Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar

Spanish Journal of Agricultural Research 2011 9(2), 627-640
ISSN: 1695-971-X
eISSN: 2171-9292

Irrigation performance and gross water productivity in furrow-irrigated ornamental tree production

G. Arbat[1]*, J. Puig-Bargues[1], M. Duran-Ros[1], J. Barragan[2] and F. Ramirez-de-Cartagena[1]

[1] *Department of Chemical and Agricultural Engineering and Technology. University of Girona. Campus Montilivi, s/n. 17071 Girona. Spain*

[2] *Department of Agricultural and Forestry Engineering. University of Lleida. Alcalde Rovira Roure, 177. 25198 Lleida. Spain*

Abstract

In the ornamental plant production region of Girona (Spain), which is one of the largest of its kind in southern Europe, most of the surface is irrigated using wide blocked-end furrows. The objectives of this paper were: (1) to evaluate the irrigation scheduling methods used by ornamental plant producers; (2) to analyse different scenarios in order to assess how they affect irrigation performance; (3) to evaluate the risk of deep percolation; and (4) to calculate gross water productivity. A two-year study in a representative commercial field, planted with *Prunus cerasifera* 'Nigra', was carried out. The irrigation dose applied by the farmers was slightly smaller than the required water dose estimated by the use of two different methods: the first based on soil water content, and the second based on evapotranspiration. Distribution uniformity and application efficiency were high, with mean values above 87%. Soil water content measurements revealed that even at the end of the furrow, where the infiltrated water depth was greatest, more than 90% of the infiltrated water was retained in the shallowest 40 cm of the soil; accordingly, the risk of water loss due to deep percolation was minimal. Gross water productivity for ornamental tree production was € 11.70 m^{-3}, approximately 20 times higher than that obtained with maize in the same region.

Additional key words: blocked-end furrow; irrigation efficiency; irrigation uniformity; ornamental plant nursery

Resumen

Características del riego y productividad bruta del agua en el riego por surcos aplicado a la producción de planta ornamental

En la zona de producción de planta ornamental de Girona (España), que es una de las mayores del sur de Europa, la mayor parte de la superficie es regada por surcos. Los objetivos del presente artículo son: (1) evaluar la programación de riegos que realizan los productores de planta ornamental; (2) analizar diferentes escenarios para ver como afectan la calidad del riego; (3) evaluar el riesgo de percolación profunda; (4) calcular la productividad bruta del agua. Se realizó un estudio de dos años en un campo comercial de *Prunus cerasifera* 'Nigra'. La dosis de agua aplicada por los agricultores fue ligeramente inferior a la dosis de riego requerida estimada por dos métodos distintos: el primero basado en el contenido de agua en el suelo y el segundo en la evapotranspiración. La uniformidad de distribución y eficiencia de aplicación fueron altos, con valores medios por encima del 87%. Las medidas de contenido de agua en el suelo revelaron que al final del surco, donde la lámina de agua infiltrada fue mayor, más del 90% del agua infiltrada se retuvo en los primeros 40 cm del suelo; en consecuencia, el riesgo de pérdidas de aguas debido a la percolación profunda fue mínimo. La productividad bruta del agua en la producción de árboles ornamentales fue de 11,70 € m^{-3}, aproximadamente 20 veces mayor que la obtenida en maíz en la misma región.

Palabras clave adicionales: eficiencia de riego; productividad bruta del agua; surco bloqueado; uniformidad de riego; vivero de planta ornamental.

* Corresponding author: gerard.arbat@udg.edu
Received: 22-07-10; Accepted: 12-04-11.

Abbreviations used: *AE* (application efficiency), *CR* (cut-off ratio), *DPR* (deep percolation ratio), *DU* (low quarter distribution uniformity), ET_0 (accumulated potential evapotranspiration), FDR (frequency domain reflectometer), GLM (general linear models procedure), *GWP* (gross water productivity expressed in monetary units), IRR (irrigation event), *IWD* (infiltrated water depth), TDR (time domain reflectometry).

Introduction

The ornamental plant production sector in Girona province (north-eastern Spain) is of great economic importance. Covering an area of 1,200 ha, it is one of the most important production regions in southern Europe (Pagès, 2008). Furrow irrigation is widely used in ornamental tree plantations in the lower reaches of the Ter River (Girona province), and has special characteristics with respect to the furrow irrigation method traditionally used for other crops. For instance, in the production of ornamental species the soil is plowed to form very wide furrows, which facilitate the optimum development of the trees, and allow the movement of the machinery needed to cultivate them and exploit the full area of the field. Another specific feature of ornamental fields is the characteristic shortness of the furrows, which rarely exceed 100 m in length, allowing the farmer to control different fields at the same time. Maintaining this type of surface irrigation system under conditions of water scarcity is controversial, given that regional water management plans promote the use of microirrigation, which is generally considered to be more efficient in its use of water. However, with favourable soil conditions and adequate irrigation practices, furrow irrigation can be just as efficient as microirrigation systems (Hanson *et al.,* 1995).

In view of the lack of available technical data on this type of furrow irrigation used for ornamental tree production and the growing concern about the use of water resources of the Ter River basin and also in other areas, a detailed study of the efficiency and the gross water productivity of ornamental plant production was considered important, especially in view of its great economical importance to the region.

When evaluating the performance of a surface irrigation system, or on working towards improving its design, it is common to use simulation codes based on Saint-Venant equations. Zero-inertia or kinematic wave solutions (simplifications of the full Saint-Venant hydrodynamic model) are frequently applied.

User friendly codes such as WinSRFR (Bautista *et al.*, 2009b; USDA, 2009) or SIRMOD (Walker, 2003) are available, and have been used in numerous scientific papers. These hydraulic models can calculate the infiltrated depth along the furrow from input variables such as flow rate, irrigation time, slope of the furrow and infiltration function. Similar codes have been widely used for different purposes: (i) to assess current irrigation practices (Pereira *et al.*, 2007); (ii) to establish management recommendations in blocked-end furrows (Cahoon *et al.,* 1995); and (iii) to evaluate irrigation performance under different scenarios (Playán *et al.,* 2000).

In most of these codes, infiltration is estimated using empirical equations such as those of Kostiakov or Kostiakov-Lewis, even though they do not take into account different soil types or soil conditions (Mailhol and Merot, 2008). Other approaches have been designed to incorporate soil effects into surface and subsurface models. Mailhol (2003) and Mailhol and Merot (2008) considered soil water properties by coupling Horton's infiltration equation to the kinematic wave solution. Some existing models coupled the Saint-Venant equations for surface flow with the Richards equation for subsurface flow (Tabuada *et al.,* 1995; Saucedo *et al.,* 2005; Zerihun *et al.,* 2005; Wöhling *et al.,* 2006). Recently, Weill *et al*. (2009) used a single Richards-type equation to take into account surface and subsurface flow. Nevertheless, these sophisticated models are still cumbersome to use and, what is more, when applied they have not always provided a faithful representation of the infiltration process (Bautista *et al.,* 2009a).

Continuous measurements of soil water content in different soil locations provide detailed knowledge of the soil water distribution and evaluate the risk of water loss due to deep percolation. Mailapalli *et al*. (2008), using time domain reflectometry (TDR) in furrow irrigation, suggested that TDR measurements could be used to estimate infiltration and to manage furrow irrigation systems in real time.

In blocked-end furrows it is often advisable to terminate the inflow before the advancing water front reaches the end of the furrow, in order to reduce deep percolation loss at the end of the furrow and thus improve irrigation performance (Cahoon *et al.,* 1995). A useful tool for managing irrigation in blocked-end furrows is the cut-off ratio (*CR*), defined as the ratio of the length of the furrow covered by the advancing water front during inflow to the total length of the furrow when the irrigation is cut off. Cahoon *et al*. (1995) drew up tables showing the optimum *CR* value for different field slopes and soil textures.

