

Furrow-irrigated chufa crops in Valencia (Spain). II: Performance analysis and optimization

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Abstract

Chufa (*Cyperus esculentus* L. var. *sativus* Boeck.) is a traditional crop in the Mediterranean region of Spain, where it is only furrow irrigated. This article analyzes the irrigation performance for this crop, conducting field studies over three consecutive seasons in Valencia (Spain). Irrigation schedule was based on the volumetric soil water content, which was measured with capacitance sensors. Infiltrability was measured with blocked-furrow infiltrometers. An area velocity flow module measured the water flow, the cross-sectional geometry of furrows was determined using furrow profilometers, and times for advance and recession were recorded. WinSRFR software was used to analyze every irrigation event, determining the application efficiency (AE) and distribution uniformity of the minimum (DU_{min}), and to optimize the combination of furrow inflow (q) and cut-off time (T_{co}). Average values obtained for AE were 30.1%, 25.6%, and 26.7% in 2007, 2008, and 2009, respectively, and the corresponding DU_{min} values were 0.54, 0.61, and 0.67. Optimized results showed that it is possible to reach AE and DU_{min} values up to 87% and 0.86, respectively. However, understanding the q - T_{co} relationship that maximizes both AE and DU_{min} is more important than knowing the specific values. A function that related q and T_{co} was obtained for the typical plot dimensions, and this was validated in 2011. Therefore, this function can be used in most of the plots in the cultivation area.

Additional key words: application efficiency; cut-off time; distribution uniformity; furrow inflow rate; irrigation management; vegetable crop.

Introduction

In a companion paper (Pascual-Seva *et al.*, 2013, this issue) the interest in chufa (*Cyperus esculentus* L. var. *sativus* Boeck., also known as tigernut) cultivation has been reported, both in Spain and in the world, as well as the characterization of the irrigation on the Huerta of Valencia irrigation district, and the productive response of chufa crop to two irrigation strategies was studied.

The increase of irrigation water use efficiency can be achieved by both the increase of crop yield (that has been studied in the companion paper) and the reduction of gross water use through improvements in irrigation efficiency (Playán & Mateos, 2006). In turn, according

to Playán *et al.* (2000) and Neira *et al.* (2005), an analysis of current irrigation performance must precede any attempt to improve irrigation efficiency, since, detecting specific problems that could affect the water management, enables to recommend solutions to achieve higher efficiencies.

Irrigation system evaluation by field tests in normal conditions determines the parameters that are involved in water application, such as efficiency (average measure of water losses) and uniformity (water distribution in different parts of the plot). This information can help in making decisions to improve the irrigation system both from the economical and design point of view (Merriam *et al.*, 1980). Irrigation efficiency and distribution efficiency terms can be ambiguous depending

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Abbreviations used: AE (application efficiencies); D_{app} (average depth of the water applied to the field); D_{av} (average depth of the water infiltrated to the field); D_{min} (minimum depth of the water applied to the field); D_{req} (average depth of the water required to fill the root zone); DOY (day of the year); DU (distribution uniformity); DU_{min} (distribution uniformity of the minimum); EY (experimental year); FC (field capacity); n (roughness coefficient); Q (water flow); q (furrow inflow); RP (refill point); T_{co} (cut-off time); $VSWC$ (volumetric soil water content).

on the considered inputs and outputs (Burt *et al.*, 1997). The present study used the application efficiency (*AE*) term as described by Lord & Ayars (2007) as well as the distribution uniformity of the minimum (DU_{min}) term as described by Strelkoff & Clemmens (2007).

The furrow irrigation design has been traditionally based on intuition and empirical data taken from successful projects rather than on theory. The prediction of surface irrigation behavior is complicated due to many analytical problems. However, nowadays, it is possible to design and provide operation recommendations based on simulations (Strelkoff & Clemmens, 2007).

To improve irrigation performance, mathematical models of the surface irrigation processes have been developed during the last decades. These models consider several variables, including plot dimensions, slope, hydraulic roughness, furrow discharges, and irrigation time. The interaction among these variables determines the advance times, recession times and infiltrated water depth as well as the corresponding efficiencies and uniformities (Jurriens *et al.*, 2001). In the 1970s and 1980s, models included many diagrams and formulas, which made them difficult to be applied by non-specialized people. However, this all changed with advances in computer programming and the availability of personal computers. Thus, irrigation engineers started to make computer programs for the mathematical models so that more users could apply these models without practical problems (Jurriens *et al.*, 2001).

Diverse research groups of different research institutes and universities have developed various computer programs for surface irrigation analysis. Two of the remarkable software are WinSRFR (ALARC, 2009; Bautista *et al.*, 2009a), which was developed by the US Arid Land Agricultural Research Center, and SIRMOD (Walker, 2003), developed by Utah State University. Both are one-dimensional models and they are similar in many aspects; their accuracy has been tested in a wide range of conditions (McClymont *et al.*, 1999).

