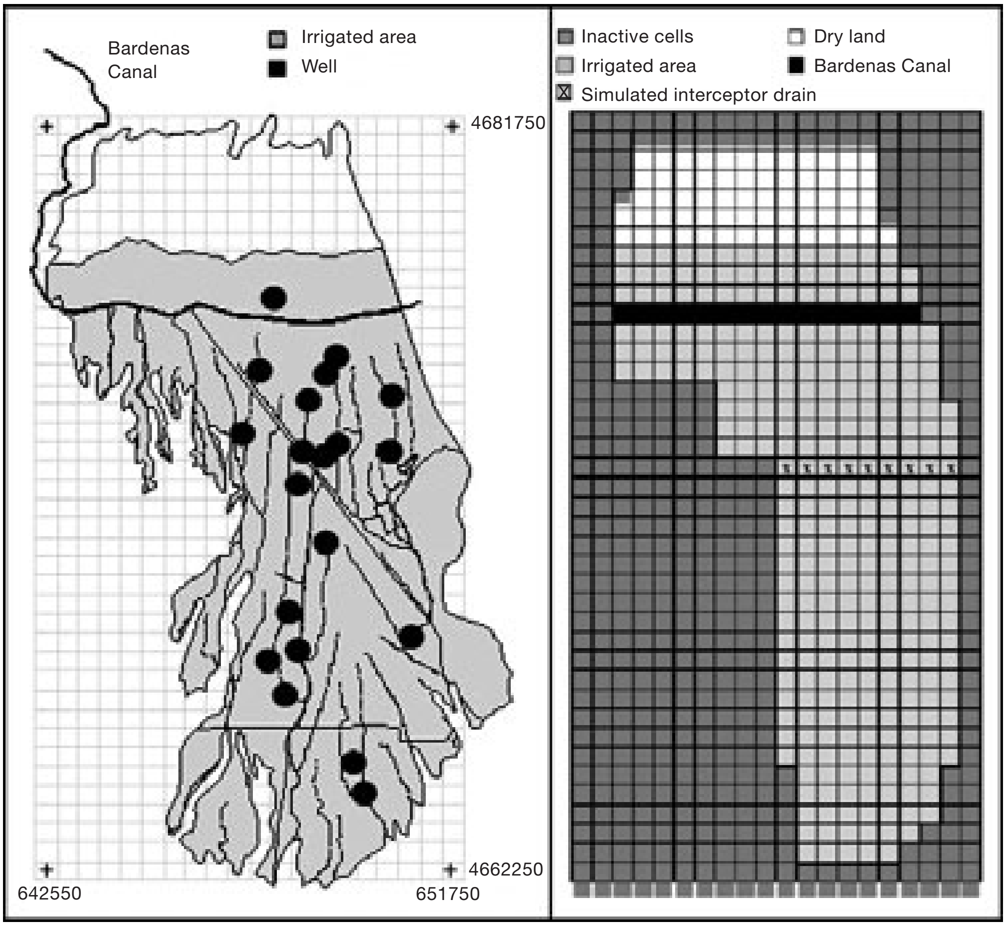

Figure 2. Spatial discretizacion of Miralbueno aquifer. The numbers in the corners indicate the UTM coordinates in meters.

the longitude of the drain inside the cell and *W* (m) the width of the same.

The model was used taking a fictitious initial phreatic level as a starting point and repeating the conditions of every period of simulation successively (autumn, winter, spring and summer) to reach an annual stationary regime.

The model was validated comparing the piezometry calculated by Modflow with values observed during the highest and lowest irrigation periods (11 July 2000 and 14 February 2001 respectively) in 20 of the aquifer's wells (Fig. 2; Causapé, 2003). Regression between phreatic level calculated and measured, and t statistical test of matched samples (Hayes, 2005) was carried out.

Simulation of possible future scenarios

Three possible scenarios were simulated with average data for seasons (autumn, winter, spring and summer) to reach annual stationary regimes.

