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Irrigation evaluation and simulation at the Irrigation District V of Bardenas (Spain)

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Abstract

The surface Irrigated District V of the Bardenas Canal (Zaragoza, Spain) was evaluated, and alternatives were assessed to improve on-farm irrigation performance. Field work consisted of a soil survey and a campaign of irrigation evaluation. The results of the irrigation evaluations were extrapolated to the whole district using a hydrodynamic surface irrigation model. An average irrigation discharge of 152 L s^{-1} results in a relatively low irrigation time (2.8 h ha^{-1}). Shallow soils, a limited conveyance network, and poor irrigation management practices determine that the application efficiency in the district is low, with an average of 49%. The district wide irrigation efficiency only reaches reasonable values when the system operates under water scarcity (49% in 2000 versus 66% in 2001). The simulation of surface irrigation indicated that the optimum irrigation time in the current situation is 1.7 h ha^{-1}. The optimization of the irrigation time would lead to an average application efficiency of 76%. Improved irrigation management can therefore result in substantial water conservation in the district.

Keywords: Bardenas Canal; On-farm irrigation; Efficiency; Evaluation; Modelling

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1. Introduction

The modernization of an irrigated area must start with a diagnosis of its current situation (Losada, 1994). Following this procedure the specific problems affecting water use can be addressed, and alternatives can be designed that – once evaluated – may lead to feasible solutions. Irrigation districts are the basic unit for collective water management in a watershed, and therefore constitute the first level where such studies should be performed. Following this consideration, Faci et al. (2000) and Playán et al. (2000) presented an evaluation of water management in the 3579 ha of the Almudévar Irrigation District (Huesca, Spain). As a first step, all factors affecting water use in this surface irrigated district were identified (soils, climate, conveyance structures and management policies). In a second step irrigation performance was assessed. Finally, irrigation modernization alternatives were introduced and analysed using technical and economical criteria. Dechmi et al. (2003a, 2003b) presented a study on water use in the sprinkler irrigated district of Loma de Quinto (Zaragoza, Spain), with 2606 ha. This work consisted of field irrigation evaluations, the application of a ballistic sprinkler irrigation model and a crop model. As a result, management parameters for optimizing irrigation uniformity in the district were obtained.

The objectives of this work were to diagnose the water management standards of the Irrigation District V (five) of the Bardenas Canal (Zaragoza, Spain), and to determine the main principles leading to an improvement of irrigation performance. The proposed methodology combines field work and computer simulation. The modernization of the traditional Irrigation District V (IDV) is addressed from the preference of the farmers of improving their surface irrigation systems. Two paths were considered for this purpose: improving water structures and improving water management. The selected methodology facilitated the comparisons of both alternatives in this particular case.

2. The Irrigation District V (IDV) of the Bardenas Canal

The IDV can be considered representative of the large irrigation projects built in Spain by the mid 20th century. The district is located in the Ebro Valley, North Eastern Spain (Fig. 1). The total irrigated area is 15,545 ha, of which 450 ha are sprinkler irrigated and the rest are surface irrigated. The district is included in the Bardenas Canal Project, which started operation in 1959, after completion of the construction of the Yesa dam in the Aragón river (Bolea, 1986). The canal provides water for about 60,000 ha in the provinces of Zaragoza and Navarra.

The climatic characterization of the study area was performed using thermopluviometric data for the 1965–1994 period from the Santa Anastasia weather station, located within the premises of the IDV (42°07′58″, 1°13′27″W, 321 m a.m.s.l.). According to these data the climate in the IDV is temperate (the mean temperature is 14 °C), with a large temperature difference between winter and summer (the mean minimum temperature of the coldest month, January, is 1.7 °C, while the mean maximum temperature of the warmest month, July, is 31.3 °C). The mean annual precipitation is 419 mm, unevenly distributed during the year, with the largest precipitation falling in spring (136 mm) and

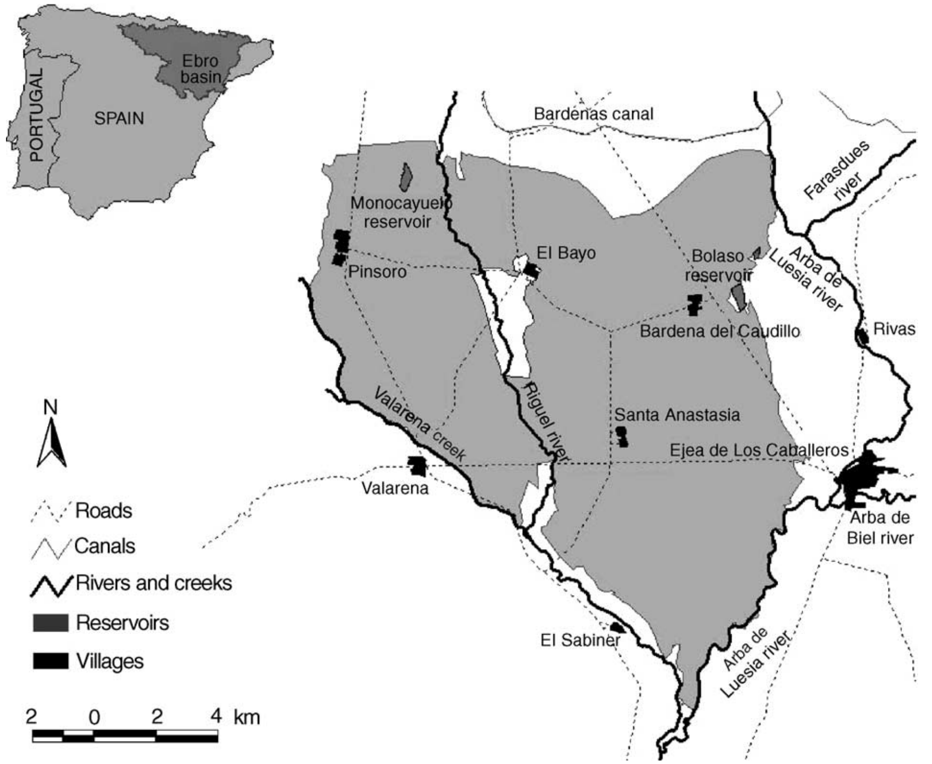

Fig. 1. Location of the Irrigation District V (IDV) of the Bardenas project in Spain.

fall (123 mm). A dry period typically extends from July to September. The mean annual reference evapotranspiration (ET_0), determined following the Hargreaves method (Jensen et al., 1990), is 1084 mm. The largest average monthly ET_0 occurs in July, with 190 mm (6.1 mm day^{-1}), while the lowest occurs in December, with 21 mm (0.7 mm day^{-1}).

According to the geomorphologic map presented by Basso (1994), and the soil surveys performed by the Instituto Nacional de Reforma y Desarrollo Agrario (1974) and by Martínez-Beltrán (1978), two geomorphologic units (with different soil types) can be distinguished in the study area. The first unit corresponds to residual platforms (locally called *sasos*), sitting on tertiary materials (lutite and sandstone). Their soils are characterized by a shallow depth, the presence of a calcareous horizon with a varying degree of cementation, loam texture, a large content of stones, and good internal drainage, resulting in a low salinity. This unit occupies 11,054 ha in the IDV. The second unit covers the remaining district area (4491 ha) and corresponds to the alluvial terraces of the Riguel river (crossing the IDV from North to South) and its tributary creeks. The soils in this unit are deep, stone-free, and have a clay loam texture. Soil salinity can be present in depressed locations, close to the rivers. Fig. 2 presents the geographical distribution of these units in the IDV.

