Analysis of an irrigation district in northeastern Spain:

II. Irrigation evaluation, simulation and scheduling

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ABSTRACT

In the first paper of this series, the Loma de Quinto Irrigation District (LQD) was characterized, and water use was assessed. In this work, the analysis of the LQD is completed with field irrigation evaluations, solid-set sprinkler irrigation simulations and irrigation scheduling for optimal crop yield. The results of the irrigation evaluations indicated that the average Christiansen Coefficient of Uniformity (*CU*) for solid-sets, centre-pivots and linear-moves was 68.0 %, 75.5 %, and 80.0%, respectively. In solid-sets *CU* was severely reduced by wind speed. However, in centre-pivots and linear-moves *CU* was higher in evaluations with wind speeds between 2 and 6 m s⁻¹ than under calm conditions. The evaluation data set was used to validate a ballistic solid-set sprinkler irrigation simulation model. The performance variables used for model validation were *CU* and the Potential Application

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Efficiency of the Low Quarter. Both variables were adequately predicted in the range of the observed values. The model was used to extend the evaluation results to all the solid-set plots in the LQD. *CU* maps were produced for different wind speeds and operating pressures. These maps can be used to identify plots with low irrigation performance. The effect of irrigation scheduling on crop yield and net benefit was analysed using the CropWat simulation model. Simulations of the 1997 irrigation practices performed on a limited number of plots detected a 12 % decrease in crop yield due to deficit irrigation and/or large irrigation intervals. The introduction of an optimal irrigation schedule (avoiding yield reductions) would imply increasing the alfalfa seasonal irrigation depth by 101 mm, and applying light, frequent irrigation events. Due to labour scarcity in the LQD, the implementation of the optimal schedule would require a high degree of irrigation automation, which is currently unavailable. Taking into consideration the value of the additional yield and the costs of the extra irrigation water depth and the automation devices, the resulting net benefit would be 50 € ha⁻¹. The purpose of this analysis of the LQD is to contribute to the Diagnostic Analysis phase of an incipient Management Improvement Program at the LQD. In order to complete this phase, an interdisciplinary committee will perform a study not just on irrigation but on a wide scope of irrigated agriculture in the LQD.

Keywords: Sprinkler irrigation, irrigation uniformity, simulation model

INTRODUCTION

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 of an incipient Management Improvement Program (Clyma and Lowdermilk, 1988; Dedrick et al., 2000). In a companion paper, the irrigation management problems at the LQD and the factors affecting local water management were analysed. This district is located in the Ebro valley (NE Spain), and irrigates 2,606 ha, with a wide variety of sprinkler irrigation systems. The conclusions of the first paper of the series indicated that the solid-sets were operated at a low pressure (270 kPa on the average), considering the wide sprinkler spacing used in most of the solid-set area (21 x 18 m) and the predominant nozzle diameters (5.1 and 2.4 mm). The centre-pivot and linear-move irrigation machines were equipped with fixed spray plate sprinklers, showing a certain degree of obsolescence. The study showed that crops were often water stressed throughout the irrigation season, with water applications below the net irrigation requirements. Irrigation management was limited by the presence of strong winds and by the lack of automation devices. In this second paper of the series, the analysis of irrigation water use will focus on two additional issues: irrigation uniformity and the relationship between water use and crop yield.

A high uniformity is required to attain a satisfactory level of irrigation efficiency. Several uniformity measures have been proposed, with the Christiansen Coefficient of Uniformity (*CU*) being the most used for sprinkler irrigation (Merriam and Keller, 1978). A sprinkler water distribution pattern depends on system design parameters (such as sprinkler spacing, operating pressure, and nozzle diameter) and on environmental variables (wind speed

and direction) (Keller and Bliesner, 1990). Wind speed affects not only uniformity, but also evaporation and wind drift losses. The Ebro valley is characterised by an intense wind from the NW-W direction, called "Cierzo". Due to the relevance of sprinkler irrigation in the valley, several empirical equations have been proposed for the estimation of wind drift and evaporation losses (Faci and Bercero, 1991; Ramón, 1998; Faci et al., 2001). The independent variables most commonly used in these equations are wind speed, air temperature and/or air humidity.

