Analysis of an irrigation district in northeastern Spain:

I. Characterisation and water use assessment

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ABSTRACT

In this work, the Loma de Quinto irrigation district, located in Zaragoza (Spain) was characterised, and water use was assessed. The study was performed to contribute to the Diagnostic Analysis phase of an incipient Management Improvement Process in this sprinkler-irrigated district. The objectives of this first paper of the series include: 1) characterizing the irrigation systems, soil types and crops; 2) evaluating irrigation performance through the relationship between on-farm water use and net irrigation requirements; and 3) identifying factors affecting on-farm water use. In order to accomplish these objectives, statistical analyses of field data, district records on water use and farmers' interviews were performed. Technical deficiencies were detected in solid-sets, centre-pivots and linear-moves. A Seasonal Irrigation Performance Index (*SIPI*),

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defined as the percentage of net irrigation requirements to seasonal water billing, was determined at each plot and for each of the three study years. The average interannual *SIPI* amounted to 127 %, indicating that crops in the district were consistently water stressed. An analysis of the *SIPI* for the main crops in the district revealed that water stress was more intense in drought resistant and/or heavily subsidized crops (*SIPI* for sunflower was 142 %). The average irrigation interval (12.3 days) and irrigation depth (44 mm) were too high for some of the soils in the district. Farmers adjusted the irrigation interval to meet the seasonal change in irrigation requirements. The irrigation depth was reduced in windy days. In two of the three study years, large plots used less water than small plots, at a rate of about -5 mm ha^{-1}. The high cost of irrigation water in relation to crop revenues, the technical deficiencies of the irrigation systems, and the limitations imposed by climate and soils appeared to be major causes of local water management problems. In a companion paper, irrigation evaluations and simulations are presented, and irrigation schedules for optimal crop yield are proposed and evaluated *via* simulation.

Keywords: Sprinkler irrigation; irrigation performance; water use; farm management

INTRODUCTION

In many irrigation projects around the world, water use efficiencies are below the expected levels (Clemmens and Dedrick, 1992). Low efficiency can be attributed to inadequate irrigation structures, poor on-farm management and/or insufficient water availability. Currently, farmers are confronted with severe economical and environmental pressures. In the European Union, the Common Agricultural Policy (CAP) seeks to ensure the sustainability of agricultural systems without creating surpluses. Agricultural products must become more competitive in markets that are increasingly open at the international level (de Juan et al., 1996). In this context, farmers must change their production systems so that water is considered not only as a limited resource, but also as a production factor and a relevant economic input.

A number of on-farm irrigation performance indexes have been defined (Merriam and Keller, 1978; Burt et al., 1997). These indexes quantify water management, and serve to identify problematic areas within an irrigated area. However, they do not inform on the reasons for the observed level of performance or provide guidance on how to improve it. Addressing performance problems is complex since improvement in farm water management must be viewed in the context of overall farm management. A Management Improvement Program (Dedrick et al., 1993; Dedrick et al., 2000) is an effective way to identify both the strengths and the weaknesses of irrigated agriculture.

The concept of Management Improvement Program (MIP) has evolved over the past 20 years. Its main objective is to improve the performance and sustainability of irrigated agriculture. According to Dedrick et al. (2000), the MIP process incorporates: 1) a thorough understanding of the performance of irrigated agriculture in an area; 2) involvement by key decision makers in a joint decision process; and 3) implementation of the planned changes by responsible operational managers. The MIP consists of three phases: diagnostic analysis, management planning and performance improvement. In the Maricopa-Stanfield Irrigation and Drainage District (MSIDD), located in central Arizona, an interorganizational demonstration management improvement program was implemented in 1990 to assess its usefulness in the evaluation of the performance management.

In the Ebro valley (Spain), irrigation districts have a varied technological level. Surface irrigation, using borders and level basins, is the most common irrigation method. In general, these irrigation systems are characterised by a low efficiency. Typical problems include: distribution systems with capacity below the peak demand; inflexible delivery rate and duration (usually in 24 hour shifts); and poor on-farm land levelling (Faci et al., 2000; Playán et al., 2000). These authors analysed a surface irrigated district representative of the Ebro valley: the Almudévar Irrigation District (AID). The study characterised the district's water management problems and evaluated modernisation scenarios. The authors concluded that the irrigation systems needed improvement and that the water distribution system was not able to provide a flexible and dependable water supply to the farmers. Consequently, they proposed a modernisation strategy based on the improvement of the conveyance structures and on conversion from surface to sprinkler irrigation. Currently, the Government of Spain is working on a program to modernise many irrigation districts. At the same time, public and private investments are being used to develop new irrigated areas using pressurised irrigation systems. These systems can attain irrigation efficiencies greater than 80 % if adequately designed and managed (Keller and Bliesner, 1990; Clemmens and Dedrick, 1994). Little information is available in Spain about the current levels of irrigation efficiency under sprinkler irrigation systems. Therefore, assessing irrigation performance in these modern districts is an important issue to improve water management and preserve the quality of the environment.

In this series of two papers, an analysis of water use and irrigation performance in the Loma de Quinto District (LQD) is presented. This analysis represents a contribution to the Diagnostic Analysis phase (Clyma and Lowdermilk, 1988; Dedrick et al, 2000) of an incipient MIP for the LQD. The next step will be to discuss this report in a multidisciplinary committee which will perform the Diagnostic Analysis not just on water issues, but on the current state of irrigated agriculture.