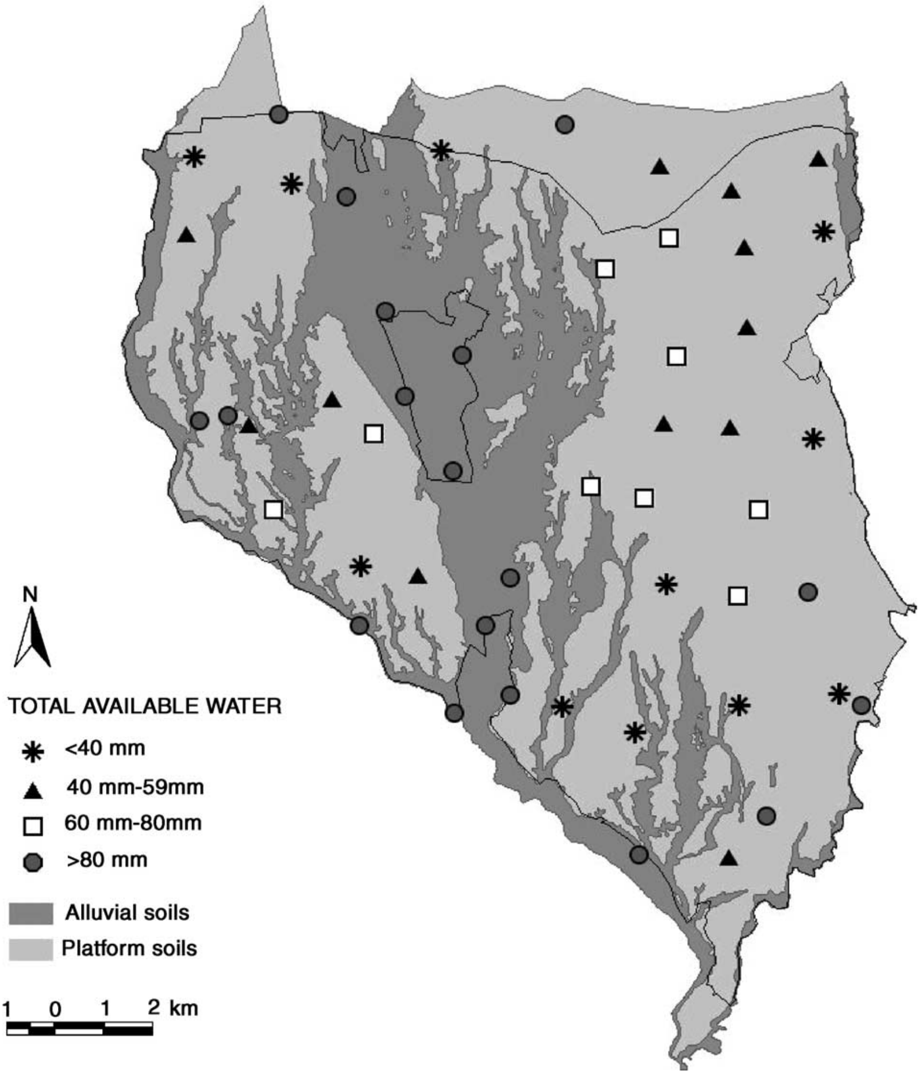

Fig. 2. Location of the surveyed soil profiles in the IDV, with indication of their total available water (TAW). The background geomorphologic map has been adapted from Basso (1994) at a 1:25,000 scale.

A total of 891 land owners compose the district, owning a total of 1698 plots, according to the 2001 management database of the IDV. The average area of the plots is 11.5 ha, although only 28% of them have an area larger than the average. About 60% of the farms in the district include two or more separate plots. One-third of the irrigated farms in the IDV have an area smaller than 10 ha; another third falls in the range of 10–15 ha and the final third surpasses 15 ha.

Although the area devoted to each crop strongly varies from year to year, there is a general pattern. Most of the area is occupied by field crops (corn and alfalfa), with a small fraction of horticultural crops (tomato and pepper). According to the 2001 management district database corn and alfalfa occupied 40 and 35% of the district area, respectively. Winter cereals accounted for 6%, horticultural crops for 3%, and other crops (mostly forages), occupied the remaining 11%.

Water conveyance structures are a network of concrete ditches which, starting at the Bardenas Canal, deliver water to the plots. A total of eight canal turnouts and the corresponding secondary canals feed 92 tertiary ditches. A number of broad crested weirs (Bos et al., 1984) were installed at the end of the 1990s to estimate the volume of water deliveries to the farmers. For this purpose, the district ditch riders record the irrigation discharge and the number of hours attributed to each farmer. At the farm level, farmers perform free-draining border irrigation, with some furrow irrigation associated with horticultural crops. Irrigation return flows are collected and conveyed by a network of 57 drainage collectors, which deliver water to nine main collectors. The main collectors discharge into the Riguel and Arba de Luesia rivers, which compose the natural drainage system of the district.

These irrigation structures were designed to irrigate winter cereals, the main crop at the time of construction (the 1960s) (De los Ríos, 1966). However, the evolution of irrigated agriculture produced an intensification of the crops. This resulted in a sharp increase in water demand (De los Ríos, 1984), which required a daily irrigation period of 24 h. Even with this continuous irrigation operation, the distribution network lacks capacity to satisfy the crop water requirements. As a result, the intervals between irrigations are too long during the peak months of the season. Responding to this limitation, the IDV connected the drainage and irrigation networks in a number of points with the objectives of reusing drainage water and maintaining irrigation intervals within reasonable limits. At present such intervals can reach 12–14 days in July and August. At two of these connections in-line reservoirs have been built (Fig. 1): Moncayuelo (0.3 hm^3) and Bolaso (0.9 hm^3). These reservoirs store irrigation return flows from the district and from other irrigated areas located upstream. They are also used as management tools to reconcile water supply and demand.

Water management is performed by the ditch riders of the IDV. During the first and last weeks of the irrigation season, when water demand is low, farmers present water orders to the ditch riders, who allocate the service discharge of a tertiary canal to the farmer for a negotiated period of time. During the peak of the season, when the irrigation network cannot meet irrigation needs, a rotation system is adopted, changing the objective from satisfying demands to equity in access to water. According to the classification system proposed by Clemmens (1987) for water delivery systems, the system used during the low-demand months is negotiated arranged, with fixed discharge. During the peak of the season the system is varied frequency rotation. This transition of delivery pattern during the season is frequent in many surface irrigation districts in the Ebro valley of Spain.

At the district offices, located in Ejea de los Caballeros, a relational database is used to support water management. In the database, the irrigated plot, the owner, the area occupied by each crop and the volume of water allocation are recorded, among other data. This database is applied to bill farmers for their water use. Proportional billing was introduced in 2001, as a relevant part of an ongoing Management Improvement Program (Dedrick et al., 2000) started in 1996, responding to a severe drought. The research reported in this paper represents an additional contribution to that program.

3. Materials and methods

3.1. Soil survey

The determination of the soil physical properties in the IDV followed a soil sampling campaign performed during the winter of 2000. The sampling design took into consideration the results of previous works by Martínez-Beltrán (1978) and Basso (1994). A total of 50 soil profiles were described in the irrigated area: 40 in the platforms and 10 in the alluvial areas (Fig. 2). In the platforms the soil profile description followed excavation of observation pits. In the alluvial soils an auger was used in all cases. Soil profiles were described to a depth of 1.20 m or to a limiting depth. Samples were collected from each horizon. The depth and texture of each soil horizon were described in situ. The stoniness, bulk density, field capacity and wilting point were determined at the laboratory from the soil samples following the methods of the Soil Survey Laboratory (1996). Bulk density was only determined in four soil profiles from which undisturbed soil cores were extracted. This process was severely limited by the soil stoniness. For the determination of field capacity and wilting point two replications were performed for each sample, using pressures of 0.033 and 1.5 MPa, respectively (Soil Survey Division Staff, 1993).

