Irrigation Modernization and Water Conservation in Spain: The Case of *Riegos del Alto Aragón*

by

Lecina, S.[1], Isidoro, D.[2], Playán, E.[3], Aragüés, R.[2]

Abstract

This study analyzes the effects of irrigation modernization on water conservation, using the Riegos del Alto Aragón (RAA) irrigation project (NE Spain, 123.354 ha) as a case study. A conceptual approach, based on water accounting and water productivity, has been used. Traditional surface irrigation systems and modern sprinkler systems currently occupy 73 % and 27 % of the irrigated area, respectively. Virtually all the irrigated area is devoted to field crops. Nowadays, farmers are investing on irrigation modernization by switching from surface to sprinkler irrigation because of the lack of labour and the reduction of net incomes as a consequence of reduction in European subsidies, among other factors. At the RAA project, modern sprinkler systems present higher crop yields and more intense cropping patterns than traditional surface irrigation systems. Crop evapotranspiration and non-beneficial evapotranspiration (mainly wind drift and evaporation loses, WDEL) per unit area are higher in sprinkler irrigated than in surface irrigated areas. Our results indicate that irrigation modernization will increase water depletion and water use. Farmers will achieve higher productivity and better working conditions. Likewise, the expected decreases in RAA irrigation return flows will lead to improvements in the quality of the receiving water bodies. However, water productivity computed over water depletion will not vary with irrigation modernization due to the typical linear relationship between yield and evapotranspiration and to the effect of WDEL on the regional water balance. Future variations in crop and energy prices might change the conclusions on economic productivity.

---

[1] Ager ingenieros, ingeniería rural y civil S.L. c/ Mayor 53, 2ºB 50001 Zaragoza, Spain.

[2] Soil and Irrigation Department (associated with EEAD-CSIC). Agrifood Research and Technology Centre of Aragon (CITA), Aragon Government. Avenida de Montañana 930, 50059 Zaragoza, Spain.

[3] Dept. Soil and Water, Aula Dei Experimental Station, CSIC. P.O. Box 13034, 50080 Zaragoza, Spain.

Present address of S. Lecina (✉): Soil and Irrigation Department (associated with EEAD-CSIC). Agrifood Research and Technology Centre of Aragon (CITA), Aragon Government. Avenida de Montañana 930, 50059 Zaragoza, Spain. E-mail: slecina@aragon.es Phone: +34 976 713 834

Keywords: irrigation efficiency, sprinkler irrigation, surface irrigation, water accounting, water depletion, water quality, water productivity.

Introduction

The economic growth of Spain during the last decades has substantially increased national water demand. However, water availability has barely increased because of the lack of significant increases in water storage capacity. These facts have strengthened competition for water resources, and cyclical droughts have brought social conflicts between uses, users and regions within Spain (INE, 2006; MARM, 2006).

The Spanish Government has implemented reforms to manage water demand. One of the most ambitious plans is irrigation modernization. Spain has around 3.5 M ha of irrigated land, and although this area only represents 13 % of total agricultural land, it generates about 50 % of the agricultural Gross Domestic Product (Forteza del Rey, 2002). Before the establishment in 2002 of these irrigation modernization plans, traditional surface irrigation amounted to 59 % of the irrigated area, and 71 % of this area used structures more than 25 years old (MARM, 2002). The irrigated area of Spain is mostly located in land-locked provinces (72 %) (INE, 1999). Surface irrigation is predominant on these provinces, in which field crops occupy 74 % of the irrigated area (MARM, 2007).

The two National Irrigation Modernization Plans (*Plan Nacional de Regadíos* and *Plan de Choque de Modernización de Regadíos*) were designed with two main objectives: 1) to increase the competitiveness of the irrigation sector, preparing it for the liberalization of agricultural markets and the reduction of subsidies, and 2) to save 3,000 Mm^3 water per year, a volume expected to alleviate the effects of cyclical droughts on alternative uses. This foreseen water saving represents about 15 % of the yearly average national agricultural water use. These plans will invest a total of 7,400 M € during this decade to improve the irrigation structures of nearly 2 M ha. The decision to engage in these irrigation modernization projects is taken by farmers and irrigation districts, since farmers contribute with at least 34 % of the investment in collective irrigation structures (MARM, 2002; MARM, 2006).

These 3,000 Mm^3 prospects on water saving are based on reductions in water use due to expected improvements in on-farm irrigation efficiency. The efficiency concept has traditionally been used to design irrigation systems and to schedule irrigation. However, several authors have pointed out (mainly since the 1990s) that this concept is not appropriate for assessing the hydrological impact of irrigation in a basin (Willardson et al, 1994; Seckler, 1996; Perry, 1999; Seckler et al., 2003; Jensen, 2007; Perry, 2007). Efficiency does not take into account issues such as water reuse, the distinction between total water use and water consumption, the influence of location of use within the basin, and water quality. These issues are particularly important for water management in a context of water scarcity. The abovementioned authors, as well as others (Huffaker, 2008; Ward and Pulido-Velázquez, 2008), reported examples of misunderstandings in water management practices and water conservation programs due to an inadequate use of the efficiency concept.

Several authors have proposed the distinction between the “classical” concept of irrigation efficiency and the “neoclassical” concept (Keller et al., 1996; Seckler et al., 2003; Haie and Keller, 2008; Mateos, 2008). This approach includes the abovementioned hydrological issues in a new formulation called “effective efficiency”. However, Perry (2007) and Perry et al. (2009) consider that this terminology could lead to misconceptions despite its proper hydrological basis.

Water accounting has been proposed as an alternative to the irrigation efficiency approaches for hydrological purposes (Willardson et al, 1994; Molden and Sakthivadivel, 1999; Clemmens et al., 2008; Perry et al., 2009). This methodology applies the law of conservation of mass through water balances. Balances identify the destination of the water used and distinguish between consumptive and non-consumptive uses. Several fractions among balance components have been proposed to characterize the performance of irrigated areas and other water uses.

Water accounting is a valuable tool to characterize water use in a basin. However, there is also a need to assess how well water is used in relation to agricultural production. Water productivities applied to irrigation represent the output obtained per water input. A number of indices have been proposed to estimate water productivity, depending on the use of physical or economic terms and on the expression of water input (i.e. water use or water consumption) (Molden, 1998; Molden et al., 2003;

Hussain et al., 2007; Molden et al., 2009). Likewise, different space scales can be considered, as well as average or marginal production values. These indicators are used to describe overall performance and to support decision making processes about investments or water allocation strategies, among other applications. Irrigation modernization can contribute to increase water productivity. However, Playán and Mateos (2006) and Perry et al. (2009) pointed out from a general perspective that irrigation modernization projects aiming at increasing crop production would actually increase water consumption in a basin.

This study applies the water accounting and water productivity concepts to the assessment of irrigation modernization in terms of water conservation. The analysis has been applied to the case study of the *Riegos del Alto Aragón* irrigation project (RAA), representative of large irrigation projects in interior Spain and in similar semi-arid areas. The objective of this work is to contribute to the optimization of water use in irrigation projects. The application of water accounting concepts to irrigation modernization constitutes a secondary objective of this study.

This publication is divided into five sections including this introduction. The second section presents the main characteristics of RAA and the socio-economic factors which lead farmers to invest on irrigation modernization by switching from surface to sprinkler irrigation. The third section discusses the differences between these irrigation systems in RAA from a productive and a hydrological perspective. The fourth section applies the water accounting approach to determine water balances, fractions and productivities in RAA before and after irrigation modernization. Finally, the fifth section summarizes the most important conclusions of this work.

The *Riegos del Alto Aragón* (RAA) irrigation project

General characteristics

RAA is located in NE Spain, in the central Ebro River Basin (Figure 1). Development of this irrigation project started in 1915, intensified in the 1940s to 1960s and is still ongoing. The current irrigated area is 123,354 ha, covering a territory of 2,500 km^2, and with an altitude ranging from 200 to 425 m above mean sea level. RAA is distributed among five sub-basins: Gállego, Flumen, Alcanadre, Cinca and Ebro. Irrigation water originates at the Central Pyrenees Mountains and its quality for irrigation is high (electrical conductivity < 0.4 dS m^{-1}; sodium adsorption ratio < 2 (mmol l^{-1})$^{0.5}$) (Isidoro and Aragüés, 2007).

The local climate is semiarid Mediterranean continental, with a mean annual temperature of 14.5 ºC, and an annual precipitation oscillating between 300 mm in the South and 450 mm in the North. A dry period typically extends from July to September. The annual reference evapotranspiration (Hargreaves and Samani, 1985) varies from 949 mm in the North to 1,149 mm in the South. The average wind speed (at 2.0 m height) is about 1.9 m s^{-1} in the North and 2.6 m s^{-1} in the South.

Two geomorphologic units (with respective dominant soil types) can be distinguished in RAA. The first corresponds to platforms sitting on tertiary materials covered with gravel. Platform soils are highly productive because of their low slope and adequate drainage. These soils often result in low surface irrigation application efficiency due to their low available water holding capacity (AWHC) and high infiltration (Playán et al., 2000). The second unit corresponds to slopes and alluvial terraces, characterized by high AWHC but poor drainage. Some of the soils in this unit are naturally salt-affected, while others were man-made salinized because of improper land levelling, lateral seepage, low internal drainage and development of shallow water tables. Spots of saline-sodic soils occur in this geomorphologic unit, although sodicity is generally associated to areas lacking gypsum (Herrero and Snyder, 1997).

The RAA project uses six head reservoirs with a total storage capacity of 930 Mm^3, 223 km of main canals, 2,000 km of secondary canals, and 3,000 km of drainage collectors. Almost all irrigation canals and ditches are lined. In addition to irrigation water delivery, the project supplies domestic water to a population exceeding 66,000 inhabitants, ten industrial areas, and 765 livestock farms.