One of the standard practices to characterise water use in an irrigated area is to conduct irrigation evaluations. In sprinkler irrigation, the most valuable outcome of the evaluation process is irrigation uniformity. In the latest years, field evaluations have often been used to calibrate irrigation simulation models. The use of such models permits to estimate irrigation performance under untested operating and meteorological conditions and to extend the characterization of irrigation uniformity to untested plots. Irrigation simulation models can be used to improve irrigation performance, and therefore to save water and to increase farm profitability (Clemmens et al., 1999; Playán et al., 2000). Several authors have simulated solid-set sprinkler irrigation water application using ballistic models (Fukui et al., 1980, Seginer et al., 1991, Tarjuelo et al., 1994, Carrión et al., 2001).

In the last decade, a number of computer models have been developed to simulate crop growth and soil water balance. Among them, the CropWat software (Smith, 1993; Clarke et al., 1998) was specifically designed to estimate net irrigation requirements, to develop irrigation schedules, and to assess the reduction in crop yield due to water stress in the different crop development stages. Crop models have proven useful to identify the factors

controlling plant growth and water use (Cavero et al., 2000). Therefore, they can be used to link irrigation management practices to estimates of farm profitability.

The objectives of this second paper of the series include: (1) Evaluate the uniformity of the main irrigation systems in the LQD: solid-sets, centre-pivots and linear-moves; (2) Calibrate a ballistic sprinkler irrigation model and apply it to the estimation of *CU* in the solid-sets of the LQD under different wind conditions and operating pressures; and (3) Simulate the effects of current and optimal irrigation management practices on crop yield and net benefit.

MATERIALS AND METHODS

Irrigation system evaluations

A total of 32 field evaluations of sprinkler irrigation systems were conducted in the LQD during 1987, 1988 and 1999, following the methodology described by Merriam and Keller (1978) and Merriam et al. (1980). 13 evaluations were performed in solid-set systems. In all cases, sprinklers formed a triangular layout. In 11 evaluations the sprinkler spacing was coded as T21x18. The “T” indicates triangular spacing, as opposed to rectangular (“R”), the first number indicates the spacing between sprinklers in a line (m) and the second number indicates the spacing between lines (m). As discussed in the companion paper, this sprinkler spacing is used in 79 % of the solid-set area in LQD. In the remaining two evaluations the spacing was T18x18, which is used in 12 % of the total solid-set area. In each evaluation, operating pressure, sprinkler discharge and water distribution were measured. A 3 m x 3 m

square catch can network was set up within a sprinkler area to characterise water distribution. In two cases the test duration was selected by the farmers (6.0 hours, following their customary practices). In the rest of the cases, the experiment was shorter than a regular irrigation event (from 1.7 to 3.0 hours).

In centre-pivots and linear-moves 10 and 9 field evaluations were conducted, respectively. All the evaluated irrigation machines were manufactured by ValmontTM and were equipped with fixed spray plate sprinklers located 4.5 m over the soil surface, except for two linear-move machines with spray sprinklers at 1.0 and 2.0 m over the soil surface. In most of the evaluations it was not possible to measure the working pressure because manometers were not installed or were out of order. Catch cans were located along a line extending radially from the pivot point, and along a line parallel to the linear-move machine. In both cases a 3 m spacing was chosen.

Wind speed was measured three times during each evaluation. Catch can data were used to calculate *CU* (Christiansen, 1942):

$$CU = \left(1 - \frac{\sum_{i=1}^n |d_i - \bar{d}|}{n \bar{d}} \right) 100 \quad [1]$$

where:

$\bar{d}$ = Average precipitation collected in the catch cans (mm).

d_i = Precipitation collected at catch can number i (mm).

n = Total number of catch cans.

In centre-pivots catch can data was weighed according to the area represented by each catch can (Faci and Bercero, 1990).