The results of these determinations were used to estimate the total available water (TAW, mm) in each soil profile, considering one value of bulk density for each of the soil types. The following equation was used for this purpose (Walker and Skogerboe, 1987; Allen et al., 1998):

$$\mathrm{TAW} = 10^3 \sum_{i=1}^{n_\mathrm{h}} z_i(\theta \mathrm{f}c_i - \theta \mathrm{w}p_i)\frac{\rho_{\mathrm{b}i}}{\rho_\mathrm{w}}(1 - S_i) \tag{1}$$

where z_i is the depth of soil horizon i (m), $\theta \mathrm{f}c_i$ the gravimetric water content of soil horizon i at field capacity, $\theta \mathrm{w}p_i$ the gravimetric water content of soil horizon i at wilting point, $\rho_{\mathrm{b}i}$ the bulk density of soil horizon i (Mg m^{-3}), ρ_w the water density (Mg m^{-3}), S_i the volumetric stoniness of horizon i, and n_h the number of soil horizons of the profile to a depth of 1.20 m or to a limiting depth.

In order to assess the validity of the laboratory results for soil water retention, the gravimetric water content was determined at 12 additional soil samples, following the Soil Survey Laboratory (1996). These samples were obtained just before and 2 days after an irrigation event in 12 border-irrigated plots located in platform and alluvial soils with crops of corn and alfalfa.

The target irrigation depth (Z_r) was determined from TAW. Z_r expresses the amount of water (mm) to be added to the soil by irrigation in order to set the soil water to field capacity. In order to determine Z_r, consideration was given to the fact that different crops can extract between 40 and 75% of TAW without relevant water stress (Cuenca, 1989; Allen et al., 1998).

3.2. On-farm irrigation evaluation

The purposes of irrigation evaluation were to determine on-farm irrigation performance and to characterize soil infiltration. During 1999 and 2000 a total of 50 irrigation evaluations were performed within the irrigated area of the IDV. Thirty-eight of them were performed in platform soils, while the remaining 12 evaluations were performed in alluvial soils (Fig. 3). Five evaluations were performed in furrow irrigation, while 45 evaluations were performed in free-draining borders. In all cases the methodology proposed by Merriam and Keller (1978) was adopted.

The plots to be evaluated were chosen according to their geometry and land levelling. Borders were selected which were rectangular in shape, and had recently been laser levelled. During the irrigation evaluation the farmer performed the normal irrigation practices. A measuring tape was used to determine the border dimensions. The slope and

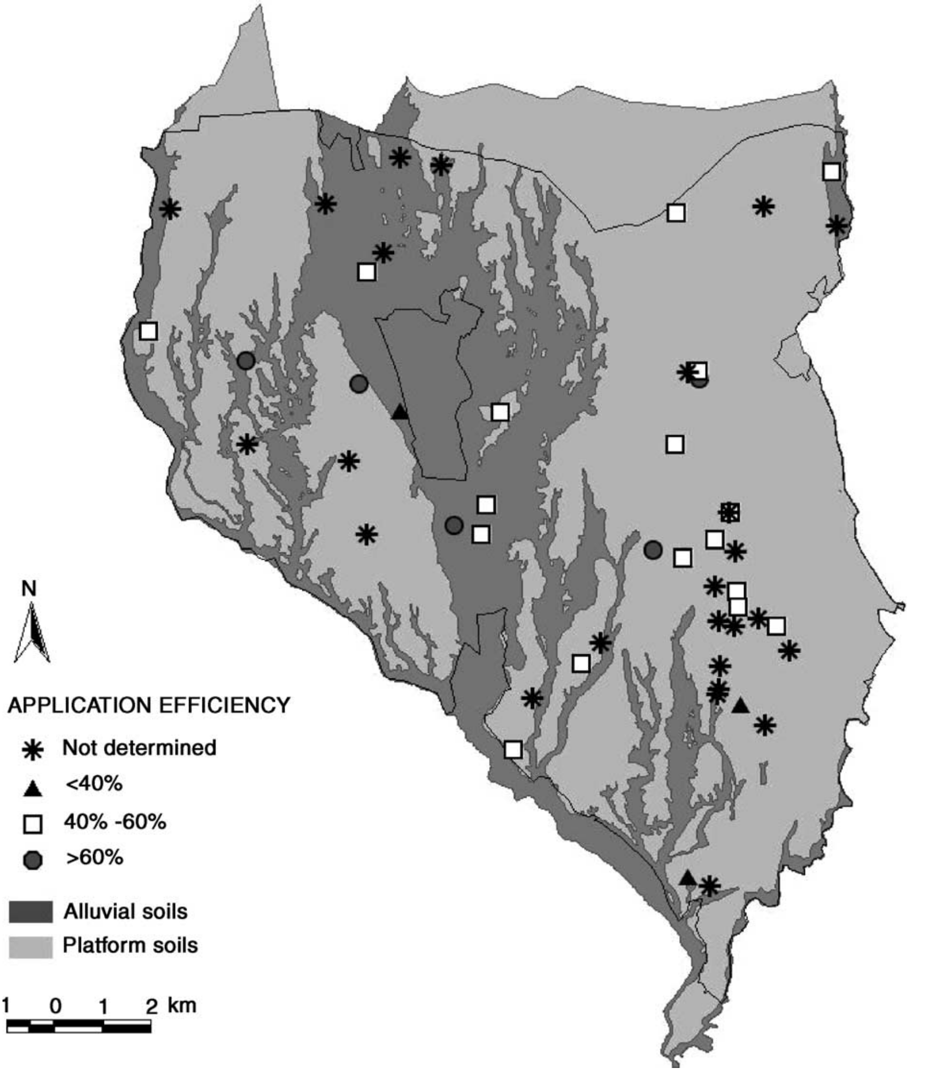

Fig. 3. Location of the irrigation evaluations performed in the IDV, with indication of their application efficiency. The background geomorphologic map has been adapted from Basso (1994) at a 1:25,000 scale.

the standard deviation of soil surface elevation were determined from soil surface elevation measurements performed every 10–30 m along the border using a total topographic station. Both parameters resulted from regression of elevation versus distance along the border.

The inflow irrigation discharge was measured using a mini-propeller meter. The advance phase was determined from recordings of the advance time to reference points located along the border every 10–30 m. The flow depth at the upstream end of the border was measured shortly before cutoff. A number of flow depth measurements were performed across the border, every 3–4 m. The average of all measurements was used to represent flow depth at this point and time.

In four borders where conditions permitted, surface runoff was monitored. The runoff discharge was measured using the mini-propeller meter or a float. A hydrograph was established from discrete discharge measurements, and its time integration yielded the runoff volume.

Infiltration and roughness were determined from advance and flow depth using SIRMOD, a hydrodynamic one-dimensional surface irrigation model (Walker, 1993). Such a model was iteratively executed using tentative values of the coefficient k and the exponent a from the Kostiakov infiltration equation (Kostiakov, 1932), and Manning n. The three parameters were adjusted until the model satisfactorily reproduced the experimental values of flow depth and irrigation advance for each evaluation (Playán et al., 2000).