RAA is divided into 53 irrigation districts. Due to its gradual transformation over the past century, water structures are heterogeneous. For this reason, and following the water delivery terminology proposed by Clemmens (1987), three groups of irrigation districts can be distinguished: 1) Districts transformed in recent years with on-demand pressurized water conveyance networks, sprinkler irrigation systems and volumetric water meters (11,686 ha); 2) Districts transformed in the 1980s and early 1990s, with pressurized networks and sprinkler systems, but with arranged water distribution based on prepaid volumes of water (21,168 ha); and 3) Surface irrigation districts transformed prior to the 1980s, mostly using border irrigation. In these districts water delivery is arranged, based on previous volumetric water orders (90,500 ha). In the three groups of districts the daily irrigation period is 24 h. RAA is still expanding: 12,000 new hectares are being developed in the South to sprinkler irrigation with on-demand pressurized networks. Total planned irrigated area is around 175,000 ha (CGRAA, 2004).

Land tenure is very heterogeneous, but generally small. Farms are often larger in the new sprinkler irrigation districts than in the old surface irrigation districts. Before irrigation modernization, average farm and plot sizes in the sprinkler irrigated districts were 12.45 ha and 3.27 ha, respectively, whereas in the surface irrigation districts average farm size was 8.51 ha and average plot size 1.87 ha.

Field crops have traditionally been majority in RAA. However, the cropping pattern has evolved from winter cereals until the 1980s to summer crops, like corn and alfalfa, thereafter. These crops present higher water requirements than winter cereals. This cropping pattern intensification and the progressive expansion of the irrigated area have resulted in a sharp increase in water use during the last decades.

The RAA billing scheme is binomial. District services are charged in proportion to the irrigated area, while costs associated to water are charged in proportion to farmer’s water use. The proportion of total costs charged by area and volume of water varies from district to district. On the average, 60 % and 40 % of total charges are billed by volume in sprinkler and surface irrigation districts, respectively. In 2003 and 2004, the average charges were 0.013 € m^{-3} and 62.50 € ha^{-1} in sprinkler irrigation and 0.005 € m^{-3}

and 46.50 € ha^{-1} in surface irrigation. The average impact of these charges, as a percentage of total crop production costs, was about 10 % in surface irrigated areas and 20 % in sprinkler irrigated areas.

When RAA faces water scarcity problems, water allocation thresholds are imposed to farmers. These thresholds are based on water use instead of water consumption, in accordance with existing water rights (also based on water use). These allocation thresholds are determined for each irrigation district taking into account historical water allocations and the prevailing on-farm irrigation technology (surface *vs.* sprinkler irrigation). Thresholds are expressed in units of m^3 ha^{-1}, and are revised monthly by the project Board.

At present, 52,218 ha are being modernized in RAA. A fraction of this area has been finalised in the last three years and is starting operation. The area subject to modernization represents 58 % of the surface irrigated area before the beginning of modernization, and corresponds to 30 % of the expected area to be modernized in the Ebro River Basin along this decade in accordance with the Government's plans. At the same time, a process of land consolidation is underway in some project areas to increase plot size. In these cases, irrigation modernization begins right after completion of land consolidation.

In addition to modernization of irrigation structures, RAA is also modernizing its water management tools and procedures. Customized tools are required for this purpose (Lozano and Mateos, 2008; Wriedt et al., 2009). In 2001, the project Board adopted the ADOR software for the daily water management of their districts. ADOR was developed and implemented in RAA by a group of public researchers (Playán et al., 2007) in co-operation with the project and district managers and other agents. This specialised database allows managing water delivery, plots, water users, water uses and structures over a Geographical Information System (GIS). ADOR is also used for billing operational and maintenance services, as well as the amortization of collective irrigation structures.

The completion of modernization in RAA requires a total investment of about 500 M €. On the average, the investment required to switch from surface to sprinkler irrigation is about 9,000 € ha^{-1}, including collective on-demand water conveyance structures and on-farm irrigation systems. This cost is similar to the local market value of the land.

The average annual amortization is about 300 € ha^{-1}, including public subsidies to initial investments and/or interest rates.

The need for modernization: from surface to sprinkler irrigation

There are a number of reasons explaining farmers' investment in modernizing their irrigation structures. The abovementioned liberalization of agricultural markets is bringing direct consequences over farm profits. This policy has brought sharp decreases in subsidies applied to the crop area, among other measures. In Europe, the discussion about the extinction of the Common Agricultural Policy (CAP) in 2013 is currently open among policymakers. This change has so far resulted in RAA in a reduction of the average subsidies to the production of corn and winter cereals from 450 and 250 € ha^{-1}, respectively, at the beginning of 2000s, to a current amount of 110 € ha^{-1} and 60 € ha^{-1}. In the central Ebro Valley, CAP subsidies amounted to 43 % of net farm incomes at the end of the 1990s, and currently amount to 26 % (CESA, 2001 and 2008).

Open global markets increase competition among producers. As a result, the prices of agricultural commodities are much more variable now. These prices are no longer regulated by CAP and depend on multiple and changing factors in time and space, such as world weather, economic and population growth, energy prices, and investments in rural development. Just like in other agricultural commodities stock exchanges, the average annual variability of grain prices at the local *Lonja del Ebro* has increased from 5 % to 20 % in the last five years. This trend has contributed to increase the uncertainty of farms' net profits and is expected to continue through the upcoming years (OECD-FAO, 2009; IBRD, 2009). The productive structure and management of farms must be competitive and flexible to cope with fast changing market conditions. Decisions on irrigation investments should take this fact into consideration (Turral et al., 2009).

The decreasing availability of agricultural labour is another factor influencing decisions about investments in irrigation modernization. Most of the RAA area presents a population density of about eight inhabitants per square kilometre. Moreover, young people continue to leave the rural areas because of difficult labour conditions, low incomes, and low technology level of agricultural jobs compared to urban jobs. Only 19 % of the local population is less than 25 years old (IAE, 2008).

Water scarcity and environmental restrictions imposed to irrigated agriculture are not currently decisive factors fostering farmers' decisions on irrigation modernization, but could become important in the medium and long terms. The change of land uses in the Central Spanish Pyrenees Mountains, from crops and pastures to scrubs and forests due to the depopulation of this territory, has decreased stream flows by about 30 % since the mid-20th century (Beguería et al., 2003). Moreover, the negative trend of snow accumulation has changed the seasonal distribution of the inflows to the reservoirs during this period, reducing the natural water storage capacity of the Pyrenees (López-Moreno et al., 2008). Although the Ebro River Basin Authority has adjusted dam operation to cope with these trends and to satisfy increasing water demands, the frequency and severity of water shortages have increased along the last years in this region. If current trends in plant cover and snow accumulation continue into the future, farmers' water supply could be seriously jeopardized.

The European Water Framework Directive (European Union, 2000) requires achieving "good environmental status" in all water bodies before 2015. Two vulnerable zones to nitrate pollution from agricultural sources have already been declared in RAA. Environmental restrictions on agricultural activities will undoubtedly be reinforced in the coming years.

Differences between surface and sprinkler irrigation in RAA

Switching from surface to sprinkler irrigation is the option selected by farmers to modernize their irrigation structures. This change leads to improvements in farm productivity, but entails radical changes in water use patterns.

An analysis was performed on differences in crop yields and water balance components between surface and sprinkler irrigation in RAA. The crop and water use data available in ADOR for each RAA irrigation district during the 2003 and 2004 irrigation seasons constituted the main data source for this analysis. 2003 was the first year of ADOR operation in RAA. None of the reported modernization processes involving a change in irrigation systems was completed at that time. An analysis of the agrometeorological data series (1961-2002) (Martínez-Cob, 2004) indicated that the return probability of crop water requirements was 39 % in 2003 and 29 % in 2004. Water availability was not a limiting factor in both years.

Crop data were either extracted from ADOR following a yearly farmers' crop declaration, or from the Government databases used to determine the CAP subsidies. Crops were associated to each plot of each irrigation district. GIS coverages were used to support data analysis. Water use data by crop was based on farmers' water orders and volumetric water meters readings recorded in ADOR. The minimum volume of a single water order in RAA is 1,000 m^3 in surface irrigation districts and 500 m^3 in sprinkler irrigation districts.

Productivities by crop and irrigation system were computed following the guidelines indicated by Molden et al. (1998) and Playán and Mateos (2006). Gross land productivity was obtained as the ratio between the gross value of production and the cropped area. The gross value was calculated as yield multiplied by price. Net land productivity was obtained as the ratio between the net margin of production and the cropped area. The net margin was calculated as gross value plus subsidies, minus direct costs and amortizations. Yields, prices and costs were obtained by surveys among the irrigation districts managers and from Government statistics (MARM, 2004 and 2005). Gross and net water productivities were computed in the same way, using the average water use obtained from ADOR.

Crop yield differences under sprinkler and surface irrigation were analysed from previous research campaigns in RAA and in neighbouring areas of the central Ebro Valley. These results were also used to characterize the water balance components typical of each irrigation system.

Cropping patterns, yields and productivities

Table 1 shows the RAA cropping patterns by irrigation system in 2003 and 2004 as an average. These patterns were very similar in both seasons. Corn and alfalfa occupied 60 % of the total irrigated area. These crops, together with rice, have the highest water requirements and provide the largest economic returns among field crops. Corn, alfalfa and rice were cultivated in 63 % of the surface irrigated areas, and 75 % of the sprinkler irrigated areas. In contrast, winter cereals and fallow plots were present in 29 % of the surface irrigated areas, and 16 % of the sprinkler areas. Incentives to CAP subsidized land set-aside and the presence of salt-affected soils explain the relevance of fallow areas (8 % of the irrigated area) (Nogués et al., 2000). Two crops per season were produced in 8 % of the sprinkler irrigated areas, mainly in the South of RAA, where summer seasons are long enough.