Several studies have shown that infiltration from furrows is not a one-dimensional process but a two-dimensional, existing other models, as TRIDISUL (Tabuada *et al.*, 1995), HYDRUS-2D (Simunek *et al.*, 1999) and FURINF (Schmitz, 1993), that could guarantee higher accuracy. But, due to their complexity, as in other complex model systems, their main use tends to be for comprehensive researches (Wöhling & Schmitz, 2007). In the present study a small water depth is required and given that it is difficult to obtain high efficiencies in

sandy soils, the precision of one-dimensional models (with lower complexity than two-dimensional models) is considered enough to describe the irrigation performance parameters. The accuracy obtained with WinSRFR has been considered suitable for the present analysis.

The aim of this study was to determine the actual volumes of water used in chufa cultivation and the corresponding application efficiency (*AE*) and distribution uniformity of the minimum (DU_{min}) values. An additional aim of this study was to propose irrigation parameters [furrow inflow (*q*) and cut-off time (T_{co})] to considerably improve both *AE* and DU_{min} values.

Material and methods

Field experiments

Field studies were conducted over three consecutive years (2007, 2008, and 2009) in two adjacent plots of a commercial farm near the Valencia Polytechnic University campus in Spain (39° 29' N and 0° 20' W). This farm is representative of the plots in the region. One plot was used in 2007 and 2009, and the other plot was used in 2008 to avoid soil exhaustion problems related to crop repetition. According to the Papadakis' agroclimatic classification system (Elías & Ruiz, 1977), the climate is subtropical Mediterranean with hot, dry summers and an average annual rainfall of approximately 450 mm, which is irregularly distributed throughout the year with 40% of the rainfall occurring in autumn.

The soil textural type is sand in the 2007 and 2009 plot and loamy sand in the 2008 plot. The soils are deep, and they are classified as anthropic torrifluvents according to the USDA's Soil Taxonomy (Soil Survey Staff, 2010). The analyses performed in this study indicated that the soils had slightly or moderately alkaline pH levels and that they were fertile (moderate organic matter content and high available phosphorous and potassium concentrations).

In this area, water comes from the Rascanya Canal, which flows from the Turia River ($EC = 1.38 \text{ dS m}^{-1}$; $SAR_{(adjusted)} = 1.21$; $pH = 7.2$). The irrigation water has no restrictions in terms of salinity for non-sensitive crops, as chufa, or permeability (Ayers & Westcot, 1994).

The standard cultivation practices described by Pascual *et al.* (1997) were followed during the crop period. Planting was performed on May 8th in 2007 (128th day of the year; DOY), April 11th in 2008 (101th

DOY), and April 27th in 2009 (117th DOY). Tubers (120 kg tubers ha⁻¹) were planted in ridges, which were 0.20 m high, and the ridge top center spacing was 0.60 m. The furrow length was 82.5 m in 2007 and 2009, and was 66 m in 2008. The number of furrows simultaneously irrigated was 26, 24, and 40 in 2007, 2008, and 2009, respectively.

The average furrow slope was approximately 0.3%. This study was designed to identify improvements that growers could easily apply without large investments. Therefore, precision land leveling was not considered in this study although its importance in achieving high performances and water savings is known (Pereira *et al.*, 2002; Horst *et al.*, 2005). In this sense, laser technology is used to achieve a leveled field surface after chufa tuber harvesting. The land leveling in chufa cultivation depends on the crop management of plants grown between chufa in the crop rotation.

Three ECH₂O EC-5 capacitance sensors with ECH₂O Utility software (Decagon Devices Inc., Pullman, WA, USA) were placed at a depth of 0.10 m, and they were connected to an Em50 data-logger (Decagon Devices Inc., Pullman, WA, USA) to monitor the volumetric soil water content (*VSWC*). The irrigation was scheduled so that each event began (refill point; *RP*) when the *VSWC* reached approximately 60% of the field capacity (*FC*; Pascual-Seva *et al.*, 2013, this issue). Variations of *VSWC* were used to determine the *in situ* values corresponding to *FC*, which is defined as the amount of water held in the soil after excess water has drained away and the rate of the downward movement of water has materially decreased (Veihmeyer & Hendrickson, 1931), and therefore reaching a plateau in *VSWC* variations.

In each event, irrigation management was representative of the practices in the region. The end of the chufa irrigation period is considered as the time when the straw is burned, which takes place before tuber harvesting. In this experiment, the dates of straw burning were November 6th in 2007, November 7th in 2008, and October 26th in 2009.