The next step was to determine the irrigation performance indexes (Burt et al., 1997). These indexes included the application efficiency (E_a) and the low-quarter distribution uniformity (DU_{lq}). E_a expresses the percentage of irrigation water contributing to Z_r. DU_{lq} can be defined as the percentage of the average low-quarter infiltrated depth to the average infiltrated depth. In order to determine these performance indexes, an ad hoc hydrodynamic one-dimensional model was used. A calibration coefficient was used to adjust the normal-flow downstream boundary condition to the runoff field observations. In this way, the average flow constriction derived from the presence of an outlet work composed of one or two low-pressure concrete pipes with a diameter of 200–300 mm was introduced in the model. Since this calibration parameter is not foreseen in the commonly used surface irrigation simulation models, a free-draining border irrigation simulation model was built as a one-dimensional version of the two-dimensional simulation model B2D (Playán et al., 1994a, 1994b).

3.3. A simulation approach to district application efficiency

The information gathered in the soil survey, and the inventory of district structures and policies, together with the results of the irrigation evaluations, led to an evaluation of the current district performance and to the analysis of different future scenarios. The main tool used for this purpose was the hydrodynamic simulation model of surface irrigation reported in the previous section. The model was used to reproduce irrigation events in the district (Lecina et al., 2001). Furrow irrigation was not considered in this study, due to the small geographic extent of this irrigation system.

Since it would be unmanageable to perform irrigation simulations in all the borders within the district, special land units were created, characterized by certain homogeneity in their irrigation related properties (Playán et al., 2000). In this work, the irrigation land units corresponded to the area irrigated sequentially when the rotational delivery system is adopted in the district. These areas, referred to as irrigation ''turns'' by the district managers, comprise a variable number of plots and borders. All the borders within a turn are irrigated from the same irrigation ditch. In all cases, the area irrigated from one of the tertiary canals is divided in a number of turns responding to the organizational constraints of water delivery. A total of 147 turns were identified in the district, whose cartographic representation, managed in a geographic information system (GIS), was obtained from a combination of cadastral cartography, the irrigation and drainage network and the local knowledge supplied by the district ditch riders.

In each turn, the parameters required to define a representative border were determined. These parameters included the irrigation discharge, the average border length and width (measured at the cartographical restitution of an aerial photograph), the average field slope (extrapolated from the irrigation evaluations), the target irrigation depth, and the average soil infiltration (determined from the aggregation of the irrigation evaluation results). Simulations were run for all turns, representing all the borders in the IDV.

The reproduction of the current water performance was based on the cutoff time determined in the irrigation evaluations. In all evaluations, the cutoff time was longer than required to refill the soil water deficit. A simulation was performed in each turn to determine the optimum cutoff time. This optimum can be defined as the minimum cutoff time ensuring that all the points in the border attained an infiltrated depth of at least Z_r. The irrigation evaluations were equally optimized, and the ratio of real to optimum irrigation time was obtained for each soil type. This ratio was used to estimate the ''real'' irrigation time for each turn under the current water management practices.

In those turns where two soil types are present, two irrigation simulations were performed, one for each soil type. An area weighted average was performed on the results of both simulations, to reflect the influence of both soil types. The estimation of both areas was accomplished using the spatial analysis tools of the ESRI™ ArcView® software.

In addition to analysing the current situation (scenario 1), two future scenarios were evaluated (scenarios 2 and 3). In these, actions were alternatively directed towards water management and water conveyance structures. The scenarios were characterised as follows:

- Scenario 1: Reproducing the current irrigation situation.
- Scenario 2: Improving district water management by optimizing the cutoff time. This option ensured the fulfilment of crop water requirements, while using the minimum amount of irrigation water. As a result, in this scenario the application efficiency is equivalent to the potential application efficiency, according to Burt et al. (1997).
- Scenario 3: This scenario was based on the improvement of the irrigation structures to achieve an irrigation discharge of 200 L s^{-1} in the whole district. Additionally, the cutoff time was optimized as in scenario 2.

3.4. A hydrologic approach to district irrigation efficiency

Using the previous approach, the application efficiency was extrapolated to each turn and finally to the irrigation district. However, in order to estimate the global irrigation efficiency in the district it is necessary to combine application efficiency with irrigation scheduling and crop water requirements, conveyance efficiency from the canal to each border, as well as the effect of drainage water reuse for irrigation.

Determination of these aspects would require additional research work whose detail level is not in balance with the rest of the research performed in the IDV. Instead, a hydrologic approach was used to estimate global irrigation efficiency in the district. For this purpose, the seasonal irrigation performance index (SIPI) (Faci et al., 2000) was used. This index can be determined as the percentage of the seasonal crop water requirements to the seasonal volume of billed water. SIPI is a simplified version of the irrigation efficiency (IE) concept proposed by Burt et al. (1997). Irrigation efficiency is defined as the percentage of applied water which is used to satisfy beneficial uses, like crop evapotranspiration, for a given period of time. The differences between SIPI and IE are due to the reduction in crop evapotranspiration due to water stress and to inaccuracies in water billing. SIPI has been applied so far to irrigated plots (Faci et al., 2000; Dechmi et al., 2003a). In this research the SIPI concept was applied to the whole district, and therefore, estimations of global irrigation efficiency were obtained.

SIPI was determined in the study area for the years 2000 and 2001. The meteorological data required to determine crop water requirements were obtained from an automated agrometeorological weather station installed for this purpose in the district (42°10′13″, 1°12′50″W, 380 m a.m.s.l.). The methods reported by Allen et al. (1998) were used to determine the reference evapotranspiration. The crop coefficients proposed by Martínez-Cob et al. (1998) for the region were used to calculate crop evapotranspiration. The district database was used to estimate the acreage of each crop in the study years. Finally, water delivery data from the Bardenas Canal was obtained from the Ebro Basin Water Authority (CHE).

4. Results and discussion

4.1. Soil survey

Table 1 presents the analytical results of the soil survey in IDV. Platform soils are loam textured, with a bulk density of 1.52 Mg m^{-3}. Their main characteristics are the high stoniness (22% in volume on the average) and the small soil depth (0.87 m on the average, Fig. 2). An important variability exists in this last parameter as a result of the existence of soil horizons dominated by calcium carbonate deposits with varying degrees of cementation. As an extreme, the horizon can be fully cemented, forming a petrocalcic horizon, locally called "*mallacán*", which can limit the soil rooting depth to a minimum of 0.26 m. Consequently, soil TAW is very variable, ranging from 15 mm in areas where a petrocalcic layer is present to 156 mm. The average TAW is 60 mm for all surveyed platform soils. The sampling density used in this study did not permit delineation of areas with homogeneous values of TAW within the platforms. As a result, the large spatial variability of TAW within this soil unit could not be mapped.

The soil depth of the alluvial soils exceeded 1.20 m at all sampling points. The texture is clay loam, with a bulk density of 1.40 Mg m^{-3}. Stoniness was not observed. The TAW determined from these data was high, averaging 182 mm.

Table 1
Average results of soil sampling in the IDV for 10 profiles in alluvial soils and 40 profiles in the platforms soils

		Alluvial soils	Platform soils
Effective depth (m)	Average	1.20	0.87
	Minimum–maximum	>1.20	0.26–1.65
Stoniness (vol.%)	Average	0	22
	Minimum–maximum	0	4–53
Total available water (mm)	Average	182	60
	Minimum–maximum	137–250	15–156

For the determination of Z_r from hydrological data, an average crop evapotranspiration of 70–80 mm was considered characteristic of an irrigation interval of 12 days, during the peak month of the season. This value is lower than the TAW for alluvial soils, but larger than the TAW for platform soils. In the alluvial soils the estimated value for Z_r roughly corresponds to 50% of TAW, representing a level of soil water extraction which would not affect crop yield. In the platforms, however, the estimated value of Z_r is larger than the TAW. This implies that platform soils would be subjected to an intense water depletion, thus casting doubts about the viability of the crops in these soils. In fact, the crop water requirement between two irrigation events exceeds the soil water holding capacity. However, the fact is that the crops complete their vegetative cycle even in the soils with lowest TAW within the platforms.