Table 2 presents water use, yield and economic productivities averaged by irrigation systems and crops in RAA. Yields and gross land productivities were 25-33 % higher in sprinkler than in surface irrigated areas, whereas net land productivities were 29-45 % higher in sprinkler irrigated areas. Crops with higher water use -corn and alfalfa- presented net land productivities about 130 % and 60 % higher than winter cereals, respectively. Net water productivity was 75-93 % higher in sprinkler than in surface irrigated crops.

Differences between irrigation systems in cropping patterns, yields, water uses and productivities are due to several factors. Although surface irrigation systems can perform just as well as pressurized systems, proper design and management are required (Clemmens and Dedrick, 1994). The development of diesel-powered land grading machinery allowed the expansion of irrigated areas outside fluvial terraces in the first half of last century. However, the soils in these new irrigated areas were in many cases not adequate for surface irrigation, because of their low available water holding capacity and high infiltration rates. This is often the case of platforms in the central Ebro Valley (Herrero and Snyder, 1997; Nogués et al., 2000; Nogués and

Herrero, 2003). When these surface irrigated areas were designed and built, this irrigation technique was the only available in Spain. In addition, irregular topography, small land tenure and a low mechanization level negatively influenced on-farm design (De los Ríos, 1984).

Furthermore, the open channel tertiary ditches were designed 50 years ago for low-productivity agriculture based on winter cereals (De los Ríos, 1966). Intensification of local agriculture led to a sharp increase in water use. As a consequence, a daily irrigation period of 24 h is currently required in RAA surface irrigated areas. Even under this continuous operation regime, the conveyance network lacks capacity to satisfy crop water requirements. The low conveyance capacity of the old distribution networks often results in surface irrigation intervals of about 10-14 days during the peak months, even when a large part of the irrigated area is devoted to winter cereals or is left as fallow (Faci et al., 2000). In soils with AWHC lower than 100 mm (platforms), this interval is excessively long and results in partial satisfaction of crop water requirements. Consequently crop yields fall below potential levels because of the typical linear relationship between crop biomass and transpiration, (Howell, 1990; Steduto et al., 2007; Farré and Faci, 2009).

Local farmers using surface irrigation tend to apply large irrigation depths by using long irrigation times because of the uncertainty about when to irrigate again (Faci et al., 2000). In soils with low AWHC, these large irrigation depths do not improve crop water supply and extend the irrigation intervals to all farmers, further decreasing yields. The results of several field irrigation evaluation campaigns carried out in RAA point out that the average irrigation time is about 5 h ha^{-1}, with an average discharge of 70 l s^{-1} (Playán et al., 2000; Lecina et al., 2000) and an average application efficiency (Burt et al., 1997) of about 60 % (Playán et al., 2000; Lecina et al., 2000). Although the variability of these parameters in RAA is high, the long irrigation times and the small plot areas imply high labour requirements, including night irrigation during summer time. For these reasons, one person can hardly irrigate more than 50 ha in the RAA surface irrigated areas. Although Playán et al. (2000), Lecina et al. (2005), and Lecina and Playán (2006a) pointed out that water management practices could be substantially improved in surface irrigation districts in the central Ebro Valley, the decreasing labour availability makes this goal unrealistic without additional investments.

In contrast, the higher conveyance capacity of pressurized networks permits more intensive cropping patterns in sprinkler irrigated areas, including two crops per season (Tedeschi et al., 2001; Cavero et al., 2003). Moreover, the effective cropped area increases by 7 % in comparison to the old surface irrigated areas because plots are larger and the dikes used to build the irrigation borders are no longer needed. This figure was obtained for RAA comparing the effective cropped area of the plots obtained from the Government databases used to pay the CAP subsidies, and the total area obtained from the Government cadastral databases used to raise taxes. The flexibility and reliability of pressurized networks and the generalized use of on-farm electronic irrigation controllers permit accurate irrigation scheduling. Sprinkler irrigation application efficiencies average 80 % (Sánchez, 2008), and automation strongly reduces labour requirements. Thus, it is estimated that one person can handle about 200 ha of modernized irrigated land. Although energy-related water costs are higher in sprinkler than in surface irrigation systems, the advantages of sprinkler irrigation explain its clear increase in productivity (Table 2). This increased productivity is the main reason for farmers to invest in modernizing their irrigation structures and management in RAA.

Water balance components

The principles of water accounting established by Molden and Sakthivadivel (1999) and Perry et al. (2009), identify irrigation water use as any deliberate application of water for irrigation purposes and distinguish four sinks of irrigation water use: 1. Beneficial evapotranspiration; 2. Non-beneficial evapotranspiration; 3. Non-recoverable runoff/percolation; and 4. Recoverable runoff/percolation. The two first sinks constitute the consumed fraction over the total water use. Total evapotranspiration and non-recoverable runoff/percolation represent the fraction of total water use that is depleted in a basin. Depletion entails that water is not available to further use because its destination is the atmosphere (water consumption) or other sinks (non-recoverable runoff/percolation) where: 1) it is not economically exploitable, such as saline water bodies and deep aquifers; or 2) its quality prevents its reuse.

Beneficial evapotranspiration is equivalent to crop evapotranspiration. Isidoro et al. (2004) and Lecina and Playán, (2006a, 2006b), using subregional water balances and combined irrigation-crop models, reported that in the surface irrigated districts of the

Ebro Basin the estimated actual evapotranspiration was 15-20 % lower than the potential evapotranspiration due to limitations of irrigation structures and development of crop's water stress. This effect on crop evapotranspiration has been described in other traditional surface irrigated areas in the world (Allen et al., 2005). In contrast, Cavero et al. (2003) reported that the actual crop evapotranspiration in modern RAA sprinkler irrigated areas was close to its potential. The cropping patterns contribute to increase the local differences in beneficial evapotranspiration between both irrigation technologies. An intense cropping pattern in sprinkler districts involves higher areas of summer crops like alfalfa and corn, with higher water requirements.

Non-beneficial evapotranspiration is made up by evapotranspiration from non-productive plants (like weeds or phreatophites) and direct evaporation from water bodies. Wind drift and evaporation losses (WDEL) can also be considered as non-beneficial water consumption in sprinkler irrigation (Burt et al., 1997). Pressurized networks virtually eliminate direct evaporation and leakages that could be used by non-productive plants. However, the in-line reservoirs required for on-demand sprinkler irrigation increase the water surface exposed to direct evaporation. Krinner et al. (1994) estimated in a number of Spanish irrigation projects (including RAA) that non-beneficial evapotranspiration was about 20 % of the difference between the water volume released at the head of the projects and the water volume received by farmers. This estimation results in a very small water volume in comparison with the rest of water balance components.

The most important difference in non-beneficial evapotranspiration between surface and sprinkler districts in RAA is due to WDEL. The central Ebro Valley is characterized by strong winds, locally called "cierzo", particularly in the area near the Ebro River. A number of research works based on field irrigation evaluations in the Ebro Basin have reported that WDEL may range, depending on wind speed, between 10 and 20 % of the total water applied (Faci and Bercero, 1991; Dechmi et al., 2003a; Playán et al., 2005; Sánchez, 2008). However, during sprinkler irrigation the microclimate is modified. Martínez-Cob et al. (2008) reported that this effect can reduce WDEL (due to its contribution to crop evapotranspiration) by 15 % during daytime solid-set irrigated corn, equivalent in the study area to approximately 3 % of the applied water.

Runoff/percolation is generated at on-farm and conveyance structure levels. Several research works based on field irrigation evaluations and drainage measurements in subregional water balances (Playán et al., 2000; Isidoro et al., 2004; Lecina et al., 2005; Playán et al., 2008) concluded that runoff and percolation can represent 40 % of the total water applied in surface irrigated areas. Most of this volume is percolation, since blocked-end borders are very common in RAA. Runoff mainly occurs in paddy rice fields and operational network spills. In sprinkler irrigated areas the volumes of runoff/percolation are typically low. In RAA, Tedeschi et al. (2001) and Cavero et al. (2003) measured these volumes as 8 % of total water inputs in the average.

Virtually all runoff/percolation volumes generated in RAA return to rivers. The water quality of these returns allows in most cases for their reuse for irrigation, either directly or mixed with fresh irrigation water. Mean annual nitrate concentration and total dissolved solids (TDS) measured in the irrigation return flows (IRF) of the RAA surface irrigated areas, with soils rich in gypsum, were 28 mg NO_3-N l^{-1} and 1,715 mg l^{-1}, respectively (Isidoro et al., 2006a, b). In the case of sprinkler areas with presence of shallow and impervious lutites high in salts and sodium, these concentrations were 120 mg NO_3-N l^{-1} and 6,983 mg l^{-1} (Cavero et al., 2003; Tesdechi et al., 2001). As a general rule, even in the absence of saline strata, the IRF resulting from surface irrigated areas have lower salt and other pollutant concentrations than the IRF from sprinkler irrigated areas, but the exported loads from surface irrigated areas are higher due to its higher IRF volumes (Aragúés and Tanji, 2003).