Wichelns (2002) highlights the usefulness of reallocating water from lower- to higher-valued uses to improve water productivity. In areas where water is scarce, as it has been during drought periods in the Ter basin (DOGC, 2007), a sensible strategy to improve water productivity (€ m^{-3}) is to cultivate crops with a high return per unit of water (Allan, 1999; Playán and Mateos, 2006). De Juan *et al.* (2003) pointed out that water productivity can vary greatly for different crops. Ornamental trees, which are a high value product, are supposed to achieve a high return per unit of water, but there is no technical information available to confirm this.

The specific objectives of this study were to: (i) evaluate irrigation scheduling methods and the performance of the surface irrigation systems currently used by ornamental plant producers; (ii) establish different scenarios incorporating different field lengths, flow rates and cut-off criteria in order to assess how they affect irrigation performance; (iii) assess the risk of deep percolation in current irrigation practices, using measurements of soil water content; (iv) calculate gross water productivity for ornamental plant production (*Prunus cerasifera* 'Nigra') using furrow irrigation, and v) compare these values with those expected for alternative crops in the same region.

Material and methods

Description of the field experiences

The field tests were carried out in a commercial plantation of *Prunus cerasifera* 'Nigra' located in the municipality of Celrà, in the province of Girona (north-eastern Spain). The plantation had an area of approximately 0.5 ha (100 m long × 52 m wide). It was planted in February 2003 with three- and four-year-old trees with trunk circumferences of between 8 and 10 cm measured at 1 m above the ground level. The trees were planted 1 m apart in rows 1.6 m apart.

In accordance with the categories used in the soil taxonomy system of the Soil Survey Staff (2006), the soil was classified as Typic Xerofluvents with a loam-type texture. In four monitored furrows, soil samples at the inlet, at 33 m, at 66 m and at the end of the furrows were taken in 20 cm increments to a depth of 1.60 m. The soil samples confirmed a uniform loam soil profile up to a depth of approximately 1.20 m, a sandy layer was observed at that depth. The volumetric soil water contents (± SD) at –33 and –1,500 kPa from samples taken at 30, 60 and 90 cm depth were 0.341 (± 0.008) and 0.110 (± 0.022) respectively, resulting in a very high soil water holding capacity which reduced deep percolation risks. Mean soil bulk density (± SD) from 0 to 90 cm depth was 1.44 (± 0.04) g cm^{-3}.

Irrigation was carried out using furrows 100 m long with a mean slope of 0.005 m m^{-1}. The furrow width at the base was 1 m, the distance between the furrow ridges was 1.6 m, and the height of the ridge was 0.15 m, as can be seen in Figure 1. To prevent surface run-off, during irrigation the ends of the furrows were blocked with a dike made of soil.

The irrigation criterion used by the farmer was based on soil appearance (USDA, 1998) since this is the criterion most commonly used by ornamental plant producers in the region.

During 2006, four out of nine irrigation events were monitored, while in 2007 all seven irrigation events were analysed. The flow rate at the furrow inlet; the

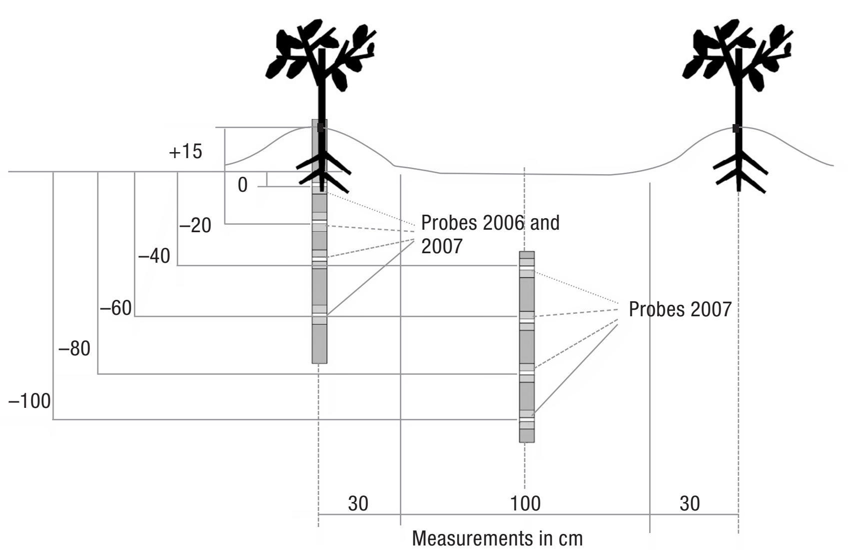

Figure 1. Furrow geometry showing the position of the soil water sensor probes and the position of the trees.

start and finishing time of the irrigation event; the advance and recession time; and the surface water depth at 1, 33, 66 and 99 m from the inlet at different times were measured in four different furrows.

The flow rate was measured as the volume of water collected with a bucket divided by the time. Its accuracy ranged from 2.5% to 5% depending on the amount of water collected during the tests. The flow rate was measured frequently to detect changes during the irrigation events.

Using frequency domain reflectometry (EnviroSCAN®), hourly measurements of soil water content were taken at 1, 33, 66 and 99 m from the inlet of one of the furrows. In 2006 measurements were taken in the ridge at depths of 0, 20, 40 and 60 cm. In 2007, these and further measurements were taken in the middle of the furrow at depths of 40, 60, 80 and 100 cm, as shown in Figure 1. The position of the sensors was conditioned by the method of cultivation. That involved working the soil with a stubble cultivator along the furrow base before each irrigation event, and meant that, in the middle of the furrow, sensors could not be installed at a soil depth of less than 40 cm.

As it will be discussed further on (see section titled «Results-Distribution of irrigation water in the soil»), the soil water sensors located at 1, 33 and 66 m from the furrow inlet at the position of the ridge showed little sensitivity to most of the irrigation events. The same happened for the sensors located deeper than 40 cm in the centre of the furrow base. Therefore only the sensors located at 1 m from the furrow extremity at 0, 20, 40 and 60 cm depth in the ridge and at 40 and 60 cm depth in the centre of the furrow base consistently reflected the soil water content changes due to the irrigation events.

The manufacturer of the frequency domain reflectometer (FDR) provided a standard calibration equation for loam soils that was used to calculate volumetric soil water content from scaled frequency values. Soil water content readings determined with the FDR showed good agreement with those obtained using the gravimetric method: when a 1:1 line was fixed, a statistically significant ($p < 0.05$) determination coefficient of 0.74 was observed.

Evaluation of the irrigation events

Every irrigation event was evaluated using measurements taken in four different furrows and by applying the WinSRFR 3.1 code (USDA, 2009). The case was simulated as a blocked-end furrow with a zero-inertia model. This would be equivalent to treating the case as having a one-metre wide border that concentrates the required irrigation water dose (D_{req}) from 1.60 m to 1.00 m.

The parameters needed to compute the irrigation performance are given below.

Water depth applied to the field

The applied water depth (D_{app}, L m^{-2}) was computed from:

$$D_{app} = \frac{Q\, t_{co}\, 60}{L\, W}\ , \qquad [1]$$

where Q is the mean flow rate in a furrow (L s^{-1}), t_{co} is the cut-off time (min), L is the length of the furrow (100 m) and W is the distance between two consecutive furrows (1.60 m).

Required or target application depth based on soil moisture

The required or target application depth (D_{req1}, mm) was calculated from:

$$D_{req1} = \left(\theta_{33} - \theta\right) d\ , \qquad [2]$$

θ_{33} being the volumetric soil water content at –33 kPa (cm^3 cm^{-3}); θ the mean volumetric soil water content (cm^3 cm^{-3}), measured at 1, 33, 66 and 99 m from the inlet, at a depth of 20 cm in the ridge; and d the effective depth of the root zone (mm).