This finding seems to be due to a combination of factors. Among them, horizontal water flows over the petrocalcic horizon, a decrease in soil evaporation due to the surface stoniness, and the stress-induced decrease in crop water requirements (Allen et al., 1998) that is reflected in a certain yield loss. Additionally, uncertainties in the determination of wilting point and field capacity could result in an underestimation of TAW in loam soils, as pointed out by Gijsman et al. (2002). This last factor was illustrated by the results of the determination of gravimetric soil water content in samples obtained before and after an irrigation event. These results showed that the soil water content after the irrigation event was coincident with the laboratory measured field capacity. However, soil water before the irrigation event averaged 90% of the wilting point. This capacity of water extraction beyond the wilting point, particularly in the superficial horizons, was observed in previous experiences with corn and sunflower (Cabelguenne and Debaeke, 1998), and would result in a certain potential yield loss. Finally, during the interval between saturation (following an irrigation event) and field capacity – which in practice is approximated as 2 days – the crop may use part of the gravitational water which is considered lost to deep percolation.

Given consideration to all these issues, a target irrigation depth of 65 mm was adopted for platform soils, while 80 mm were considered characteristic of alluvial soils.

4.2. *On-farm irrigation evaluation*

Table 2 presents the aggregated results of the irrigation evaluations, distinguishing three categories: borders on alluvial soils, borders on platform soils, and furrows. All furrow evaluations were performed on platform soils, since these soils are very adequate for

Table 2
Results of the irrigation evaluations performed at the IDV

		Borders in alluvial soils	Borders in platform soils	Furrows in platforms
Area (m^2)	Average	8900	10,733	10,089
	CV (%)	47.69	31.83	3.76
	Number of samples	11	33	5
Length (m)	Average	208	257	270
	CV (%)	46.82	28.86	20.06
	Number of samples	11	33	5
Width (m)	Average	43	43	30
	CV (%)	22.37	22.60	50.00
	Number of samples	11	33	5
Slope (‰)	Average	0.88	1.94	1.32
	CV (%)	82.10	88.91	31.72
	Number of samples	11	31	5
Standard deviation of soil surface elevation (mm)	Average	17.7	14.7	10.6
	CV (%)	60.69	46.75	24.31
	Number of samples	11	33	5
Discharge (L s^{-1})	Average	103	136	108
	CV (%)	35.13	40.29	24.46
	Number of samples	11	33	5
Irrigation time (h ha^{-1})	Average	2.99	2.87	3.17
	CV (%)	27.51	40.62	30.52
	Number of samples	11	33	5
Advance time (h ha^{-1})	Average	3.38	2.70	2.28
	CV (%)	25.10	28.33	16.57
	Number of samples	6	17	3
Irrigation depth (mm)	Average	106	128	139
	CV (%)	35.27	32.21	35.81
	Number of samples	11	33	5
Manning n	Average	0.29	0.19	0.06
	CV (%)	36.40	29.98	16.64
	Number of samples	6	17	3
Kostiakov k (m min^{-1})	Average	0.0148	0.0095	0.0090
	CV (%)	49.58	27.75	10.10
	Number of samples	6	17	3
Kostiakov a	Average	0.31	0.44	0.45
	CV (%)	17.5	10.36	13.70
	Number of samples	6	17	3
Application efficiency (%)	Average	61.76	52.86	34.67
	CV (%)	16.98	16.54	15.19
	Number of samples	6	17	3
Low quarter distribution uniformity (%)	Average	84.20	85.89	85.70
	CV (%)	8.32	8.08	2.59
	Number of samples	6	17	3

horticultural crops. The evaluated crops were alfalfa, corn and sunflower (in the borders), and tomato and pepper (in the furrows). In order to estimate infiltration, roughness and irrigation performance, evaluations were selected which were free of incidences decreasing the reliability of the results. Among the common incidences, different kinds of experimental errors, and the fact that the soil water content before irrigation was higher or lower than normal.

The border size averaged about 1 ha, with a moderate variability. Borders are larger in platforms than in alluvial soils. The field slope has a wide range of variation. On the average, the slope is large in platforms (1.94‰ versus 0.88‰ in alluvial soils), while furrows show an intermediate slope (1.32‰). These data suggest that farmers have taken soil infiltration rates into consideration in their modifications of the field slope. As a result, a steeper slope has been used in borders infiltrating water faster (coarser textures in platforms than in alluvial soils). In the case of furrows on platform soils, farmers' declared objective was to ''add enough water to the soil'', and therefore they used a milder slope, resulting in a slow water flow and a larger wetted perimeter. The standard deviation of soil surface elevation ranged between 10 and 40 mm. The average value was 10.6 mm for furrows and 17.7 and 14.7 mm for borders in alluvial and platform soils, respectively. These values indicate that laser levelling is often practiced in the IDV. This technique greatly favours the practice of surface irrigation, improving irrigation performance and decreasing the time of advance (Playán et al., 1996).

The irrigation discharges present a large variability among irrigation ditches, although in most of the cases they exceed 100 L s^{-1}. Discharges are larger in borders on platform soils (138 L s^{-1}), than in furrows and borders on alluvial soils (108 and 103 L s^{-1}, respectively). This finding can be supported by the need to obtain a faster advance in soils with high infiltration. In furrows, it is a common practice to decrease the irrigation discharge (and therefore the flow level) once the plants are fully developed, in order to avoid water damage to the plant and its fruits.

The irrigation times, although largely variable as a function of the irrigation discharge, are of about 3 h ha^{-1} in platforms and alluvial soils. This similar irrigation time is an indication of the effect of farmers' decisions on irrigation performance. Using large irrigation discharges and increasing the field slope, farmers decreased the irrigation time in platforms, avoiding larger water losses and longer irrigation intervals. The irrigation time in furrows is slightly larger than in borders, due to the lower discharge and to the farmers' practice of delaying cutoff to increase the irrigation depth.

The irrigation depth is generally high, with an average of 117 mm in alluvial soils, 120 mm in the platforms and 143 mm in furrows. Large as these values may seem, they are not infrequent in some surface irrigation systems in the Ebro valley of Spain (Playán et al., 2000; Zapata et al., 2000).

Hydraulic roughness, represented by the value of Manning n, ranged from 0.11 to 0.31 for alfalfa, from 0.08 to 0.18 for corn and sunflower, and from 0.05 to 0.07 for furrow irrigated tomato and pepper. Variations in Manning n within a given crop are due to the different crop developmental stages when the evaluations were performed, plus the presence of different degrees of surface stoniness in the different soils.