The objectives of this first paper of the series include: 1) characterizing the irrigation systems, soil types and crops present in the LQD; 2) evaluating irrigation performance through the relationship between on-farm water use and net irrigation requirements; and 3) identifying factors affecting on-farm water use. In order to accomplish these objectives, statistical analyses of field data, district records on water use and farmers' interviews were performed.

THE STUDY AREA

The LQD was selected as the study area because farmers and district managers are interested in improving the profitability and sustainability of irrigated agriculture. From a technical point of view, the district is interesting because of the high cost of irrigation water (in comparison with crop revenues), the existence of water use records, the use of a wide variety of sprinkler irrigation systems, the limitations on irrigation operation imposed by the wind, and the variability in crops and soil types. The LQD is located about 40 km Southeast of Zaragoza, Spain (Figure 1). The district is an extension of an old irrigation district, the Traditional Quinto District (TQD), which diverts water from the Ebro river. The TQD, consisting of about a thousand hectares of surface irrigated land, was the basis of the Quinto economy for centuries. Since 1987 farmers in Quinto cultivate the old irrigated area plus the sprinkler irrigated LQD. The LQD is located in a plateau about a 100 m above the TQD.

The LQD covers 2,606 ha, divided in 490 cadastral plots, and services 284 farmers (Lasierra, 1993). Each farmer cultivates a number of cadastral plots, which are usually spread throughout the district. Plot size varies between 0.2 and 71.8 ha. A variety of sprinkler irrigation systems (solid-set, centre-pivot and linear-move), are used to irrigate field crops (alfalfa, corn, sunflower and wheat). Fruit trees are produced in a few plots equipped with micro irrigation systems. District soils are shallow, have low organic matter, and are high in calcium carbonate and gypsum. The Quinto climate is semiarid, with an average annual rainfall of 266 mm and an average reference evapotranspiration (ET_0) of 1,243 mm. A relevant feature of the Quinto climate is the presence of an intense wind from the NW-W, locally called "*cierzo*". This wind produces large wind drift and evaporation losses and severely reduces irrigation uniformity in solid-sets (Faci and Bercero, 1991).

Irrigation water is pumped from the Ebro River to a reservoir located at an elevation of 132 m. Due to the energy requirement, the cost of water (0.034 € m^{-3} in 1997) is very high in comparison with other districts of the Ebro basin growing field crops with surface irrigation (about 0.006 € m^{-3}). Water is supplied through a 60 km network of pressurised pipes. No additional pumping is required to convey water from the reservoir to the plots, although some farmers use booster pumps to increase the available pressure. All the hydrants are equipped with volumetric water meters. The distribution system is limited rate demand, as defined by Clemmens (1987).

The board of the LQD manages the district. The board is composed of district farmers, who are elected by fellow farmers, occupying the positions of president, financing administrator and consultants. The LQD hires personnel such as the secretary and a number of technicians to operate and maintain the pumping station, the irrigation network, and the reservoir.

MATERIALS AND METHODS

Temporal and spatial units of the study

The current level of irrigation management was analysed using records of irrigation practices for three different irrigation seasons, chosen according to their ET_0 (dry, average and humid) and to the availability of crop maps. The selected years were 1989, 1995 and 1997. The spatial unit of the study was the cadastral plot. This choice was dictated by the structure of the LQD management database and by the use of a geographic information system (GIS) containing cadastral information for mapping purposes.

Irrigation systems and cropping patterns

A 1997 field survey was used to prepare maps of district irrigation systems and crop spatial distribution (Dechmi et al., 1998). Farmers have not changed their irrigation systems since district operations began, so the same irrigation systems map was used for all three years of the study. Crop maps for the 1989 and 1995 irrigation seasons were obtained from Casterad (1990). In 1998, a field survey was conducted to collect LQD irrigation systems characteristics in each plot (Tejero, 1999). This information includes sprinkler spacing, sprinkler line azimuth, pivot or ranger length, nozzle(s) diameter(s), operating pressure and nozzle height.

District water records

Since farmers irrigate on demand, the district personnel does not take an active role in organizing water use. The district technicians write down all the water meter readings monthly, and the district secretary uses a computer database to store the readings, determine the volumes of water used and prepare a monthly water bill for each farmer. Some hydrants supply water to a single farmer, while others are shared by a number of farmers. In the latter case, the secretary splits the cost of water according to the name, date and water volume recorded by the farmers themselves. A custom-made software is used to perform the database operations. This tool stores additional information, such as the size of the plots, the name and code of the owner, and the name of the irrigator

A general and a detailed study of water use in the district were conducted. In both cases we used information on water billing, and assumed that these volumes corresponded to actual water use. The technology applied in the LQD for water conveyance and measurement (pipes and water meters) makes this assumption much more reasonable than for districts using open ditches for water delivery, such as the AID (Faci et al., 2000). The general analysis examined the seasonal volume of water billed during the three years of study for entire district area. The detailed analysis focused on 17 plots (accounting for 44 ha), irrigated with solid-sets from 10 shared hydrants during the 1997 the irrigation season. These plots were selected because the individual irrigation dates and volumes were available at the district database. Alfalfa (10 plots), corn (4 plots) and wheat (3 plots) were grown on these plots.