In all evaluations the irrigation materials present in the field (often dating from 1987) were used. The effect of nozzle wear on irrigation uniformity was therefore included in the evaluation results, and could not be independently evaluated. Throughout the years, nozzle wear increases discharge and modifies water distribution (Ozkan et al., 1992).

Development, validation and application of a ballistic solid-set sprinkler irrigation simulation model

The reported solid-set irrigation evaluations results were used to validate a sprinkler irrigation model. The model uses ballistic theory to simulate the flight of water drops from the sprinkler nozzle to the soil surface. Model development followed the procedures reported by Fukui et al. (1980), Tarjuelo et al. (1994), Carrión et al. (2001) and Montero et al. (2001). Figure 1 presents a functional diagram of the proposed simulation model. A solid-set sprinkler simulation proceeds as follows:

1. Obtain the drop size distribution curve corresponding to a combination of nozzle diameter (principal and auxiliary nozzles) and operating pressure. The empirical relations developed by Kincaid et al. (1996) were used.
2. Introduce in the model the empirical parameters $k1$ and $k2$ to adjust the coefficient of aerodynamic resistance as proposed by Tarjuelo et al., 1994, following Seginer et al. (1991). This adjustment has been shown to improve sprinkler irrigation simulation

performance. The values of $k1$ and $k2$ proposed by Montero (1999) were used in this work.

3. Estimate wind drift and evaporation losses ($WDEL$, %). The equation used for this purpose was the one proposed by Faci and Bercero (1991) for the specific conditions of the LQD.

$$WDEL = 20.44 + 2.70 W \quad [2]$$

Where W is the wind speed (m s^{-1}).

$WDEL$ reduces the sprinkler discharge reaching the soil, and therefore the application depth.

4. Compute the trajectory of a single droplet of a given diameter, launched at given vertical and horizontal angles, and under a given wind speed and direction. The differential equations derived from ballistic theory are used for this purpose. The results of this phase are the coordinates of the droplet landing point.
5. Combine the landing point for drops of different diameters with the drop size distribution curve to obtain the spatial distribution of water application resulting from a single sprinkler.
6. Overlap the water application of a single sprinkler in accordance with the desired sprinkler spacing. The result of this phase is the spatial distribution of water application within a sprinkler overlap area. Simulated irrigation performance is evaluated dividing the sprinkler overlap area into a number of sub areas acting as catch cans. The catch can irrigation depth is computed for each sub area.
7. Determine the performance parameters CU and the potential application efficiency of the low quarter (PAE_{lq}). In determining PAE_{lq} , $WDEL$ were considered as net water losses. Following Burt et al. (1997) PAE_{lq} was determined as:

$$PAE_{lq} = \left(\frac{\text{avg. depth of irrig. water contributing to target}}{\text{avg. depth of irrig. water applied such that } d_{lq} = \text{target}} \right) 100 \quad [3]$$

where d_{lq} is the low quarter irrigation depth.

Solid-set and weather data as well as model parameters constitute the input required for the simulation software. Regarding the solid-set, data include: diameter of the principal and auxiliary (if any) sprinkler nozzles, vertical angle of the sprinkler jet, nozzle height, operating pressure, azimuth of the sprinkler line and sprinkler spacing. Weather data include wind speed and direction. Model parameters include the number of drop diameters (180 diameters, ranging from 0.02 to 7.00 mm), the number of initial horizontal angles (180 angles, spaced 2°), the number of catch cans (324, distributed in a regular 18 x 18 network), and the values of $k1$ and $k2$.

In order to verify the predictive capability of the model, the 13 solid-set field evaluations were simulated and field results were compared with simulation results using scatter plots and regression lines for CU and PAE_{lq} .

Once the model predictive capability was established, it was applied to simulate all plots in the LQD equipped with solid-sets. Different scenarios were produced combining variations in operating pressure and wind speed. The selected values for operating pressure were 200 kPa (low, inadequate, but not rare in the LQD), and 300 kPa (in the low range of adequate pressure, and just over the average pressure measured in the companion paper, 270 kPa). For wind speed, values of 1 m s⁻¹ (very mild) and 3 m s⁻¹ (common, moderate speed)

were used. In the application of these four scenarios to the LQD, the inventory of sprinkler and solid-set characteristics reported by Tejero (1999) was used for each plot.