Reuse of runoff/percolation volumes in several irrigation projects located in the central Ebro River Basin has been calculated as 30 % of total water use (Causapé et al., 2006; Causapé, 2009). Most of the remaining runoff/percolation volumes are eventually reused by downstream users in the Ebro River Basin. RAA is located 250 km upstream from the Mediterranean Sea (Figure 1). Only a small fraction of these IRF volumes are not recoverable. A few small salt lakes intercept a fraction of these IRF. In some cases, return flows contribute to maintain natural bird refuges (i.e., the *Sariñena* lagoon) whereas in other cases, they interfere with the natural water balance of protected ecosystems like the *Saladas de Monegros* (Castañeda and García-Vera, 2008).

The wide variety of methodologies applied to obtain the water balance components in the abovementioned research works reveals the complexity of implementing water accounting in irrigated areas. Thus, actual crop evapotranspiration was estimated from irrigation and crop simulation models. Non-beneficial evapotranspiration in canals was estimated from canal water measurements. Non-beneficial evapotranspiration due to WDEL was measured in field sprinkler irrigation evaluations. Finally, runoff and percolation were measured in drainage canals and field irrigation evaluations. Despite this complexity, results obtained from these research works show sensible hydrological differences between surface and sprinkler irrigation systems in RAA. These differences affect the water balance in this irrigation project and will modify the hydrology of the Ebro River Basin when the irrigation modernization process is completed.

Water balances and productivities in RAA: effects of irrigation modernization

The water balance components in surface and sprinkler irrigated areas were used to compute balances for each irrigation district and in the entire RAA project for the 2003 and 2004 irrigation seasons. In surface irrigated areas, evapotranspiration was considered 15 % lower than potential due to limitations of irrigation structures. A range of WDEL between 12 % (North) and 20 % (South) was applied. Other non-beneficial evapotranspiration was estimated as 1 % in both irrigation systems. Runoff/percolation was considered to be 40 % of total water applied in surface irrigated areas and 8 % in sprinkler irrigated areas. The catchment area of the small lagoons present in RAA was considered to estimate non-recoverable runoff/percolation. Soil water content variation between the beginning and the end of the irrigation season was considered negligible.

An area of 2,600 ha was not included in this study because part of it was under construction in 2003 and the rest was occupied by drip irrigated vineyards. Water use data were obtained from the aggregated district water orders to the Ebro River Basin Authority (in charge of the operation of dams), recorded in ADOR. These water orders are expressed in multiples of 1,000 m^3 and refer to headgates in conveyance canals. The cropping patterns corresponding to each district were also obtained from ADOR. Crop water requirements were computed following the methodology proposed by Allen et al. (1998). A total of 12 agrometeorological stations distributed throughout RAA were used to determine reference evapotranspiration. The spatial domain of each station was established in a GIS according to the spatial pattern of the reference evapotranspiration obtained by Martínez-Cob (1996) in the central Ebro Valley. Local crop coefficients were used (Martínez-Cob et al., 1998).

The following fractions (m^3 m^{-3}) based on the water balance components proposed by Willardson et al. (1994), Molden and Sakthivadivel (1999) and Perry et al. (2009) were applied to each irrigation district:

$$DF = \frac{ET_B + ET_{NB} + RP_{NR}}{WU} \qquad [1]$$

where DF is the depleted fraction, ET_B the beneficial evapotranspiration, ET_{NB} the non-beneficial evapotranspiration, RP_{NR} the non-recoverable runoff/percolation and WU the total water use. The complementary to DF is the recoverable fraction (RF, expressed as the ratio between recoverable runoff/percolation and total water use).

$$CF = \frac{ET_B + ET_{NB}}{WU} \qquad [2]$$

where CF is the consumed fraction. The complementary to CF is the non-consumed fraction (NCF, expressed as the ratio between total runoff/percolation and total water use).

$$TBF = \frac{ET_B}{WU} \qquad [3]$$

where TBF is the total beneficial fraction.

$$DBF = \frac{ET_B}{ET_B + ET_{NB} + RP_{NR}} \qquad [4]$$

where DBF is the depleted beneficial fraction.

Economic land and water productivities were computed for each irrigation district following the guidelines indicated in the previous section. Water productivities were calculated using both water use and water depleted.

Four future post-modernization scenarios were considered to assess the impact of irrigation modernization. These were established as a function of different percentages of modernized areas and intensification of cropping patterns. The crop water requirements applied to the estimation of water balances in these scenarios corresponded to a 50 % return probability, based on meteorological data series (Martínez-Cob, 2004). A pre-modernization scenario, corresponding to the average of the 2003 and 2004 seasons, was also considered for comparison with the future scenarios at the same return probability of crop water requirements. The scenarios were characterised as follows:

- Pre-modernization scenario: reproduces the average 2003 and 2004 cropping patterns (Table 1) prior to modernization. 27 % of RAA is sprinkler irrigated.

- Scenario A1: the current modernization of 52.318 ha (20 irrigation districts) is considered completed. 69 % of RAA is sprinkler irrigated. Cropping patterns assigned to this scenario are the same as the pre-modernization scenario.

- Scenario A2: as in A1, 69 % of RAA is sprinkler irrigated, but cropping patterns are different then in the pre-modernization scenario. Summer field crops increase by 16 % in the sprinkler irrigated areas and decrease by 12 % in the surface irrigated areas (Table 1). These variations with respect to the pre-modernization scenario correspond to the most and least intensive patterns found in the irrigation districts in 2003 and 2004. Increased productivities in sprinkler irrigated areas and loss of competitiveness in surface irrigated areas are considered in this scenario.

- Scenario B1: completes modernization of all the surface irrigated areas in RAA, so that the entire project is sprinkler irrigated. Cropping patterns correspond to the pre-modernization scenario for this irrigation system.

- Scenario B2: as in B1, 100 % of RAA is sprinkler irrigated, but cropping patterns are intensified as in the A2 scenario.

Pre-modernization scenario

Table 3 shows the aggregated results of water balances, fractions and productivities by irrigation system for the pre-modernization scenario (PRE). Total RAA water use was 711.5 Mm^3 (5,892 m^3 ha^{-1}). Water use in surface irrigation (5,762 m^3 ha^{-1}) was lower than in sprinkler irrigation (6,247 m^3 ha^{-1}). Total runoff/percolation (i.e. non-consumed volume) was five times higher in surface (1,951 m^3 ha^{-1}) than in sprinkler (395 m^3 ha^{-1}) irrigated areas, while total evapotranspiration (i.e., consumed volume) was considerably higher in sprinkler (5,852 m^3 ha^{-1}) than in surface (3,811 m^3 ha^{-1}) irrigated areas. The beneficial evapotranspiration explains 53 % of this difference as a result of higher yields and more intensive cropping patterns in sprinkler irrigation. The rest is mainly due to the negative effect of WDEL in sprinkler irrigation.

Almost all runoff/percolation returned to rivers in surface and sprinkler irrigated areas (93 % and 98 %, respectively). Subregional water and pollutant balances carried out in surface irrigated areas of RAA show that average loads in irrigation return flows were 82 kg NO_3-N ha^{-1} yr^{-1} and up to 20 Mg ha^{-1} yr^{-1} of salts when gypsum was present

(Isidoro et al., 2006a). In the case of sprinkler irrigated areas, the average exported loads in IRF were 31 kg NO_3-N ha^{-1} yr^{-1} (Cavero et al., 2003) and up to 14 Mg ha^{-1} yr^{-1} of salts when saline lutites were present (Tedeschi et al., 2001). In other surface irrigated areas within the Ebro Basin with lower amounts of salts in the soil or subsoil, salt loading in IRF varied between 3 and 5 Mg ha^{-1} yr^{-1} (Causapé et al., 2006). The effect of these IRF on the quality (in terms of concentration of salts and other agricultural pollutants) of the receiving water bodies depends on loads rather than concentrations (Aragüés and Tanji, 2003). Since loads in IRF of surface irrigated areas are generally higher than those of sprinkler irrigated areas, it is expected that irrigation modenization in RAA will improve the quality of the receiving water bodies. This issue is further examined in the next section on future scenarios.

Water depletion was 76 % of total water use. This depleted fraction (DF) was notably higher in sprinkler (0.94) than in surface (0.69) irrigated areas. Water depletion in sprinkler districts (5,860 m^3 ha^{-1}) was 48 % higher than in surface districts (3,953 m^3 ha^{-1}) as a result of more intensive cropping patterns, better satisfaction of crop water requirements and large WDEL in sprinkler districts. The values of DF and CF (consumed fraction) were similar due to the low non-recoverable runoff/percolation volumes (lower than 2 % of total water use). The beneficial or crop evapotranspiration represented 69 % of total water use (65 % in surface districts and 77 % in sprinkler districts). The total beneficial fraction (TBF) has often been used for estimating irrigation efficiency at district or project scale (Seckler et al., 2003). If the efficiency approach was used to assess the effects of modernization, it will be concluded that modernized districts will save water because TBF in sprinkler districts (0.77) is higher than in surface districts (0.65). However, this conclusion will be misleading because TBF does not consider the portion of runoff/percolation collected by rivers that may be reused downstream from RAA.

The depleted beneficial fraction (DBF) is more adequate than TBF for assessing the impact of irrigation modernization on water availability at the basin scale, because it only considers water depletion (Willardson et al., 1994). DBF for total RAA currently reaches 0.91 (Table 3), and this already high value leaves a limited margin for real water savings. In addition, DBF is lower in sprinkler (0.83) than in surface (0.95) districts, indicating that non-beneficial water depletion is higher in sprinkler than in surface irrigation due to WDEL.

Water depletion and water use are higher in sprinkler irrigation than in surface irrigation, but its economic performance is also higher (Table 3, economic indicators). Net land productivity in sprinkler irrigation (748 € ha^{-1}) is about 51 % higher than in surface irrigation (495 € ha^{-1}). Figure 2 shows a linear and positive relationship between gross land productivity and water depletion by irrigation district. The three districts with the highest values of these variables are located in the South of RAA (nº 51, 52 and 53 in Figure 3), where evapotranspiration is highest. The cropping patterns in these districts are the most intensive within RAA, and their irrigation technology is also the most modern.

