Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)
Available online at www.inia.es/sjar
http://dx.doi.org/10.5424/sjar/2013112-2902

Spanish Journal of Agricultural Research 2013 11(2), 529-546
ISSN: 1695-971-X
eISSN: 2171-9292

Limitations to adopting regulated deficit irrigation in stone fruit orchards: a case study

N. Zapata[1]*, E. Nerilli[2], A. Martinez-Cob[1], I. Chalghaf[3], B. Chalghaf[4], D. Fliman[1] and E. Playan[1]

[1] *Department of Soil and Water, EEAD-CSIC. Zaragoza, Spain*
[2] *Instituto Agronomico Mediterraneo di Bari, IAMB. Bari, Italy*
[3] *Department of Soil and Irrigation, CITA-DGA. Zaragoza, Spain*
[4] *Département de Géomatique Appliquée. Faculté des Lettres et Sciences Humaines. Université de Sherbrooke. Quebec, Canada*

Abstract

Fruit production development is resulting in large commercial orchards with improved water management standards. While the agronomic and economic benefits of regulated deficit irrigation (RDI) have long been established, the local variability in soils and climate and the irrigation system design limits its practical applications. This paper uses a case study approach (a 225 ha stone fruit orchard) to unveil limitations derived from environmental spatial variability and irrigation performance. The spatial variability of soil physical parameters and meteorology in the orchard was characterized, and its implication on crop water requirements was established. Irrigation depths applied during 2004-2009 were analysed and compared with crop water requirements under standard and RDI strategies. Plant water status was also measured during two irrigation seasons using stem water potential measurements. On-farm wind speed variability amounted to 55%, representing differences of 17% in reference evapotranspiration. During the study seasons, irrigation scheduling evolved towards deficit irrigation; however, the specific traits of RDI in stone fruits were not implemented. RDI implementation was limited by: 1) poor correspondence between environmental variability and irrigation system design; 2) insufficient information on RDI crop water requirements and its on-farm spatial variability within the farm; and 3) low control of the water distribution network.

Additional key words: drip irrigation evaluation; irrigation requirements; stem water potential; wind spatial variability.

Introduction

Fruit production development in Spain and in many other countries of the world is resulting in large orchards with high management standards. Proper irrigation design and management are required in these areas to guarantee the quality demanded by the market and to ensure sustainability.

Regulated deficit irrigation (RDI) strategies have received relevant interest in the literature as tools to achieve significant reductions in irrigation water use. RDI was developed in Australia in peach and pear

* Corresponding author: v.zapata@csic.es
Received: 22-03-12. Accepted: 22-03-13.

Abbreviations used: $DU_{lqGlobal}$ (global low quarter distribution uniformity); $DU_{lqOther}$ (low quarter distribution uniformity due to other causes); $DU_{lq\Delta p}$ (low quarter distribution uniformity due to differences in emitter pressure); EMP (early maturing peach); *ETc* (crop evapotranspiration, mm); *ETo* (reference crop evapotranspiration, mm); FI to FIV [fruit growth stages for peach (Naor, 2006)]; *GIR* (gross irrigation requirements, mm); *K* (parameter); K_a (parameter for the estimation of $\mathrm{DU}_{\mathrm{lqGlobal}}$); *Kc* (crop coefficient); $\mathrm{Kr}_{\mathrm{RDI}}$ (reduction coefficient for regulated deficit irrigation); MAE (mean absolute error); LMP (late maturing peach); *MIT* (measured irrigation time, h); MMP (medium maturing peach); *n* (number of emitters per tree); *NIR* (net irrigation requirements, mm); *p* (operating pressure, kPa); *q* (emitter flow rate, L h^{-1}); RAW (readily available water); RDI (regulated deficit irrigation); RMSE (root mean square error); *SID* (scheduled irrigation depth, mm); *SIT* (scheduled irrigation time, h); Std (standard irrigation management); *SWP* (stem water potential, MPa); VC_{IA} (variation coefficient intra-irrigations); VC_{IE} (variation coefficient inter-irrigations); *x* (exponent).

orchards (Chalmers *et al*., 1981; Mitchell *et al*., 1986). This advanced technique is based on the fact that plant sensitivity to water stress varies between phenological stages and that water stress at specific periods of vegetative growth can help control growth and vegetative-fruit competition (Chalmers *et al*., 1981; Mitchell & Chalmers, 1982; Cameron *et al*., 2006). Fereres & Soriano (2007) reported that RDI has enjoyed more success in tree crops and vines than in field crops.

Practical protocols are required for farmers to apply such advanced irrigation techniques. Farmers require answers to issues such us: what are the standard crop water requirements, when to apply deficit irrigation, and how much deficit to apply in comparison to the standard requirements. A number of references have reported on deficit irrigation experiments in orchards. The large variability in soil, meteorology, crop species, varieties and irrigation treatments of the reported scientific work, difficult the elaboration of practical procedures for implementing RDI in commercial orchards.

The establishment of commonly accepted local, standard crop water requirements is the basis for the application of deficit irrigation techniques. The FAO-56 method (Allen *et al*., 1998), despite its maturity, greatly benefits from experimental testing and adjustment. Experimentation leading to the determination of local crop coefficients is very much needed in regions specialized in fruit production, since Kc recommendations are often site and year specific, and have been reported to depend on local reference crop evapotranspiration (ETo) rates, rainfall, and crop management practices (Snyder *et al*., 2000). In addition, research leading to the determination of the local duration of the different periods and their adjustment through different growing seasons is much needed.

Regarding irrigated agriculture, wind speed plays a relevant role in the estimation of reference evapotranspiration and crop water requirements, especially in windy areas such as the Ebro Valley (Martínez-Cob & Tejero, 2004; Martínez-Cob *et al*., 2010). Wind spatio-temporal variability is much higher than that of other meteors of agricultural interest, such as air temperature and relative humidity (Martínez-Cob *et al*., 2010). The Spanish network of agrometeorological stations (SIAR, www.magrama.gob.es/siar/informacion.asp) covers most of the irrigated areas in Spain and provides records that are assumed to be representative of a certain homogenous area surrounding the station. When promoting advance irrigation techniques, especially in windy areas, the representativeness of the meteorological available data should be analyzed.

The stress-tolerant phases in peach have been identified as stage II, the lag phase of fruit growth (Chalmers *et al*., 1981), and postharvest (Johnson *et al*., 1992). Several authors have proposed different levels of deficit irrigation depending on soil characteristics (Girona *et al*., 2005) and different periods of deficit depending on peach cycles (Goldhamer *et al*., 2002; Gelly *et al*., 2004; Dichio *et al*., 2007; for early, medium and late maturing peaches, respectively). Girona *et al.* (2003) reported that water deficit during postharvest for peach orchards should be carefully managed to avoid reduction in bloom and fruit loads during the subsequent growing season. The sustainability of RDI imposes limits to the magnitude of water stress.

Antunez-Barria (2006) reported that sweet cherries showed tolerance to mild water stress. As a consequence, these authors saw potential to adopt deficit irrigation strategies to commercial production systems. However, research has been scarce on the deficit level that should be applied. For instance, Marsal *et al.* (2009) suggested reducing 50% of crop water requirements at postharvest. Papenfuss & Black (2010) applied different levels of deficit from pit hardening to harvest on tart cherries. These authors reported that the concentration of soluble solids and the color (chroma) of intact fruit increased with the severity of the irrigation deficit and were inversely correlated with fruit water content.

In apricot, in the absence of dwarfing rootstocks, several management practices aiming at controlling vegetative growth have been analyzed, with RDI resulting particularly successful (Arzadi *et al*., 2000). Torrecillas *et al.* (2000) studied the effect of deficit irrigation during different apricot phenological stages (stages I, II and postharvest). These authors stated that withholding irrigation during fruit growth periods (stages I and II) decreased the fruit growth rate. However, when irrigation was restored a compensatory fruit growth rate was observed.

The success of RDI techniques strongly depends on the appropriate use of on-farm irrigation systems. In the last two decades, drip irrigation has become very popular in fruit productive areas. Irrigation evaluation procedures for drip systems have evolved following technological developments. Merriam *et al.* (1973) developed one of the first field evaluation manuals for drip irrigation systems. The Irrigation Training and Research Centre (ITCR, San Luis Obispo, CA, USA) standardized procedures for drip irrigation system evaluation (Burt, 2004), defining uniformity components for a complete irrigation system.

Salvador *et al.* (2011), analyzing crop water requirements and its application in the Ebro valley of Spain, reported that deficit irrigation (not necessarily RDI) is becoming common in the local peach and cherry orchards. There are not many references in the literature quantifying the overtaking of these irrigation practices in commercial orchards, on how farmers are adopting advanced irrigation techniques and on which are the limitations to implement them. The research reported in this paper was supported by a 225 ha case study stone fruit orchard located in the Ebro valley. The orchard had high management standards, and counted on a professional, full-time irrigation manager. The general objective of this paper was to establish the limitations imposed by environmental variability and irrigation performance on the adoption of RDI at the orchard level. Specific objectives were: 1) to assess the variability in soil water retention; 2) to characterize the small-scale spatial variability of meteorological variables affecting reference evapotranspiration; 3) to assess irrigation performance at the different cropping zones of the study orchard; 4) to characterize the theoretical irrigation water requirements for the different crops of the farm, under standard and RDI strategies, accounting with the literature and the environmental variability of the study case; and 5) to compare them with the applied irrigation depths.

Material and methods

The case study

The case study for this research was *La Herradura* stone fruit orchard (225 ha), located in Caspe (Zaragoza, north eastern Spain). Geographical coordinates are 41° 17' N latitude and 0° 00' 08" E longitude. This orchard was selected as representative of high management standards, and can be illustrative of modern fruit orchards in an international context. The orchard is located next to a meander of the Ebro River, flooded by the *Mequinenza* dam. The orchard topography is quite rough, with elevation ranging from 120 to 200 m above mean sea level. The crops at the orchard included cherry (*Prunus avium*, 44 ha), apricot (*Prunus armeniaca*, 29 ha) and peach (*Prunus persica*, 154 ha). Peach trees were divided in early maturing peach (EMP, 51 ha), medium maturing peach (MMP, 51 ha) and late maturing peach (LMP, 52 ha). Fig. 1 presents the crop distribution in *La Herradura* farm.