Simulation of irrigation scheduling and its effect on crop yield and net benefit

Since historical information on crop yield is not available in the LQD, irrigation scheduling simulation techniques were used to evaluate the influence of irrigation management on crop yield and water use in the LQD. The CropWat software (Smith, 1993; Clarke et al., 1998) was used to simulate current farmer management practices (irrigation dates and depths) and an optimal irrigation schedule (leading to potential yield). Simulation was applied to the 1997 irrigation season in the plots of the detailed analysis presented in the companion paper.

Complete irrigation records were only available for 11 of the 17 plots included in the detailed analysis. Crops of these plots were alfalfa, corn and wheat. These plots were generally under-irrigated in the study year. We evaluated the increase in irrigation water use and crop yield derived from introducing an optimal irrigation scheduling. In the alfalfa plots we also evaluated the net benefit of optimizing irrigation management. The optimal yield of alfalfa hay was set to 15,000 kg ha⁻¹ year⁻¹ (according to the farmers' experience), with a market value of 0.096 €kg⁻¹. The unit cost of irrigation water in the LQD was 0.034 €m⁻³.

RESULTS AND DISCUSSION

Irrigation system evaluations

Table 1 presents the results of the 13 irrigation evaluations performed in solid-set systems. Average CU 's are presented for classes of sprinkler spacing, operating pressure and wind speed. CU variability was large, ranging from 38.8 % to 88.1 %, with an average value of 68.0 %. For solid-sets, Keller and Bliesner (1990) considered this value relatively low (up to a threshold of 75 %). For the most common irrigation equipment in the LQD (T21x18 sprinkler spacing, 5.1 and 2.4 mm nozzles) and an adequate operating pressure (300 - 400 kPa, as discussed in the companion paper), Ramón (1998) performed irrigation evaluations under controlled conditions. For wind speeds below 1.0 m s^{-1} , the resulting CU was 91.1 %. The average CU of a series of evaluations performed with wind speeds below 5.6 m s^{-1} was 86.1 %. Irrigation uniformity in the LQD seems to be limited by the use of single nozzles, inadequate pressure, nozzle wear and high wind speeds.

The highest CU value (88.1 %) was recorded in a 18x18 plot, with relatively low pressure (210 kPa), and wind speed of 2.8 m s^{-1} . Faci and Bercero (1991) found a threshold value of wind speed for solid-sets in the LQD of 2.1 m s^{-1} beyond which irrigation uniformity sharply decreased. This critical value is close to the wind speed recorded during the best-performing evaluation. These results suggest that the potential uniformity of the T18x18 spacing could be higher than recorded, particularly if the operating pressure was closer to 300 kPa and the wind speed was lower. The lowest value of CU (38.8 %) corresponds to a plot with a T21x18 spacing, a pressure of 280 kPa and a high wind speed (5.2 m s^{-1}). The large spacing and the high wind speed appear to be the main causes of this low CU .

When the sprinkler spacing is considered, the T18x18 spacing performed much better than the T21x18 spacing ($CU = 87.3 \%$, 23 points higher than the average CU). The second considered factor affecting CU is the operating pressure. High pressures (over 400 kPa) resulted in lower values of CU . As expected, the average CU obtained with low wind speeds is higher than the one obtained with high wind speeds, with a difference of about 13 %. In some evaluations with the same spacing and pressure, similar values of CU were obtained independently of the wind speed (see evaluations 4 and 9 in Table 1). These results suggest that CU may be affected by other wind-related factors, like the wind direction or the time variability of the wind speed and direction.

The effect of the irrigation duration can be illustrated by the two evaluations performed with a T18x18 spacing (evaluations 12 and 13, Table 1). The most relevant difference between both evaluations is the irrigation duration (2 and 6 hours, respectively). A high CU was obtained in the long irrigation event ($CU = 88.1 \%$) although the average wind speed was double than the wind speed measured during the short irrigation event. When the wind speed and direction are highly variable, as the irrigation duration increases the chances to obtain a high CU increase.