Net water productivity computed over water use is about 40 % higher in sprinkler (0.120 € m^{-3}) than in surface (0.086 € m^{-3}) areas (Table 3). The increase in land productivity per unit area is more than proportional to the increase in water use. This productivity is important for growers during drought years. Nevertheless, net water productivity computed over water depletion is practically the same in both irrigation systems (about 0.126 € m^{-3}) because the relative advantages of sprinkler *vs.* surface systems in terms of land productivity and water depletion are similar in magnitude. The low values of crop yields, the linear relationship between yield and evapotranspiration characterizing these field crops when yields are higher than 40-50 % of their potential (Molden et al., 2009), and the effect of WDEL explain this fact. Similar results were reported at plot scale in other Spanish irrigation projects (Playán and Mateos, 2006). Water productivity over water depletion is important from a society point of view because it represents the economic output obtained from the water which has been physically removed from the basin.

Future scenarios

Table 3 summarizes water balances, fractions and productivities resulting from the four post-modernization scenarios by irrigation system. The improvement of crop water supply resulting from the increment in sprinkler irrigated area, and the intensification in cropping patterns produce a progressive increment of beneficial evapotranspiration. The increase of this balance component relative to the pre-modernization scenario ranged between 12 % (scenario A1) and 34 % (scenario B2). Non-beneficial evapotranspiration strongly increased due to the WDEL of the new sprinkler irrigation systems: 105 % in scenario A1 and 206 % in scenario B2. The consumed fraction (CF) attained values between 0.82 (scenario A1) and 0.92 (scenario B2). The effect on total evapotranspiration of increasing the sprinkler irrigated area (i.e., increasing WDEL) was higher than the effect of intensifying the cropping patterns under the conditions of the proposed scenarios.

Runoff/percolation notably decreased following the on-farm improvement in efficiency for the future scenarios. Decreases varied between 28 % (A1) and 68 % (B1). Decreases in scenario B2 resulted slightly lower than in B1 due to increased crop water requirements in the last scenario. Reductions in non-recoverable runoff/percolation were small in absolute values due to the low relevance of this balance component. The progressive increment in total evapotranspiration increased water depletion between 17 % (90 Mm^3) in scenario A1 and 43 % (233 Mm^3) in scenario B2 (Figure 3). These increments imply an equivalent reduction in water availability in the Ebro River Basin.

Decreases of total runoff/percolation were lower than increases of total evapotranspiration in all future scenarios. For this reason, switching from surface to sprinkler irrigation implied an increment in total water use ranging from 5 % (35 Mm^3) in B1 to 17 % (123 Mm^3) in B2. The partial modernization scenarios (A1 and A2) resulted in intermediate increases because the districts currently under modernization have higher TBF and lower water use per hectare than the other surface irrigation districts. Additionally, DF increased from 0.76 in the pre-modernization scenario to 0.84 in the scenarios implying partial modernization and 0.92 in the scenarios implying total modernization.

The TBF increased from 0.69 to 0.73 (partial modernization scenarios) and 0.78 (total modernization scenarios) because increments in crop evapotranspiration were higher than increments in water use. However, the DBF slightly decreased, from 0.91 to around 0.86 because the increment of WDEL was much higher, in relative terms, than the increment of beneficial evapotranspiration.

The quality of water bodies receiving the RAA irrigation return flows will improve as a consequence of the reduction in runoff/percolation. This improvement will constitute a positive externality of irrigation modernization for society. Tedeschi et al. (2001), Cavero et al. (2003), and Isidoro et al. (2006a,b) reported that, for the conditions of RAA, substantial reductions in the load of exported pollutants (salts and nitrates) are to be expected. In the case of nitrates, the adoption of sprinkler fertigation techniques would also benefit water quality. However, these authors point out that the concentration of these pollutants will increase in IRF, limiting their possible use for irrigation.

Quílez et al. (2010) applied the CIRFLE model (Aragüés et al., 1990) in the Bardenas I irrigation district located in the central Ebro River Basin to evaluate water quality benefits derived from the transformation of currently surface irrigated systems to sprinkler irrigation. CIRFLE estimated that the TDS of IRF will increase by 35 % (from actual 806 mg l^{-1} to predicted 1,092 mg l^{-1}). In contrast, the volume and salt mass of IRF will decrease respectively by 60 % (from 0.62 to 0.25 m) and 46 % (from 5.0 to 2.7 Mg ha^{-1}). Although these figures will vary depending, among other factors, on soil characteristics and irrigation management, they substantiate that irrigation modernization will significantly reduce salt loading in irrigation return flows, therefore benefiting the quality (i.e., decreased salt concentrations) of the receiving water bodies.

RAA is divided in five sub-basins. The natural flows of these rivers and streams are very low or even non-existent in summer, and IRF often constitute their main flows. Fluvial ecosystems and water users benefit from these IRF. Modernization will have a negative effect on these users due to reductions in water volume and increases in pollutant concentrations. The River Basin Authority should face this problem by programming controlled water spills from reservoirs or restoring a flow regime similar to the natural flow regime. Either of these solutions would foster intense social discussion.

Another outcome of irrigation modernization is the increase in gross and net productivity between 21 % (scenario A1) and 49 % (scenario B2) (Table 3). Water productivities computed over water use will also increase between 13 % (scenario A1) and 28 % (scenario B1). In contrast, water productivity computed over water depletion will hardly change because of the abovementioned features of field crops and WDEL. This result implies that irrigation modernization will not increase the agricultural outputs obtained from the water resources removed from the basin. However, irrigation modernization will increase the economic activity of the agricultural sector between 27 and 68 M € (Table 3). This increase would have a cascade economic effect, extending the impact of irrigation modernization to related economic sectors. A multidisciplinary study would be required to estimate this effect on water productivity computed over water depletion at regional scale (Hussain et al., 2007).

In the case of individual farmers, switching from surface to sprinkler irrigation involved an average increase in net land productivity between 265 € ha^{-1} (A1 and B1 pre-modernization cropping pattern scenarios) and 395 € ha^{-1} (A2 and B2 intensified cropping pattern scenarios). These increases are quite similar to farmer's yearly amortization of about 300 € ha^{-1} when switching from surface to sprinkler irrigation. Although irrigation modernization is required for achieving farm sustainability, these results suggest that -besides cropping pattern intensification- additional improvements in farm productive structure, i.e., increasing the plot and farm sizes and optimizing the use of machinery, would also be required to ensure economic sustainability. Introducing new crops is another way for increasing productivities. The market value of horticultural crops and orchards is much higher than that of field crops, but they have high labour requirements. The decreasing labour availability in RAA reduces the set of feasible crops to those that can be largely mechanized.

High-quality irrigation scheduling could lead to reduced WDEL and increased water productivities in the windy conditions of the central Ebro Valley (Dechmi et al., 2003b; Cavero et al., 2008). The new conveyance networks installed as part of the modernization process could be used to implement advanced scheduling systems that will permit irrigation only during low-wind periods (Zapata et al., 2007; Zapata et al., 2009). The reported 4 % decrease in WDEL (from 14 % to 10 %) would not be enough to offset the increase in total water use and water depletion, but would reduce this increase between 21 Mm^3 (scenario A1) and 33 Mm^3 (scenario B2) and increase water productivity in an equivalent percentage (results not shown).

The results obtained in the post-modernization scenarios will also depend on factors other than irrigation, like the evolution of agricultural and energy prices. English et al. (2002), De Fraiture et al. (2009) and the European Commission (2009), among other authors, have reported that the uncertainty about these commodity markets will have a growing influence on crop production and water use. Years 2007 and 2008 were characterized by extreme crop prices and production costs. Applying these prices and costs to the analysed scenarios, productivities fluctuated between -55 % and 20 % with respect to the average 2003 and 2004 seasons (results not shown). In these changing conditions, only competitive farms will continue to operate in the agricultural markets and will determine water use in the future.

Conclusions

Irrigation modernization entails a change in water use practices with hydrological implications at the basin scale. When the purpose of this process is to raise crop production, particularly of field crops, water consumption will increase due to concomitant increases in crop evapotranspiration.

In the case of inland irrigation projects like RAA, where the location of the project and the quality of the irrigation return flows (IRF) allow their downstream reuse, irrigation modernization involves a reduction in water availability in the basin. Switching from traditional surface irrigation to modern sprinkler systems further contributes to these effects because of wind drift and evaporation losses (WDEL), particularly in windy areas as those typically present in the Ebro River Basin. Additionally, this fact implies a reduction of the previous depleted beneficial fraction. If the application efficiency of surface irrigated plots was moderate, an additional consequence of irrigation modernization would be an increase in water use and in the depleted fraction (the increase in water consumption is higher than the reduction in runoff/percolation).

Reduced IRF due to the modernization process leads to decreased exported pollutant loads that will significantly improve the quality of the receiving water bodies in the basin. However, direct users of IRF will have access to less water than before, and with higher pollutant concentrations. A change in the operation of reservoirs could be required to face this situation and respect existing water rights.

Increases in crop production results in desired increases in land productivity. Water productivity over water use also increases, contributing to improve farm competitiveness during drought years. Nevertheless, water productivity over water depletion hardly changes when the value of crops is low.

Future water consumption will strongly depend on the ability of farms to increase their competitiveness in a context of uncertain agricultural and energy prices. If farms are not competitive enough or if there is not enough water to satisfy the requirements of competitive farms, the irrigated area and the depleted water will decrease, particularly in areas with scarce labour availability.