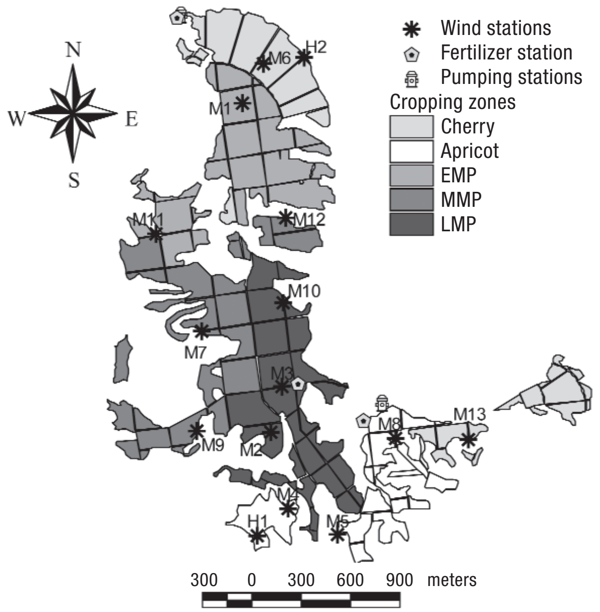


Figure 1. Map of the different fruit tree cropping zones (apricot, cherry, early maturing peach, medium maturing peach and late maturing peach). The location of the two landmark points H1 and H2 and the wind measurement points M1 to M13 is also presented.

The irrigation system is divided in 88 drip irrigated areas (irrigation subunits), each of them commanded by an automated valve: 8 for cherry, 18 for apricot, 16 for the EMP, 22 for MMP and 24 for LMP. Each irrigated area was planted to the same fruit species (and cycle, in the case of peach). However, a number of cultivars could be planted in the same area, resulting from pollination, labor demand and commercial requirements. As a consequence, a total of 55 fruit tree cultivars were cultivated at the orchard.

According to the irrigation manager, water availability was not a problem, and the pumping cost was not relevant within the general farming costs. The manager declared to implement deficit irrigation techniques to control vegetative growth and to improve fruit quality. The manager uses the design discharge of each valve to schedule the irrigation time of each irrigated area and declared to use evapotranspiration information provided by the regional irrigation advisory service to devise a weekly irrigation schedule. Only at the general pipe of the pumping stations a water metering device was installed. This measuring device was used by the irrigation manager to test the discharge of the set of valves under simultaneous operation.

At each irrigated area, the irrigation layout was as follows: manifolds supplied water from the valve to the irrigation laterals. Laterals branched from the manifold on one side or —more commonly— on both sides. Two laterals were used to irrigate each line of trees, one lateral at each side of the line. Turbulent (non pressure compensating) emitters were used at the orchard, with a design discharge of 4 L h^{-1}. Emitters were extruded in the polyethylene irrigation laterals at 1 m intervals. As a consequence of the different plating spacing, the number of emitters per tree was variable (from 5 to 9).

Soil physical properties

A non-structured soil sampling campaign was performed at the orchard. A total of 88 soil samples (0.28 samples ha^{-1}) were manually drilled until a soil depth (d) of 1.2 m if possible. The coordinates of the sampling point and the sampling depth were systematically recorded using a handheld GPS. A subsample was weighted, milled and passed through a 2 mm sieve. Volumetric stoniness (S, %) was determined for each sample from the weigh of fractions above and below 2 mm, soil bulk density (ρ_b, Mg m^{-3}) and the stone density. Soil bulk density and stone density were estimated as 1.40 and 2.65 Mg m^{-3}, respectively, in agreement with previous works in the area (Playán *et al.*, 2000). Gravimetric field capacity (FC, %) and wilting point (WP, %) were estimated at the laboratory using pressure plates (Hanks, 1992). Pressures of 0.03 and 1.5 MPa were considered representative of FC and WP, respectively. The readily available water (RAW, mm) was determined as:

$$RAW = \frac{2}{3}\, d\, \frac{\rho_b}{\rho_w}\, \frac{(FC - WP)}{100} \left(\frac{100 - S}{100}\right) 1000 \quad [1]$$

The analysis of stoniness revealed very large differences among samples. These differences corresponded to different soil units, whose limits could be easily recognized in the field. A thematic map for soil stoniness was produced based on GPS recorded observations of soil unit discrete limits. These limits often corresponded to the changes in strata responding to changes in soil surface elevation.

Wind speed and reference evapotranspiration

Wind speed variability within the orchard was characterized using three types of weather stations: 1) the *reference station* (SIAR network), located at about 10 km northwest of the orchard, and considered representative of the area at a sub-regional scale; 2) two *landmark stations* (H1 and H2), considered representative at a local scale; and 3) the *movable station*, which was installed for short periods of time at 13 different locations within the orchard (called M1 to M13, Fig. 1). This station was used for a detailed study of wind variability, since wind speed was identified in this work as the principal source of spatial variability of reference evapotranspiration within the orchard. A preliminary analysis of the time variability of wind speed and direction in the area was performed using the data series available at the SIAR *reference station* (from January 2004 to December 2009).

The two *landmark weather stations* were installed at two spots with maximum and minimum elevation within the orchard, with the goal of characterizing extreme local meteorological variability (Fig. 1). These two stations, H1and H2, were installed at an altitude of 175 m and 125 m above mean sea level, respectively. Both stations recorded data from August 2007 to September 2009, with the exception of the period May to September 2008, during which station H2 was used as a *movable station* (see below). Spot H1 was more exposed to wind than spot H2.

Both *landmark stations* were equipped with a data logger and sensors to measure air temperature, air relative humidity, incoming solar radiation and wind speed and direction. Precipitation was only recorded at H1. The brand and models of these sensors were the same as those in the SIAR *reference station* (www.magrama.gob.es/siar/descripcion.asp). Only the wind measurement sensor differed: a propeller-type anemometer was used at the SIAR reference station (Young's Model 05103, Campbell scientific, Inc., Shepshed, Leicestershire, UK), while 3-cup-rotor anemometers (model A100R, Vector InstrumentsTM, Rhyl, UK) were installed at the *landmark weather stations* (H1 and H2). Sensors were monitored every 10 s, half-hour and daily averages were stored in the data logger memory for further analysis. The meteorological variables recorded at both *landmark stations* for the periods August 2007 to April 2008 and September 2008 to September 2009 were compared using simple linear regression analyses. The statistics used to assess the regressions were the coefficient of determination (R^2), the root mean square error (RMSE, data not presented) and the mean average error (MAE, data not presented). Statistical significance was assessed at the

0.05 probability level. Among the recorded meteorological variables, only wind speed showed significant, relevant differences between H1 and H2. As a consequence, further efforts were made to characterize its spatial variability at the orchard.

During the period of May to September 2008, station H2 was used as the *movable station*. This station was moved around the orchard in order to analyze in more detail the spatial variability of wind speed within the orchard. The *movable station* was installed at 13 different sites (M1 to M13, Fig. 1) for an average period of one week each. It recorded half-hour averages of wind speed and direction, and these values were compared with the simultaneous records collected at the *landmark station* H1 using simple linear regression analysis (referred to as *on-farm* regressions), considering the H1 records as the independent variable. The Measure-Correlate-Predict technique (Derrick, 1993; Sánchez *et al.*, 2011) was used to estimate long-term wind speed at the 13 measurement sites. The technique is based on relating the short-term wind speeds measured at the prediction site to those recorded at a long-term reference site. Different correlations were established at each measurement site for the predominant wind speed directions.

Additional simple linear regressions were performed between the half-hour records of wind speed at the SIAR *reference station* on one hand, and at the different measurement points within the orchard (H1, H2, and M1 to M13), on the other. These were referred to as *off-farm* regressions. In this case, the SIAR records were used as independent variable and the *on-farm* measurements as dependent variable.

The wind speed variability was used to estimate daily ETo, following the FAO Penman-Monteith approach (Allen *et al.*, 1998) for the period 2004 to 2009 and at the different on-farm measurement sites (H1, H2 and M1 to M13). For these computations, daily meteorological variables recorded at the reference SIAR station were used at each measurement site, except for the wind speed, whose values were estimated using the local linear relationships.

Irrigation requirements

Crop evapotranspiration for standard (ETc_{Std}) and regulated deficit irrigation (ETc_{RDI}) conditions was estimated for the different crops of the study orchard following Eqs. [2] and [3], respectively. Average ETo was determined for each cropping zone (Fig. 1) accounting for the wind speed spatial variability and for the period of 2004-2009. In this work the Kc values estimated by García-Vera & Martínez-Cob (2004) were used. These authors used the single Kc FAO-56 method (Allen *et al.*, 1998) adapting them to the local climatic conditions of the Ebro river basin. Following García-Vera & Martínez-Cob (2004), the four crop stages required for the application of the FAO 56 methodology were defined as: 1) initial stage, from bud swelling to start of flowering; 2) development stage, from flowering to pit hardening; 3) mid-season stage, from pit hardening to ten days after harvest and 4) late-season stage, from ten days after harvest to leaf fall.

$$ETc_{Std} = Kc^{*}\ ETo \quad [2]$$

$$ETc_{RDI} = Kc^{*}K_{rRDI}{}^{*}ETo \quad [3]$$

In addition to the crop stages, fruit growth stages are commonly used to select the appropriate timing of RDI practices (Naor, 2006): 1) stage FI, from bloom to beginning of pit hardening; 2) stage FII, from beginning to end of pit hardening; 3) stage FIII, from pit hardening to fruit ripening (harvest); and 4) stage FIV, from harvest to leaf fall (postharvest), divided into early and late postharvest phases (before and after September 1). A seasonal RDI schedule results from the overlapping of crop and fruit growth stages, and from the use of crop coefficients and deficit irrigation coefficients (Eq. [3]).

Local observations of the duration of the phenological stages for 21 cultivars of cherry, 6 cultivars of apricot, 12 cultivars of EMP, 11 cultivars of MMP and 7 cultivars of LMP were provided by the orchard irrigation manager for 2008 and 2009. The manager followed the BBCH methodology (Bleiholder *et al.*, 1989) to establish the different crop and fruit development stages. Average durations were determined for the crops and for the two years of available data.