Table 2 summarizes the 10 centre-pivot evaluations. 6 additional evaluations were conducted but not included in this table because both their operating pressure and wind speed were not available. However, they were considered in the determination of the average uniformity indexes. The average CU was 75.5 %. Only one evaluation presented a particularly low CU (58.6 %). In the rest of the evaluations, CU ranged from 70.4 % to 90.0 %.

Table 3 presents the results of 9 linear-move sprinkler evaluations. As with centre-pivots, 2 additional incomplete evaluations were not included in the Table, but their results were used to estimate average uniformity parameters. The average linear-move *CU* was 80 %. All the evaluations presented *CU*'s higher than the threshold established by Keller and Bliesner (1990) for "moderately low" uniformity ($CU = 75\%$), except for one case with $CU = 50.7\%$. In the linear-moves where farmers had lowered the spray nozzles from 4.5 to 1.5 m, *CU* increased from 75.9 % to 83.8 %. Montero et al. (1999) – analysing pivot performance – did not find a significant effect of nozzle height on *CU*.

In the two types of machines, average *CU* was higher with a wind speed between 2 and 6 m s^{-1} than with wind speeds below 2 m s^{-1} . This can be explained by the findings of Faci et al. (2001), who reported that isolated fixed spray plate sprinklers apply most of the irrigation water in a circular crown. Inside the circular crown, the amount of irrigation water is minimum. Overlapping mathematically the distributions obtained with this type of nozzle, these authors found that mild and moderate winds could increase the *CU*. In previous experimental works, Hanson and Orloff (1996) observed similar results, while Hills and Barragán (1998) did not find an effect of moderate wind speeds on *CU*.

According to Cuenca (1989), the potential *CU* of centre-pivot and linear-move sprinkler machines is about 90 %. This value was reached in the LQD only in 8 % of the evaluations performed in the LQD. Adopting the current technology in sprinkler nozzles for irrigation machines and reducing the nozzle height would surely result in an increase in *CU* and a decrease in *WDEL*.

Validation and application of a ballistic solid-set sprinkler irrigation simulation model

The field evaluations performed in solid-set irrigation systems and reported in Table 1 were simulated in order to provide a validation for the proposed ballistic model. Two evaluations were discarded for the validation of CU . These evaluations presented extreme wind speeds (over 6 m s^{-1}), beyond the range for which Faci and Bercero (1991) developed the $WDEL$ predictive equation. Two additional evaluations were discarded for the PAE_{lq} validation, since the volume of water collected in the catch cans exceeded the applied irrigation depth. The comparison between measured and simulated values of CU and PAE_{lq} is presented in Figure 2. Results show that the model predictive capability is better for PAE_{lq} ($R^2 = 0.86^{***}$) than for CU ($R^2 = 0.55^{**}$). In both cases the regression intercept did not differ from 0 and the slope did not differ from 1. Both performance parameters are adequately predicted in the range of observed values.

Improvements in the model predictive capability (particularly regarding CU) could be attained addressing three factors that will require a detailed study in the future. First, the proposed model uses time averaged wind speed and direction. Short-time variability of these variables during the irrigation event can have a relevant effect on the measured values of CU and PAE_{lq} . Second, a detailed model calibration will be required to estimate $k1$ and $k2$ for each combination of sprinkler manufacturer, nozzle diameter and operating pressure. Finally, the proposed model uses the equations presented by Kincaid et al. (1996) to determine the drop size distribution. Previous ballistic models derived this information from field experiments on the application pattern of isolated sprinklers, thus determining the drop size

distribution fitting the model results to the experimental values for each combination of nozzle diameter(s), sprinkler manufacturer, and nozzle height.