Field evaluation procedures

This study determined *AE* (Lord & Ayars, 2007) and *DU_{min}* (Strelkoff & Clemmens, 2007). WinSRFR 3.1 (ALARC, 2009; Bautista *et al.*, 2009a) is the software package used to determine these parameters and also to optimize them. For this optimization, the program

compared *DU_{min}* values, so this value was the uniformity parameter presented for the entire study. The *AE* and *DU_{min}* values are described by the following equations:

$$AE = \frac{D_{req}}{D_{app}} \cdot 100, \text{ and}$$

$$DU_{min} = \frac{D_{min}}{D_{app}},$$

where *D_{req}* is the average depth (mm) required to fill the root zone; *D_{app}* is the average water depth (mm) applied to the field; and *D_{min}* is the minimum depth (mm) of water infiltrated in the field. In this study, furrows were blocked on the downstream ends. Thus, there was no runoff and, consequently, *D_{app}* was equal to the average infiltrated water depth (*D_{av}*).

The Merriam & Keller's (1978) post-irrigation volume balance method was used by WinSRFR 3.1. This method estimates the field-averaged infiltration function from the field-measured geometry, inflow, advance times and recession times, thereby, requiring the determination of different measurements, including furrow discharges, furrow cross-sections, infiltration, advance times, recession times, hydraulic roughness, and furrow slopes (Horst *et al.*, 2005).

The water flow (*Q*) was continuously measured by a flow meter (ISCO 2150 area velocity flow module; Teledyne ISCO Inc., Lincoln, NE, USA) placed on the water entrance to the experimental plots. Discharge data were measured and stored at 15 s intervals, which allowed calculating the average, minimum and maximum inflow rates as well as the variation of inflow rates. The inflow rate was considered uniformly distributed along the different furrows simultaneously irrigated, so *q* was calculated as the average *Q* divided by the number of irrigated furrows.

The furrow cross-sectional geometry was determined at a distance half of the length of the furrow before each irrigation event using furrow profilometers (Walker & Skogerboe, 1987).

Among the different options provided by the program for calculating the infiltrated depth, the Kostikov formula was used in this study. The corresponding *a* exponent was determined through *in situ* infiltrability trials using the blocked furrow infiltrometer method, which was developed by Bondurant (1957). For construction of the blocked furrow infiltrometer, a furrow segment (length of 1 m) was isolated by two metal plates (0.6 m × 0.5 m; thickness of 2 mm), which were intro-

duced into the soil to a depth of 0.30 m. A constant water level (approximately 50 mm; similar to the level during the irrigation events) was maintained in this furrow segment by a float valve arrangement. To simulate natural conditions, a section of a furrow was used as a buffer to both sides and extremes. The water level in the supply reservoir was measured every 1 min for at least 3 h, and the infiltration rate was computed from these data points. The infiltration rate may be affected by soil changes, such as surface sealing and crusting (Smith & Warrick, 2007). Therefore, the infiltration rate was determined before each irrigation event in furrows (of the same plot) that were not monitored during the irrigation events to avoid alterations in the furrow bed.

Advance and recession times were measured at 16-m and 20-m intervals along the monitored furrows in the plots with length of 66 and 82.5 m, respectively. Recession times were considered at the times when water completely infiltrated the soil at the observed points. However, when irregularities of the furrow bed caused the water to pool for a long time, the recession time was considered when water disappeared from the furrow bed in the areas close to the measurement point (Horst *et al.*, 2005).

Manning's roughness coefficient, n ($\text{s m}^{-1/3}$), for each irrigation event was based on the recommended values by the NRCS (USDA-SCS, 1991b), and this coefficient was fine-tuned considering the furrow bed roughness and the presence of lodged plants. Simulations with WinSRFR 3.1 were conducted to find the n values that minimized the difference between observed and simulated advance and recession times, which were used for analyzing the irrigation performance (Bautista *et al.*, 2009a).

Infiltrability (a exponent of the Kostiakov formula), and advance and recession times were determined in triplicate, and their average values, for each irrigation event, were entered into the WinSRFR 3.1 software program.

Optimized irrigation management

Water savings can be achieved by improving irrigation performances, *i.e.*, increasing the AE and DU parameters, which depend upon many factors, such as q , T_{co} , n , infiltration characteristics of the soil, cross-sectional characteristics of the furrow and furrow slope (Horst *et al.*, 2005). However, because this study focused on the field assessment of water saving potential by adop-

ting easily accessible technologies related to furrow irrigation, only factors that can be easily adapted by growers were considered as follows: q and T_{co} .

To optimize these factors, the Operation Analysis World in the WinSRFR 3.1 program was used. This program supplies performance contours that depict the variation of AE and DU_{min} (among others) as a function of q and T_{co} . These contour plots are generated by interpolation from simulation results computed at discrete grid points on a rectangular solution region, and the limits are defined by the user (Bautista *et al.*, 2009a). These plots also present a dotted line representing the solutions that satisfy the irrigation requirement everywhere (*i.e.*, minimum depth equals the required depth). The optimal q - T_{co} combination, which maximizes both AE and DU_{min} , does not fall exactly on this line, but it is near to the line and can be easily found by trial and error (Bautista *et al.*, 2009b).

In this study, the optimal q - T_{co} combination was determined for every irrigation event until the first of September. After this date, lodged plants disrupted the water flow advance because the plants provoked flooding and made it impossible to adequately control the irrigation.