The water accounting methodology should be implemented to avoid misunderstandings about the hydrological impacts of irrigation, such as unrealistic expectations in water saving in the study area. Complete development of this methodology will require increased efforts in water use data collection, so that accurate water balances can be developed on a routine basis.

Acknowledgements

Thanks are due to the staff of the *Comunidad General de Riegos del Alto Aragón* and its irrigation districts, and the *Oficina del Regante* (irrigation extension office of the Government of Aragón) for their support during the period of data collection (2003 and 2004). Thanks are also due to the rest of researchers of our Departments for the review of a preliminary version of this study.

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper no. 56. FAO. Rome, Italy. 300 pp.

Allen, R.G., Clemmens, A.J., Burt, C.M., Solomon, K., O'Halloran, T. 2005. Prediction accuracy for projectwide evapotranspiration using crop coefficients and reference evapotranspiration. J. Irrig. and Drain. Engrg. 131(1):24-36.

Aragüés, R., Tanji, K.K., Quílez, D., Faci, J. 1990. Conceptual irrigation project hydrosalinity model. In: Agricultural salinity assessment and management. Chapter 24. Am. Soc. Civil Eng. New York, USA.

Aragüés, R., Tanji, K.K. 2003. Water Quality of Irrigation Return Flows. In: Encyclopedia of water science. Stewart B.A., Howell T.A. (eds.). 502-506. Marcel Dekker, Inc. New York, USA.

Beguería, S., López-Moreno, J. I., Lorente, A., Seeger, M., García-Ruiz, J. M. 2003. Assessing the effect of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 32(4), 283-286.

Burt, C.M., Clemmens, A.J., Strelkoff, T.S., Solomon, K.H., Bliesner, R.D., Hardy, L.A., Howell, T.A., Eisenhauer, D.E. 1997. Irrigation performance measures: Efficiency and uniformity. J. Irrig. and Drain. Engrg. 123(6), 423-442.

Castañeda, C., García-Vera, M. A. 2008. Water balance in the playa-lakes of an arid environment, Monegros, NE Spain. Hydrogeology Journal 16(1), 87-102.

Causapé, J., Quílez, D., Aragüés, R. 2006. Irrigation efficiency and quality of irrigation return flows in the Ebro River Basin: An overview. Environmental Monitoring and Assessment 117(1-3), 451-461.

Causapé, J. 2009. Agro-environmental evaluation of irrigation land I. Water use in Bardenas irrigation district (Spain). Agric. Wat. Manage. 96(2), 179-187.

Cavero, J., Beltrán, A., Aragües, R. 2003. Nitrate exported in the drainage water of two sprinkler irrigated watersheds. J. Environ. Qual. 32, 916-926.

Cavero, J., Jiménez, L., Puig, M., Faci, J. M., Martínez-Cob, A. 2008. Maize Growth and Yield under Daytime and Nighttime Solid-Set Sprinkler Irrigation. Agronomy Journal 100(6), 1573-1579.

CESA. 2001. Informe sobre la situación económica y social de Aragón en 2001. Consejo Económico y Social de Aragón. Zaragoza, Spain. 245 pp.

CESA. 2008. Informe sobre la situación económica y social de Aragón. 2008. Consejo Económico y Social de Aragón. Zaragoza, Spain. 245 pp.

CGRAA. 2004. Gestión de la demanda y el embalse de Biscarrués. Comunidad General de Riegos del Alto Aragón. Huesca, Spain. 59 pp.

Clemmens, A.J. 1987. Arranged delivery schedules. In: Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems. Proceedings of the Irrigation Division, ASCE, Portland, OR, USA, pp. 57–80.

Clemmens A.J., Dedrick A.R. 1994. Irrigation techniques and evaluations. In: Adv. series in agricultural sciences. Tanji K.K.,Yaron B. (eds.). 64-103. Springer-Verlag. Berlin, Germany.

Clemmens, A. J., and Molden, D. J. 2007. Water uses and productivity of irrigation systems. Irrig. Sci. 25(3), 247-261.

Clemmens, A. J., Allen, R. G., Burt, C. M. 2008. Technical concepts related to conservation of irrigation and rainwater in agricultural systems. Water Resources Research 44, 16 pp.

De Fraiture, C., Molden, D., Wichelns, D. 2009. Investing in water for food, ecosystems, and livelihoods: An overview of the comprehensive assessment of water management in agriculture. Agric. Wat. Manage. In Press, Corrected Proof. doi:10.1016/j.agwat.2009.08.015.

De los Ríos, F. 1966. Colonización de las Bardenas, Cinco Villas, Somontano y Monegros. Institución “Fernando el Católico”. Zaragoza, Spain. 56 pp.

De los Ríos, F. 1984. El agua en la cuenca del Ebro. Institución “Fernando el Católico”. Zaragoza, Spain. 141 pp.

Dechmi, F., Playán, E., Faci, J.M., Tejero, M., Bercero, A. 2003a. Analysis of an irrigation district in northeastern Spain: II: Irrigation evaluation, simulation and scheduling. Agric. Wat. Manage. 61, 93-109.

Dechmi, F., Playán, E., Cavero, J., Faci, J. M., Martínez-Cob, A. 2003b. Wind effects on solid set sprinkler irrigation depth and yield of maize (*Zea mays*). Irrig. Sci. 22(2), 67-77.

English, M. J., Solomon, K. H., Hoffman, G. J. 2002. A paradigm shift in irrigation management. J. Irrig. and Drain. Engrg. 128(5), 267-277.

European Comission. 2009. Agricultural commodity markets. Outlook 2009-2018. Directorate-General for Agriculture and Rural Development. European Commission. Bruxelles, Belgium. 168 pp.

European Union. 2000. Directive 2000/60/EC of the European Parliament and of the Council establishing a framework for the Community action in the field of water policy. Official Journal L327, 22/12/2000.

Faci, J.M., Bercero, A. 1991. Efecto del viento en la uniformidad y en las pérdidas por evaporación y arrastre en el riego por aspersión. Investigación Agraria. Prod. Prot. Veg. 6(2):97–117.

Faci, J.M., Bensaci, A., Slatni, A., Playán, E. 2000. A case study for irrigation modernisation: I. Characterisation of the district and analysis of water delivery records. Agric. Wat. Manage. 42, 313-334.

Farré, I., J.M. Faci. 2009. Deficit irrigation in maize for reducing agricultural water use in a Mediterranean environment. Agric. Wat. Manage. 96, 383-394.

Forteza del Rey, V. 2002. El Plan Nacional de Regadíos. Agricultura 842, 554-556.

Haie, N., Keller, A. A. 2008. Effective efficiency as a tool for sustainable water resources management. Journal of the American Water Resources Association 44(4), 961-968.

Hargreaves, G.H., Samani, Z.A. 1985. Reference crop evapotranspiration from temperature. Appl. Eng. Agric. 1(2), 96–99.

Herrero, J., Snyder, R. L. 1997. Aridity and irrigation in Aragon, Spain. Journal of Arid Environments 35(3), 535-547.

Howell, T. A. 1990. Grain, Dry-Matter Yield Relationships for Winter-Wheat and Grain-Sorghum Southern High-Plains. Agronomy Journal 82(5), 914-918.

Huffaker, R. 2008. Conservation potential of agricultural water conservation subsidies. Water Resources Research 44.

Hussain, I., Turral, H., Molden, D., Ahmad, M. U. D. 2007. Measuring and enhancing the value of agricultural water in irrigated river basins. Irrig. Sci. 25(3), 263-282.

IBRD. 2009. Global Economic Prospects. Commodities at the crossroads. International Bank for Reconstruction and Development. The World Bank. Washington DC, USA. 180 pp.

IAE. 2009. Estadísticas demográficas de Aragón. Instituto Aragonés de Estadística. Zaragoza, Spain. Available at http://portal.aragon.es/portal/page/portal/IAEST/IAEST_0000/IAEST_03/IAEST_0301/IAEST_030100 [Viewed: Marzo 2009].

INE. 1999. Censo agrario. Instituto Nacional de Estadística. Madrid, Spain. Available at http://www.ine.es/inebmenu/mnu_agricultura.htm#1 [Viewed: November 2007].

INE. 2006. Estadísticas sobre medio ambiente. Instituto Nacional de Estadística. Madrid, Spain. Available at http://www.ine.es/inebmenu/mnu_medioambiente.htm [Viewed: November 2007].

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

Isidoro, D., Quílez, D., Aragüés, R. 2006a. Environmental impact of irrigation in La Violada District (Spain): I. Salt export patterns. Journal of Environmental Quality 35(3), 766-775.

Isidoro, D., Quílez, D., Aragüés, R. 2006b. Environmental impact of irrigation in La Violada District (Spain): II. Nitrogen fertilization and nitrate export patterns in drainage water. Journal of Environmental Quality 35(3), 776-785.

Isidoro, D., Aragüés, R. 2007. River water quality and irrigated agriculture in the Ebro basin: An overview. International Journal of Water Resources Development 23(1), 91-106.

Jensen, M. E. 2007. Beyond irrigation efficiency. Irrig. Sci. 25(3), 233-245.

Keller A., Keller, J., Seckler, D. 1996. Integrated water resource systems: Theory and policy implications. Research Report 3, International Water Management Institute. Colombo, Sri Lanka. 16 pp.

Krinner, W., García, A., Estrada, F. 1994. Method for estimating efficiency in Spanish irrigation systems. J. Irrig. and Drain. Engrg. 120(5), 979-987.

Lecina, S., Monserrat, J., Cots, L. 2000. El uso del agua en el regadío de Flumen (II). Zona noroccidental de la Acequia de Rufas (Huesca). Riegos y Drenajes XXI 112, 39-41.