The effective depth of the root zone was considered to be 350 mm, in accordance with the major root density observed in soil pits excavated at the same plantation.

Required or target application depth based on evapotranspiration

The required or target application depth (D_{req2}, mm) was calculated from:

$$D_{req2} = (ET_0\ K_c) - P_e\ , \qquad [3]$$

where ET_0 is the accumulated potential evapotranspiration from the previous irrigation (mm), K_c is the crop coefficient and P_e is the accumulated effective precipitation for the same period (mm), which was considered to be 80% of the total precipitation (Dastane, 1974). The precipitation data were obtained from the meteorological station at Celrà, located a few metres from the field. The values of ET_0 came from the automated meteorological station of Cassà de la Selva, since this station was able to supply all the data needed to compute the ET_0 using the Penman-Monteith method (Allen *et al.,* 1998).

A constant value of K_c equal to 1 was used for the irrigation period studied, because crop coefficient values for ornamental plants in the area were not available.

The irrigation campaign for 2006 started on 15th April and ended on 6th September (145 days); the P_e was 111 mm and the ET_0 619 mm. In 2007 the campaign began on 7th June and ended on 27th September (113 days), with a P_e and ET_0, respectively, of 117 mm and 440 mm.

Irrigation performance indexes

Irrigation performance can be quantified using parameters that measure water distribution uniformity and irrigation efficiency. The low quarter distribution uniformity (*DU*), application efficiency (*AE*) and deep percolation ratio (*DPR*) used in this paper are defined and explained by Burt *et al*. (1997). These parameters, defined as follows, were calculated using a target application depth of D_{req2}.

Distribution uniformity is characterized by *DU*:

$$DU = \frac{D_{lq}}{D_{\inf}} 100 , \quad [4]$$

where D_{lq} is the infiltrated water depth in the 25% of the field that is the least irrigated (mm) and D_{inf} is the mean infiltrated depth (mm).

Efficiency is characterized using two indexes: *AE* and *DPR*. *AE* is calculated from the equation:

$$AE = \frac{D_z}{D_{app}} 100 , \quad [5]$$

where D_z is the infiltrated water depth contributing to the target water depth (mm), and is computed as follows:

$$D_z = D_{\inf} - D_{dp} , \quad [6]$$

where deep percolation (D_{dp}, mm) is defined as the volume of infiltration beyond D_{req2} divided by the area of a furrow.

The *DPR* is defined as:

$$DPR = \frac{D_{dp}}{D_{app}} 100 , \quad [7]$$

When there is no run-off, the sum of *AE* and the *DPR* should be 100%.

Statistical analysis

The proc GLM, general linear models procedure from the SAS package v.9.2 (SAS Institute, Cary, NC, USA) was used to statistically analyse the flow rate, the irrigation dose, the irrigation performance indexes and the infiltration parameters in the four monitored furrows. To compare the different sets of means, Duncan's multiple range test was conducted, with a significance level of 0.05.

Infiltration equation and soil roughness

Infiltration was estimated using the Kostiakov equation (KE):

$$Z = K\,\tau^{a} , \quad [8]$$

where Z is the infiltration depth at time τ, and K and a are empirical parameters.

K and a were fixed in two separate steps. Previous estimates of the parameters K and a in KE were calculated from advance data using the Elliot-Walker analysis implemented in WinSRFR 3.1 code (USDA, 2009). On the basis of these previous results the parameter a was fixed at 0.1533 for each furrow and irrigation event, while the coefficient K was readjusted for each irrigation event using the characteristic infiltration depth and its corresponding duration (Bautista *et al.,* 2009a). KE was used instead of the extended Kostiakov equation (EKE):

$$Z = K\,\tau^{a} + b\,\tau , \quad [9]$$

where b is the constant infiltration rate when the infiltration time is large enough. KE was used because it is appropriate when infiltration time is relatively short (Philip, 1957), as it was the case here, and does not require that an extra empirical parameter be added to the equation. In fact, different trials were conducted using EKE and in each case the values of the extra parameter b were close to 0.

Different values of soil roughness were tested in the simulations carried out with WinSRFR 3.1 code to determine which one gave more realistic advance and recession times and flow depth readings (Bautista *et al.,* 2009a). On that basis, a roughness value of 0.04 has been taken into account in all the results presented in this work.

Making predictions using a code like WinSRFR 3.1 is risky because the results are based on empirical infiltration functions, such as KE, which are dependent on particular soil conditions, such as initial water content, and extrapolation to different conditions could give unrealistic results. Bakker *et al*. (2006) used the arithmetic means of the infiltration parameters to avoid results that were dependent on particular conditions. In the present study, the particular infiltration values for each furrow were considered in the simulations. Nevertheless, when the arithmetic means of the flow rate and parameter K (corresponding to the four measured furrows) were used to simulate each irrigation event, the irrigation performance indexes barely changed, demonstrating that the results depended very little on the particular conditions of each furrow during an irrigation event. It must be pointed out that soil conditions and flow rates were very close in all the different furrows so the infiltration parameters were expected to be similar.

Identifying scenarios to assess the influence of field length, flow rate and cut-off criteria on irrigation performance

Different scenarios were considered to extend the experimental results to other common field situations in the same irrigation district. The effects of furrow length, flow rate and *CR* were studied (Table 1).

Estimate of the infiltrated water depth from measurements of soil water content

The infiltrated water depth (*IWD*) produced by each irrigation event at 1 m from the extremity of the furrow (where the soil water sensors consistently registered the change of the soil water content due to the irrigation events), at 0, 20, 40 and 60 cm depth at the ridge and 40, 60, 80 and 100 cm depth at the furrow base, was estimated as:

$$IWD = (\theta_{\max} - \theta_i)\, h \quad , \qquad [10]$$

where θ_{max} is the maximum soil water content measured between 24 and 48 h after the irrigation event at 1 m from the extremity of the furrow (m^3 m^{-3}), θ_i was the soil water content measured before the irrigation event at 1 m from the extremity of the furrow (m^3 m^{-3}) and h the soil depth associated with a sensor (mm). The h value was 200 mm for all the measurements except for those at 40 cm depth in the centre of the furrow, where it was assumed to be 400 mm, as there were no shallower soil water content measurements (Fig. 1).

The *IWD* could be underestimated because the determination of θ_{max} did not consider evapotranspiration, which could have been important in the 24-48 hours following an irrigation event, especially at the position of the furrow ridge where the root extraction was presumably high.

Table 1. Irrigation variables considered in the current situation and in the different irrigation scenarios

Scenario	Furrow length (m)	Flow rate (L s^{-1})	Cut-off ratio (*CR*)
Current (IRR7-2007, Furrow 2)	100	1.65	1.00
Scenario 1	50	1.65	1.00
Scenario 2	200	1.65	1.00
Scenario 3	100	0.83	1.00
Scenario 4	100	3.30	1.00
Scenario 5	100	1.65	0.95
Scenario 6	200	3.30	0.86
Scenario 7	100	3.30	0.90

In scenarios 5, 6 and 7 *CR* was selected in order to maximize the distribution uniformity (DU).

Gross water productivity

The trunk circumference was measured at 1 m above the ground level in 20 selected trees located at different positions in the field. As the price of ornamental trees is a function of the trunk circumference, the gross water productivity (*GWP*) of *Prunus cerasifera* 'Nigra' was calculated from:

$$GWP = \frac{\left(P_n - P_0\right) D}{I\, n} \quad , \qquad [11]$$

where *GWP* is expressed in monetary units (€ m^{-3}), P_n the price of the tree as a function of the trunk circumference in the year n (€ tree^{-1}), P_o the price of the tree as a function of the trunk circumference corresponding to the year of planting (€ tree^{-1}), D the number of trees per hectare, n the number of years since planting, and I the irrigation dose per year (m^3 ha^{-1}). The mean value for the years 2006 and 2007 was used to compute *GWP*.