Validation

The q - T_{co} relationship has to be validated before it can be used by the growers. Therefore, this relationship was tested in the same plot that was used in 2007 and 2009 (which length was 82.5 m) in the first three irrigation events in 2011. This agrees with Walker (1989) who suggested evaluating q and T_{co} values for the first irrigation event following planting, when roughness and intake are maxima, and for the third or fourth irrigation event, when these conditions have been reduced by previous irrigations. For the test in 2011, planting was performed on April 5th. As in 2007, 2008, and 2009, standard cultivation practices were followed during the crop period in 2011. Irrigation management was carried out under normal grower control. The RP , and therefore, the D_{req} value for each irrigation event were similar to the value used in the analyzed experiments. In 2011, the irrigation events were on May 26th, June 16th, and June 27th.

Before the irrigation was started and once Q was roughly stabilized, q was calculated and it was considered to determine T_{co} . Irrigation performance was tested similarly to the previous experiments.

Results and discussion

Furrow characteristics

Table 1 presents the cumulative infiltration curves [a and k values and corresponding coefficients of determination (R^2)], obtained with the blocked furrow infiltrometer and fitted to the Kostiakov equations. For every curve, the R^2 value was large (> 0.83), and the significance level was $p \leq 0.01$. All determined values of a ranged from 0.40 to 0.69, which agreed with the values reported in the literature for furrows (ranging from 0.19 to 0.69) (Bautista & Wallender, 1993; Clemmens & Bautista, 2009).

Simulations were conducted to test the effect of n values on the advance and recession times for each irrigation event (Bautista *et al.*, 2009b) resulting in that 0.08 minimizes the difference between observed and simulated advance and recession curves for the first event and 0.04 for the following event. The n values were increased according to the furrow bed conditions (lodged plants) up to 0.12 in 2007 and 2008, and 0.15 in 2009. These values were in the range considered by the program (ALARC, 2009), which were in accordance to those recommended by the NRCS (USDA-SCS, 1991a, b).

Furrow cross-section data obtained by means of profilometers were introduced into the program which adjusted them to a trapezoid shape.

Actual irrigation performances

The FC values were 0.27, 0.28, and 0.27 $\text{m}^3 \text{m}^{-3}$ for 2007, 2008, and 2009, respectively, with corresponding RP values of 0.16, 0.17, and 0.16 $\text{m}^3 \text{m}^{-3}$. Considering that the root zone depth was estimated as the maximum development of root masses (20 cm based on phenological measurements; Pascual-Seva, 2011), D_{req} was considered to be 22 mm for all irrigation events.

There were 15, 13, and 12 irrigation events in 2007, 2008, and 2009, respectively, with a total of 40 irrigation events for the experiment. Each irrigation D_{av} value was determined by integrating q and T_{co} . The seasonal D_{av} value was 1201, 1320, and 1140 mm in 2007, 2008, and 2009, respectively, and the seasonal rainfall water input was 498, 438, and 320 mm in 2007, 2008, and 2009, respectively.

Table 2 shows the Q values (average, minimum, and maximum) and the corresponding coefficient of variation (CV) in each irrigation event of 2007, 2008 and 2009. Among and within the different irrigation events, Q varied considerably. In each irrigation event, the CV ranged from 3.03 (August 14th, 2008; $Q = 64.2 \text{ L s}^{-1}$) to 26.43% (May 18th, 2009; $Q = 66.8 \text{ L s}^{-1}$). The average seasonal Q value of 2007, 2008, and 2009 irrigation events was 38.7, 48.3, and 75.8 L s^{-1} , respectively. The extreme Q values were 27.3 and 98.6 L s^{-1} , which are easily manageable for irrigators and growers. The Q values increased from 2007 to 2009 due to both the larger

Table 1. The a and k parameters of the Kostiakov equation and corresponding R^2 values from dates obtained with the blocked furrow infiltrometers before each irrigation event

2007				2008				2009			
Date	k	a	R^2	Date	k	a	R^2	Date	k	a	R^2
24-05	14.05	0.57	0.986	28-04	13.34	0.58	0.998	18-05	7.91	0.69	0.933
06-06	10.61	0.53	0.995	17-06	10.03	0.57	0.995	02-06	7.57	0.58	0.859
14-06	12.75	0.49	0.986	25-06	11.04	0.52	0.990	11-06	4.27	0.64	0.914
21-06	4.85	0.65	0.994	03-07	10.07	0.44	0.855	22-06	6.40	0.53	0.918
27-06	6.91	0.59	0.992	10-07	16.99	0.44	0.990	29-06	9.00	0.47	0.832
05-07	6.38	0.57	0.964	22-07	10.56	0.46	0.998	06-07	5.93	0.51	0.929
12-07	5.30	0.63	0.964	30-07	13.35	0.47	0.993	20-07	6.82	0.52	0.866
19-07	7.28	0.53	0.989	07-08	10.16	0.52	0.989	29-07	6.22	0.50	0.883
26-07	8.59	0.55	0.992	14-08	14.70	0.40	0.958	17-08	4.49	0.56	0.858
02-08	4.69	0.66	0.977	28-08	17.00	0.42	0.987	26-08	9.29	0.49	0.842
13-08	7.68	0.54	0.973	08-09	12.68	0.44	0.980	03-09	5.59	0.54	0.881
20-08	5.84	0.63	0.989	18-09	14.05	0.47	0.987	14-09	4.76	0.62	0.897
30-08	9.87	0.55	0.986	06-10	12.23	0.50	0.972				
10-09	8.52	0.58	0.966								
04-10	11.14	0.45	0.988								