Figure 3a presents the average values of CU obtained with the simulation model in each solid-set LQD plot using combinations of two operating pressures (200 and 300 kPa) and two wind speeds (1 and 3 m s⁻¹). The maximum values of CU obtained in the different plots and sprinkler spacings correspond to the combination of adequate pressure and low wind speed. These simulated values of CU reached 84 % on the average. The plots equipped with the narrowest spacing (T15x15) also present high CU values with low pressure and mild wind and with adequate pressure and strong wind. The lowest CU values were observed in the plots equipped with the largest spacing (T21x18) except for the combination of low pressure and strong wind. In this case the average value of CU was higher than that obtained in the same conditions for narrower spacings, such as T18x15 and T18x18.

The dependence of PAE_{lq} on the sprinkler spacing, pressure and wind speed is similar to that found for CU (Figure 3b). The most interesting result is that PAE_{lq} values are low, about 60 % in the best cases. This is partly due to the relevance of $WDEL$ in the LQD. Faci and Bercero (1991) found that during the summer time, even in calm conditions, water losses amounted to 20 % of the applied water. On the other hand, individual irrigation PAE_{lq} values are often low because the spatial variability of the applied water is high. However, in sprinkler irrigation, most of this variability is associated to the wind speed, which has a strong random behaviour. Therefore, low PAE_{lq} values in individual irrigation events may be compatible with a high seasonal irrigation efficiency.

Figure 4 presents the spatial distribution of simulated *CU* in the LQD solid-set plots with a pressure of 300 kPa, and wind speeds of 1 m s⁻¹ (a) and 3 m s⁻¹ (b). When the wind speed was low, 67 % of the solid-set area presented a *CU* higher than 84 %, the value recommended by Keller and Bliesner (1990) for this type of sprinkler systems. The rest of the plots presented *CU* values ranging between 78 % and 84 %. Under high wind conditions, most of the plots (82 % of the solid-set area), presented *CU* values below 84 %. The presented spatial analysis can be used to identify plots showing uniformity problems. These plots should be considered as primary targets of programs devoted to improve on-farm irrigation performance. The first step would be to confirm the model predictions with field irrigation evaluations.

Simulation of irrigation scheduling and its effect on crop yield and net benefit

Table 4 presents the simulation of the current irrigation practices and the optimal irrigation schedule for the 11 considered plots. In the simulation of the current irrigation practices, the real irrigation dates and depths applied by the farmers were considered. Simulation results showed that the corn plot was the only one presenting a null yield reduction, with a moderate volume of deep percolation losses. In the rest of the plots crop yield reductions ranged from 9.6 % to 16.8 %. The optimal irrigation schedules developed for the 10 plots presenting yield reductions were characterised by larger seasonal irrigation depths and more irrigation events than the current farmers' practices.

The difference between the current and the optimal seasonal irrigation depths was relevant for plots 1, 7, 8 and 9. In these plots, large additional amounts of irrigation water

were required in the optimal schedule to eliminate yield reduction. The rest of the plots presented moderate differences in the seasonal water application, and the elimination of yield reduction was obtained via a considerable reduction in the deep percolation losses. Farmers' irrigation in these plots was not properly scheduled in terms of timing and depth, and the soil water holding properties were not taken into consideration. In all these cases, the optimal schedule resulted in an increase in the number of irrigation events (7 additional irrigations on the average) and in a decrease on the irrigation depth per irrigation event.

An estimation of the additional yield and additional water costs associated to the introduction of the optimal irrigation schedule in the alfalfa plots is presented in Table 5. The average gross irrigation depth should be increased from 644 mm to 745 mm. The difference between these benefits and costs resulted in an average additional income of 140 € ha⁻¹. A relevant factor has not yet been introduced in this simplified analysis: the labour required to perform the additional irrigation operations. According to the farmers' interview presented in the companion paper, 86 % of the LQD farmers do not have irrigation automation devices. This is a relevant limitation to the introduction of the optimal irrigation schedule, since farmers will probably not adhere to an irrigation schedule requiring more manual operations and an accurate control of the irrigation timing. The generalization of on-farm automation devices in the LQD is the key factor for the implementation of the optimal irrigation schedule proposed in this article. Automating the irrigation systems in place in the LQD would require an investment equivalent to a yearly payment of about 90 € ha⁻¹. Including the irrigation automation cost, the net benefit of introducing an optimal irrigation schedule would be reduced to a moderate 50 € ha⁻¹. An additional benefit could be derived from a reduction of the current labour costs due to automation. However, in the optimal schedule farmers would

still have to check the proper functioning of the irrigation equipments, and therefore labour requirements would probably not be reduced by automation. The benefits of irrigation automation exceed the limits of the economic analysis, since automated operation is essential to the social sustainability of the LQD due to labour scarcity in rural Spain.