The trunk circumference in February 2003 was between 8 and 10 cm and the price (P_o) was € 36.40 tree^{-1}. In January 2007 half of the trees had a trunk circumference of between 10 and 12 cm while the circumferences of the other half were between 12 and 14 cm, with a price of € 56.80 and 81.50 tree^{-1} respectively (Vivers Planas, 2008). The mean price (P_n) was therefore taken as € 69.20 tree^{-1}.

GWP for other agricultural products was calculated to compare it with the *GWP* for ornamental trees. For other agricultural products the *GWP* was calculated as:

$$GWP = \frac{\left(Y - Y_0\right) P_p}{I} \quad , \qquad [12]$$

with Y being the yield obtained with irrigation (kg ha^{-1}), Y_0 the yield obtained without irrigation (in the climate context this value was considered to be equal to zero) , and P_p the selling price of the product (€ kg^{-1}) in the region from January to October 2008 (DAR, 2008).

Results

Required water dose, applied water dose, flow rate and the Kostiakov coefficient during the different irrigation events

The required water dose based on both methods, *i.e.* soil moisture (D_{req1}), evapotranspiration (D_{req2}) yielded very similar average values than the applied water dose (D_{app}): 58 mm, 59 mm and 55 mm respectively (Table 2). Nevertheless, in some irrigation events important differences were found between the values of D_{req1}, D_{req2} and D_{app} (Table 2).

The trees appeared very healthy over the entire field, so it can be assumed they received all the water they needed and can infer that the required doses D_{req1} and D_{req2} calculated from Equations 2 and 3 slightly overestimated their water needs.

The Q, based on all the irrigation events, was 1.17 L s^{-1}, but there were significant differences between the different irrigation events (Table 2). The D_{app} tended to increase in those events where the flow rate was higher. It is noteworthy that the lowest applied doses were given in the final irrigation events (IRR8-2006, IRR9-2006 and IRR7-2007) of each season, when the soil was not previously tilled, and cumulative infiltration was reduced, as shown in Figure 2. On the other hand, the coefficient K of the Kostiakov equation (Table 2) was smaller in irrigation events carried out without any previous soil tillage. As the soil infiltration rate decreased when the soil was not tilled, the water advanced faster along the furrow surface and the farmer's response was to reduce the flow rate.

The Q and the water dose applied did not differ significantly (with p-values of 0.916 and 0.534 respectively) between the different furrows of the field (Table 3).

Irrigation performance indexes for each irrigation event

The *DU* for each independent irrigation event (Table 4) was higher than 80%, with an average value of 87.9% and a standard deviation of ± 2.7%. On the

Table 2. Applied water dose (D_{app}), required water dose based on soil moisture (D_{req1}), required water dose based on evapotranspiration (D_{req2}), flow rate, and Kostiakov coefficient (K) for each irrigation event

Irrigation event	Date	D_{app} (mm)	D_{req1} (mm)	D_{req2} (mm)	Flow rate (L s^{-1})	K (mm h$^{-0.1533}$)
IRR6-2006	12th July	57.9^{c}	62.1	67.3	1.18^{cde}	49.8^{c}
IRR7-2006	28th July	83.0^{a}	66.0	83.7	1.13^{dfge}	69.2^{a}
IRR8-2006[1]	9th August	42.8^{d}	61.1	44.0	0.81^{g}	37.5^{ed}
IRR9-2006[1]	6th September	36.5^{de}	49.5	37.2	0.96^{fg}	33.7^{ef}
IRR1-2007	7th June	43.7^{c}	62.6	—[2]	1.24^{cd}	40.8^{d}
IRR2-2007	20th June	58.4^{c}	61.4	64.5	1.00^{fge}	50.4^{c}
IRR3-2007	4th July	55.5^{c}	60.6	56.9	1.29^{c}	50.2^{c}
IRR4-2007	23th July	69.3^{b}	61.7	86.1	1.91^{a}	64.4^{ba}
IRR5-2007	6th August	63.2^{bc}	58.5	51.0	1.63^{b}	58.2^{b}
IRR6-2007	10th September	59.6^{c}	46.8	45.7	0.92^{g}	50.6^{c}
IRR7-2007[1]	27th September	33.1^{e}	45.4	42.7	0.78^{g}	30.1^{f}
Mean	—	54.8	57.8	57.9	1.17	48.6
Std. Dev.	—	14.9	7.1	17.1	0.34	12.3

For each column, mean values for each irrigation event with the same letter are not significantly different ($p < 0.05$). [1] The soil was not tilled before irrigation. [2] It has not been possible to calculate D_{req2} for the first irrigation event because, according its definition, it needs to be computed taking into account the accumulated potential evapotranspiration from the previous irrigation event of the same irrigation season.

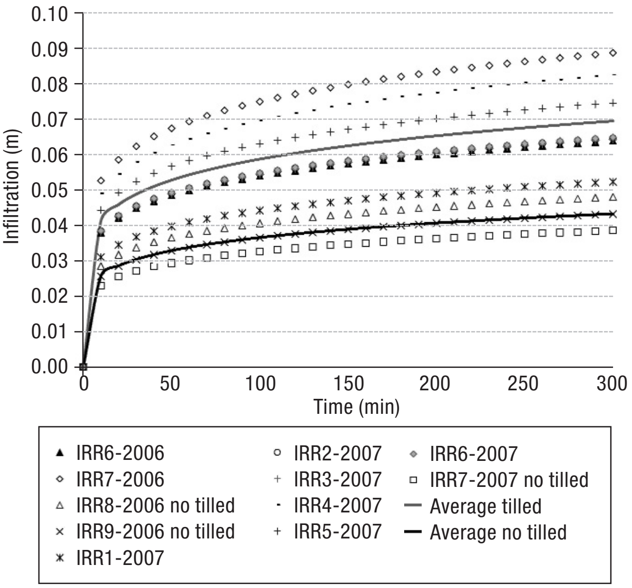

Figure 2. Infiltration curves for each irrigation event.

Table 3. Mean values of the flow rate and applied water dose (D_{app}) per irrigation event on the irrigation campaigns of 2006 and 2007

Furrow	Flow rate (L s^{-1})	D_{app} (mm)
1	1.16	52.8
2	1.20	55.1
3	1.17	56.0
4	1.15	55.2

Mean values are not significantly different ($p > 0.05$).

other hand, *AE* (Table 4) showed a mean value of 93.4% ± 7.1%.

Excluding the two irrigation events IRR5-2007 and IRR6-2007, in which the D_{app} was notably higher than the D_{req2}, the losses due to deep percolation were minimal. The average value of *DPR* was 6.6% ± 7.1%. These water losses were concentrated at the end of the furrow, where water accumulated above the soil surface after each irrigation event.

As an example, the infiltration diagram in one of the furrows for the third irrigation event in 2007 (IRR3-2007, Fig. 3-current situation) shows that in this event most of the water losses due to percolation were concentrated in the last 15 m of the furrow. The shapes of the infiltration diagrams for the other irrigation events were very similar.