In all events, $p \leq 0.01$.

Table 2. Date, flow rate (average, Q ; minimum, Q_{min} ; and maximum, Q_{max} , L s⁻¹), and coefficient of variation (CV ; %) in each irrigation event

No.	2007					2008					2009				
	Date	Q	Q_{min}	Q_{max}	CV	Date	Q	Q_{min}	Q_{max}	CV	Date	Q	Q_{min}	Q_{max}	CV
1	24-05	36.5	13.5	48.3	19.3	28-04	33.9	22.6	48.3	16.6	18-05	66.8	31.7	102.0	26.4
2	06-06	27.3	17.9	42.2	14.9	17-06	47.4	40.0	57.1	8.7	02-06	67.2	58.0	77.5	5.9
3	14-06	32.7	11.0	56.0	23.7	25-06	39.5	32.3	49.5	11.0	11-06	57.4	47.4	82.8	14.5
4	21-06	33.1	21.0	45.0	19.3	03-07	49.9	41.6	76.9	13.3	22-06	89.8	55.5	107.7	11.4
5	27-06	31.7	21.0	40.0	13.1	10-07	54.6	43.8	77.5	16.8	29-06	57.2	45.8	80.1	13.0
6	05-07	36.4	28.0	53.0	18.0	22-07	50.2	40.7	59.3	6.7	06-07	66.5	57.6	87.9	6.5
7	12-07	35.1	22.1	41.4	10.8	30-07	60.2	43.3	68.5	8.7	20-07	77.6	72.5	102.6	7.0
8	19-07	40.6	24.9	48.6	13.5	07-08	63.8	33.9	83.4	19.0	29-07	67.0	41.1	90.8	20.7
9	26-07	39.5	29.1	44.6	7.1	14-08	64.2	43.3	77.1	3.0	17-08	96.4	48.0	131.0	15.5
10	02-08	33.3	28.8	37.2	5.2	28-08	45.3	32.4	51.3	14.1	26-08	79.2	69.8	92.7	5.8
11	13-08	49.2	37.7	59.1	11.9	08-09	32.4	22.4	40.5	10.3	03-09	85.7	45.1	130.1	23.4
12	20-08	50.1	34.3	65.6	11.9	18-09	40.8	26.1	49.3	9.1	14-09	98.6	66.1	140.3	17.4
13	30-08	46.6	34.1	55.7	11.9	06-10	46.5	26.2	53.1	3.2					
14	10-09	42.6	34.0	49.8	8.0										
15	04-10	46.3	37.2	62.7	13.2										
Av		38.7	26.3	49.9	13.4		48.3	34.5	60.9	10.8		75.8	53.2	102.1	14.0
SE		1.80	2.18	2.21	1.29		2.87	2.26	3.90	1.39		4.14	3.54	6.15	2.04

Average values (Av) and standard error (SE) correspond to all irrigation events.

flow rate in the canal, as the consequence of the delivery policy and to the greater number of furrows to simultaneously irrigate.

All the irrigation events could be satisfactorily modeled with the WinSRFR 3.1 program given that the mass balance error was lower than 1% and the root-mean-square errors of the advance and recession times were lower than 30% of the corresponding values in all cases (data not presented), thresholds stated by Maheshawari & McMahon (1993), therefore the analysis can be considered valid and the AE and DU_{min} values could be determined. Table 3 shows the q , T_{co} , D_{av} , AE , and DU_{min} values in each irrigation event as obtained by the WinSRFR 3.1 software program.

The average q values in 2007, 2008, and 2009 were 1.6, 1.9, and 1.9 L s⁻¹, respectively. The minimum and maximum average q registered values were 1.1 and 2.5 L s⁻¹, respectively, which ranged among the limits considered for gradient furrows (0.4-2.5 L s⁻¹) by Hart *et al.* (1980) and among the limits of inflow (0.9-2.4 L s⁻¹) used by Oyonarte *et al.* (2002). The erosion was negligible when comparing the cross-sections before the consecutive irrigation events. In this sense, the maximum flow velocity (that depends on a large variety of factors, among others soil type, furrow geometry, slope, roughness, and intake) was approximately 6 m min⁻¹, which was lower than the maximum flow velo-

city value (13-15 m min⁻¹) suggested in sandy soils to avoid erosion (Walker, 1989).