In their study of a surface irrigation district, Clemmens and Dedrick (1992) found that the irrigation depth presented an inverse, significant relationship with the level of irrigation management. In fact, farmers using scheduling techniques reduced their seasonal irrigation depth by 250 mm. In that case, irrigation scheduling was used to increase irrigation efficiency. In the LQD the problem is different: proper irrigation scheduling will allow farmers to obtain higher yields (approaching potential yields) with a moderate increase in water use.

CONCLUSIONS

In this second paper of the series, the analysis has been extended to include irrigation evaluations, simulation of solid-set sprinkler irrigation and the relationship between irrigation scheduling and crop yield. The following conclusions can be drawn from this work:

- The irrigation evaluations show that a number of factors affect irrigation uniformity in the LQD. Optimising these factors requires proper design (sprinkler spacing, nozzle selection) and an adequate selection of the operating conditions (pressure, irrigation duration or wind speed).
- According to the solid-set system evaluations, *CU* in the LQD is low (68.0 % on the average). Irrigation uniformity seems to be limited by the use of large sprinkler spacings,

single nozzles, inadequate pressure, nozzle wear and high wind speeds. In evaluations with low available pressure, narrow sprinkler spacings (T18x18) attained acceptable uniformity.

- Linear-move irrigation machines and centre-pivots presented higher *CU* than solid-sets. The average *CU*'s were 80.0 % for linear-moves and 75.5 % for centre-pivots. Uniformity was not severely affected by wind speed. A higher average *CU* was obtained with wind speed values between 2 and 6 m s⁻¹ than under calm conditions.
- The validation of the proposed ballistic solid-set sprinkler irrigation simulation model showed that the performance parameters *CU* and *PAE_{lq}* could be adequately predicted in the range of the observed values.
- The ballistic model was used to extend the results of the irrigation evaluations to the entire district. *CU* maps were produced for different conditions of wind speed and operating pressure. These maps can be used to identify plots with poor irrigation performance. Field evaluations should be performed in these areas to confirm model estimations before introducing changes in irrigation design and/or management.
- Crop yield simulation in a limited number of LQD plots in 1997 detected a water stress induced yield reduction of 12 % on the average. Water stress was caused by deficit irrigation and/or large irrigation intervals. Frequently, the water applied during each irrigation event exceeded the soil water holding capability, therefore resulting in presumably large deep percolation losses.
- For the alfalfa plots, the application of an optimal irrigation scheduling detected the need to increase the seasonal number of irrigations and to decrease the irrigation depth per irrigation event. Such a policy would lead farmers to attain maximum crop yield at the expense of an additional irrigation depth of 101 mm. A simplified economic analysis

revealed that the net benefit of introducing the optimal irrigation schedule (considering increased yield, water cost and irrigation automation cost) would be a moderate 50 €ha⁻¹.

In this series of two papers, an analysis of water use and irrigation performance in the LQD has been presented. The conclusions of this work could be extended to many similar irrigation districts of NE Spain and other areas of the world sharing similar irrigation technology, soils and climate. In order to complete the Diagnostic Analysis phase of the incipient Management Improvement Program at the LQD, an interdisciplinary committee will take up the task of confronting our findings with additional data and points of view on the current state of irrigated agriculture in the district.

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Table 1. Summary of the main characteristics of the irrigation evaluations performed in solid-set systems.