Soils

Soil properties analysed in this study were soil depth (*p*, m) and total available water (*TAW*, mm). *TAW* was defined according to Walker and Skogerboe (1987), and computed after the following expression:

$$TAW = 10^3 p(\theta_{FC} - \theta_{WP}) \frac{\rho_b}{\rho_w}(1 - S) \qquad [1]$$

Where:

θ_{FC} = Gravimetric water content ratio at 0.03 Mpa (field capacity),

θ_{WP} = Gravimetric water content ratio at 1.50 MPa (wilting point),

ρ_b = Soil bulk density (Mg m^{-3}),

ρ_w = Water density (Mg m^{-3}), and

S = Volumetric ratio of stoniness.

For the general study, the 19 soil units defined by Artieda (1998) in the Quinto soil map were grouped into five classes according to their p and TAW (Table 1). For the 17 plots analysed in detail, p and S were determined *in situ*. Pressure plates were used to determine θ_{FC} and θ_{WP}, with two replicates per sample. In total, 39 samples were collected, using two or three samples per plot (characterising different soil horizons). ρ_b was set to 1.5 Mg m^{-3}, based on studies in the area (Artieda, 1998).

Farmers interview

Farmers' water management and farming practices were analysed through an interview prepared and conducted in 1998. Twenty-one farmers were randomly selected for the interviews. The questionnaire consisted of 67 multiple choice questions about the farmer's irrigation systems and management practices. Other questions were devoted to establish if the farmers cultivated plots on lease and to compare irrigated agriculture in the LDQ and TQD (Tejero, 1999).

Net irrigation requirements

Irrigation requirements were estimated using the standard FAO procedures, as described by Doorenbos and Pruitt (1977) and Allen et al. (1998), and implemented in the CROPWAT software (Smith, 1993; Clarke et al., 1998). Following these procedures, Penman-Monteith reference evapotranspiration (ET_0), crop coefficients (Kc), crop evapotranspiration (ETc), effective precipitation (PE) and net irrigation requirements (NIR, mm) were estimated.

These estimations relied on mean monthly meteorological data recorded at the Quinto climatic station, located at a North latitude of 41º 25´ 25´´, a West longitude of 0º 30´ 30´´ and an altitude of 190 m. The data used included: maximum and minimum air temperature, maximum and minimum relative air humidity, precipitation, sunshine duration and wind speed. Missing minimum air humidity and sunshine duration data were replaced with data from the Zaragoza climatic station.

Duration of the crop development phases and primary crop coefficients (*Kc*) were obtained from Martinez-Cob et al. (1998). Monthly effective precipitation (*PE*) for 1989 and 1995 was determined using the USDA method (Cuenca, 1989). In view of the abnormally large rainfall recorded in 1997, *PE* for this season was calculated using the empirical method of effective precipitation (Smith, 1993). Net irrigation requirements were determined for the dominant crops (alfalfa, corn, sunflower and wheat).

Water use, irrigation efficiency and seasonal irrigation performance index

The performance measure used to characterise water use in the LQD was the Seasonal Irrigation Performance Index (*SIPI*), as defined by Faci et al. (2000) and applied to the AID. The *SIPI* is defined as the percentage of net irrigation requirements (*NIR*) to seasonal water use, estimated from billing records (*WU*, mm). *SIPI* represents a simplification of the irrigation efficiency standard concept defined by Burt et al. (1997), and Clemmens and Burt (1997). However, if a crop is water stressed, the value of the *SIPI* can be higher than 100 %. In fact, if the *SIPI* is higher than the potential application efficiency of the irrigation system, the crop will be water stressed.

Clemmens and Dedrick (1994) presented values of potential application efficiency for well designed and managed irrigation systems. Solid-sets range from 70-85 %, while pivots and rangers range from 75-90 %. We estimated an average value of potential application efficiency of 80 % for all irrigation systems in the district. This value was considered as a threshold separating full irrigation (*SIPI* < 80 %) from deficit irrigation (*SIPI* > 80 %). The *SIPI* was computed for each representative crop and year of the study.

Identifying factors affecting water use

Contingency tables were used to test possible interactions between the crops and three other categorical variables: type of irrigation system, type of farmer (owner or leaser) and soil *TAW* class. The goal of this analysis was to determine if these factors affected the choice of crop for each plot and study year.

Two types of correlation analyses were conducted for the detailed study. Their purpose was to gain insight on farmers' irrigation decision making, with particular reference to the main climatic limiting factor: wind speed. The first type of analysis involved data from individual irrigation events. The selected variables were: irrigation depth (mm), irrigation interval (days), wind speed (m s^{-1}) and date of each irrigation event (*DOY*, day of the year); The second type of analysis involved seasonal variables: the seasonal depth of water applied to each plot (mm), the average wind speed during the irrigation days (m s^{-1}), the average irrigation depth (mm), the average irrigation interval (days) and the *SIPI* (%).

Multiple regression with dummy variables was applied to study the interaction between quantitative and categorical variables in the general study, following the procedures used by Clemmens and Dedrick (1992) to analyse water use in the MSIDD. The dependant variables considered in this work were the seasonal water use and the *SIPI*. The plot area and the total area managed by the farmer in the LDQ were introduced as independent quantitative variables. These variables were included to assess the relationship between water use and land tenure, under the hypothesis that large plots or more professional farmers would promote water conservation. The independent categorical variables were the type of crop, the irrigation system, the soil class and the type of farmer (owner *vs.* leaser). The statistical model was developed by first including all the factors and then removing insignificant factors individually and iteratively.