Reduction coefficients for the RDI irrigation strategies (Kr_{RDI}) were established following Girona *et al.* (2003, 2005) for peaches, Marsal *et al.* (2009) for cherries, and Pérez-Pastor *et al.* (2009) and Pérez-Sarmiento *et al.* (2010) for apricots. Table 1 presents the Kr_{RDI} values summarized from the cited works. For cherry, apricot and early maturing peach, the RDI strategy reduced water application only at postharvest stage (FIV). For medium and late maturing peach, the adopted RDI strategy reduced water application at fruit growth stages FII and FIV (pit hardening and postharvest, respectively).

Table 1. Reduction coefficients for the RDI strategy (K_{rRDI}) at different fruit growth stages for cherry, apricot, early maturing peach (EMP), medium maturing peaches (MMP) and later maturing peaches (LMP)

Crop	K_{rRDI}		
	FII	$FIV_{initial}$	FIV_{final}
Cherry	—	0.50	0.50
Apricot	—	0.40	0.40
EMP	—	0.40	0.60
MMP	0.25	0.15	0.60
LMP	0.25	0.25	0.25

Net irrigation requirements for standard and RDI strategies (NIR_{Std} and NIR_{RDI}, respectively) were determined by subtracting the daily effective precipitation from daily ETc or ETc_{RDI}. The daily effective precipitation was determined as 75% of daily precipitation (Dastane, 1978). Gross irrigation requirements for both standard (GIR_{Std}) and RDI (GIR_{RDI}) strategies were determined assuming an application efficiency of 90%, characteristic of drip irrigation systems (Clemmens & Dedrick, 1994). Gross irrigation requirements for both strategies were compared with observed irrigation water applications based on the criteria of the farm manager.

Scheduled and measured irrigation water application

The farm manager based daily irrigation scheduling on: 1) the data published by the SIAR network of agrometeorological stations; 2) the gradual implementation of RDI in order to limit pruning and to improve fruit quality; 3) an inspection of the crop status; 4) the readings of some soil water sensors installed at the orchard; and 5) fertigation requirements. According to the manager, fertilizer application occasionally required water in excess of crop water requirements, particularly at the beginning of the season. The daily time table of the irrigation schedule, scheduled irrigation time (SIT, hours) and the nominal water flow of each subunit valve were registered at the orchard manager's computer. Weekly scheduled irrigation depth (SID, mm) was obtained for each cropping zone in 2004, 2005 and 2006. Daily SID data was obtained for each valve in 2007, 2008 and 2009.

Ten volumetric flow meters were installed at specific control points of the water delivery network, two per cropping zone, in 2008 and 2009. Control points were named C1-C10. Each flow meter was installed at the upstream end of a drip irrigation hose. The flow meters were equipped with a pulse emitter (one pulse was emitted each 10 L of flow) and a data logger. These data allowed estimating the temporal variability of irrigation discharge at each control point. Two types of coefficients of variation were determined: intra-irrigation (VC_{IA}) and inter-irrigations (VC_{IE}). Measured irrigation times (MIT) were compared with those scheduled by the orchard manager (SIT). The estimated irrigation depth was also compared with the computed standard and RDI gross irrigation requirements.

Irrigation system evaluation

The irrigated area containing each of the ten control points was selected to perform an irrigation system evaluation. Evaluations were performed following the ITRC rapid procedure (Burt, 2004). This methodology was designed to identify problems due to pressure differences between emitters and other causes of non-uniformity (clogging, manufacturing variation, ageing and friction). Measurements must be taken across an entire irrigated area (defined as a subunit in the irrigation evaluation methodology). The methodology is summarized in the following four steps:

1. The emitter discharge equation was determined for each subunit (Eq. [4]). The emitters installed at the orchard were turbulent (non pressure-compensating). As a consequence, they showed a strong pressure-discharge response. The individual flow rate (q) was measured at 16 contiguous emitters located at the upstream end of the hose. Measurements were performed at the operating pressure (p) and half of the operating pressure (Burt, 2004). The x exponent and the k parameter were determined by regression for the group of emitters:

$$q = k\, p^{x} \qquad [4]$$

2. The low-quarter distribution uniformity due to variations in emitter pressure ($DU_{lq\Delta P}$) was determined for each subunit (Eq. [5]). For this matter, pressure measurements were performed at four tree lines distributed along the subunit. At each of the two hoses irrigating the selected tree lines, pressure was measured at four locations.

$$DU_{lq\Delta P} = \frac{\text{Average of low – quarter estimated flows}}{\text{Average of all estimated flows}} \qquad [5]$$

3. The low-quarter distribution uniformity due to other causes ($DU_{lqOthers}$) was determined following Eq. [6]. Emitter flow rates were measured at three hoses within each subunit (Burt 2004). DU was determined at each location (DU_i), and $DU_{lqOther}$ was estimated as the average of the three locations using:

$$DU_{lqOther} = 1 - \frac{1}{\sqrt{n}}\left(1 - \frac{\sum_{i=1}^{3} DU}{3}\right) \qquad [6]$$

where n is the number of emitters per tree.

4. The global low-quarter distribution uniformity ($DU_{lqGlobal}$) was determined following the statistical method proposed by Clemmens & Solomon (1997) (Eq. [7]):

$$DU_{lq\Delta Global} = \sqrt{1-(1-DU_{lq\Delta p})^2 + (1-DU_{lqOther})^2 + \frac{[(1-DU_{lq\Delta p})^2 (1-DU_{lqOther})^2}{K_a^2}} \qquad [7]$$

where K_a is a factor that depends upon the type of data distribution. As suggested by Burt (2004), a typical value of 1.27 was used.

Stem water potential

Stem water potential (SWP) was measured at solar midday using a pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA, USA), according to McCutchan & Shackel (1992). Samples were collected at the surroundings of the ten control points during the 2008 and 2009 irrigation seasons. At each control point, six mature leaves located on the shaded side of the central part of the third and fourth trees along the line (three leaves per tree) were measured between 12:00 and 13:00 UTC. Coverage of the 2008 season was partial, with measurements starting on July 10.

Results and discussion

Soil physical properties

Soil stoniness thematic units can be described as follows: a) low stoniness (< 5%) for which average and standard deviation of RAW were 113 mm and 31 mm, respectively; b) medium stoniness (5%-20%) for which average and standard deviation of RAW were 70 mm and 7 mm, respectively; and c) high stoniness (> 20%) for which average and standard deviation of RAW were 41 mm and 15 mm, respectively. Due to the sampling density and the large spatial variability of RAW, it was not possible to map this variable with more detail. The magnitude of RAW spatial variability was similar to that reported in other areas of the central Ebro River basin (Playán *et al.*, 2000; Lecina *et al.*, 2005). The lowest observed values of RAW are compatible with the usual local irrigation requirements and practices (daily replacement of the crop water requirements), avoiding important deep percolation losses. The same can not be said about large precipitation events, which will result in strong differences in effective precipitation and deep percolation. Differences in RAW should be accounted when defining a RDI strategy since the level of deficit irrigation are also dependent on soil characteristics (Girona *et al.*, 2005).

The comparison of the boundaries of soil units and the different cropping zones allow concluding that soil information was not used at the orchard design and at the irrigation system design phases. As a consequence, the farm manager's irrigation scheduling can not adequately accommodate the variability of soil water properties within the orchard (Boland *et al.*, 2006; Fulton *et al.*, 2011).

Spatial variability of wind speed

Fig. 2 presents regression analyses of the four meteors used to determine ETo between the two landmark stations. Significant statistical differences could not be found in air temperature, air relative humidity and solar radiation. On the other hand, significant and important differences were found for wind speed between H1 and H2. The coefficient of determination of the linear regression, R^2, was 0.93. However, wind speed at station H2 was (on the average) 52% of the wind speed at H1. When reference evapotranspiration was determined at both stations, differences in wind exposition at the two landmark points resulted in relevant differences in evapotranspiration: ETo at station H2 was only 80% of ETo at station H1. Since significant meteorological differences were only found for wind speed, the spatial variability of reference evapotranspiration within the orchard relied on the characterization of the spatial variability of wind speed.

The largest half-hour meteorological data series available in the area correspond to the SIAR reference station: from January 2004 to September 2009. Martínez-Cob *et al.* (2010) reported that the predominant wind directions in the Ebro river basin are West-Northwest and East-Southeast (locally named *Cierzo*

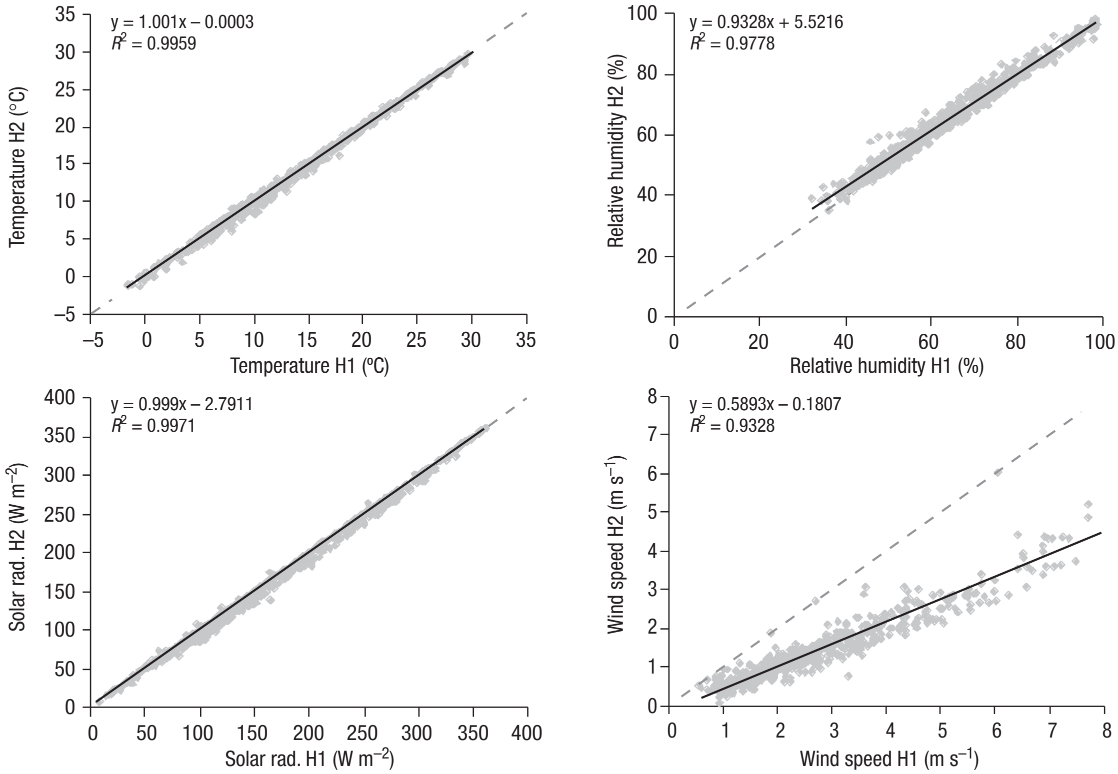


Figure 2. Regression analysis of meteorological variables: air temperature (°C), air relative humidity (%), solar radiation (W m^{-2}) and wind speed (m s^{-1}) between the two landmark points of the orchard, H1 and H2. Dashed lines represent the 1:1 lines.