Fig. 4 presents the infiltration functions derived from the irrigation evaluations. The graphical representation has been grouped by soil type and – in the case of platforms – by

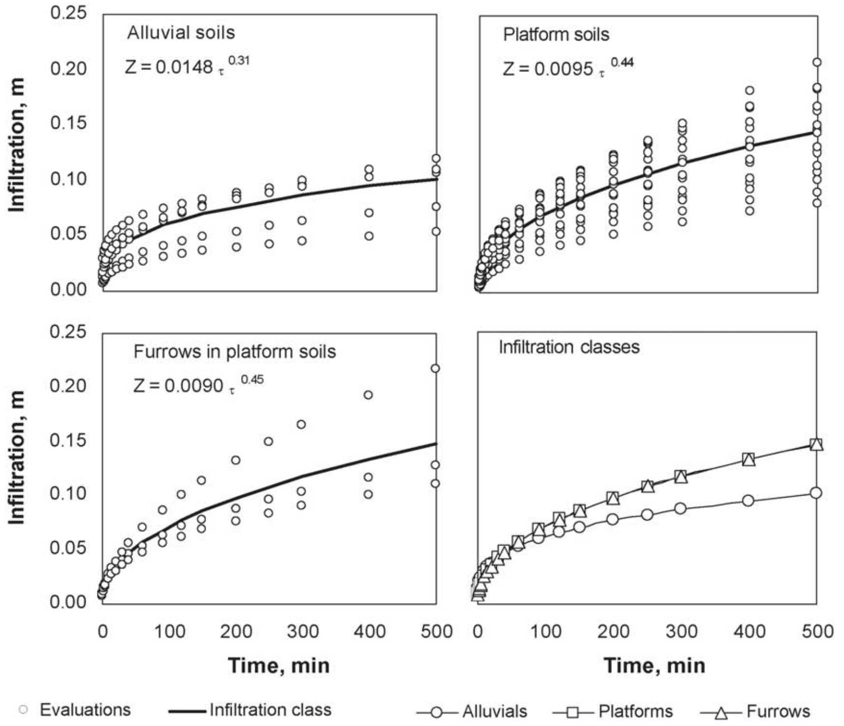

Fig. 4. Infiltration functions corresponding to borders in alluvial and platform soils, and to furrows in platform soils. The figures present results from the irrigation evaluations (symbols) and average infiltration curves (lines) and equations.

the irrigation system (border versus furrow irrigation). Based on these infiltration characteristics, three infiltration functions were derived and later applied to the simulation of irrigation in the IDV. The large variability of infiltration curves within each soil type is typical for this soil property in the Ebro basin of Spain (Zapata and Playán, 2000). This was particularly relevant in platform soils.

Infiltration in platform soils is larger than in alluvial soils, due to their coarser texture and high stoniness. However, infiltration was not as large as in other platform soils in the Ebro valley, in which the texture is coarser (Playán et al., 2000). The differences in infiltration between borders and furrows in platforms are conceptually due to the geometry of the furrows and to the flow level in them. In this particular case, the differences between the average curves are not relevant.

Application efficiency reached 53% in the platforms, with uniform frequencies in the range of 40–75%. This level of efficiency in the platforms could be lower if it had not been for the large irrigation discharge and field slope. In furrows, application efficiency ranged between 27 and 39% (with an average of 35%), as a consequence of the lower discharges and slopes, and of the small furrow spacing (0.6 m on the average). The average irrigation efficiency in alluvial soils was 62%, ranging from 51 to 81%. These values of E_a, which can be classified as low, reveal that these soils are better suited for surface irrigation than the platform soils. Fig. 3 displays the spatial variability of the application efficiency obtained in the irrigation evaluations.

DU_{lq} was always greater than 62%. In the platform soils (borders and furrows) the average uniformity was 86%, while the average value for alluvial soils was 84%.

In order to determine surface runoff the uniform outflow discharge boundary condition often used in surface irrigation models was multiplied by an ad hoc coefficient of 0.03. This coefficient adjusted the simulated surface runoff to the experimental runoff hydrographs. This modification roughly reduced the surface runoff to one half, as compared to uniform flow conditions. As a result, deep percolation losses are much more important in the IDV than surface runoff losses (36.5% versus 10.6% in platform soils; 27.0% versus 11.2% in alluvial soils). The introduction of the runoff coefficient also resulted in a 8% reduction in DU_{lq}, due to the additional infiltration at the downstream end of the field. The effect on E_a was minimal, since the average infiltration exceeds Z_r throughout the field length. Consequently, the volume of water losses remains sensibly constant, and changes from runoff to deep percolation as the outflow is constricted.

In an area of about 10% of the platform soils, evaluations were not performed since the plots are neither divided into borders nor levelled. Without additional insight, it can be assumed that irrigation performance in these plots where the irrigation method is wild flooding (Walker and Skogerboe, 1987) is significantly lower than in the rest of the district.

4.3. A simulation approach to district application efficiency

The characterization of the water conveyance network revealed that the average irrigation discharge is $152\ L\ s^{-1}$, fluctuating between 100 and $350\ L\ s^{-1}$ among the different "turns", in rough agreement with the discharges observed during the evaluations. As for the border dimensions, the average length was 241 m, with an average area of $9644\ m^2$.

The following step was to analyse the effect of the soil type and Z_r on irrigation performance for each scenario. The average characteristics of each turn were considered, and the two major soil types in the district were characterized by their infiltration functions and target irrigation depths. In the platform soils, given the large spatial variability of TAW (directly related to the variability in soil depth), different values of Z_r were considered. The response of application efficiency and irrigation time to a Z_r ranging from 40 mm (platform soils with a petrocalcic horizon at a depth of 40–50 cm) to 80 mm (platform soils with a depth of about 100 cm) is presented in Fig. 5 for each scenario. Application efficiency linearly ranges from 30 ($Z_r = 40$ mm) to 60% ($Z_r = 80$ mm) in the current situation (scenario 1), with the irrigation time being $2.7\ h\ ha^{-1}$ in all cases.

Regarding the two hypothetical scenarios (2 and 3), the irrigation time fluctuates between 1 and $2\ h\ ha^{-1}$, while the E_a ranges from 50 to 80%. In this case, the response to Z_r is not linear. In fact, in both scenarios E_a grows linearly to a maximum of 80%, which is attained with a target irrigation depth of 60–65 mm. This is due to the fact that the irrigation time remains invariable with Z_r, since this cutoff time is the minimun required for water to reach the downstream end of the border. For soils retaining more than 60–65 mm it is necessary to apply more water in order to satisfy a larger Z_r, which requires increasing the irrigation time. However, a relevant part of the increased volume of irrigation water is lost

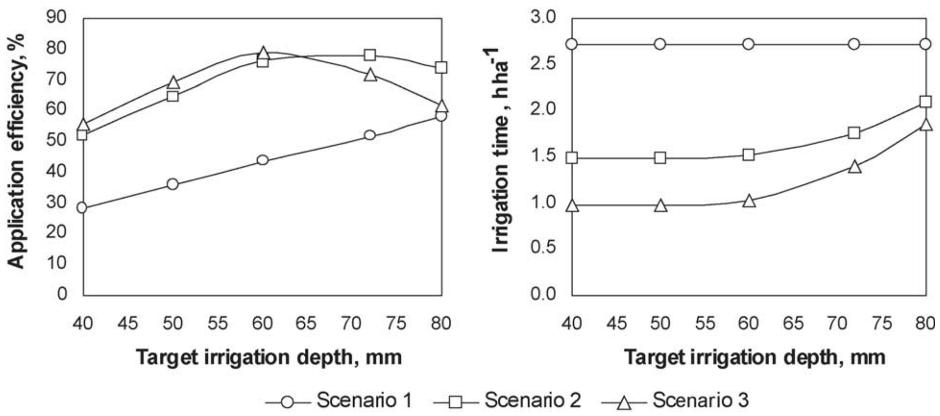

Fig. 5. Average application efficiency and irrigation time for the platform soils as a function of the target irrigation depth (Z_r) for the three simulated scenarios.

to deep percolation and surface runoff, and therefore E_a decreases. As a consequence, and under the average conditions of discharge and border dimensions, the depth of 60–65 mm would be the minimum amount of water to be applied to any point of a border ensuring that advance is complete. The differences in E_a response to Z_r in the two future scenarios are small. In fact, their evolution with the target irrigation depth is parallel and very similar up to a value of Z_r = 60–65 mm. From this point on, the trajectories are separated as a consequence of the increased water velocity for a discharge of 200 L s^{-1}. As a consequence, the increase in the irrigation time is larger in scenario 3 than in scenario 2, in order to ensure that the target irrigation depth is attained. Water application is therefore larger for scenario 3, and so are the water losses.