The T_{co} value of the first irrigation event of each season was greater than those for the following events due to the small flow velocity resulting from the low soil compaction and high roughness (Walker, 1989) for tillage operations. In general, the T_{co} value decreased with increasing q values, and the T_{co} value increased when plants were lodged at the end of the cultivation cycle. It should be noted that, to avoid a cut-off of water due to canal maintenance, the fifth irrigation in 2008 was moved forward to July 10th, presenting a small T_{co} value because the $VSWC$ at the beginning of this event was higher than usual, thus, resulting in a faster flow and, consequently, a smaller T_{co} value.

In the first event, the D_{av} value was (as T_{co}) considerably greater than the values in the remaining events with a value of 146, 178, and 142% greater than the average values of the other events in 2007, 2008, and 2009, respectively. For this reason the average values in Table 3 do not include the corresponding values of the first irrigation events.

The average AE values (Table 3) were 30.1, 25.6, and 26.7 for 2007, 2008, and 2009, respectively (20.6, 13.5, and 17.3% for the first irrigation event of each season). This variability was not infrequent, with larger differences among AE values being obtained in diffe-

Table 3. Average furrow inflow rate (q ; L s⁻¹), cut-off time (T_{co} ; min), average depth of water infiltrated (D_{av} ; mm), application efficiency (AE ; %), and distribution uniformity of the minimum (DU_{min} ; -) in each irrigation event

No.	2007					2008					2009				
	q	T_{co}	D_{av}	AE	DU_{min}	q	T_{co}	D_{av}	AE	DU_{min}	q	T_{co}	D_{av}	AE	DU_{min}
1	1.5	63	113.7	20.6	0.74	1.3	85	164.0	13.5	0.81	1.7	61	127.5	17.3	0.90
2	1.1	41	55.0	39.5	0.64	1.8	29	78.6	28.2	0.53	1.7	32	67.3	32.7	0.79
3	1.4	42	73.0	32.0	0.65	1.5	28	62.0	35.7	0.50	1.4	34	53.8	40.9	0.79
4	1.4	35	58.1	39.1	0.58	1.9	31	87.2	25.4	0.57	2.2	31	77.7	27.9	0.49
5	1.3	40	64.4	34.4	0.53	2.1	18	57.1	39.0	0.46	1.4	30	52.0	42.3	0.84
6	1.5	43	78.3	28.3	0.52	1.9	36	104.6	21.3	0.62	1.7	41	79.5	27.6	0.51
7	1.5	46	81.7	27.2	0.48	2.3	26	87.8	24.7	0.61	1.9	40	97.1	22.3	0.89
8	1.7	32	65.2	33.9	0.56	2.5	25	95.9	23.8	0.59	1.7	47	93.9	23.7	0.58
9	1.7	36	72.2	30.9	0.54	2.5	28	101.6	21.2	0.67	2.4	46	133.0	16.6	0.68
10	1.4	37	62.2	35.5	0.47	1.7	25	64.7	33.8	0.55	2.0	43	101.9	21.4	0.68
11	2.1	32	80.2	28.2	0.53	1.3	65	122.3	18.2	0.74	2.1	49	123.6	17.7	0.64
12	2.1	38	96.2	26.7	0.49	1.6	52	123.6	17.9	0.77	2.5	36	105.2	20.9	0.49
13	1.9	43	95.9	22.0	0.53	1.8	46	122.7	17.7	0.76					
14	1.8	48	104.3	21.7	0.52										
15	1.9	44	100.5	21.9	0.60										
Av	1.6	39.8	77.7	30.1	0.55	1.9	34.1	92.3	25.6	0.61	1.9	39.0	89.5	26.7	0.67
SE	0.08	1.32	4.35	1.60	0.015	0.11	3.19	6.86	2.09	0.030	0.11	2.05	7.95	2.62	0.043

Average values (Av) and standard error (SE) correspond to all irrigation events, except for the first event.

rent years in the same plots (Kruse & Heermann, 1977; Khatri & Smith, 2006). These values were considered low when compared to potential values previously reported (Bos, 1980; Elliot & Walker, 1982; Solomon *et al.*, 2007). Nevertheless, these AE values were similar or only slightly lower than those obtained under normal grower control as others have reported (Smith *et al.*, 2005). These small values were partially justified by the small D_{req} value due, in turn, to the shallow chufa plant root system (20 cm). Keller (1965) showed the effect of stored water depth on field irrigation efficiency for surface irrigation methods and presented (with actual field practices for downslope furrows in studies carried out in Idaho by C. H. Pair) efficiency values close to 10% for a stored water depth of 25 mm. The efficiency value reported by Keller (1965) was less than the values obtained in the present study.

When considering the average seasonal data, the D_{av} value increased and the AE value decreased with increasing q values. However, these relationships were not significant ($p \leq 0.05$).