Lecina, S., Playán, E., Isidoro, D., Dechmi, F., Causapé, J., Faci, J.M. 2005. Irrigation evaluation and simulation at the irrigation district V of Bardenas (Spain). Agric. Wat. Manage. 73, 223-245.

Lecina, S., Playán, E. 2006a. A model for the simulation of water flows in irrigation districts: II. Application. J. Irrig. and Drain. Engrg. 132(4):322-331.

Lecina, S., Playán, E. 2006b. A model for the simulation of water flows in irrigation districts: I. Description. J. Irrig. and Drain. Engrg. 132(4), 310-321.

López-Moreno, J. I., Beniston, M., García-Ruiz, J. M. 2008. Environmental change and water management in the Pyrenees: Facts and future perspectives for Mediterranean mountains. Global and Planetary Change 61(3-4), 300-312.

Lozano, D., Mateos, L. 2008. Usefulness and limitations of decision support systems for improving irrigation scheme management. Agric. Wat. Manage. 95(4), 409-418.

Martínez-Cob, A. 1996. Multivariate geostatistical analysis of evapotranspiration and precipitation in mountainous terrain. Journal of Hydrology 174(1-2), 19-35.

Martínez-Cob, A., Faci, J.M., Bercero, A. 1998. Evapotranspiración y necesidades de riego de los principales cultivos en las comarcas de Aragón. Institución "Fernando el Católico". Zaragoza, Spain. 223 pp.

Martínez-Cob, A. 2004. Revisión de las necesidades hídricas netas de los cultivos de la cuenca del Ebro. Confederación Hidrográfica del Ebro. Zaragoza, Spain. (Unpubl.) 111 pp.

Martínez-Cob, A., Playán, E., Zapata, N., Cavero, J., Medina, E. T., Puig, M. 2008. Contribution of evapotranspiration reduction during sprinkler irrigation to application efficiency. J. Irrig. and Drain. Engrg. 134, 745-756.

Mateos, L. 2008. Identifying a new paradigm for assessing irrigation system performance. Irrig. Sci. 27(1), 25-34.

MARM, 2002. Plan Nacional de Regadíos. Ministerio de Medio Ambiente, Medio Rural y Marino. Madrid, Spain. Available at http://www.mapa.es/es/desarrollo/pags/pnr/principal.htm [Viewed: November 2007].

MARM, 2004. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de explotaciones agrícolas de Aragón en 2003. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain. 78 pp.

MARM, 2005. Análisis de la economía de los sistemas de producción. Resultados técnico-económicos de explotaciones agrícolas de Aragón en 2004. Ministerio de Medio Ambiente y Medio Rural y Marino. Madrid, Spain. 74 pp.

MARM, 2006. Plan de Choque de Modernización de Regadíos. Ministerio de Medio Ambiente, Medio Rural y Marino. Madrid, Spain. Available at http://www.plandechoque-ahorrodeagua.es [Viewed: November 2007].

MARM, 2007. Encuesta sobre superficies y rendimientos de cultivos. Informe sobre regadíos en España. Ministerio de Medio Ambiente, Medio Rural y Marino. Madrid, Spain. 26 pp.

Molden, D.J., Sakthivadivel, R., Perry, J., Fraiture, C., Kloezen W.H. 1998. Indicators for comparing performance of irrigated agricultural systems. Research Report 20, International Water Management Institute, Colombo, Sri Lanka. 26 pp.

Molden, D., Sakthivadivel, R. 1999. Water accounting to assess use and productivity of water. International Journal of Water Resources Development 15(1/2), 55-71.

Molden, D.J., Murray-Rust, H., Sakthivadivel, R., Makin I. 2003. A water productivity framework for understanding and action. In: Water productivity in agriculture: limits and opportunities for improvements. Kijne, W., Barkers, R., Molden, D. (Eds). CAB International. Wallingford, United Kingdom, 368 pp.

Molden, D., Oweis, T., Steduto, P., Bindraban, P., Hanjra, M. A., Kijne, J. 2009. Improving agricultural water productivity: Between optimism and caution. Agric. Water Manage. In Press, Corrected Proof. doi:10.1016/j.agwat.2009.03.023

Nogués, J., Herrero, J., Rodríguez-Ochoa, R., Boixadera, J. 2000. Land evaluation in a salt-affected irrigated district using an index of productive potential. Environmental Management 25(2), 143-152.

Nogués J., Herrero J. 2003. The impact of transition from flood to sprinkler irrigation on water district consumption. Journal of Hydrology 276, 37-52.

OECD-FAO. 2009. Agricultural Outlook 2009-2018. Highlights. Organisation for Economic Co-operation and Development – Food and Agriculture Organization of the United Nations. Paris, France. 79 pp.

Perry, C. J. 1999. The IWMI water resources paradigm - definitions and implications. Agric. Wat. Manage. 40(1), 45-50.

Perry, C. 2007. Efficient irrigation; Inefficient communication; Flawed recommendations. Irrigation and Drainage 56 (4), 367-378.

Perry, C., Steduto, P., Allen, R. G., Burt, C. M. 2009. Increasing productivity in irrigated agriculture: Agronomic constraints and hydrological realities. Agric. Water Manage. 96(11), 1517-1524.

Playán, E., Slatni, A., Castillo, R., Faci, J.M. 2000. A case study for irrigation modernisation: II. Scenario Analysis. Agric. Wat. Manage. 42, 335-354.

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sánchez, I. 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric. Wat. Manage. 76:139-159.

Playán, E., Mateos, L. 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric. Wat. Manage. 80, 100-116.

Playán E., Cavero J., Mantero I., Salvador R., Lecina S., Faci J.M., Andrés J., Salvador V., Cardeña G., Ramón S., Lacueva J.L., Tejero M., Ferri J., Martínez-Cob A. 2007. A database program for enhancing irrigation district management in the Ebro Valley (Spain). Agric. Wat. Manage. 87, 187-199.

Playán, E., Pérez-Coveta, O., Martínez-Cob, A., Herrero, J., García-Navarro, P., Latorre, B., Brufau, P., Garcés, J. 2008. Overland water and salt flows in a set of rice paddies. Agric. Wat. Manage. 95(6), 645-658.

Quílez, D., Isidoro, D., Aragüés, R. 2010. Conceptual irrigation project hydrosalinity model. In: Agricultural salinity assessment and management. Rev 1. Chapter 30. Am. Soc. Civil Eng. New York, USA. (in press).

Sánchez, I. 2008. Factores técnicos meteorológicos y agronómicos que afectan a la calidad del riego por aspersión en sistemas estacionarios. PhD dissertation. Universidad de Lleida. Lleida, Spain. 317 pp.

Seckler, D. 1996. The new era of water resources management: from "dry" to "wet" water savings. Research Report 1, International Water Management Institute. Colombo, Sri Lanka, 18 pp.

Seckler, D., Molden, D., Sakthivadivel, R. 2003. The concept of efficiency in water-resources management and policy. In: Water productivity in Agriculture: limits and opportunities for improvement. Kijne, W., Barkers, R., Molden, D. (Ed.). CAB International, Wallingford, United Kingdom, pp. 37-51.

Steduto, P., Hsiao, T. C., Fereres, E. 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25(3), 189-207.

Tedeschi, A., Beltran, A., Aragüés, R. 2001. Irrigation management and hydrosalinity balance in a semi-arid area of the middle Ebro river basin (Spain). Agric. Wat. Manage. 49(1), 31-50.

Turral, H., Svendsen, M., Faures, J. M. 2009. Investing in irrigation: Reviewing the past and looking to the future. Agric. Wat. Manage. In Press, Corrected Proof. doi:10.1016/j.agwat.2009.07.012

Ward, F. A., Pulido-Velázquez, M. 2008. Water conservation in irrigation can increase water use. Proceedings of the National Academy of Sciences of the United States of America, 105(47), 18215-18220.

Willardson, L.S., Allen, R.G., Frederiksen, H.D. 1994. Elimination of irrigation efficiencies. In: 13th Tech. Conf. USCID, USCID (Ed.), Denver (Colorado), USA, 17 pp.

Wriedt, G., Van der Velde, M., Aloe, A., Bouraoui, F. 2009. Estimating irrigation water requirements in Europe. Journal of Hydrology 373(3-4), 527-544.

Zapata, N., Playan, E., Martinez-Cob, A., Sanchez, I., Faci, J. M., Lecina, S. 2007. From on-farm solid-set sprinkler irrigation design to collective irrigation network design in windy areas. Agric. Wat. Manage. 87, 187-199.

Zapata, N., Playán, E., Skhiri, A., Burguete, J. 2009. Simulation of a Collective Solid-Set Sprinkler Irrigation Controller for Optimum Water Productivity. J. Irrig. Drain. and Engrg. 135(1), 13-24.

List of tables

Table 1. *RAA cropping patterns (% irrigated land) by irrigation system in 2003 and 2004 as an average and for the future A2 and B2 scenarios in which an intensified pattern in sprinkler irrigation is considered.*

Table 2. *Water use, yield, and land and water productivity by irrigation system and crop in RAA (average of 2003 and 2004).*

Table 3. *Pre-modernization (PRE) and post-modernization (A1, A2, B1 and B2) scenarios in RAA: estimated irrigation water balances, hydrologic and economic indicators. Scenarios B1 and B2 consider that the entire RAA is sprinkler irrigated.*

Table 1. *RAA cropping patterns (% irrigated land) by irrigation system in 2003 and 2004 as an average and for the future A2 and B2 scenarios in which an intensified pattern in sprinkler irrigation is considered.*

	Irrigation system	Corn	Alfalfa	Winter cereals[1]	Rice	Sunflower	Others	Falllow	Two crops p. season[2]
Average 2003 and 2004	Sprinkler	50	25	9	0	1	8	7	8
	Surface	25	29	21	10	5	3	8	0
	Total	32	28	17	7	4	4	8	2
Scenarios A2 and B2(3)	Sprinkler	57	29	2	0	2	5	5	26
	Surface	15	23	26	15	7	3	11	0
	Total	44	27	9	5	4	5	7	18

(1) Barley and wheat.