and *Bochorno*, respectively). Thus, the wind speed values recorded at the SIAR station were divided in two groups according to their respective wind direction (WD). Wind directions 180°-360° were classified as West (WD), while wind directions 0°-180° were classified as East (ED). A 64% of the data registered at the SIAR reference station showed a West wind direction, while 36% had an East wind direction. Considering all measurement locations, wind speeds from the West were larger and more intense than those from the East, except for the period between mid July and mid August 2008, when the East was the most frequent and intense wind direction.

Table 2 presents the regression analysis between the landmark station H1 as independent variable, and the rest of wind speed measurement spots as dependent variables (*on-farm regressions*). Regression analysis for spots SIAR, M7, M8, M9, M11, M12 and M13 showed different models depending on the wind direction. Regression analyses for spots M2 and M8 indicated that local wind speed was not strongly related with wind speed at the reference sites SIAR and H1 (values of $R^2 < 0.5$). This finding may be attributed to the sheltering produced by the surrounding topography, resulting in local wind patterns. Similar results were obtained for spot M9 when the wind blew from the West, indicating that this point was equally sheltered from this wind direction.

O*n-farm* regressions were used for prediction purposes. All regression statistics (not just R^2, but also RMSE and MAE, data not presented) resulted better for H1 than for SIAR. The analyzed time series lasted from 2004 to 2009, and was only available for the reference SIAR measurement spot. Predicted values at the on-farm spots were obtained in two steps: 1) estimation of a complete wind speed time series for 2004 to 2009 at H1; and 2) estimation of a complete wind speed time series for 2004 to 2009 at the remaining on-farm spots.

Spatial variability of reference evapotranspiration

Wind speed variability was used to estimate reference evapotranspiration at the different wind station points and at the spots H1 and H2 for the period 2004 to 2009. Table 3 presents wind and ETo estimates for each cropping zone. For example, wind speed and ETo

Table 2. Regression analysis between wind speed at station H1 (independent variable) and at the other measurement points (SIAR, H2 and M1-M13)

Location	H1 as independent term*					
	Intercept		Slope		R^2	
	East	West	East	West	East	West
SIAR	–0.02	0.49	1.07	0.69	0.81	0.82
H1	0.00		1.00		1.00	
H2	–0.18		0.59		0.86	
M1	0.38		0.60		0.62	
M2	0.59		0.44		0.36	
M3	0.00		0.64		0.86	
M4	0.00		1.00		0.91	
M5	0.15		0.75		0.81	
M6	0.00		0.49		0.65	
M7	0.00		0.64	1.00	0.86	0.91
M8	0.92	0.32	0.21	1.21	0.49	0.37
M9	0.00	0.32	1.00	1.21	0.91	0.37
M10	0.15		0.75		0.81	
M11	0.15	0.00	0.75	0.49	0.81	0.65
M12	0.00		1.00	0.64	0.91	0.86
M13	–0.29	1.14	1.20	0.55	0.82	0.86

* Two regression models are presented when the analysis considering the wind direction resulted better than the general model.

at the EMP zone were predicted from the daily average wind speed at points M1 and M11. The weight of each point was similar in all cropping zones. The only exception occurred at the cherry cropping zone. In this case, the M13 spot only accounted for 12% of the average wind speed and ETo, in agreement with the percentage of cherry trees surrounding this spot. The variability in wind speed and ETo between the measurement points was smoothed by the averaging process required for the estimation of average ETo in the cropping zones. If cropping zones would have been designed according to ETo, irrigation scheduling could have been much more responsive to the local water requirements.

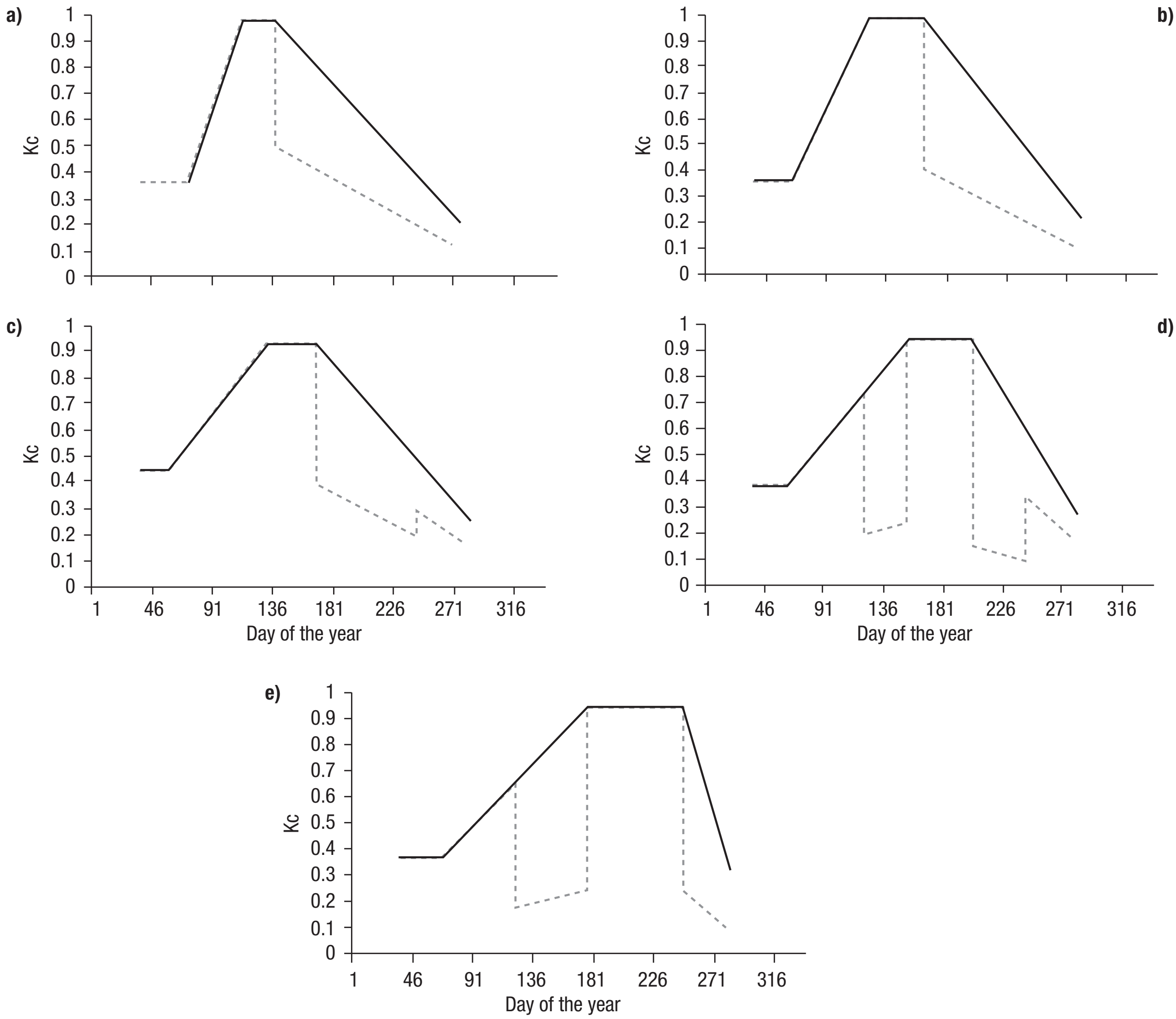
Adequate irrigation management requires the determination of local, standard crop water requirements. Our results have shown that the spatial variability of ETo needs to be taken into consideration at the study orchard in order to schedule irrigation at the cropping zones. In the current orchard design, the cropping zones include relevant ETo variability. For instance, average ETo values of 1,194 mm yr^{-1} (M6) and 1,468 mm yr^{-1} (M13) have been determined within the cherry area.

Irrigation requirements and scheduled irrigation application

The FAO-56 initial stage started on February 5 for all crops (Fig. 3). Table 4 presents the average length (days) of the four FAO-56 phases. The largest difference among crops for the duration of the initial stage was 10 days, observed between LMP and apricot. Large differences were observed for the duration of the development, mid-season and late-season stages, particularly between the extreme cases: LMP and Cherry (Table 4). Cherry presented the shortest development and mid-season stages, and the longest late-season stage. The duration of FII (from beginning to end of pit hardening) was determined as 29 and 63 days for MMP and LMP, respectively. The standard deviation of the duration of these phases was 7 and 5 days, respectively.