When both future scenarios are compared to the current situation (scenario 1), relevant differences are observed in the application efficiencies. These differences are particularly large for small values of Z_r, as a consequence of the large current irrigation times, as compared with the times required for the same discharges (scenario 2). The optimum irrigation time is about 55% of the current irrigation time for values of Z_r up to 60–65 mm. For values of Z_r beyond 65 mm, this percentage grows to 78% (Z_r of 80 mm). These differences in irrigation time are very relevant to the district as a whole, given their importance on the duration of the irrigation interval, which is strictly applied during the rotation water delivery schedule.

In the simulations for alluvial soils, for the current situation (scenario 1) the abovementioned value of Z_r = 80 mm was considered. However, in scenario 2, and scenario 3 a value of Z_r = 72 mm was adopted. This reduction was due to the fact that the optimization of irrigation time in alluvial soils permits reduction in the minimum water depth applied to each border. The reduction in Z_r can contribute to a reduction of the irrigation interval.

The average E_a resulting from scenario 1 was 52%. The perspectives are much more favourable for scenario 2, since the E_a would reach peak values of about 80%. The optimized cutoff time would be 58% of the current time, leading to a reduction in the daily irrigation period and in the irrigation interval. Scenario 3 was not simulated for alluvial soils, since the use of large discharges in this soil type did not yield better results than those obtained in scenario 2. Consequently for alluvial soils, the results of scenario 2 were used for scenario 3, and the increase in the service capacity of the irrigation network should only be performed for platform soils.

The average irrigation performance indexes were determined for the whole district and for the three scenarios (Table 3). Three cases were simulated for each alternative, considering target irrigation depths for the platform soils of 40 mm, the minimum value in this type of soils, 72 mm, which is approximately similar to the crop water requirements during the irrigation interval, and 65 mm, which is approximately the average value of Z_r for the platforms in the district. The spatial distribution of these results can be appreciated in Figs. 6 and 7, considering a value of Z_r in the platforms of 65 mm. Other figures (not presented) were elaborated to display the simulation results for different values of Z_r in platforms. The goal was to release maps that could be analysed by the farmers, particularizing the simulation results to the soil characteristics of their own plots.

From the perspective of the IDV, the best scenario would correspond to an optimization in the irrigation time (scenario 2), which would lead to an efficiency of 76%, with irrigation times below 2 h ha^{-1}. Scenario 3 (increasing the discharge to 200 L s^{-1}) would not relevantly increase the application efficiency, since the irrigation discharges currently used in the area are relatively high. However, the use of this large discharge would lead to a further decrease in the irrigation time which could reduce the irrigation interval: for a Z_r value of 60–65 mm, the optimum irrigation time with this discharge is about 35% of the current irrigation time. However, the large investments required to implement this solution would not be justified, except in specific areas where the current discharge is lower than the average.

These results provide evidence that farmers tend to apply a large volume of water, well in excess of crop requirements, in order to ensure that the whole border is adequately irrigated. The difference between the optimum irrigation depth and the current irrigation depth is in most cases not used by the crops, and results in unnecessarily long irrigation intervals, with negative consequences for water allocation in the IDV.

Table 3
Average and extreme values of the application efficiency and the irrigation time of the 147 irrigation turns within the IDV for the simulated scenarios, considering different target irrigation depths in platform and alluvial soils

Scenario	Z_r platform soils (mm)	Z_r alluvial soils (mm)	Efficiency (%)			Irrigation time (h ha^{-1})		
			Average	Maximum	Minimum	Average	Maximum	Minimum
1	40	80	35.2	64.6	19.6	2.83	4.43	1.07
	65	80	49.3	70.4	19.1	2.78	6.27	1.27
	72	80	51.9	71.3	24.0	2.79	5.52	1.42
2	40	72	60.3	86.6	35.9	1.55	2.68	0.57
	65	72	76.3	87.0	29.6	1.72	4.05	0.80
	72	72	79.2	87.0	36.4	1.74	3.64	0.93
3	40	72	62.9	86.6	33.4	1.18	2.11	0.76
	65	72	78.3	88.0	23.7	1.32	3.80	1.01
	72	72	75.1	86.9	34.0	1.48	2.92	1.11

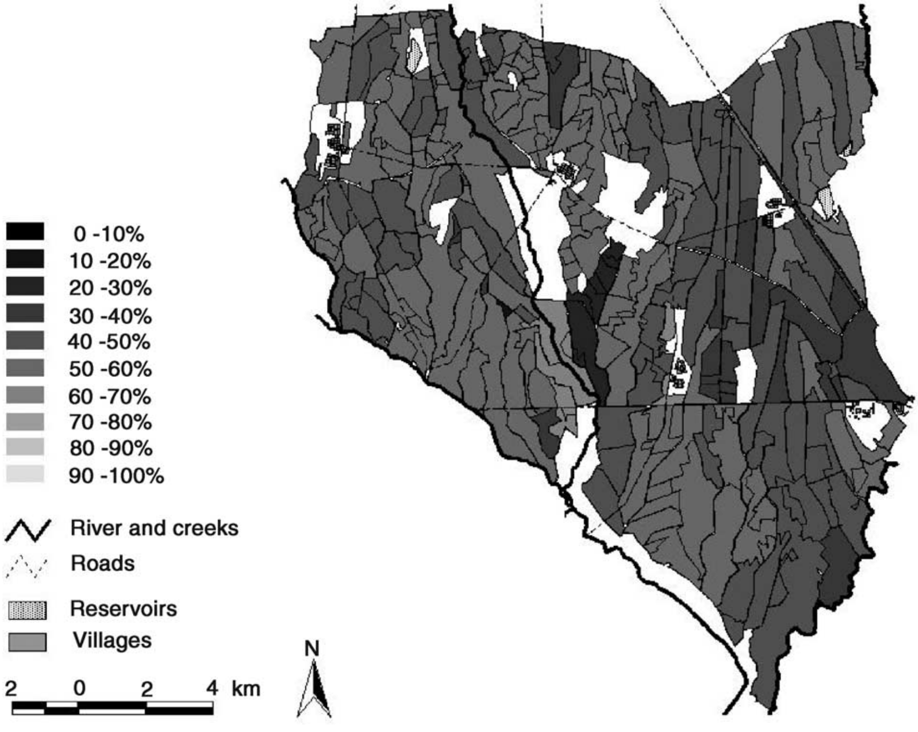

Fig. 6. Application efficiency map in the IDV for the current situation (scenario 1), considering a target irrigation depth (Z_r) for platform soils of 65 mm.

Scenario 2 would result in a reduced water application in each border, with light, frequent irrigations, leading to a more efficient crop water use, and even to higher yields (due to the reduced irrigation intervals). Achieving these results would require more rigour in the irrigation cutoff by the farmers. This would be limited by the structure of the farms and the water conveyance network. In fact, the geographical dispersion of the plots belonging to each farmer results in numerous trips to the fields to manage irrigation, reducing the farmer's abilities to manage the cutoff time, particularly during the peak of the season. On the other hand, the current daily irrigation period of 24 h results in specific limitations when irrigation is performed during the night.