RESULTS AND DISCUSSION

Characterization of irrigation systems, soils and crops

The spatial distribution of irrigation systems is depicted in Figure 2. Solid-sets are used mainly in the North and Northeast areas, while centre-pivots and linear-moves are common in the Southwest, where plots are larger. This distribution can also be related to soil surface elevation, which is higher in the South. Higher pressures are available to operate the solid-set systems in the northern part of the LQD. The average area of solid-set plots is 4.0 ha. The most common sprinkler spacing is triangular, with sprinklers at every 21 m in the line and the lines separated 18 m. This spacing is used in 79 % of the total solid-set area. Most of the plots (54 %) are equipped with 5.1 and 2.4 mm diameter nozzles. The average operating pressure in the solid-set systems was 270 kPa. For similar hardware and operating conditions, Tarjuelo (1995) recommended an operating pressure in the range of 300-400 kPa, sensibly higher than the average observed value.

Solid-set uniformity can be severely reduced in the presence of strong winds. A common wind defence is to set the sprinkler lines perpendicular to the dominant winds (Keller and Bliesner 1990). In the case of triangular sprinkler spacings, this recommendation becomes more complicated, due to the fact that three possible sprinkler lines (forming angles of 60º) could be drawn around any given sprinkler (Fig. 3). In this particular case, the best protection against wind is an orientation with one of the lines (the horizontal line in Fig. 3) perpendicular to the wind direction. Therefore, the minimum angle between the dominant wind and a sprinkler line is 30º. In this case, the distance between sprinklers in a direction perpendicular to the wind is minimum, with a value of 10.5 m. As a result, the applied irrigation water attains a reasonable coverage of the soil. In the worst case one of the sprinkler lines is parallel to the wind direction. In this case the sprinkler spacing in the wind direction attains a maximum value of 18 m. This results in strips of non-irrigated land during windy irrigations.

In order to assess the wind protection characteristics of the LQD solid-sets, plots were classified according to the sprinkler line azimuth. Considering the axes of symmetry in Fig. 3, Azimuths were reduced to an interval of 5º to 65º, divided in six 10º-intervals. Accordingly, the average wind Azimuth of 293º was reduced to an orientation of 53º (subtracting 240º). Figure 4 confronts a histogram of the sprinkler line orientation groups with the dominant wind direction. The best sprinkler line orientation would be between 15º and 25º (approximately 30º angle with the dominant wind direction). Plots with optimally oriented lines represent 19.5 % of the total solid-set area (Figure 4). In the LQD, 58.9 % of the sprinkler lines present adequate orientations (considered between 5 and 35º), suggesting that the design principle was only slightly considered. Additional wind protection could have been obtained at the design phase through a more careful sprinkler line orientation.

The average area of the plots irrigated with centre-pivots is 13.6 ha. Centre-pivot systems are usually equipped with low pressure fixed spray plate sprinklers of different diameters located on top of the lateral, at 4.5 m over the soil surface. Recent developments in irrigation technology, such as rotating spray plate sprinklers (Faci et al., 2001) have not been introduced in the area. In 12 % of centre-pivots, farmers have lowered the nozzles in order to conserve irrigation water. In some cases, nozzles have only been lowered at the outer part of the centre-pivot. The average area of the plots irrigated with linear-move systems is 7.2 ha. These machines are also equipped with low pressure fixed plate spray sprinklers. In half of the linear-move machines the spray sprinklers are located at an elevation of 4.7 m over the soil surface. In the rest, the spray sprinklers have been lowered to an average height of 2.6 m.

A common trait of the LQD systems is the lack of irrigation automation. The interview revealed that 86 % of the farmers did not use any automation equipment, while the remaining 14 % used automation in some farms. The lack of automation devices poses a severe limitation to irrigation scheduling and to adapting the irrigation depth to the soil *TAW*.

Soils in the LQD show a large variation in water holding capability (Table 1). Most soils (70 % of the area) have values of *TAW* ranging from 60 to 140 mm. Because of its low *TAW*, the S1 class shows relevant limitations for irrigation, and requires frequent, light irrigations. Soil classes S4 and S5 have a high *TAW* (160 to 300 mm) but are fine textured, saline and exhibit low infiltration and poor aeration. Therefore, they have low agronomic value.

Main crops in the LQD were wheat and corn in 1989, and alfalfa in 1995 and 1997 (Table 2). The category "mixed crops" was relevant in the three years of study. It includes the plots in which farmers divide the total area to grow more than one crop at a time. This is a common practice in large plots.

Evaluation of irrigation performance

Seasonal water diversions in the LQD varied strongly during the study years. According to the pumping station records, the highest diversion occurred in 1995 (21.7 10^6 m^3), while in 1989 and 1997 diversions were much lower (10.9 10^6 m^3 and 13.2 10^6 m^3, respectively). The average *WU* was 477, 995 and 585 mm, for the 1989, 1995 and 1997 years, respectively. Table 3 presents the distribution of the district plots in classes of *WU* for the three years of study. The variability in water application may reflect differences in crops, soils, irrigation systems and irrigation management. The effect of the crop on *WU* is illustrated in Table 4. The associated coefficients of variation ranged from 27 to 63 %, indicating that additional factors determine *WU*.