#	Sprinkler Spacing (m)	Operating Pressure (kPa)	Average Wind Speed (m s^{-1})	Nozzle Diameter(s) (mm)	Irrigation Duration (h)	CU (%)
1	T21x18	380	2.5	5.1	2.5	77.5
2	T21x18	430	0.3	5.1	2.0	76.4
3	T21x18	450	0.3	5.1	2.0	70.0
4	T21x18	450	11.7	5.1	2.4	72.5
5	T21x18	460	2.3	5.1	2.3	67.0
6	T21x18	460	5.8	5.1	2.6	50.3
7	T21x18	450	6.1	5.1	2.0	66.3
8	T21x18	460	5.5	5.1	1.7	48.9
9	T21x18	460	3.5	5.1	3.0	72.2
10	T21x18	280	5.2	4.4 and 2.2	2.1	38.8
11	T21x18	360	5.0	4.8 and 2.2	6.0	66.2
12	T18x18	220	1.4	5.1 and 2.2	2.0	86.5
13	T18x18	210	2.8	5.1 and 2.2	6.0	88.1
Spacing average	T18x18					87.3
	T21x18					64.5
Pressure average		< 300				71.1
		300 - 400				71.9
		> 400				65.8
Wind average			< 2.0			77.7
			> 2.0			65.1

Table 2. Summary of the main characteristics of the irrigation evaluations performed in centre-pivot sprinkler machines.

Evaluation #	Pivot Length (m)	Number of catch cans	Operating Pressure (kPa)	Wind Speed (m s⁻¹)	CU (%)
1	280	60	220	1.4	70.4
2	280	60	220	-	90.0
3	280	60	220	-	73.9
4	340	52	260	3.5	86.1
5	208	39	280	1.3	73.1
6	208	39	280	0.8	83.6
7	195	65	-	2.6	85.5
8	204	68	-	1.7	58.6
9	141	47	-	0.5	77.0
10	159	53	-	3.3	76.6
Wind average				< 2.0	72.5
				> 2.0	82.7

“-“ indicates missing data

Table 3. Summary of the main characteristics of the irrigation evaluations performed in linear-move sprinkler machines.

Evaluation #	Linear-move length (m)	Number of catch cans	Operating Pressure (kPa)	Wind Speed (m s^{-1})	CU (%)
1	280	50	70	0.5	82.8
2	280	50	100	0.0	87.2
3	280	50	120	3.9	78.9
4	-	32	-	5.7	87.3
5	-	32	-	0.4	50.7
6	190	63	-	2.0	86.5
7	105	82	-	1.9	78.6
8	240	37	-	4.5	77.0
9	261	87	-	1.8	95.9
Wind average				< 2.0	79.1
				> 2.0	81.6

“-“ indicates missing data

Table 4. Simulated current and optimal irrigation schedule, and difference between the current and the optimal seasonal irrigation depths (DSID) for the considered alfalfa, wheat and corn plots during the 1997 irrigation season.

Plot #	Crop	Current				Optimal		DSID (mm)
		Seasonal Irrigation Depth (mm)	Number of Irrigations	Deep Percolation Losses (mm)	Yield Reduction (%)	Seasonal Irrigation Depth (mm)	Number of Irrigations	
1	Alfalfa	509	18	39	17	736	23	227
2	Alfalfa	682	18	128	10	729	27	47
3	Alfalfa	713	18	134	11	729	27	16
4	Alfalfa	737	20	160	10	750	25	13
5	Alfalfa	706	20	136	11	750	25	44
6	Alfalfa	723	19	180	13	750	25	27
7	Alfalfa	580	15	98	12	759	23	179
8	Alfalfa	505	13	61	13	759	23	254
9	Wheat	113	2	0	17	315	7	202
10	Wheat	302	8	35	16	350	10	48
11	Corn	506	16	58	0	-	-	-

Table 5. Estimated value of the additional yield and additional water cost associated to the introduction of an optimal irrigation schedule in the considered alfalfa plots during the 1997 irrigation season.

Plot	Additional Yield (€ha⁻¹)	Additional Water Cost (€ha⁻¹)	Difference (€ha⁻¹)
1	241	78	163
2	145	18	127
3	157	6	151
4	138	6	132
5	169	12	157
6	193	12	181
7	175	60	115
8	181	84	97
Average	175	35	140

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