Distribution of irrigation water in the soil

During the 2007 irrigation season, the evolution of the soil water content in the middle of the furrow (33 m from the furrow inlet) showed little variation beneath 40 cm of soil (Fig. 4, above). This behaviour was common at positions 1, 33 and 66 m along the furrow, which would indicate that water losses due to deep percolation were not important in most of the field. Special mention should be made at 1 m from the extremity of the furrow location, where increases in soil water content were achieved to a depth of 80 cm (Fig. 4, below). As revealed earlier, at the end of the furrow water

Table 4. Distribution uniformity of the low quarter (*DU*), application efficiency (*AE*), and deep percolation ratio (*DPR*) in the evaluated irrigation events

Irrigation event	Date	*DU* (%)	*AE* (%)	*DPR* (%)
IRR6-2006	12th July	85.1[bc]	96.7[a]	3.3[c]
IRR7-2006	28th July	81.7[c]	95.0[a]	5.0[c]
IRR8-2006[1]	9th August	90.0[ba]	92.4[ba]	7.7[cb]
IRR9-2006[1]	6th September	89.2[ba]	97.2[a]	2.8[c]
IRR1-2007	7th June	90.4[a]	—	—
IRR2-2007	20th June	88.7[ba]	97.9[a]	2.1[c]
IRR3-2007	4th July	85.6[bac]	95.3[a]	4.7[c]
IRR4-2007	23th July	90.3[a]	98.5[a]	1.5[c]
IRR5-2007	6th August	89.0[ba]	86.0[b]	14.0[b]
IRR6-2007	10th September	88.7[ba]	76.4[c]	23.6[a]
IRR7-2007[1]	27th September	88.3[ba]	98.6[a]	1.4[c]
Mean	—	87.9	93.4	6.6
Std. Dev.	—	2.7	7.1	7.1

For each column, mean values for irrigation events with the same letter are not significantly different ($p < 0.05$). [1] The soil was not tilled before the irrigation.

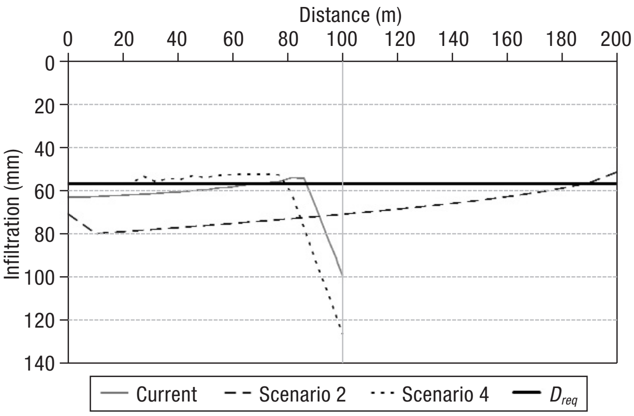

Figure 3. Infiltrated water depth *versus* the required water dose (D_{req}) for the current situation (IRR3-2007-furrow 2), scenario 2 and scenario 4.

accumulated for several hours after each irrigation event, and infiltrated deeper than in other positions. Simulations with WinSRFR 3.1 also showed a greater *IWD* than in the other positions, as can be seen in Figure 3-current situation.

Aside from the end of the furrow (at 1 m from the extremity of the furrow), the soil water content at a depth of 40 cm showed differences between the ridge and the base of the furrow, as can be seen in Figure 5-above. While the soil water content at the ridge was practically unaltered, increases were clearly observed at the base of the furrow during irrigation events and rainy periods. This would confirm that the distribution of water in the soil was two-dimensional in the plane defined by the furrow. Nevertheless, at 1 m from the extremity of the furrow, where the accumulated water depth on the surface of the soil was higher, the water content at the furrow base and ridge was very similar, as Figure 5-below shows. Therefore, it would be expected that the infiltrated water across the furrow width (1.60 m) was also similar and, consequently, the infiltration of water at 1 m from the extremity of the furrow could be considered one-dimensional.

Soil water sensors are often used in irrigation management, but in this case the sensors installed in the ridge at 1, 33 and 66 m along the furrow showed little sensitivity to most of the irrigation events and did not reflect what was happening at the furrow base. That is because the soil was not wetted in the ridge where the soil water sensors were located. On the other hand, the

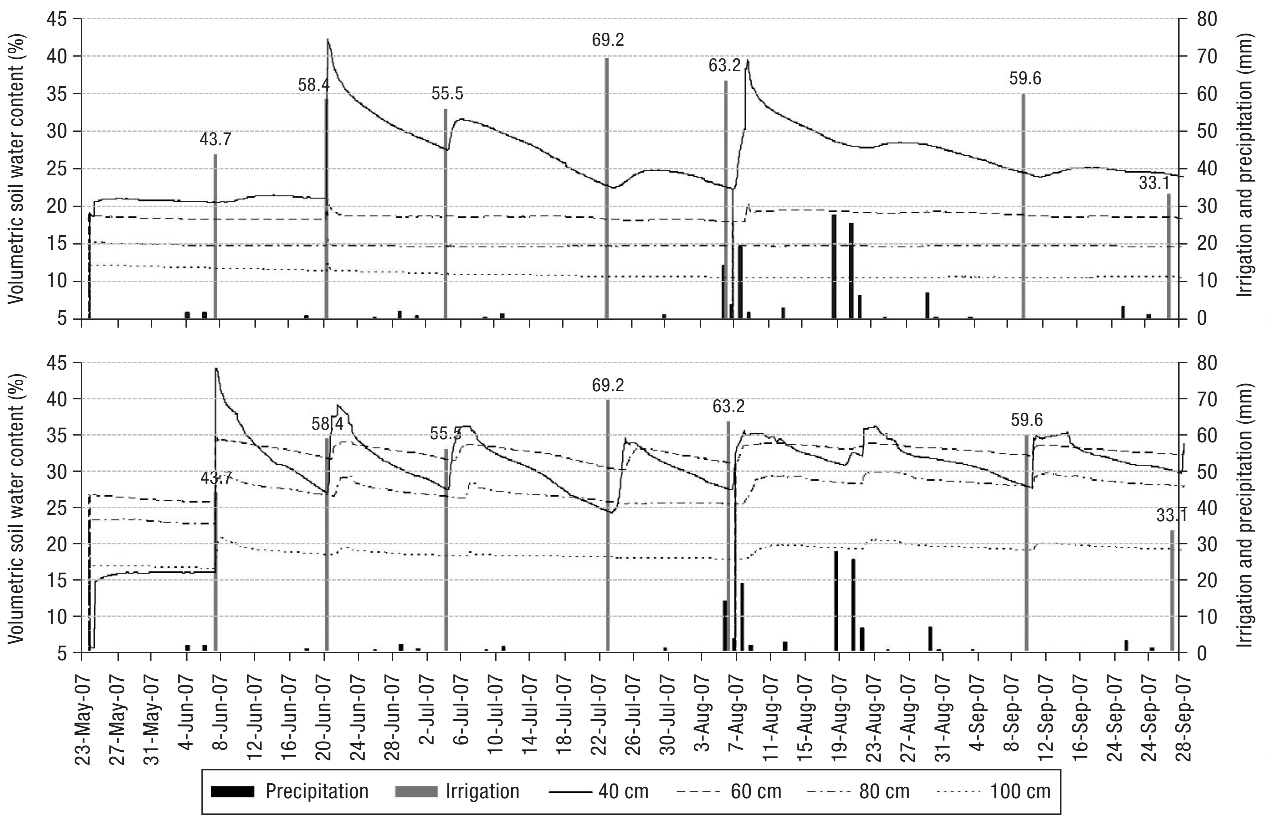

Figure 4. Evolution of soil water content in the middle of the furrow at different soil depths, at 33 m from the furrow inlet (above) and at 1 m from the extremity of the furrow (below).