Construction of an intercepting drain of aquifer water for its reuse in flood irrigation

The simulation of this scenario involves the construction of a drain perpendicular to flow direction which connects with the waterproof substratum so that it can recover the greatest possible flow. The location of this drain coincides with row number 19 of the model (Fig. 2) where the waterproof substratum is about 5 m and therefore easily accessible by a digger. The drain would connect with Bolaso reservoir (internal regulation of irrigation waters in CRV).

Construction of wells for drip irrigation of vegetables with groundwater

Wells were simulated in each cell of the irrigation area which would extract the necessary volume of water (250 mm in spring and 350 mm in summer) for

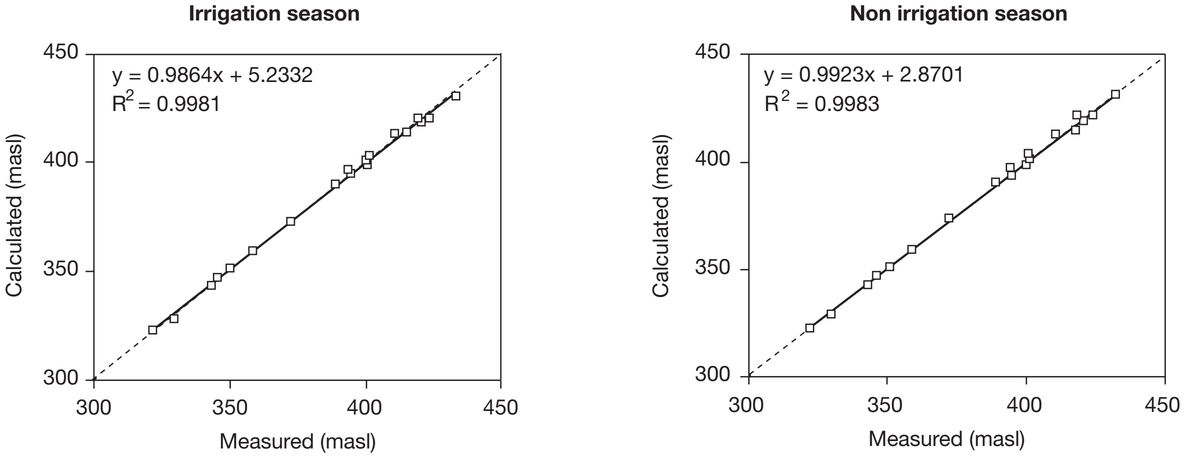

Figure 3. Model validation. Comparison between phreatic levels (masl: meters above sea level) calculated by the model and phreatic levels measured in irrigated and non irrigated seasons in 20 wells of the Miralbueno aquifer (Causapé, 2003).

drip irrigation of 2.5 ha of vegetables (10% of the surface of each cell). Equally the recharge through flood irrigation diminished in proportion to the surface area planned for drip irrigation.

Change to pressurized irrigation systems

This scenario was simulated diminishing the recharge to the Miralbueno aquifer from irrigation surpluses by 85%, resulting from the reduction in demand for irrigation water and from greater application efficiency (Causapé *et al.*, 2004b). In this modernization scenario filtrations from the Bardenas Canal would also be eliminated.

Results and Discussion

Validation of the model

The values observed in 20 Miralbueno aquifer wells (Causapé, 2003) are conditioned by the characteristics of each well and moment of measurement. However, they may be considered to be representative data for the location and for irrigation and non-irrigation seasons.

In the t test of matched samples, no differences were detected between the observed values (Causapé, 2003) and those calculated by the model. It also confirmed that the parameters *a* and *b* of the regressions Phreatic $\text{Level}_{\text{calculated}} = a + b \cdot \text{Phreatic Level}_{\text{observed}}$ (Fig. 3) did not differ significantly from 0 and 1 respectively. In both cases a significance level of 95% was used.