The average DU_{min} values of the 2007, 2008, and 2009 irrigation events were 0.54, 0.61, and 0.67, respectively. The minimum and maximum DU_{min} registered values were 0.46 (July 10th irrigation event in 2008 coincided with the smallest D_{av} value) and 0.90 (May 18th irrigation event in 2009 coincided with the largest

D_{av} value), respectively. The DU_{min} values obtained in the first events of each season were high (0.74, 0.81, and 0.90) as a consequence of the corresponding high D_{av} values (114, 164, and 128 mm).

Optimized irrigation management

The optimization results are presented in Table 4. All of the optimized q values ranged from 0.60 to 2.40 L s⁻¹, which were between the limits for gradient furrows (0.40 to 2.50 L s⁻¹) as considered by Hart *et al.* (1980), except for the q value (2.75 L s⁻¹) corresponding to the April 28th irrigation event in 2008. In the first irrigation event of each season, the optimized q values were higher than the actual values used in the irrigation events, which was contrary to what occurred in the remaining events.

The AE and DU_{min} values followed similar trends [AE (%) being approximately 100 times DU_{min} (-)]. Therefore, all of the reported statements related to AE in this study are also applicable to DU_{min} . In the first irrigation event of each season, the maximized AE values (70.5, 66.4, and 67.2% for 2007, 2008, and 2009, respectively) were similar to those obtained by Camacho *et al.* (1997) and by Mateos & Oyonarte (2005), which were considered reasonable and satisfactory results.

Table 4. Performances of irrigations [application efficiency (AE ; %) and distribution uniformity of the minimum (DU_{min} ; -)] carried out until the first of September when the furrow inflow (q ; $L s^{-1}$) and the cut-off times (T_{co} ; min) were optimized

No.	2007				2008				2009			
	q	T_{co}	AE	DU_{min}	q	T_{co}	AE	DU_{min}	q	T_{co}	AE	DU_{min}
1	2.21	11.4	70.5	0.72	2.75	7.8	66.4	0.66	2.40	11.3	67.2	0.69
2	1.14	20.4	76.8	0.78	0.89	19.8	83.0	0.82	1.52	14.7	81.2	0.83
3	1.29	18.0	73.2	0.74	0.79	22.8	81.4	0.80	0.88	25.6	80.7	0.79
4	0.60	36.0	82.5	0.83	1.78	9.6	87.1	0.86	1.41	15.6	82.4	0.81
5	0.77	29.4	79.3	0.79	0.98	18.6	79.2	0.78	0.90	27.1	74.3	0.75
6	1.22	19.2	76.5	0.75	2.10	8.4	83.1	0.82	1.17	18.6	82.9	0.82
7	0.84	27.0	79.7	0.81	2.14	7.8	87.0	0.86	1.55	15.1	77.5	0.76
8	0.87	25.8	80.7	0.80	1.76	10.2	86.5	0.85	1.83	13.2	74.4	0.73
9	0.92	24.0	82.0	0.81	2.35	10.8	63.0	0.62	2.38	10.2	73.3	0.72
10	0.58	40.2	77.3	0.76	1.73	9.6	86.7	0.85	2.08	12.0	70.6	0.70
11	1.21	18.6	81.2	0.80								
12	1.31	18.0	78.0	0.78								
13	1.25	19.8	73.3	0.73								
Av	1.00	24.7	78.4	0.78	1.61	13.1	81.9	0.81	1.52	16.9	77.5	0.77
SE	0.12	2.21	1.02	0.01	0.21	1.77	2.75	0.03	0.18	1.84	1.69	0.02

Average values (Av) and standard error (SE) correspond to all irrigation events until the first of September, except for the first event.

In the remaining events, better results were reported (on average 78.4, 81.9, and 77.5% for 2007, 2008, and 2009, respectively), which were considerably higher than those (57.4% in a sloping furrow for a D_{req} of 80 mm, and 76.1% in a sloping furrow for a 50% cutback flow and the same D_{req}) reported by Clemmens *et al.* (2007).

Given that each irrigation event is unrepeatable, more important than knowing the specific values is to know the relation between the optimized q and T_{co} values.

For each plot these relationships (without the data of the first irrigation after planting in each year) are represented in Fig. 1 and fitted with a power law function, obtaining the following equations that related optimized T_{co} and q :

Plot with length of 66 m (2008):

$$T_{co} = 17.603 \cdot q^{-0.920} (R^2 = 0.9045; p \leq 0.01)$$

Plot with length of 82.5 m (2007 and 2009):

$$T_{co} = 22.868 \cdot q^{-0.920} (R^2 = 0.9880; p \leq 0.01).$$

Given that the curves were similar, the following single equation was also considered (a large R^2 value should permit its generalization and its utilization in a typical plot length of 60-90 m in the cultivation area):

$$T_{co} = 21.542 \cdot q^{-0.998} (R^2 = 0.8996; p \leq 0.01).$$

These equations permit T_{co} to be selected according to the q used in each event. In these cases, high AE and DU_{min} values would be obtained reaching values as

large as those shown in Table 4. With regard to the first irrigation events, q would be selected on the basis of the corresponding results shown in Table 4.