Table 3. Yearly average wind speed (m s^{-1}) and ETo (mm yr^{-1}) for the reference station (SIAR-Caspe), the two landmark stations (H1 and H2) and the five cropping zones of the orchard [cherry, apricot, early maturing peach (EMP), medium maturing peaches (MMP) and later maturing peaches (LMP)]. The number of points used to determine wind speed and ETo at the different cropping zones are listed. Interannual averages of wind speed and ETo are displayed

Fruit/trees Zones	Measurement points	Average wind speed (m s^{-1})							ETo (mm yr^{-1})						
		2004	2005	2006	2007	2008	2009	Ave.	2004	2005	2006	2007	2008	2009	Ave.
	SIAR-Caspe	2.7	2.9	2.6	2.7	2.6	2.7	2.7	1,330	1,486	1,510	1,443	1,377	1,468	1,436
	H1	3.0	3.3	2.9	3.1	2.9	3.0	3.0	1,370	1,529	1,551	1,501	1,416	1,496	1,477
	H2	1.6	1.7	1.5	1.6	1.5	1.6	1.6	1,134	1,257	1,272	1,229	1,175	1,215	1,214
Cherry	M6, M13, H2	1.7	1.8	1.6	1.7	1.7	1.7	1.7	1,153	1,278	1,295	1,250	1,196	1,240	1,235
Apricot	M4, M5, M8, H1	2.7	2.9	2.6	2.7	2.6	2.7	2.7	1,300	1,446	1,469	1,417	1,345	1,415	1,399
EMP	M1, M11	2.0	2.1	1.9	2.0	1.9	2.0	2.0	1,212	1,343	1,367	1,312	1,258	1,313	1,301
MMP	M2, M7, M9, M11	2.2	2.4	2.2	2.3	2.2	2.3	2.3	1,258	1,395	1,420	1,365	1,304	1,367	1,352
LMP	M3, M10, M12	2.1	2.3	2.0	2.1	2.0	2.1	2.1	1,227	1,359	1,380	1,336	1,271	1,327	1,317



Figue 3. Seasonal evolution of Kc for standard (continuous line) and RDI (dashed line) conditions, and for cherry (a), apricot (b), EMP(c), MMP (d) and LMP (e) fruit trees.

Local Kc values were obtained for each cropping zone (Fig. 3). These data were further combined with the values of daily ETo corresponding to the different cropping zones to obtain daily crop evapotranspiration under standard irrigation management (ETc_{Std}). Fig. 3 also presents the reduction in Kc resulting from the application of the RDI strategy.

Table 5 presents annual precipitation, seasonal values of estimated ETc, NIR and GIR under standard and RDI conditions, and seasonal values of farm mana-

Table 4. Length of the crop development stages (FAO-56 phases), in days, for the different crops. Standard deviations are presented corresponding to the different varieties and years of observation (2008 and 2009)

Crop	Initial		Development		Mid-season		Late-season	
	Average	SD	Average	SD	Average	SD	Average	SD
Cherry	30.0	2.5	40.0	6.2	25.0	7.7	139.0	6.1
Apricot	22.2	4.8	56.8	3.4	36.7	9.3	125.8	10.8
EMP	25.5	3.2	64.7	2.9	45.2	8.7	126.6	9.4
MMP	29.2	2.1	67.1	5.0	75.6	13.2	90.1	17.7
LMP	32.0	1.5	76.5	5.6	111.8	17.0	44.9	18.6

Table 5. Annual precipitation, crop evapotranspiration (ETc), net irrigation requirements (NIR), gross irrigation requirements (GIR) and farm manager's scheduled irrigation depths (SID) for cropping zones and years of study (2004-2009). Results are presented for the standard and regulated deficit irrigation strategies (Std and RDI, respectively)

Cropping zone	Agrometeorological variable (mm yr^{-1})	2004	2005	2006	2007	2008	2009	Average	SD
	Precipitation	334	295	248	259	358	277	295	43
Cherry	ETc_{Std}	648	743	759	699	678	701	705	41
	ETc_{RDI}	414	495	499	459	453	462	464	31
	NIR_{Std}	513	613	668	546	526	582	575	59
	NIR_{RDI}	279	372	419	312	305	352	340	51
	GIR_{Std}	579	690	745	616	591	654	646	64
	GIR_{RDI}	319	421	469	357	346	398	385	55
	SID	—	682	785	—	523	554	636	121
Apricot	ETc_{Std}	805	923	946	867	836	877	876	53
	ETc_{RDI}	539	639	652	588	561	601	597	44
	NIR_{Std}	669	789	841	707	675	750	738	68
	NIR_{RDI}	402	513	567	438	410	487	470	64
	GIR_{Std}	751	886	937	797	756	842	828	74
	GIR_{RDI}	456	578	634	497	463	549	529	70
	SID	—	—	—	—	422	540	481	83
EMP	ETc_{Std}	759	862	885	816	790	827	823	46
	ETc_{RDI}	531	622	632	574	553	590	583	39
	NIR_{Std}	619	725	774	653	622	697	682	62
	NIR_{RDI}	391	488	536	415	392	468	448	59
	GIR_{Std}	696	816	867	736	697	783	766	69
	GIR_{RDI}	444	552	600	471	442	527	506	64
	SID	—	—	702	621	604	487	604	89
MMP	ETc_{Std}	830	933	963	890	857	899	895	48
	ETc_{RDI}	524	610	605	561	563	575	573	32
	NIR_{Std}	692	796	852	727	689	768	754	64
	NIR_{RDI}	386	478	506	403	403	452	438	48
	GIR_{Std}	777	894	954	820	774	862	847	71
	GIR_{RDI}	438	542	566	459	457	512	496	52
	SID	—	—	617	614	518	507	564	60
LMP	ETc_{Std}	856	949	983	918	883	914	917	45
	ETc_{RDI}	611	686	717	666	660	662	667	35
	NIR_{Std}	718	811	871	756	716	780	776	59
	NIR_{RDI}	474	556	627	515	506	544	537	53
	GIR_{Std}	806	911	975	852	804	876	871	66
	GIR_{RDI}	535	627	702	584	572	612	605	57
	SID	—	—	612	549	484	493	535	59

ger's SID for the period of study and for each cropping zone. The inter-seasonal variability of crop ETc, NIR and GIR was low (the respective average CVs amounted to 5, 9 and 12%). The inter-year variability of precipitation was slightly higher (CV of 15%). The inter-seasonal variability of SID was moderate, with CVs of 19, 17, 15, 11 and 11%, for cherry, apricot, EMP, MMP and LMP, respectively. A time trend could be observed in peach SID during the years of study, with a clear decrease in water application. Considering all cropping zones and years, the SID linearly decreased by 53 mm yr^{-1} (with $R^2 = 0.59$), while the decrease rate in GIR_{Std} only amounted to 14 mm yr^{-1}. These results indicate a gradual shift towards deficit irrigation. Figs. 4 and 5 present the daily evolution of cumulative SID, GID_{Std} and GIR_{RDI}. For cherry, SID reproduced the pattern of GIR_{RDI} until the late postharvest stage. At that point, SID intensified, resulting in a final application intermediate to GIR_{RDI} and GID_{Std} (Fig. 4). For apricot, a severe, sustained deficit irrigation strategy was observed in 2008 and 2009. The SID line was always well below the GIR_{RDI} line (Fig. 4). The RDI strategy used

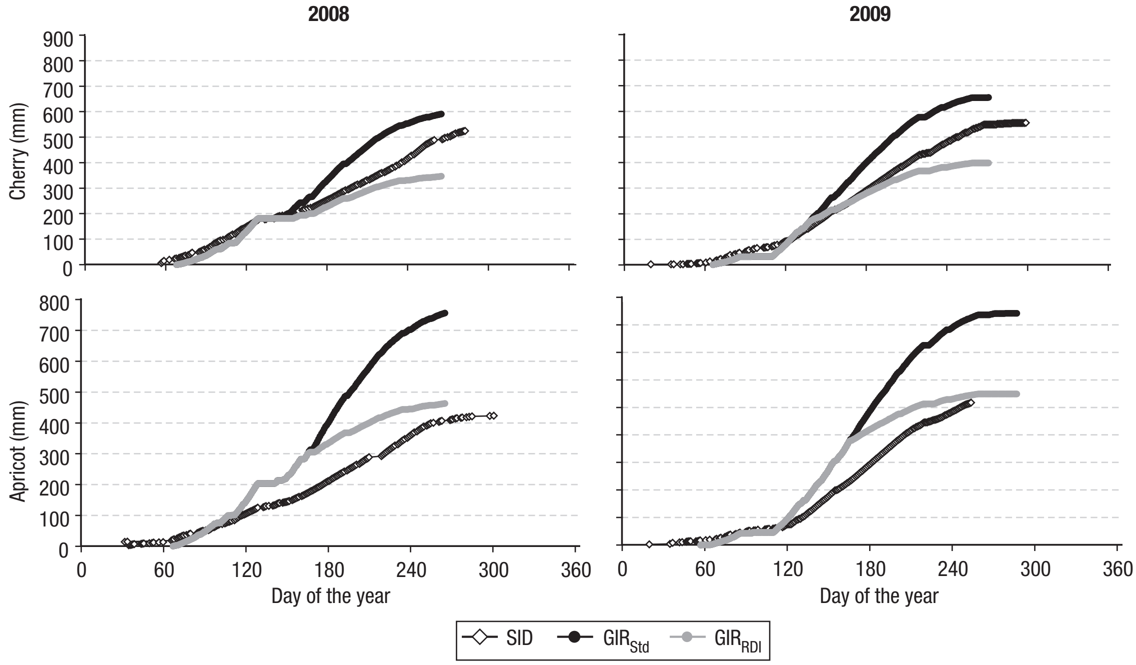


Figure 4. Seasonal evolution of the farm manager´s scheduled irrigation depth (SID, mm) and the estimated gross irrigation requirements under standard (GIR_{Std}) and regulated deficit irrigation (GIR_{RDI}) conditions for cherry (upper part of the figure) and apricot (lower part of the figure) for 2008 and 2009 irrigation seasons.

in this research for apricot only introduced deficit irrigation during postharvest. Other authors (Torrecillas *et al.*, 2000; Pérez-Pastor *et al.*, 2009; Pérez-Sarmiento *et al.*, 2010) proposed additional deficit irrigation during the FI and FII stages, as observed in the studied orchard. In the case of peach, in 2007 the evolution of SID and GIR_{Std} was very similar in all cases until approximately the late postharvest stage (Fig. 5). At that point, SID was drastically reduced or even stopped. For EMP, the evolution of cumulative SID showed some deficit at postharvest in 2008, but lower than in the RDI strategy. In 2009 the evolution of SID indicated deficit irrigation since the first stages of fruit growth (FII). In this particular case, the proposed RDI strategy only applied deficit irrigation at postharvest, since stage FII was very short in EMP (Dejong *et al.*, 1987). For MMP and LMP, during 2008 and 2009, the evolution of cumulative SID showed deficit irrigation at FII, which continued at FIII. Deficit irrigation intensified after harvest. The lack of parallelism between the SID and GIR_{RDI} during FIII indicates that irrigation requirements were not correctly satisfied at this period even for RDI conditions. Water stress sensitivity during stage FIII is very high, leading to reduced fruit growth, volume and final fruit size (Marsal *et al.*, 2004; López *et al.*, 2008).