Simulation of the current scenario

The simulation of the current scenario sample as the average phreatic level of the aquifer responds to the seasonal variability of the recharge (Fig. 4). In autumn the levels are high due to the effect of storage of the high summer irrigation drainages and the autumnal rains. The low precipitations and absence of irrigation in winter mean that it reaches the annual minimum phreatic level. Then irrigation application in spring elevates the phreatic levels again to reach the absolute annual maximum in summer.

The execution of water balances every season relates the increases and decreases of the phreatic level with

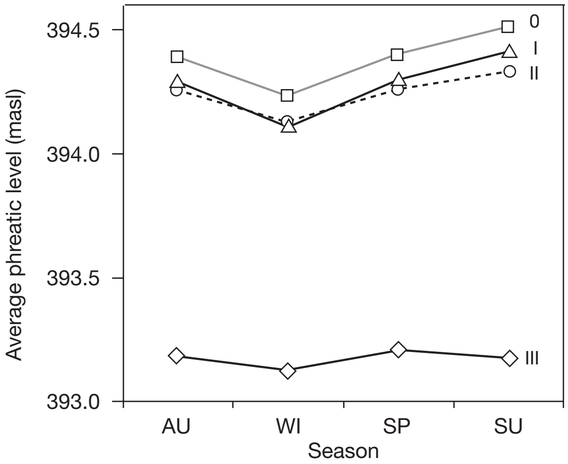

Figure 4. Average phreatic level of Miralbueno aquifer in the current scenario (0), after interception drain construction (I), after construction of wells for drip irrigation of vegetables (II), and after generalized change to pressurized irrigation systems (III).

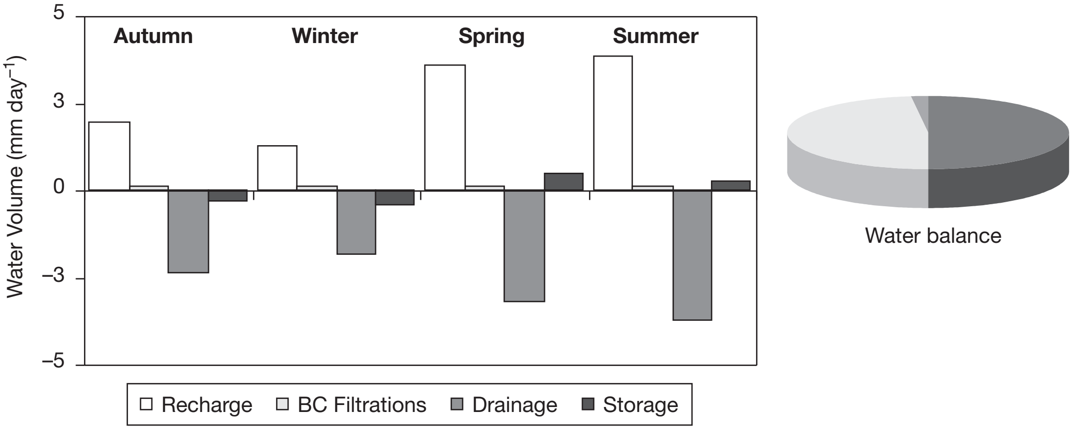

Figure 5. Water balance in the Miralbueno aquifer in the current scenario.

the gains (spring and summer) or losses (autumn and winter) of water stored in the aquifer (Fig. 5). The annual storage of water in the aquifer is practically null caused by the serial simulation of several years to reach the stationary regime.

The water regime described by the model responds to that indicated by Causapé (2003). However, using average values and too lengthy periods of simulation in the modelling diminishes the range of variation of the phreatic level compared to that observed by Causapé (2003). At any rate, the small seasonal water storage in the aquifer, compared to the volume of water introduced through irrigation or drainage each season (Fig. 5), leads to the deduction that the aquifer's phreatic level is mainly controlled by the dense drainage network as a consequence of the high permeability of the aquifer.