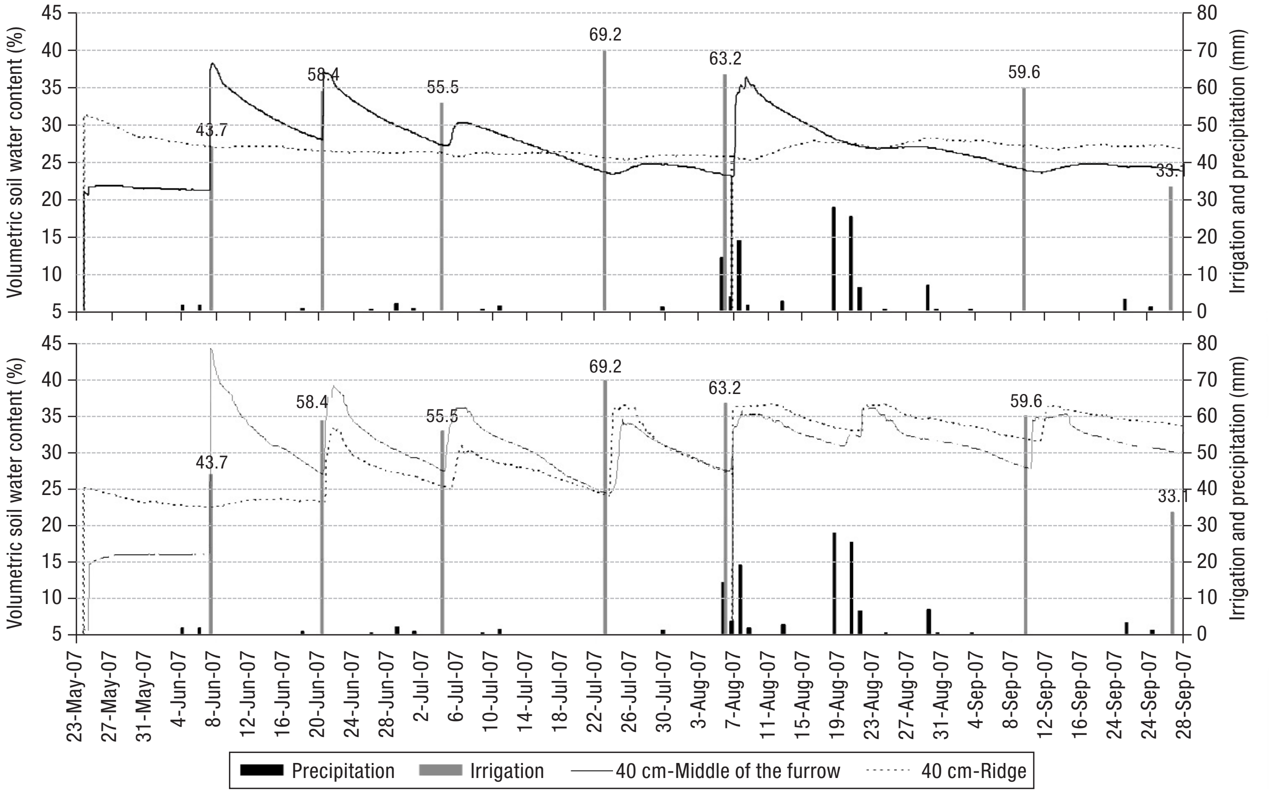

Figure 5. Evolution of soil water content in the middle of the furrow at 40 cm depth, at 1 m from the furrow inlet (above) and at 1 m of the extremity of the furrow (below).

sensors located at 1, 33 and 66 m along the furrow base were installed too deep — the shallowest sensor was at 40 cm— so they did not detect some of the irrigation events, as can be seen for instance in the first irrigation event of 2007 (Fig. 4, above). Only the soil water probes located at 1 m from the extremity of the furrow registered a change of soil water content consistent with the irrigation dose applied. The soil water probes should be installed closer than 40 cm to the surface to reflect the water dose infiltrated at the furrow base, but this was not possible here because, as explained in the materials and methods section, the soil was tilled using a stubble cultivator before most of the irrigation events.

Figure 6 presents measurements in the ridge to show how the *IWD* was distributed at the extremity of the furrow, where the water could infiltrate deeper and there was thus a higher risk of water loss due to deep percolation. From the soil water content measurements taken in the ridge at the end of all the irrigation events, following the procedure described to calculate the *IWD* in the materials and methods section, and considering all the irrigation events, it was possible to calculate that 88.6% of the infiltrated water was stored in the shallowest 20 cm, and 99.0% in the shallowest 40 cm of the soil. When the soil water content measurements at the middle of the furrow were considered, around 90% of all the infiltrated water was stored in the shallowest 40 cm of the soil.

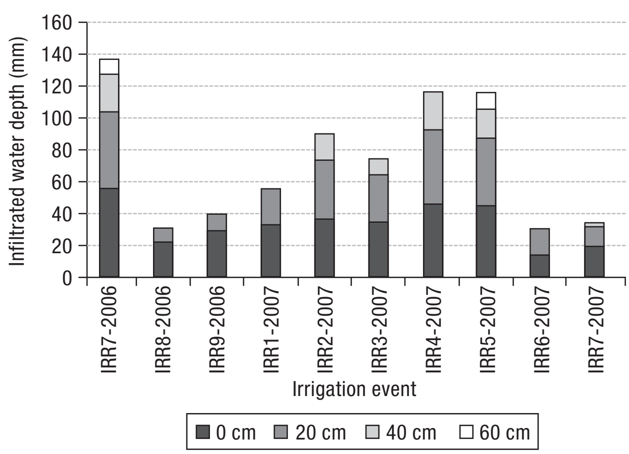

Figure 6. Distribution of infiltrated water at different depths, computed from the soil water contents measured in the ridge using FDR equipment located at 1 m from the extremity of the furrow.

Analysing scenarios: the influence of field length, flow rate and cut-off criteria on irrigation performance

The results of the simulation for each scenario are shown in Table 5.

The reduction in field length from 100 to 50 m (scenario 1) did not improve the *DU* but did increase the *AE* due to a slight reduction in the D_{app}.

When the field length was 200 m (scenario 2), the *DU* and the *AE* were smaller than the current values and the water loss due to deep percolation was higher. The irrigation time per irrigation event increased by 11% (from 108 h ha^{-1} in the current situation to 120 h ha^{-1} in scenario 2) and the D_{app} also increased by 11%. As it can be seen in Figure 3-scenario 2, water infiltrated to a greater depth near the inflow than at the end of the furrow. In this situation irrigation performance could be improved by increasing the flow rate and cutting off the irrigation before the advancing water front reaches the end of the furrow, as will be examined in scenario 6.

On the other hand, increasing the number of furrows irrigated at the same time would reduce the flow rate in every furrow, but it could potentially reduce the irrigation time in the whole field because more surface area can be irrigated at the same time. Using lower flow rates could also mean not having to manage the t_{co}, which could vary from one furrow to another due to advance variability. In scenario 3, in order to evaluate the effect of the flow rate reduction on the irrigation performance, the flow rate was half that of the current situation and the diminution of *DU* was considerable (from 90.3% to 72.1%). The irrigation time per irrigation event and furrow was approximately double that of the current situation and the D_{app} increased by 7%. Of the total applied water, 13.2% was lost due to deep percolation. Taking into account the reduction in the irrigation performance indexes, increasing the number of furrows at the expense of reducing the flow rate would not be a good alternative.

In scenario 4, when the flow rate was 3.30 L s^{-1}, twice that of the current situation, most of the water losses due to deep percolation took place at the end of the furrow (Fig. 3-scenario 4). In comparison with the current situation, the *DU* was reduced by up to 84.1% (Table 5) even though the *AE* barely changed. In this case, applying a *CR* below 1 could improve irrigation performance, as will be shown in scenario 7.

When the *CR* was 0.95 (scenario 5), the *DU* and the *AE* improved slightly in comparison with the current situation.

When the *CR* was 0.86 (scenario 6), the improvement in the *DU* and the *AE* was noticeable in comparison with scenario 2.