The irrigation strategies suffered relevant changes between 2005 and 2009. The adequate stages for deficit irrigation have been described for the crop species and cycles present at the orchard (Chalmers *et al.*, 1981; Johnson *et al.*, 1992; Torrecillas *et al.*, 2000; Girona *et al.*, 2005; Antunez-Barria, 2006). However, the deficit levels are cultivar, soil and fruit load dependent (Girona *et al.*, 2005). Parallelism between SID and GIR_{RDI} resulted evident during some periods of the analyzed seasons and crops, but in specific periods irrigation was not in deficit. The manager scheduled irrigation to avoid deficit irrigation at the stages sensitive to water stress (FIII). In general, during the beginning of the irrigation season, SID exceeded gross irrigation requirements. This was particularly evident during the 2007 season (Fig. 5), and can be due to an underestimation of early spring precipitation events or to large fertigation requirements.

RDI and water conservation

The manager's irrigation schedule resulted in water conservation respect to the standard strategy, ranging between 34 mm yr^{-1} for cherry and 347 mm yr^{-1} for apricot. However, introducing the RDI strategy would

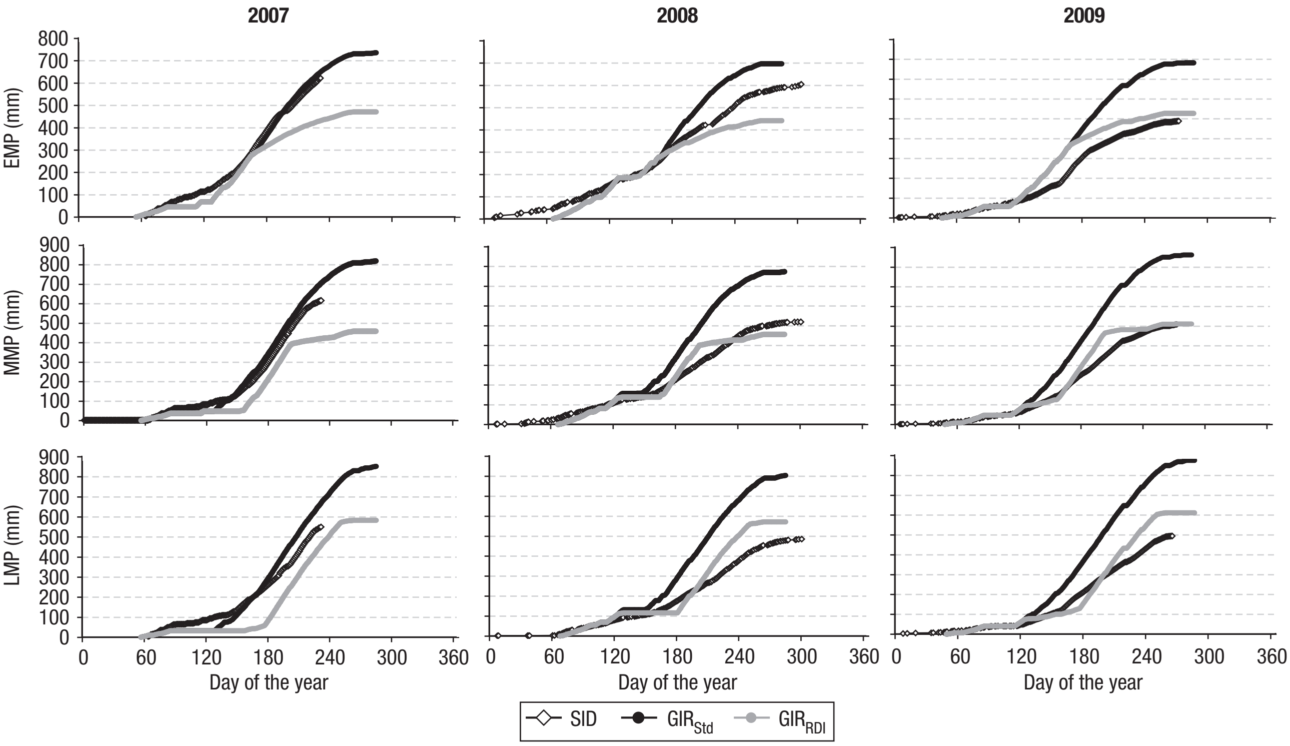


Figure 5. Seasonal evolution of the farm manager's scheduled irrigation depth (SID, mm) and the gross irrigation requirements under standard (GIR$_{Std}$) and regulated deficit irrigation (GIR$_{RDI}$) conditions for early maturing peach (EMP, upper part of the figure), medium maturing peach (MMP, centre) and late maturing peach (LMP, lower part) for 2007, 2008 and 2009 irrigation seasons.

result in large water conservation respect to the observed water use, ranging between 260 and 351 mm yr^{-1} for EMP and MMP, respectively. The manager's irrigation schedule in 2009 used less water than the RDI strategy. However, the manager's schedule cannot be considered an RDI strategy.

Scheduled and measured irrigation time

A large variability could be observed in intraday scheduled irrigation time (SIT) for the different subunit valves of a given cropping zone. For instance, in 2008, the seasonal averages of the daily SIT CV were 20, 26, 45, 30 and 40% for cherry, apricot, EMP, MMP and LMP, respectively. This variability reflects the manager's reaction to the identified sources of variability in crop water availability and requirements.

In order to compare MIT and SIT for each crop, MIT was the average of the two measurement points, while SIT represented the average of the two irrigation subunit valves. During the 2008 irrigation season, SIT was in most of the cases higher than MIT. The largest differences (11.2%) were observed for MMP, and the lowest differences were observed for apricot (1.2%). In 2009, SIT was higher than MIT for cherry (data not showed), apricot (data not showed) and medium maturing peach (Fig. 6c). However, large negative differences were observed for EMP (Fig. 6b) and LMP (Fig. 6d), 38.5% and 25.6%, respectively. These differences seem related to operational problems during the opening and closing of the valves or to irrigation programming errors. Fig. 6 permits appreciating differences in detail for different crops and time periods. These data confirm the difficulty of managing irrigation in this complex orchard.

Discharge, pressure and uniformity of the irrigation system

The average discharge measured at each control point depends on the length of the irrigation hose and on the operating pressure. In order to analyse these data, hose discharge was standardized by the hose length. Since emitters are spaced 1 m, the standardised discharge equals the average emitter discharge. This

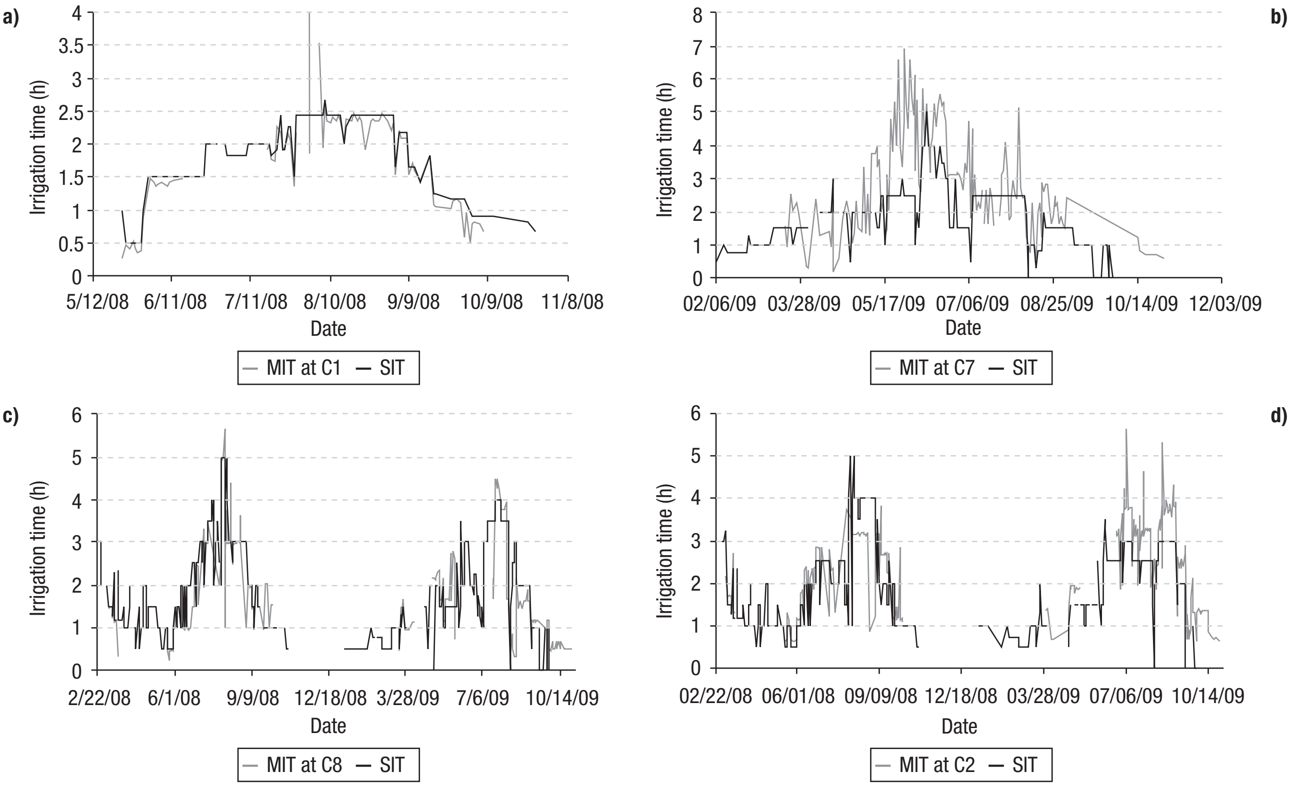


Figure 6. Measured irrigation time (MIT) obtained with the flow meters at selected control points for daily periods. Comparison with the scheduled irrigation time (SIT). Data are supplied for: a) apricot; b) early maturing peach; c) medium maturing peach; and d) late maturing peach. Date (mm:dd:yy).