Computed *SIPI* values for the studied crops suggest that farmers in the area regularly stress their crops (Table 4). Only in one case (wheat in 1995) the average *SIPI* was lower than the estimated potential application efficiency (80 %). Sunflower was severely water stressed during all the study years, with an inter-annual average *SIPI* of 142 %. Alfalfa and wheat had average values of *SIPI* of 128 % and 113 %. The inter-annual average of the *SIPI* value for corn was 111 %, the lowest among all crops. These data suggest that farmers try to optimise irrigation water use restricting application on drought resistant crops (sunflower, wheat, alfalfa), and limiting water stress on drought sensitive crops (corn). The subsidies of the European Union play a relevant role in the *SIPI*. Subsidies are applied by the hectare, and amount to a variable percentage of each crop gross income. In the case of sunflower subsidies were comparatively high in the years of study, and therefore farmers did not consider yield as the main source of income. Consequently, sunflower was systematically underirrigated. Faci et al. (2000) reported a similar finding for the AID, based on data from 1994.

The district average *SIPI* (computed in all plots) was 155 %, 95 % and 131 % for the years 89, 95 and 97, respectively. These values indicate that the *SIPI* followed inter-annual trends that could not be explained by the aridity of the analysed years. Crop water stress was considerable during the years 1989 and 1997. In 1995, which was considered as an average year with an average evaporative demand, the seasonal amount of irrigation water applied to alfalfa, corn and wheat was higher than their net irrigation requirements.

A correlation analysis between the *SIPI* values obtained in the same plots in the three study years was performed. The purpose of this analysis was to assess how on-farm irrigation performance changed in the study years. Results showed a weak correlation between the *SIPI* values of years 89 and 95 (0.168*), with no significant correlation between years 89 and 97. However, there was a strongly significant correlation between the *SIPI* values of years 95 and 97 (0.484***). This finding suggests that on-farm irrigation performance has evolved during the life of the LQD. The criteria for water allocation in each plot were particularly consistent between 1995 and 1997, after almost ten years of irrigation operation.

Results from the detailed analysis showed that the average irrigation depth per irrigation event ranged from 18 to 73 mm, with an average of 44 mm and a CV of 30 %. This irrigation depth is compatible with the interview results: 60 % of the farmers use solid-set irrigation durations of 8 hours or more. The average irrigation interval varied from 8.6 to 28.0 days, with an average of 12.3 days and a CV of 40 %. These irrigation depths and intervals are too high for sprinkler irrigation in general and for the LQD soils in particular. The irrigation systems used in the district permit to apply frequent, light irrigations, at the only additional expense of labour or automation equipment.

The previous results state that farmers underirrigate their crops in the LQD. The interview included a few questions on this topic, formulated as a comparison between water use in the LQD and the TQD. 43 % of the farmers used “more water” in the TQD than in the LQD, while the remaining 57 % used “much more water”. 89 % of the farmers reported that crop yield was higher in the TQD than in the LQD. All of the interviewed farmers obtained higher profits in the TQD. Low seasonal irrigation depths, large irrigation intervals and poor soils seem sufficient to explain the low yields. The added factor of high water cost explains the reduced economic benefit in the LQD as compared to the TQD.

Identifying factors affecting water use

The first step was the analysis of contingency tables between categorical variables of the general analysis. Only in the first year of study (1989) a statistical relationship was found between crops and irrigation systems. Farmers did not grow alfalfa and sunflower in the plots equipped with irrigation machines (linear-move and pivot), using them for corn and wheat. This trend was discontinued in the following years. Both types of farmers (owners and leasers) grow the same crops in the LQD, and distribute them throughout the district area regardless of the soil types.

The second phase of the statistical study involved the analysis of correlation matrices established between the quantitative variables of the detailed study. First, the correlation analysis was performed on individual irrigation events (Table 5). One of the most relevant characteristics of this table is that the correlation coefficients are low (below 0.3 in absolute value). This will be a constant in the rest of this study. The explanation for this fact lies in the nature of the data, which were obtained from the farmers' database. In our opinion, farmers have not been particularly careful in checking the accuracy of some variables. We believe that the water measurements are reliable, since water billing depends on these measurements and farmers use about one-fourth of their gross income to pay the water bill. Problems seem to accumulate in the estimation of the irrigated area. In some cases, not all the plot area was actually irrigated. In other cases, the water assigned to a plot seems to have been used to irrigate neighbouring plots owned by the same farmer. Our perception is that even if the farmers' database adequately allocates costs among farmers, it shows limitations when it comes to ensuring water traceability with respect to plots and crops.

A weak, negative correlation coefficient (r = -0.1411*) was found between irrigation depth and wind speed (Table 5). In windy days farmers applied light irrigations, and seemed to wait for calm days to apply the gross of water requirements. The interview confirmed that this practice was followed by 70 % of the farmers. As an additional confirmation, the average wind speed in irrigation days (for all plots in the detailed study) was 0.92 m s^{-1}, whereas the average seasonal wind speed was 1.25 m s^{-1}. According to the farmers' interview, 95 %, 85 %, and 50 % of the farmers avoided irrigating in windy days with their solid-sets, pivots and rangers, respectively.

The irrigation depth (per irrigation event) was not related to the irrigation date (Table 5), suggesting that farmers used fixed irrigation depths throughout the season, and met the irrigation requirements adjusting the irrigation interval. In fact, the irrigation interval showed a decrease in time during the irrigation season, reflecting the increased water demand during spring and mid summer. According to the interview, this procedure was followed by 76 % of the farmers. A significant, negative correlation between wind speed and irrigation date was found. Since the wind speed did not show a significant time dependence during the irrigation season (data not presented), it can be concluded that farmers became increasingly selective with the wind speed on irrigation days as the season progressed.