Simulated future scenarios

The simulation of the construction of the intercepting drain would cause a descent of about 10 cm in the average phreatic level of the aquifer during the whole annual period (Fig. 4). This behaviour would allow the recovery of water for flood irrigation for 3,400 ha in spring and 2,600 ha in summer (41% and 32% of the irrigable area of the aquifer) at a level lower than the drain. In autumn and winter the entire irrigable area could be irrigated from the aquifer at a level lower than the drain (53% of the irrigable surface) and there would be surpluses with those which: a) more surface area outside the irrigable area of the aquifer could be supplied or b) in combination with an internal regulation reservoir which already exists in the area (Bolaso reservoir), a greater surface area could be irrigated in spring and summer.

With the water shortage in some years of recent decades, the reuse of water from the drains has already been started by the CR-V. With the simple gravitational movement of water from some drains to the canals, it is estimated that the surface irrigated with drainage water is more than 25% (CR-V authority). However, the proposal of building an intercepting drain in combination with the internal regulation reservoir would increase the capacity of reuse of drainage water within the CR-V, as it would recover a greater volume of irrigation water to a higher level.

The construction of wells for drip irrigation of vegetables would cause an average decrease in the phreatic level of the aquifer similar to that caused by the construction of the previous interceptor drain. However, in this last case the decrease in spring and summer is the most striking result of the operation of the wells (Fig. 3). The simulation indicates that the aquifer has enough capacity to give drip irrigation volumes of the current surface of vegetables, provided that the wells are not concentrated in one particular sector. Nevertheless, this scenario would produce a decrease in the volume of annual water drainage of 9% (oscillating between 3% in winter and 14% in summer) which would be no longer available for reuse downstream.

At the present time, some farmers have put this measure into practice to give supplementary irrigation applications to vegetables, thus considerably increasing production. However, even though vegetables are the most profitable crops, it would be necessary for the CR-V to foment this activity, since it requires an initial investment and it would benefit the individual farmer as much as the rest of the agrarian system (reduction in the duration of time between irrigation applications).

The simulation of generalised change to pressurized irrigation systems would cause an even sharper decrease in average phreatic levels (1.20 m) and it would alter its seasonal evolution, as the spring increase cannot be maintained in summer (Fig. 4) as a consequence of the severe decrease in recharge from irrigation. This factor would also make the volumes stored each season of the year smaller and therefore the seasonal variability of the phreatic level would also decrease ($CV_{III} = 0.01\%$ compared to $CV_0 = 0.03\%$). The decrease in irrigation doses and the increase in pressurised irrigation efficiency would have repercussions, not only in phreatic levels but also in water volumes collected by the drainage network, which would diminish considerably (between 33% in winter and 62% in summer) with an annual decrease of 49%.

Conclusions

The high permeability of geological materials which constitute the Miralbueno aquifer is the main cause of the low efficiency of the flood irrigation system that it supports. In the last decade the CR-V has been planning the generalised changeover to pressurized irrigation but its high cost has meant that only 6% of the surface has been converted so far.

When the change to pressurized irrigation is complete, the phreatic level will decrease 1.20 m and the water volume collected annually by the drainage network will be 49% smaller, so problems caused to current users of the groundwater (cattle and agrarian use) and to the current users of the drainage waters (irrigated land located downstream which are supplied by them) should be considered.

While the widespread changeover to pressurized irrigation system is not possible, the CR-V reuses water from the drains to supply 25% of the surface area. However, the simulation of a traverse drain intercepting the flow and the regulation of the intercepted water would considerably increase the volume of water for reuse and its level.

The simulation of the use of groundwater for drip irrigation of vegetables (today with hydric stress problems) demonstrates that the Miralbueno aquifer can supply the current surface area of vegetables with small decreases in the phreatic level (10 cm), provided that the wells are adequately distributed.

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References

ARAGÜÉS R., TANJI K.K., 2003. Water quality of irrigation return flows. In: Encyclopaedia of water science. Marcel Dekker, NY, USA. pp. 502-506.