Two techniques could be used to decrease the cutoff time. First, the construction of small in-line reservoirs, which would provide water storage during the night and would reduce the daily irrigation period to make it coincident with the daytime period. Second, promoting the use of irrigation advance pagers using GSM technology would help farmers make more accurate estimations of the cutoff time. These portable devices are installed at the downstream area of a border and make a phone call to the farmer whenever the advance front reaches the device. As a result of these techniques, irrigation performance and crop yield would be improved. At the same time the farmers' working conditions would be largely improved, and their work would be more attractive to the new generations.

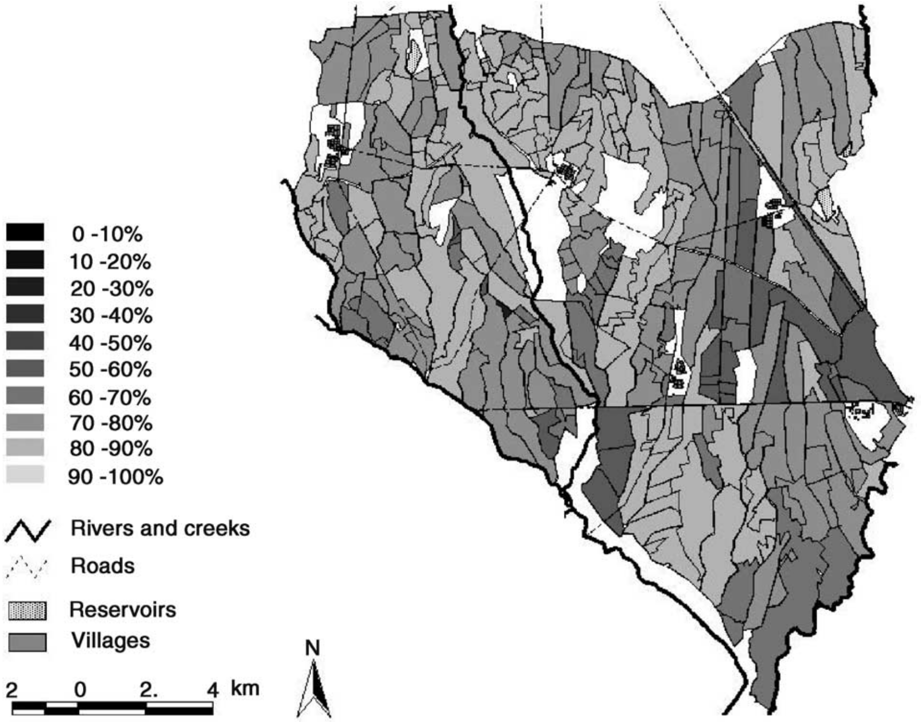

Fig. 7. Application efficiency map in the IDV for scenario 2 (optimization of the cutoff time), considering a target irrigation depth (Z_r) for platform soils of 65 mm.

Additionally, the application of a proportional water billing procedure will also have a relevant effect on water use. Before 2001 farmers only paid on the basis of the irrigated area, rather than on the amount of irrigation water used. This new billing procedure does not represent an increase in the average water bill, but introduces penalties for unjustified water uses, and discourages farmers to delay the progress of the irrigation turns and therefore to increase the irrigation interval, creating problems to all farmers in the district.

4.4. A hydrologic approach to district irrigation efficiency

The possibility to attain higher irrigation efficiencies through an improvement in irrigation management can be illustrated by the analysis of the district wide SIPI. Table 4 presents the district wide SIPI figures for 2000 and 2001. In 2000 water availability was high, and the crop water requirements were relatively small. Under such circumstances, farmers were not rigorous in establishing the cutoff time, and the operational water losses were similar in magnitude to the water reuse, since the district wide SIPI (48.7%) was similar to the average application efficiency (49.3%). On the contrary, in 2001 relevant water restrictions were applied from July on, since rainfall during the irrigation season was very scarce and the volume of water stored in the Yesa reservoir was very limited. These

Table 4
Seasonal irrigation performance indexes (SIPI) for the IDV determined as a ratio between net crop water requirements (CWRn) and the volume of water billed by the Bardenas Canal for the 2000 and 2001 irrigation seasons

Year	CWRn (hm^3)	Water billed (hm^3)	SIPI (%)
2000	82.6	169.6	48.7
2001	97.4	146.8	66.3

circumstances seem to have induced an optimization in water management (on-farm and in the conveyance system), which led to a more efficient district (the SIPI reached a value of 66.3%). Since the farmers did not appreciate a decrease in crop yield, this would be an example of the relevance of persuading the farmers to control the irrigation time.

Despite the proved importance of water management in the IDV, water management problems resulting from the low soil water retention in the platform soils would be more manageable if the farmers were to switch from surface to sprinkler or drip irrigation. Such transformation would drastically reduce the irrigation labour requirements, improve water supply to the crops, and increase crop yield. However, the farmers' limited interest in changing to drip or sprinkler irrigation makes the identified water management activities attractive for water conservation in the short term. Small collective pressurized networks, using water from the night reservoirs, would be a way to promote pressurized irrigation in the area. A similar strategy was started in 2002, with the development of a 600 ha sprinkler irrigation project using water stored in the Bolaso reservoir.

5. Conclusions

The abundance of platform soils, the current irrigation systems, the limitations of the open channel conveyance network, and the poor irrigation management practices determine that the application efficiency in the IDV is low, with an average of 49%. The use of an average irrigation discharge of 152 L s^{-1}, results in a relatively low irrigation time (about 3 h ha^{-1}). However, due to the low soil water retention, even this low irrigation time results in abundant deep percolation water losses.

The connections between the drainage and the irrigation networks permit partial reuse of the water lost to surface runoff and deep percolation. However, the district-wide irrigation efficiency only approaches its potential value when the system operates under water scarcity, presumably inducing more accurate cutoff times and a more intensive water reuse. In 2001, for example, the SIPI largely exceeded the average on farm application efficiency, with a value of 66%. These data reveal that the system can reach acceptable efficiencies, and that the need to rationalize water use is not currently perceived by the farmers. The recent introduction of proportional billing in the district will surely have a positive impact on farmers' irrigation practices.

The simulation of surface irrigation in the IDV permitted determination of the optimum cutoff time in the current situation, which amounts to less than 2 h ha^{-1} (depending on the target irrigation depth). The optimization of the irrigation time would lead to average application efficiencies of 76%. Future scenarios based on an increase of the irrigation discharge would not result in further increases of application efficiency, although the irrigation time would be additionally reduced.

The main conclusion of this study is that farmers currently use irrigation times much longer than required. In doing so, they intend to increase the volume of water stored in the soil profile, thus minimizing the water stress resulting from a large irrigation interval. In the platform soils even the minimum irrigation time ensuring complete advance results in an average water application exceeding Z_r. As a consequence, the main effect of increasing the on-farm irrigation time is to increase the irrigation interval. This effect is clearly negative to all farmers in the district, since it induces crop water stress, leads to the introduction of crops with low or no summer water requirements, and requires a daily irrigation period of 24 h.

Although management alternatives have been identified to improve the current situation, the low and heterogeneous TAW in the platform soils is a good reason to consider adoption of pressurized irrigation systems in the district. Such alternative would reduce irrigation labour requirements, improve crop water use and increase yields, representing benefits to all farmers.

This work has produced a data set and recommendations which will be useful to support decision making in irrigation district modernization. The use of surface irrigation simulation models has led to the characterization of the current water use situation, and to the evaluation of future scenarios. Furthermore, the use of simulation models that reproduce the relationship between the irrigation water, the irrigation structures, crop yield and the environment would lead to more accurate perceptions about the way an irrigation district works. Such models provide an important resource to the analysis of the economic, environmental, and social consequences of adopting different modernization scenarios, management policies or cropping patterns in the IDV.

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