A second set of correlation analyses was performed using seasonal data from each plot of the detailed study. The correlation between seasonal water use and average irrigation interval (r = -0.5563*) serves to confirm part of the previous results: those farmers applying large seasonal irrigation depths used small irrigation intervals. The lack of correlation between seasonal water use and average irrigation depth confirms that the management variable was the number of irrigation events (and therefore the irrigation interval).

The last step of the statistical analysis consisted on formulating multiple regression models using dummy variables to incorporate categorical variables. Such models were first applied to explain the variability on *WU* (Table 6). The plot area resulted significant in 1989 and 1997, with coefficients of -4.2 and -5.4 mm ha^{-1}, suggesting that large plots have a potential to conserve water. The total area managed by the farmer and the type of farmer (owner *vs.* leaser) did not result significant in any of the three study years. Since management does not seem to be the key of a lower water use, the benefits of large plots seem to be due to a better irrigation technology. Clemmens and Dedrick (1992), when analysing the MSIDD, found that the area managed by the farmer was statistically relevant on water use, and determined a coefficient of about 1 mm ha^{-1}, between four and five times smaller than the one reported in this research for plot size. In the MSIDD the type of farmer was also significantly related to water use. Faci et al. (2000), analysing the AID, identified a large dependence of water use on plot size, although they reported a number of administrative procedures increasing the volume of water billed to small farms.

The other factors affecting *WU* were the type of crop and the type of irrigation system. As expected, corn, sunflower and wheat used less water than alfalfa, although in some cases the contrast between alfalfa and corn and even sunflower was not significant. In 1995 and 1997 wheat and particularly sunflower showed a reduced water use. As for the irrigation systems, differences were not significant in 1989. In 1995 and 1997 the variable was significant, solid-sets were the systems using most water, and only one contrast was significant in each year (linear-move in 1995 and hand move in 1997). In a context of increasing labour scarcity, hand move systems showed small water use, and were associated to marginal plots.

When multiple regression was used to explain the variability on the *SIPI*, the number of significant factors increased towards the end of the study period (Table 7). In 1989, the *SIPI* could not be explained by any of the considered factors. In the 1995 irrigation season, crop type was the only significant variable, and sunflower was the only crop showing significant differences with alfalfa. Factors affecting the *SIPI* during the 1997 irrigation season were the type of crop, the irrigation system and the soil type. The statistical analysis showed that the corn *SIPI* values were 49 % smaller than the alfalfa *SIPI* values. The effect of the type of irrigation system only served to separate the hand move system from the rest of the systems. The relationship found between the soil type and the *SIPI* values indicated significant differences between low and average *TAW* values.

The determination coefficients obtained in all the regression analyses performed for water use and *SIPI* were low (ranging between 7.7 % and 41.7 %). The quality of the data sources and the variability induced by irrigation farming operations are probable causes of this dispersion.

CONCLUSIONS

The analysis of irrigation water use during three irrigation seasons (dry, average and humid) was used to characterise the performance of relatively modern irrigation systems in the LQD. The following conclusions can be drawn from this analysis:

- Most of the solid-set sprinkler systems in the LQD use wide sprinkler spacings (21 x 18 m). The current operating pressure is too low to ensure adequate water distribution. Additional wind protection could have been obtained through a narrower spacing and/or a more careful sprinkler line orientation.
- Centre-pivot and linear-move irrigation machines use fixed spray plate sprinklers. Recent developments in sprinklers for irrigation machines have not been introduced in the LQD. In about one-third of the machines, sprinklers have been lowered (from about 4.7 m to 2.6 m) to improve water conservation.
- Field crops are grown in the LQD (Alfalfa, corn, sunflower and wheat). The average *WU* was 477 mm in 1989, 995 mm in 1995 and 585 mm in 1997. This variability in water application could not be adequately explained by the aridity of the study years or the changes in the cropping pattern.
- The average interannual *SIPI* was 127 %. Farmers regularly stressed their crops, particularly those characterised by their drought resistance and those receiving large subsidies applied by the hectare.

- The average irrigation depth per irrigation event was 44 mm, and the seasonal average irrigation interval was 12.3 days. These values are too high, particularly for the soils characterised by a low *TAW*.
- Farmers seem to respond to strong winds by applying light irrigations, and reserve large irrigation events for calm days. In general, farmers modify the irrigation interval rather than the depth in order to accommodate the irrigation schedule to the *NIR*.
- Large plots used less water than small plots, at a rate of about -5 mm ha^{-1}. Similar findings (but different rates) were reported in previous works on surface-irrigated districts (Clemmens and Dedrick, 1992; Faci et al., 2000).
- Multiple regression models on *SIPI* became more complex along the three study years. In 1997 the significant dependent variables included the crop, type of irrigation system and soil type.

The high cost of irrigation water in relation to crop revenues, the technical deficiencies of the irrigation systems, and the limitations imposed by the climate and soils appear to be major causes of the water management problems identified in the LQD. The validity of our results may be limited by the origin of the water use data (the district's database). While these data are used for water billing in an area in which the cost of irrigation water represents a large percentage of the crop gross income, the database may include water allocation errors. In a companion paper, irrigation evaluations and simulations performed on different irrigation systems at the LQD will be presented. Irrigation schedules for optimal crop yield will also be proposed and evaluated *via* simulation.

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Table 1. Total available water (*TAW*), soil depth (*p*) and percent district area of the five soil classes.