Validation

Table 5 shows the measured Q , the determined q and T_{co} , and the performance analysis parameters (AE and DU_{min}) of the three irrigation events carried out in the 2011 validation experiment. In the first irrigation event, the q value was equal to $1.64 L s^{-1}$, which was considerably lower than the optimized values for the first irrigation events presented in Table 4 (given that Q was the maximum available flow in the canal). Therefore, the T_{co} value was proportionally increased compared to the values shown in Table 4. It is advisable to use

Table 5. Measured flow (Q ; $L s^{-1}$), determined furrow inflow rate (q ; $L s^{-1}$) and cut-off time (T_{co} ; min), and performance analysis parameters [application efficiency (AE ; %), and distribution uniformity of the minimum (DU_{min} ; -)] of the three irrigation events carried out in the 2011 validation experiment

No.	Date	Q	q	T_{co}	AE	DU_{min}
1	26-5	55.9	1.64	16.5	65.8	0.81
2	16-6	52.9	1.56	15.0	75.5	0.87
3	27-6	84.0	2.47	10.0	73.8	0.78

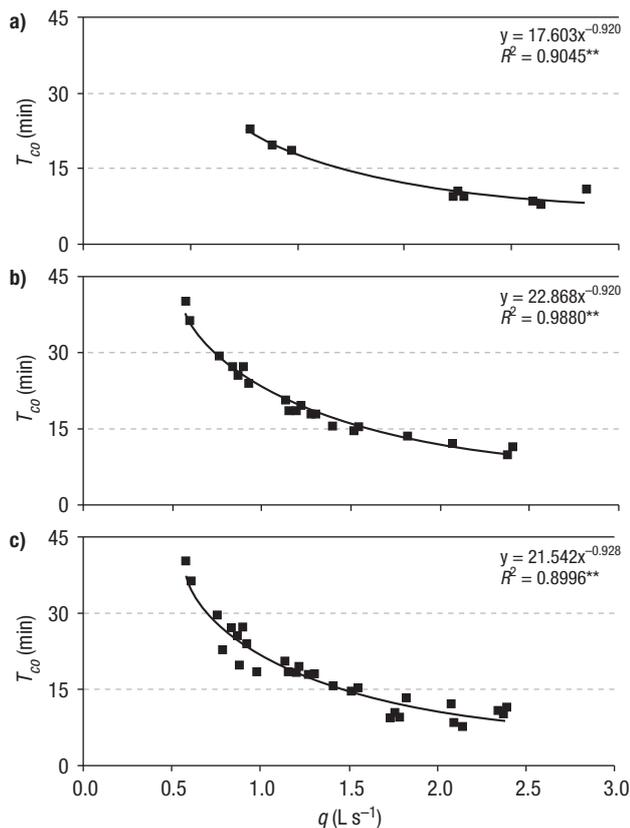


Figure 1. Relationship between optimized furrow inflow rate (q) and cut-off time (T_{co}). Values were obtained with WinSRFR 3.1 software. The graphs represent the following plot lengths: a) 66 m; b) 82.5 m; and c) 60-90 m. ** represents $p \leq 0.01$.

larger values of q , which should raise AE and DU_{min} values.

In the remaining events T_{co} was determined using the previously obtained general equation. Performance analysis resulted in large AE and DU_{min} values ($AE = 75.5\%$ and $DU_{min} = 0.87$ in the second event; $AE = 73.8\%$ and $DU_{min} = 0.78$ in the third event), which were similar to those obtained with the optimization in the same plot in 2007 (AE values ranged from 73.2 to 82.5% and DU_{min} values ranged from 0.73 to 0.83) and in 2009 (AE values ranged from 70.6 to 82.9% and DU_{min} values ranged from 0.70 to 0.83). These results validated the q - T_{co} relationship. Therefore, this relationship can be extended to most of the plots on the cultivation area as well as to other crops cultivated as part of the crop rotation with shallow root masses. This q - T_{co} relationship can improve the application efficiency in these irrigation systems, thus, leading to water savings.

As final conclusions, with the usual irrigation management of chufa crops, AE values are low mostly due to the shallow chufa plant root system. Low AE values

occurred especially in the first irrigation event of each season due to both low soil compaction and roughness of furrow beds as a consequence of the tillage operations. Using the WinSRFR 3.1 program, the q - T_{co} combination was optimized. By considering the optimized q and T_{co} values, a relationship between these parameters was obtained. This relationship was validated in 2011, which allows its use in most of the plots and crops in the cultivation area. By applying this relationship, AE and DU_{min} values would increase. Further research is needed to evaluate the water saving potential and productive response by applying the optimized q - T_{co} combination as an irrigation management strategy.

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