CAUSAPÉ J., 2003. Repercusiones medioambientales de la agricultura sobre los recursos hídricos de la comunidad de regantes nº V de Bardenas (Zaragoza). Eds Fundación Biblioteca Virtual Miguel de Cervantes, Universidad de Alicante. 153 pp. Available in www.cervantesvirtual.com [1 November, 2007]. [In Spanish].

CAUSAPÉ J., QUÍLEZ D., ARAGÜÉS R., 2004a. Assessment of irrigation and environmental quality at the hydrological basin level. II: Salt and nitrate loads in irrigation return flows. Agr Water Manage 70, 211-218.

CAUSAPÉ J., AUQUÉ L., GIMENO MªJ., MANDADO J., QUÍLEZ D., ARAGÜÉS R., 2004b. Irrigation effects on the salinity of the Arba and Riguel rivers (Spain): present diagnosis and expected evolution using geochemical models. Environ Geol 45, 703-715.

CAUSAPÉ J., QUÍLEZ D., ARAGÜÉS R., 2006. Irrigation efficiency and quality of irrigation return flows in the Ebro River Basin: an overview. Environ Monit Assess 117, 451-461.

COTS LL., CLOP M.M., LÓPEZ R., SANGRÁ J., ESTEBAN M., BARRAGÁN J.D., CUADRAT O., 2007. Indicadores de la gestión del agua en los canales de Urgell (Lérida). Riegos y Drenajes XXI 156, 26-32. [In Spanish].

CUSTODIO E., LLAMAS M., 1983. Hidrología subterránea. Ed Omega. Barcelona, Spain. 2290 pp. [In Spanish].

FAO, 2003. Water management: towards 2030. Food and Agriculture Organization of the United Nations. Available in www.fao.org/AG/magazine/0303sp1.htm [1 November, 2007].

HARBAUGH A.W., BANTA E.R., HILL M.C., MCDONALD M.G., 2000. Modflow-2000, the US geological survey modular ground-water model. User guide to modularization concepts and the ground-water flow process: US Geological Survey Open-File Report 00-92, 121 pp.

HAYES A.F., 2005. Statistical methods for communication science. Taylor & Francis, London. 304 pp.

ISIDORO D., QUÍLEZ D., ARAGÜÉS R., 2004. Water balance and irrigation performance analysis: La Violada irrigation district (Spain) as a case study. Agr Water Manage 64, 123-142.

ITGE, 1985. Investigación de los recursos hidráulicos totales de la cuenca del Arba. Instituto Tecnológico Geominero de España. Internal document. [In Spanish].

KHARE D., JAT M.K., EDIWAHYUNAN, 2006. Assessment of conjunctive use planning options: a case study of

Sapon irrigation command area of Indonesia. J Hydrol 328, 764-777.

LECINA S., PLAYAN E., ISIDORO D., DECHMI F., CAUSAPÉ J., FACI J.M., 2005. Irrigation evaluation and simulation at the Irrigation District V in Bardenas (Spain). Agr Water Manage 73, 223-245.

PLAYAN E., MATEOS L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agr Water Manage 80, 100-116.

PLAYAN E., SLATNI A., CASTILLO R., FACI J.M., 2000. A case study for irrigation modernisation: II - Scenario analysis. Agr Water Manage 42, 335-354.

SAHUQUILLO A., 1993. Los objetivos de los planes hidrológicos. Las aguas subterráneas y el medio ambiente. Revista de Obras Públicas 3318, 17-22. [In Spanish].

SONDHI S.K., RAO N.H., SARMA P.B.S., 1989. Assessment of groundwater potential for conjunctive water use in a large irrigation project in India. J Hydrol 107, 283-295.

TOZE S., 2006. Reuse of effluent water-benefits and risks. Agr Water Manage 80, 147-159.

ZAPATA N., PLAYAN E., FACI J.M., 2000. Water reuse in sequential basin irrigation. J Irrig Drain E-ASCE 126, 362-370.