(2) Corn and barley, vetch or peas.

(3) Sprinkler irrigation is the only system considered in scenario B2.

Table 2. *Water use, yield, and land and water productivity by irrigation system and crop in RAA (average of 2003 and 2004).*

Crop	**Water use**		**Yield**		**Gross Land Prod.**		**Net Land Prod.**		**Net Water Prod.**	
	Surface	**Sprink.**	**Surface**	**Sprink.**	**Surface**	**Sprink.**	**Surface**	**Sprink.**	**Surface**	**Sprink.**
	x 10^3 **m^3 ha^{-1}**	**x 10^3** **m^3 ha^{-1}**	**t ha^{-1}**	**t ha^{-1}**	**€ ha^{-1}**	**€ ha^{-1}**	**€ ha^{-1}**	**€ ha^{-1}**	**€ m^{-3}**	**€ m^{-3}**
Corn	9.0	7.5	9	12	1,218	1,624	654	950	0.073	0.127
Alfalfa	11.0	8.5	12	15	1,200	1,500	463	629	0.042	0.074
Winter cereals	3.0	2.0	4	5	536	670	300	386	0.100	0.193

Table 3. *Pre-modernization (PRE) and post-modernization (A1, A2, B1 and B2) scenarios in RAA: estimated irrigation water balances, hydrologic and economic indicators. Scenarios B1 and B2 consider that the entire RAA is sprinkler irrigated.*

	SURFACE IRRIGATION			**SPRINKLER IRRIGATION**			**TOTAL RAA PROJECT**				
	PRE	**A1**	**A2**	**PRE**	**A1**	**A2**	**PRE**	**A1**	**A2**	**B1**	**B2**
AREA (ha)	88,325	36,007	36,007	32,429	84,747	84,747	120,754	120,754	120,754	120,754	120,754
INFLOWS -water use- (Mm^3)	508.9	229.9	199.5	202.6	527.9	590.9	711.5	757.8	790.5	746.9	835.0
OUTFLOWS (Mm^3)											
Consumed volume	336.6	136.8	118.9	189.8	487.1	545.3	526.4	623.9	664.2	687.3	768.4
Beneficial evapotranspiration	331.5	134.5	116.9	157.0	412.0	461.2	488.5	546.5	578.2	583.8	652.5
Non-Beneficial evapotranspiration	5.1	2.3	2.0	32.8	75.1	84.1	37.9	77.4	86.1	103.6	115.8
Non-consumed volume	172.3	93.1	80.6	12.8	40.8	45.6	185.1	133.9	126.2	59.6	66.6
Non-Recoverable runoff/percolation	12.5	4.0	3.5	0.3	1.6	1.7	12.8	5.6	5.2	3.2	3.6
Recoverable runoff/percolation	159.8	89.1	77.1	12.6	39.2	43.9	172.3	128.3	121.0	56.4	63.1
HYDROLOGICAL INDICATORS											
Depleted volume (Mm^3)	349.1	140.8	122.4	190.0	488.6	547.0	539.1	629.5	669.5	690.5	771.9
Non-depleted volume (Mm^3)	159.8	89.1	77.1	12.6	39.2	43.9	172.3	128.3	121.0	56.4	63.1
Depleted Fraction (m^3 m^{-3})	0.69	0.61	0.61	0.94	0.93	0.93	0.76	0.83	0.85	0.92	0.92
Consumed Fraction (m^3 m^{-3})	0.66	0.60	0.60	0.94	0.92	0.92	0.74	0.82	0.84	0.92	0.92
Total Beneficial Fraction (m^3 m^{-3})	0.65	0.59	0.59	0.77	0.78	0.78	0.69	0.72	0.73	0.78	0.78
Depleted Beneficial Fraction (m^3 m^{-3})	0.95	0.96	0.96	0.83	0.84	0.84	0.91	0.87	0.86	0.85	0.85
ECONOMIC INDICATORS											
Gross production value (M€)	83.5	33.8	29.7	46.3	122.6	138.5	129.8	156.4	168.2	175.1	198.2
Gross Land Productivity (€ ha^{-1})	945	938	825	1,427	1,447	1,635	1,075	1,295	1,393	1,450	1,641
Gross Water Productivity -use- (€ m^{-3})	0.164	0.147	0.149	0.228	0.232	0.234	0.182	0.206	0.213	0.234	0.237
Gross Water Productivity -depletion- (€ m^{-3})	0.239	0.240	0.243	0.243	0.251	0.253	0.241	0.248	0.251	0.254	0.257
Net production value (M€)	43.7	17.7	15.9	24.3	64.3	70.9	68.0	81.9	86.8	91.4	101.2
Net Land Productivity (€ ha^{-1})	495	491	443	748	758	836	563	679	719	757	838
Net Water Productivity -use- (€ m^{-3})	0.086	0.077	0.080	0.120	0.122	0.120	0.096	0.108	0.110	0.122	0.121
Net Water Productivity -depletion- (€ m^{-3})	0.125	0.126	0.130	0.128	0.132	0.130	0.126	0.130	0.130	0.132	0.131

List of figures

Figure 1. *Location of Ebro River Basin and the Riegos del Alto Aragón (RAA) irrigation project in the Iberian Peninsula.*

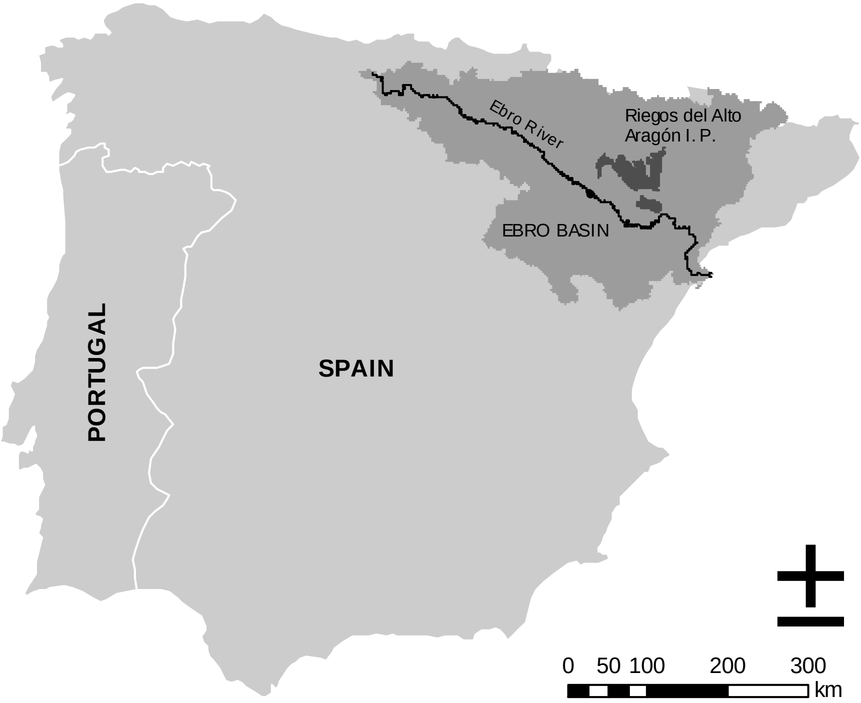

Figure 2. *Relationship between gross land productivity and irrigated-season water depletion per unit area by RAA irrigation district in 2003 and 2004.*

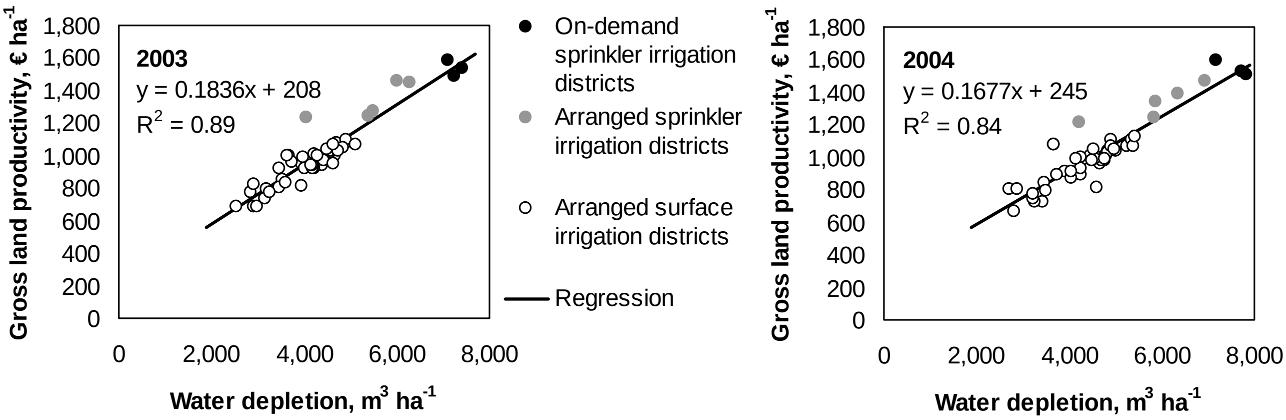

Figure 3. *Maps of irrigated-season water depletion per unit area by RAA irrigation district in the pre-modernization scenario and the A2 post-modernization scenario.*