In scenario 7 the same variables as those used in scenario 4 were considered (100 m, 3.3 L s^{-1}), but the *CR* was 0.90. As a result the *DU* and the *AE* increased considerably and the *DPR* was reduced.

Scenarios 5, 6 and 7 showed that when the *CR* was below 1 the irrigation performance indexes improved. In these three scenarios, the *CRs* that maximized the *DU* ranged from 0.86 to 0.95. However, only in scenario 6, where the field length was 200 m, the improvements in the *DU* and the *AE* were relevant.

The current situation can be considered the standard practice of farmers in most of the irrigation events in the experimental field. Beforehand it was not known whether advancing the t_{co} would improve the irrigation performance. The results of scenario 5 showed that

Table 5. Distribution uniformity of the low quarter (*DU*), application efficiency (*AE*), and deep percolation ratio (*DPR*) for the current conditions (IRR3-07-Furrow 2) and simulated for the different scenarios

Scenario	*DU* (%)	*AE* (%)	*DPR* (%)	Irrigation time (h)	D_{app} (mm)
Current	90.3	90.3	9.7	1.73	64.2
Scenario 1	89.7	94.8	5.2	0.78	57.9
Scenario 2	84.5	81.7	18.3	3.85	71.5
Scenario 3	72.1	86.8	13.2	3.59	67.0
Scenario 4	84.1	88.9	11.1	0.85	63.1
Scenario 5	92.6	93.4	6.6	1.63	60.5
Scenario 6	89.8	94.9	5.1	1.58	58.7
Scenario 7	92.2	96.5	3.5	0.76	56.4

when the *CR* was 0.95, the *DU* and the *AE* improved in comparison with the current situation. Other *CR* values, slightly higher and lower than 0.95, were simulated (results not shown in this paper), but none of them achieved greater irrigation performance indexes than scenario 5. Therefore the optimal solution for the experimental field can be achieved with the irrigation variables of scenario 5 (*i.e.*, when *CR* was 0.95).

Scenarios 1, 2 and 6 extended the results to different field lengths. In view of the simulation results of those scenarios, it can be assumed that the irrigation performance will not be reduced for furrow lengths up to 200 m, on the condition that the flow rate is increased up to 3.30 L s^{-1} and the *CR* is around 0.85. On the other hand, a reduction of the furrow length from 100 m to 50 m would not substantially improve the irrigation performance over the current situation.

Water use and gross water productivity: comparison with other crops

In 2006, an amount of 4,946 m^3 ha^{-1} of water was applied in nine irrigation events, while in 2007 a volume of 3,827 m^3 ha^{-1} was applied in seven events.

Water costs (taking into account labour, land preparation, irrigation equipment and irrigation district costs) resulted in € 0.352 m^{-3} in 2007. The total irrigation costs per ha would be € 1349 year^{-1}, divided in: labour (€ 712 ha^{-1} year^{-1}), land preparation (€ 440 ha^{-1} year^{-1}), irrigation equipment (€ 60 ha^{-1} year^{-1}) and irrigation district costs (€ 137 ha^{-1} year^{-1}).

Discussion

An examination of the 2006 and 2007 irrigation campaigns in an ornamental plant field irrigated with blocked-end furrows showed a very high *DU* and *AE*, with mean values of 87.9% and 93.4% respectively, and with little variation during the course of the seasons. Similar values of *DU* were observed by Lecina *et al*. (2005) when evaluating furrow-irrigated fields in Zaragoza, Spain (85.7% ± 2.2%) and by Hanson *et al*. (1995) in California (81.0% ± 11.3%). Smaller uniformity values (68.0% ± 13.1%) were found by Rovira (2005) when evaluating uniformity in commercial furrow-irrigated maize fields in Girona (Spain). The *AE* found in this study can be considered very high in furrow irrigation, as according to Clemmens and Dedrick (1994) the typical efficiency range is between 60% and 80%. The shortness of the furrows, the high water-holding capacity of the soil and the uniform soil conditions throughout the field help explain the high *DU* and *AE* achieved in the irrigation events.

The required application depth calculated from soil water content readings (D_{req1}) and evapotranspiration (D_{req2}) gave similar results. The irrigation dose applied by farmers who use simple soil appearance methods to decide when to irrigate was slightly smaller than the required water dose estimated from both soil water content and evapotranspiration water balance methods.

The analysis of different scenarios showed that high performance indexes could be achieved even in furrows as long as 200 m, with the condition that the inflow rate was increased to 3.30 L s^{-1} and the *CR* was around 0.90. Cahoon *et al*. (1995) suggested that the optimum *CR* value in blocked-end furrow irrigation for loam soils with a moderate slope (0.005 m m^{-1}) was 0.89, which is in accordance with the values found here. Mailhol and Merot (2008) found that *CRs* of 0.77 and 0.85 were the optimum for border lengths of 200 and 450 m respectively. However, an advance in the t_{co} would considerably reduce irrigation performance due to incomplete irrigation at the end of the field. Playán

Table 6. Annual gross water productivity for the production of the ornamental tree *Prunus cerasifera* 'Nigra' and alternative crops in the same region

Product	Water volume (m^3 ha^{-1})	Crop yield (Mg ha^{-1})	Price (€ kg^{-1})	Gross water productivity (€ m^{-3})
Prunus cerasifera 'Nigra'	4,386[1]	—	—	11.67
'Golden' apples	4,056[2]	50[2]	0.45[4]	5.55
Maize	4,696[3]	143	0.20[4]	0.59

[1] It was calculated as the mean value of 2006 and 2007. [2] Arbat (1995). [3] Rovira (2005). [4] Mean wholesale prices in the same region in 2008 (DAR, 2008).

et al. (2000) pointed out that, when discharges are very large, the *AE* becomes very sensitive to the t_{co}.

The soil water content readings confirmed that even at the end of the furrow, where the *IWD* was the highest, more than 90% of the infiltrated water was retained in the shallowest 40 cm of the soil, meaning that water losses due to deep percolation were minimal.

According to the soil water content, the distribution of water in the soil, aside from the end of the furrow, was two-dimensional in the plane defined by the furrow, in accordance with the results of Arbat *et al*. (2007), who used Richards' equation to simulate soil water distribution under the same field conditions.

The average irrigation water use in 2006 and 2007 for ornamental plant production was 4386 m^3 ha^{-1} $year^{-1}$, similar to the 4,696 m^3 ha^{-1} used for maize (Rovira, 2005) or the 4,056 m^3 ha^{-1} for apple orchards (Arbat, 1995) in the same region.

Allan (1999), Wichelns (2002) and Playán and Mateos (2006) pointed out that improving water productivity is one of the most effective ways to confront water scarcity situations. This could be achieved by switching agricultural water use to another sector, such as services or industry, which would show higher economic returns per unit of water. A less dramatic change, from the environmental and social point of view, would be to cultivate crops with a greater return per unit of water. Obviously, ornamental tree production has a limited demand and only a restricted area of the irrigated land in the region can be devoted to this production. De Juan *et al*. (2003) showed that economic water productivity can vary by a factor of almost 20 between different crops. The *GWP* for the ornamental tree *P. cerasifera* 'Nigra' was € 11.70 m^{-3}, and for apple trees and maize, alternative crops in the same region, it was € 6.60 and 0.60 m^{-3} respectively (Table 6). As can be seen, the *GWP* varies greatly between different crops; ornamental crops can double the *GWP* obtained from fruit trees and be almost 20 times higher than that obtained from maize production.

Acknowledgements

The authors would like to thank the *Associació de Viveristes de Girona* (Girona Association of Nurseries) and particularly the *Vivers Planas* nursery for permission to use their field to carry out the irrigation experiments, and also for their collaboration during the field tests. They would also like to thank Dr. Enrique Playán (CSIC, Experimental Station of Aula Dei, Zaragoza), for his valuable advice and suggestions.