value fluctuated between C10 and C3/C4 (2.6-5.1 L h^{-1} m^{-1}) (Table 6). The variability of discharge during the irrigation events largely depended on the control point. On the average, the CV of discharge within the irrigation events was 12%, while the CV of discharge between the different irrigation events was 10%. Space

Table 6. Stability of measured discharge in the control points. Coefficients of variation intra- and inter-irrigation (CV_{IA} and CV_{IE}, respectively) are presented

Cropping zone	Control point	Hose lengh (m)	Discharge			
			Average (L s^{-1})	Average per unit length (L h^{-1} m^{-1})	CV_{IA} (%)	CV_{IE} (%)
Cherry	C4	80	0.114	5.1	7.8	7.9
	C5	100	0.096	3.5	8.9	10.5
Apricot	C1	81	0.085	3.8	7.9	15.8
	C10	75	0.054	2.6	21.0	4.0
EMP	C6	99	0.113	4.1	13.4	10.5
	C7	102	0.115	4.1	7.0	12.9
MMP	C8	95	0.124	4.7	6.6	5.5
	C9	120	0.105	3.2	15.0	17.4
LMP	C2	90	0.104	4.2	17.8	5.8
	C3	65	0.092	5.1	9.8	10.0

and time variability in irrigation discharge constitutes a relevant source of variability in irrigation depth, seriously affecting irrigation performance. A detailed analysis of the water meter data revealed that the manager often adjusted the daily irrigation time of the different valves of the same cropping zone to correct the differences in discharge and its time variability. As reported in Table 6, the average irrigation discharge at C8 was significantly larger than at C9. In response to this, the manager increased irrigation duration and frequency in C9 respect to C8 (data not presented). The same pattern was observed at the two measured LMP cropping areas (C2 and C3, Table 6). On the other hand, the discharge differences between the two controlled apricot cropping areas were not effectively corrected. Dichio *et al.* (2007) concluded that the success of an RDI strategy heavily relies on the adequate design and management of drip irrigation systems. Our results indicate that, despite the manager's efforts, more control (flow meters, pressure regulators) would be required at the irrigation network in order to effectively regulate deficit irrigation in the orchard.

The manufacturing year of the emitters was 2001 for subunits C2 to C9, and 2004 for subunits C1 and C10. The average value of the *x* exponent was 0.46, reasonably close to the theoretical value of 0.50. Very relevant differences were detected on the emitter operation pressure. Irrigated areas C1, C4 and C5 showed very low working pressure (80, 70 and 57 kPa, respectively). Differences in pressure in the same cropping zone were very relevant. The results of the distribution uniformity analysis indicate that area C9 resulted in poor DU_{lq} (0.73 for the tree and 0.72 for the emitter). Non-uniformity in this irrigated area was mostly due to differences in pressure ($DU_{lq\Delta p}$ = 0.73). Area C5 presented a moderate DU_{lq} (0.85). The rest of irrigated areas showed high distribution uniformities, either referred to a single emitter or to all the emitters irrigating a tree. "Other" causes of non-uniformity were not relevant at the experimental orchard (tree $DU_{lqOther}$ ranged between 0.96 and 0.99). These values seem to indicate that the system is showing adequate ageing. However, Hanson *et al.* (1996), and Burt (2004) indicated that there is not a clear correlation between the age of the system and the $DU_{lqOther}$.

The values of DU_{lq} determined at the study orchard resulted higher than other references in the literature. In fact, the average tree DU_{lq} at the orchard (0.92) was higher than the average DU_{lq} of 0.73 reported by Hanson *et al.* (1996), or the average DU_{lq} of 0.75 reported at the Cachuma RCD (1994). Our experimental results were also higher than the average DU_{lq} of 0.86 reported by Burt (2004) for drip irrigation systems. The differences in uniformity referred to the emitter or to the tree were in all cases very small. The large observed number of emitters per tree (5-9) was not required to attain adequate uniformity.

Assessing crop water stress

In general, stem water potential measurements at both control points of a given cropping zone showed similar patterns, with the exception of MMP in 2008, EMP in August 2008 and apricot in June 2009 (Fig. 7). The periods of proposed deficit for each cropping zone in the RDI strategy are presented in the Figure by horizontal arrows. For peach trees, Marsal *et al.* (2004, 2005) reported that minimum values of around –1.5 MPa at the end of Stage II are associated with detrimental effects on fruit size at harvest. Similar results were presented by Dichio *et al.* (2007) in peach and by Marsal *et al.* (2009) in cherry. There are references in the literature pointing out that the threshold limits of SWP are variable between crops, crop development stages, soil characteristics and fruit loads. In this work, SWP = 1.5 MPa was used as a threshold limit of water stress (this threshold is represented in Fig. 7 by a horizontal dashed line). In cherry, crop water stress was important from early June to early July 2009, but no relevant stress was observed at the later postharvest period (August and September) of 2009. In general, the SWP measurements agree with the irrigation depth applied to the crops (Figs. 4 and 5). In apricot, crop water stress was observed in 2008 from mid July to mid August and in 2009 from mid June to mid July. SWP results for cherry and apricot showed some level of water stress during short periods of the recommended RDI periods. Although Fig. 5 displayed more deficit for EMP in 2009 than in 2008, SWP measurements showed less stress in 2009 than in 2008. These results could be explained by the abovementioned discrepancies between SIT and MIT. For MMP in 2009 water stress occurred at stage FII of fruit growth, and stress was maintained at the limit threshold during a large part of the rapid fruit growth (stage FIII). These results are compatible with the irrigation scheduling applied to MMP in 2008 and 2009 (Fig. 5). For LMP, slight crop water stress was found in 2009 only at a short period of stage FII of fruit growth (again in agree-

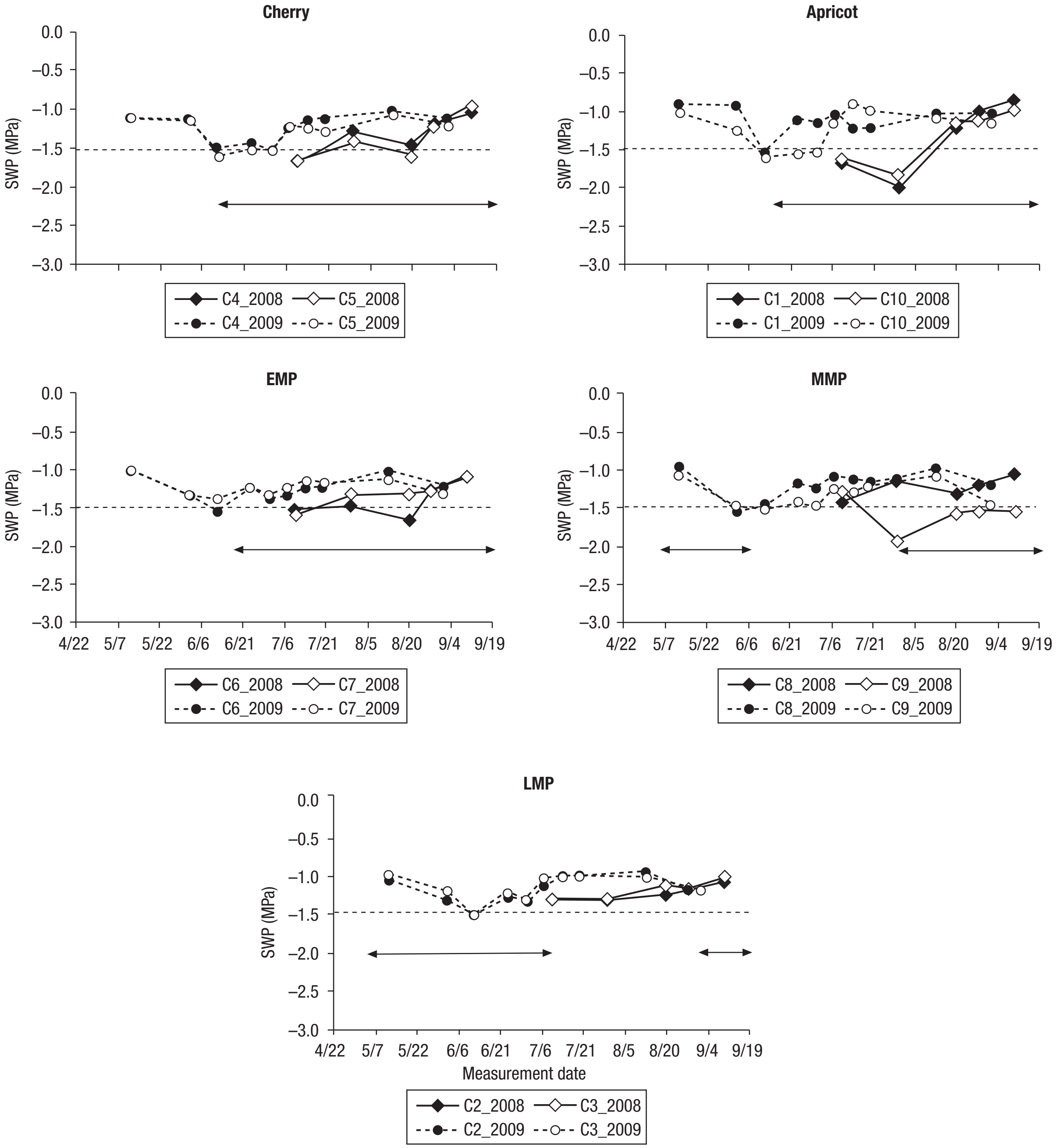


Figure 7. Midday stem water potential (SWP, average of six measurements). Two control points per cropping zone are presented for the 2008 and 2009 seasons. The RDI periods proposed in the RDI strategy were showed by the horizontal arrows. The SWP threshold limit indicative of water stress was marked by the horizontal dashed line. Measurement date (mm/dd).

ment with the schedule presented in Fig. 5); no crop water stress was identified after this period.

In general, the FII stage (fruit growth) was only partially exploited in MMP and LMP. Only at the end of this period water stress became evident in both cropping zones. Postharvest water stress appeared in cherry, apricot and EMP, particularly at the beginning of this phase. However, water stress was not present at the late postharvest period. Stress could be observed in water sensitive periods of EMP and during the whole cycle of MMP.