Soil class	S1	S2	S3	S4	S5
TAW (mm)	25	60 - 100	125 - 140	160 - 200	300
p (m)	0.30	0.60	0.80	1.00	1.20
Area (%)	19	37	33	5	6

Table 2. Crop distribution in the LQD during the study years.

Crop	Area (%)		
	1989	1995	1997
Alfalfa and pasture	4.0	43.3	43.4
Corn	33.7	7.1	13.7
Sunflower	0.6	3.9	5.4
Wheat	35.7	8.4	10.6
Orchards	2.8	1.7	1.9
Vegetables	0.5	0.6	-
Industrial crops	-	2.8	-
Fallow	2.2	3.4	2.7
Mixed Crops	16.4	22.4	22.2
No data	4.1	6.5	0.1

Table 3. Percent distribution of the district plots in classes of seasonal water use (*WU*, mm) for the three years of study.

WU (mm)	Percentage of Plots		
	1989	1995	1997
< 500	31,1	21,5	42,9
500 – 700	15,9	8,8	27,4
700 – 900	8,8	16,9	21,3
900 – 1,100	10,4	21,1	4,0
1,100 – 1,300	13,2	13,7	2,3
> 1,300	20,7	18,1	2,1

Table 4. Net irrigation requirements (*NIR*, mm), water use (*WU*, mm) and Seasonal Irrigation Performance Index (*SIPI*, %) of the main crops in the 1989, 1995 and 1997 irrigation seasons. Coefficients of variation for *WU* and *SIPI* are included in parenthesis.

	Alfalfa			Corn			Sunflower			Wheat		
	89	95	97	89	95	97	89	95	97	89	95	97
NIR (mm)	969	979	718	761	688	471	635	570	380	396	433	341
WU (mm)	773 (37)	1,163 (30)	693 (41)	600 (33)	813 (29)	602 (28)	592 (27)	719 (50)	270 (63)	338 (51)	762 (35)	434 (57)
SIPI (%)	150 (51)	92 (41)	141 (84)	152 (64)	91 (25)	89 (60)	118 (33)	126 (84)	181 (39)	150 (53)	71 (63)	117 (73)

Table 5. Correlation matrix between the variables of each irrigation event in the detailed analysis.

	Irrigation Depth (mm)	Irrigation Interval (days)	Wind Speed (km h^{-1})	Date (-)
Irrigation Depth (mm)		0.1360 *	-0.1411 *	0.0818 ns
Irrigation Interval (days)			0.0487 ns	-0.2753 ***
Wind Speed (Km h^{-1})				-0.2099 ***
Date (-)				

Table 6. Results of the multiple regression with dummy variables used to characterise the factors affecting water use (*WU*, mm) in the years of study.

Variable	Level	Coefficient (mm)		
		1989	1995	1997
Constant	-	889.4***	1267.9***	739.7***
Plot area (ha)	-	-4.2*	-	-5.4*
Crop	Alfalfa	0.0	0.0	0.0
	Corn	-245.6***	-207.9*	-86.1^{ns}
	Sunflower	-159.2^{ns}	-515.4***	-382.9***
	Wheat	-509.7***	-473.4***	-313.6***
Irrigation system	Solid-set	-	0.0	0.0
	Centre-Pivot	-	-26.8^{ns}	-7.7^{ns}
	Linear-move	-	-190.7*	-14.1^{ns}
	Hand-move	-	[†]	-612.7*

[†] In 1995 the plots equipped with hand move systems were excluded from the statistical analysis since their number was very low.

Table 7. Results of the multiple regression with dummy variables used to characterise the factors affecting the Seasonal Irrigation Performance Index (*SIPI*, mm) in the study years.

Variable	Level	Coefficient (%)		
		1989	1995	1997
Constant	-	-	93.3***	180.2***
Plot area (ha)	-	-	-	-
Crop	Alfalfa	-	0.0	0.0
	Corn	-	-14.0^{ns}	-49.4*
	Sunflower	-	71.1***	35.9^{ns}
	Wheat	-	10.9^{ns}	-6.4^{ns}
Irrigation system	Solid-set	-	-	0.0
	Centre-Pivot	-	-	3.6^{ns}
	Linear-move	-	-	8.2^{ns}
	Hand-move	-	-	504.0***
Soil type	S1	-	-	0.0
	S2	-	-	-53.7*
	S3	-	-	-55.8*
	S4	-	-	-41.6^{ns}
	S5	-	-	-22.2^{ns}

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Figure 1. Location of the LQD.