References

ALLAN T., 1999. Productive efficiency and allocative efficiency: why better water management may not solve the problem. Agric Water Manage 40(1), 71-75.

ALLEN R.G., PEREIRA L.S., RAES D., SMITH M., 1998. Crop evapotranspiration guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy. 300 pp.

ARBAT G., 1995. Incidència de la dosi de reg en els paràmetres vegetatius, productius i qualitatius de la pomera Golden. B Sc Thesis. Escola Politècnica Superior, Universitat de Girona, Girona. 77 pp. [In Catalan].

ARBAT G., PUIG-BARGUÉS J., DURAN-ROS M., BARRAGÁN J., RAMÍREZ DE CARTAGENA F., 2007. Distribución del agua en el suelo en riego por superficie: aplicación del código HYDRUS. Proc VIII Jornadas de Investigacion de la Zona no Saturada del Suelo Córdoba, Spain, Nov 14-16. 305-311. [In Spanish]

BAKKER D.M., PLUNKETT G., SHERRARD J., 2006. Application efficiencies and furrow infiltration functions of irrigations in sugar cane in the Ord River Irrigation Area of North Western Australia and the scope for improvement. Agric Water Manage 83(1-2), 162-172.

BAUTISTA E., CLEMMENS A.J., STRELKOFF T.S., 2009a. Structured application of the two-point method for the estimation of infiltration parameters in surface irrigation. J Irrig Drain Eng 135(5), 566-578.

BAUTISTA E., CLEMMENS A.J., STRELKOFF T.S., SCHLEGEL J., 2009b. Modern analysis of surface irrigation systems with WinSRFR. Agric Water Manage 96(7), 1146-1154.

BURT C.M., CLEMENS A.J., STRELKOFF T.S., SOLOMON H., BLIESNER R.D., HARDY L.A., HOWELL T.A., EISENHAUER D.E., 1997. Irrigation performance measures: efficiency and uniformity. J Irrig Drain Eng 123(6), 423-442.

CAHOON J.E., MANDEL P., EISENHAUER D.E., 1995. Management recommendations for sloping blocked-end furrow irrigation. Appl Eng Agric 11(4), 527-533.

CLEMMENS A.J., DEDRICK A.R., 1994. Irrigation techniques and evaluations. In: Advances series in agricultural sciences (Tanji K.K., Yaron B., eds). Springer, Berlin, Germany. pp. 64-103.

DAR, 2008. Preus dels productes agrícoles en llotges i mercats. Available on line in: http://www20.gencat.cat/portal/site/DAR/ [29th June 2010]. [In Catalan].

DASTANE N.G., 1974. Effective rainfall in irrigated agriculture. Irrigation and Drainage Paper 25, Food and Agriculture Organization of the United Nations (FAO). Rome, Italy. 67 pp.

DE JUAN J.A., ORTEGA J.F., TARJUELO J.M., 2003. Sistemas de cultivo. Evaluación de itinerarios técnicos. Ed Mundi-Prensa, Madrid, Spain. 836 pp. [In Spanish].
DOGC, 2007. Catalan Drought Regulation 84/2007, of 3 April, that adopts exceptional and emergency measures in relationship with the use of the water resources. Diari Oficial de la Generalitat de Catalunya. No. 4860, 12/04/2007. [In Catalan].
HANSON B., BOWERS W., DAVIDOFF B., KASAPLIGIL D., CARVAJAL A., BENDIXEN W., 1995. Field performance of microirrigation systems. In: Microirrigation for a changing world. Proc Fifth Int Microirrigation Congress, Am Soc Ag Engineers, Orlando, FL, April 2-6. pp.769-774.
LECINA S., PLAYÁN E., ISIDORO D., DECHMI F., CAUSAPÉ J., FACI J.M., 2005 Irrigation evaluation and simulation at the Irrigation District V of Bardenas (Spain). Agric Water Manage 73(3), 223-245.
MAILAPALLI D.R., RAGHUWANSHI N.S., SINGH R., SCHMITZ G.H., LENNARTZ F., 2008. Evaluation of time domain reflectometry (TDR) for estimating furrow infiltration. Irrig Sci 26(2), 161-168.
MAILHOL J.C., 2003. Validation of a predictive form of Horton infiltration for simulating furrow irrigation. J Irrig Drain Eng 129(6), 412-421.
MAILHOL J.C., MEROT A., 2008. SPFC: a tool to improve water management and hay production in the Crau region. Irrig Sci 26(4), 289-302.
PAGÈS J.M., 2008. La producción de plantas de vivero en Girona. Horticultura 204, 42-49. [In Spanish].
PEREIRA L.S., GONÇALVES J.M., DONG B., MAO Z., FANG S.X., 2007. Assessing basin irrigation and scheduling strategies for saving irrigation water and controlling salinity in the upper Yellow River Basin, China. Agric Water Manage 93(3), 109-122.
PHILIP J.R., 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Sci 84, 257-264.
PLAYÁN E., MATEOS L., 2006. Modernization and optimization of irrigation systems to increase water productivity. Agric Water Manage 80(1-3), 100-116.
PLAYÁN E., SLATNI A., CASTILLO R., FACI J.M., 2000. A case study for irrigation modernisation: II Scenario analysis. Agric Water Manage 42(3), 335-354.
ROVIRA L., 2005. El reg superficial per solcs al Baix Empordà: avaluació, diagnòstic i recomanacions. B Sc Thesis. Escola Politècnica Superior, Universitat de Girona, Girona. 108 pp. [In Catalan].
SAUCEDO H., FUENTES C., ZAVALA M., 2005. El sistema de ecuaciones de Saint-Venant y Richards del riego por gravedad: 2. Acoplamiento numérico para la fase de avance en el riego por melgas. Ingeniería Hidráulica en México 20(2), 109-119. [In Spanish].
SOIL SURVEY STAFF, 2006. Keys to soil taxonomy, 10th ed. Natural Resources Conservation Service, USDA. Washington DC. 333 pp.
TABUADA M.A., REGO Z.J.C., VACHAUD G., PEREIRA L.S., 1995. Modelling of furrow irrigation. Advance with two-dimensional infiltration. Agric Water Manage 28(3), 201-221.
USDA, 1998. Estimating soil moisture by feel and appearance. USDA, NRCS. Available on line in http://www.mt.nrcs.usda.gov/technical/ecs/agronomy/soilmoisture/index.html. [6th May 2010].
USDA, 2009. WinSRFR 3.1 Help and Manual – Surface irrigation analysis, design and simulation. USDA/ARS/Arid-Land Agricultural Research Center. Maricopa, Arizona. 188 pp.
VIVERS PLANAS, 2008. Listado de precios 2007/2008, Vivers Planas SL, Celrà, Spain. 83 pp. [In Spanish].
WALKER W.R., 2003. SIRMOD III, Surface irrigation simulation software, evaluation and design. Guide and technical documentation. Dept Biol Irrig Eng, Utah St Univ Logan, UT, USA. 138 pp.
WEILL S., MOUCHE E., PATIN J., 2009. A generalized Richards equation for surface/subsurface flow modelling. J Hydrol 336(1), 9-20.
WICHELNS D., 2002. An economic perspective on the potential gains from improvements in irrigation water management. Agric Water Manage 52(3), 233-248.
WÖHLING T., FRÖHNER A., SCHMITZ G. H., LIEDL R., 2006. Efficient solution of the coupled one-dimensional surface – Two-dimensional subsurface flow during furrow irrigation advance. J Irrig Drain Eng 132(4), 380-388.
ZERIHUN D., FURMAN A., WARRICK A.W., SÁNCHEZ C.A., 2005. A coupled surface-subsurface flow model for improved basin irrigation management. J Irrig Drain Eng 131(2), 111-128.