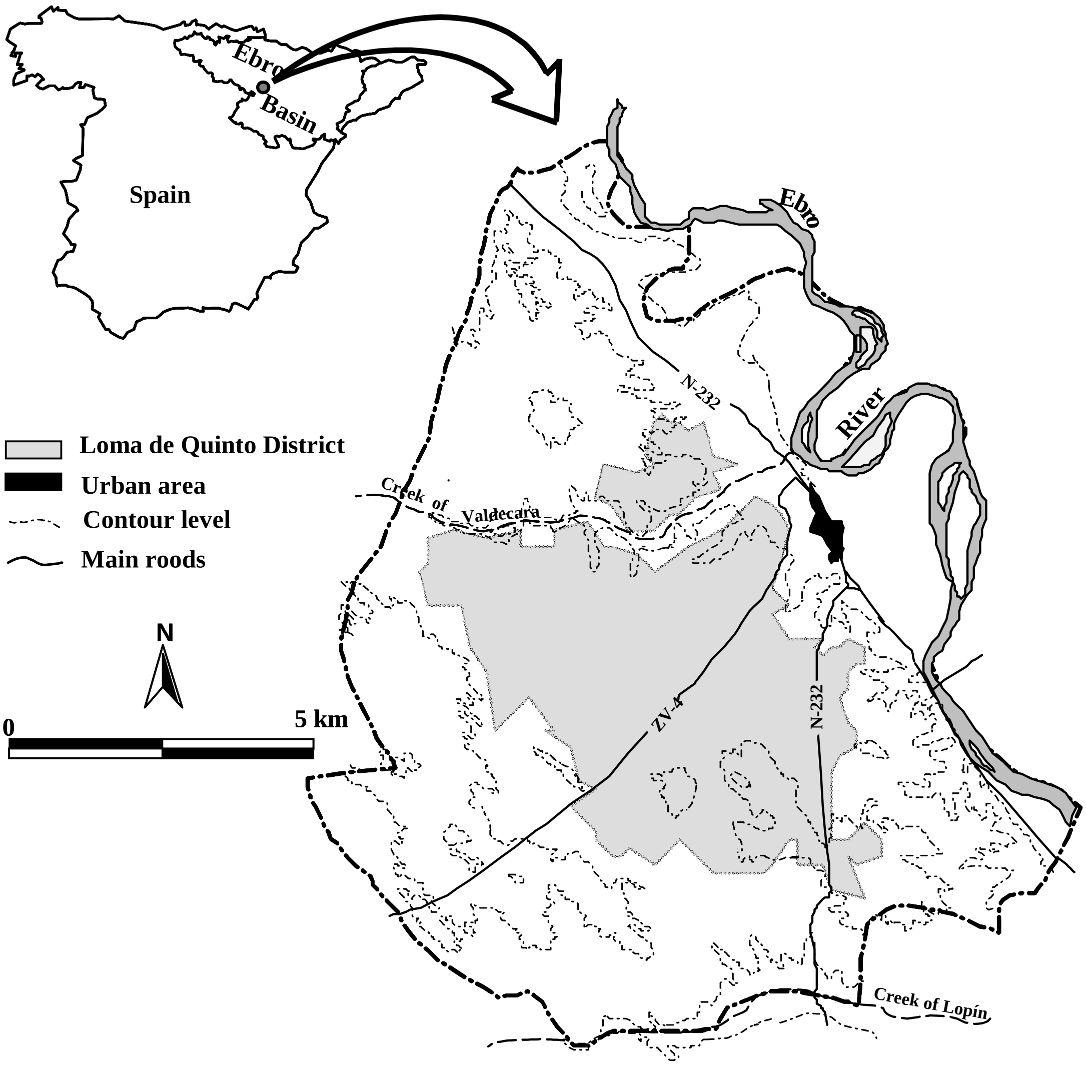

Figure 2. Map of irrigation systems in the LQD.

Figure 3. Representation of best and worst orientation cases between the wind and the sprinkler line for a triangular 21 by 18 m spacing. Dots represent sprinklers and ellipsoids represent the area wetted by each individual sprinkler.

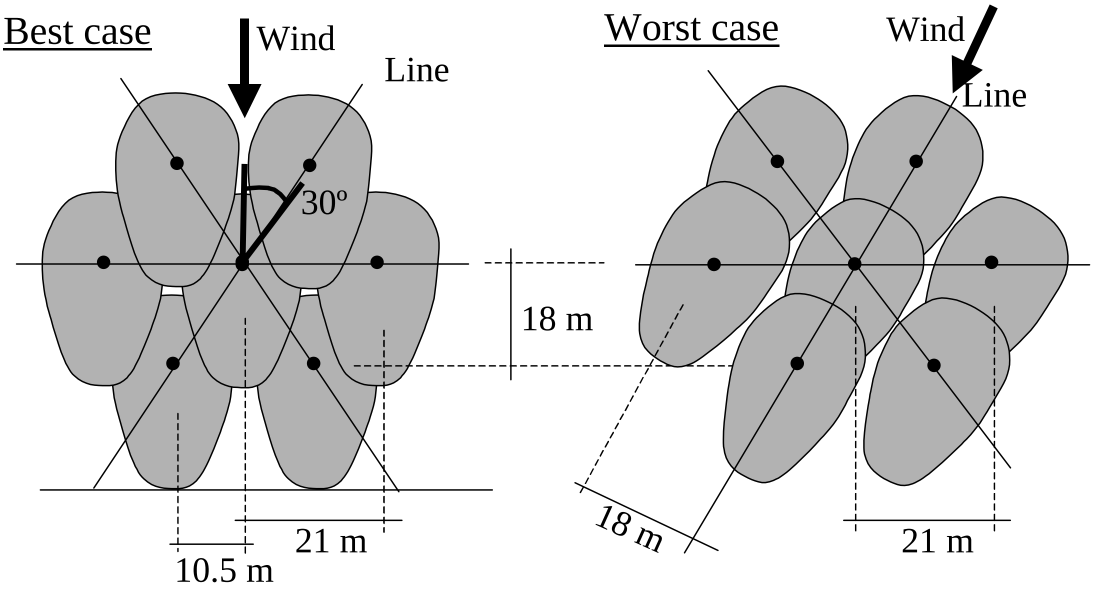

Figure 4. Histogram of sprinkler line orientation in LQD, with indication of the dominant wind direction.