Conclusions

The case study has shown evolution towards deficit irrigation between 2004 and 2009. However, the complexities derived from the spatial variability of environmental factors (soils and meteorology) and irrigation performance limited adoption of a formal RDI strategy. The lack of consideration of environmental variability at the design phase and at the management practices derived in reactive water management. In the light of the results obtained at the case study orchard, the same can be said of irrigation performance. Design decisions, such as distributing varieties in the irrigated areas according to their phenology, using pressure compensating emitters, or installing pressure regulators and volumetric meters at the valves would have led to higher irrigation performance levels. The case study has illustrated that distribution uniformity is a requirement for high irrigation performance, but it does not guarantee it. In fact, the evaluated irrigation areas are uniformly irrigated, but the variability in operating pressure (among the studied irrigated areas and in time) makes it complicated to adequately schedule irrigation for standard or RDI conditions. The manager minimised the effect of environmental and irrigation variability by modifying the daily irrigation time for each subunit valve.

According to the literature, full implementation of RDI at the study orchard would conserve additional water, lead to optimum yield quality and minimize pruning requirements. Practical procedures to compute standard and RDI irrigation requirements have been summarized for all the crops from the scientific literature. The comparison of these requirements with SDI indicates that orchard irrigation practices were shortfall but did not correspond to an RDI strategy. Stem water potential confirmed some of the trends announced by the previous analyses, and revealed additional traits. The regular use of a plant water stress indicator seems to be a requirement to succeed in commercial RDI operation.

Acknowledgement

This research was funded by the *Plan Nacional de I + D + i* of the Government of Spain through grant RIDECO-CONSOLIDER CSD2006-00067 and by CSIC through the grant PIE 2007-2009. We are very grateful to the irrigation manager at the *Herradura* orchard, José Luis Gracia, for his support and co-operation in the field work.

References

Allen RG, Pereira LS, Raes D, Smith M, 1998. Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrig Drain paper No. 56. Rome, Italy.

Antunez-Barria AJ, 2006. The impact of deficit irrigation strategies on sweet cherry (*Prunus avium* L.) physiology and spectral reflectance. PhD Diss., Washington State Univ (UMI Microform 3252310).

Arzadi K, Wood D, Lawes S, 2000. Influence of first season application of paclobutrazol root-pruning and regulated deficit irrigation on second season flowering and fruiting of mature Sundrop apricot trees. XXV Int Hortic Cong Proc - Pt 6 - Culture techniques with special emphasis on environmental implications physiological processes in plants. pp: 75-82.

Bleiholder H, Van den Boom T, Langeluddeke P, Stauss R, 1989. Einheitliche Codierung der phänologischen Stadien bei Kultur-und Schadpflanzen. Gesunde Pflanzen 41: 381-384.

Boland AM, Bewsell D, Kaine G, 2006. Adoption of sustainable irrigation management practices by stone and pome fruit growers in the Goulburn/Murray Valleys, Australia. Irrig Sci 24(2): 137-145.

Burt C, 2004. Rapid field evaluation of drip and microspray distribution uniformity. Irrig Drain Syst 18: 275-297.

Cachuma RCD, 1994. Final report. Irrigation water management program Santa Barbara and San Luis Obispo Counties. Cachuma Resource Conservation District, Santa Maria, CA, USA.

Cameron RWF, Harrison-Murray RS, Atkinson CJ, Judd HL, 2006. Regulated deficit irrigation – a means to control growth in woody ornamentals. J Hortic Sci Biotech 81(3): 435-443.

Chalmers DJ, Mitchell PD, Van Heek L, 1981. Control of peach tree growth and productivity by regulated water supply, tree density and summer pruning. J Am Soc Hort Sci 106: 307-312.

Clemmens AJ, Dedrick AR, 1994. Irrigation techniques and evaluations. Adv Series Agric Sci (Tanji KK & Yaron B, eds). Springer-Verlag, Berlin. pp: 64-103.

Clemmens AJ, Solomon KH, 1997. Estimation of global irrigation distribution uniformity. J Irrig Drain Eng ASCE 123(6): 454-461.

Dastane NG, 1978. Effective rainfall in irrigated agriculture. Irrig Drain Paper 25. FAO, Rome, Italy.

Dejong TM, Doyle JF, Day KR, 1987. Seasonal patterns of reproductive and vegetative sink activity in early and late maturing peach (*Prunus persica*) cultivars. Physiol Plantarum 71: 83-88.

Derrick A, 1993. Development of the measure-correlate-predict strategy for site assessment. Eur Comm Wind Energy Conf, Lübeck-Travemünde, Germany. 8-12 March.

Dichio B, Xiloyannis C, Sofo A, Montanaro G, 2007. Effects of post-harvest regulated deficit irrigation on carbohydrate and nitrogen partitioning, yield quality and vegetative growth of peach trees. Plant Soil 290(1-2): 127-137.

Fereres E, Soriano MA, 2007. Deficit irrigation for reducing agricultural water use. J Exp Bot 58(2): 147-159.

Fulton A, Schwankl L, Lynn K, Lampinen B, Edstrom J, Prichard T 2011, Using EM and VERIS technology to assess land suitability for orchard and vineyard development. Irrig Sci 29(6): 497-512.

García-Vera M, Martínez-Cob A, 2004. Revisión de las necesidades hídricas netas de los cultivos de la Cuenca del Ebro. Confederación Hidrográfica del Ebro (2004-PH-12.I).

Gelly M, Recasens I, Girona J, Mata M, Arbones A, Rufat J, Marsal J, 2004. Effects of stage II and postharvest deficit irrigation on peach quality during maturation and after cold storage. J Sci Food Agr 84(6): 561-568.

Girona J, Mata M, Arbones A, Alegre S, Rufat J, Marsal J, 2003. Peach tree response to single and combined regulated deficit irrigation regimes under shallow soils. J Am Soc Hort Sci 128(3): 432-440.

Girona J, Gelly M, Mata M, Arbonés A, Rufat J, Marsal J, 2005. Peach tree response to single and combined deficit irrigation regimes in deep soils. Agric Water Manage 72: 97-108.

Goldhamer DA, Salinas M, Crisosto C, Day KR, Soler M, Moriana A, 2002. Effects of regulated deficit irrigation and partial root zone drying on late harvest peach tree performance. Proc 5th Int Peach Symp, Vols 1 and 2, pp: 343-350.

Hanks RJ, 1992. Applied soil physics. Soil water and temperature applications. Springer-Verlag, NY. 176 pp.

Hanson B, Bowers W, Davidoff B, Kasapligil D, Carvajal A, Bendixen W, 1996. Field performance of microirrigation systems. Proc 5th Int Microirrigation Cong, Orlando, FL, USA, pp: 769-774.

Johnson RS, Handley DF, DeJong TM, 1992. Long-term response of early maturing peach trees to postharvest water deficits. J Am Soc Hort Sci 117: 881-886.

Lecina S, Playán E, Isidoro D, Dechmi F, Causapé J, Faci JM, 2005. Irrigation evaluation and simulation at the irrigation District V of Bardenas (Spain). Agric Water Manage 73(3): 223-245.

López G, Arbones A, Del Campo J, Mata M, Vallverdu X, Girona J, Marsal J, 2008. Response of peach trees to regulated deficit irrigation during stage II of fruit development and summer pruning. Span J Agric Res 6(3): 479-491.

Marsal J, López G, Mata M, Arbones A, Girona J, 2004. Recommendations for water conservation in peach orchards in Mediterranean climate zones using combined regulated deficit irrigation. Proc 4th Int Symp on Irrigation of Horticultural Crops. pp: 391-397.

Marsal J, López G, Girona J, Basile B, DeJong TM, 2005. Heterogeneity in fruit distribution and stem water potential variations in peach trees under different irrigation conditions. J Hortic Sci Biotech 80(1): 82-86.

Marsal J, López G, Del Campo J, Mata M, Arbones A, Girona J, 2009. Postharvest regulated deficit irrigation in Summit sweet cherry: fruit yield and quality in the following season. Irrig Sci 28: 181-189.

Martínez-Cob A, Tejero-Juste M, 2004. A wind-based qualitative calibration of the Hargreaves ETo estimation equation in semiarid regions. Agric Water Manage 64(3): 251-264.

Martínez-Cob A, Zapata N, Sánchez I, 2010. Viento y riego: la variabilidad del viento en Aragón y su influencia en el riego por aspersión. Publication No. 2948. Series Studies (Geography). Institución Fernando el Católico. Zaragoza, Spain. 200 pp.

McCutchan M, Shackel KA, 1992. Stem-water potential as a sensitive indicator of water stress in prune trees (*Prunus domestica* L. cv. 'Franch'). J ASHS 117: 607-611.

Merriam JL, Keller J, Alfaro JF, 1973. Irrigation systems evaluation and improvement. Agric Irrig Eng Dept, Utah State Univ, Logan, UT, USA.

Mitchell PD, Chalmers DJ, 1982. The effects of reduced water supply on peach tree growth and yields. J Am Soc Hort Sci 107: 853-856.

Mitchell PD, Chalmers DJ, Jerie PH, Burge G, 1986. The use of initial withholding of irrigation and tree spacing to enhance the effect of regulated deficit irrigation on pear trees. J Am Soc Hort Sci 111(6): 858-861.

Naor A, 2006. Irrigation scheduling of peach-deficit irrigation at different phenological stages and water stress assessment. Acta Hort 713: 393-399.

Papenfuss KA, Black BL, 2010. regulated deficit irrigation of '*Montmorency*' Tart cherry. Hortsci 45(10): 1437-1440.

Pérez-Pastor A, Domingo R, Torrecillas A, Ruiz-Sanchez M, 2009. Response of apricot trees to deficit irrigation strategies. Irrig Sci 27(3): 231-242.

Perez-Sarmiento F, Alcobendas R, Mounzer O, Alarcón J, Nicolas E, 2010. Effects of regulated deficit irrigation on physiology and fruit quality in apricot trees. Span J Agric Res 8(S2): S86-S94.

Playán E, Slatni A, Castillo R, Faci JM, 2000. A case study for irrigation modernisation: II Scenario analysis. Agric Water Manage 42(3): 335-354.

Salvador R, Martínez-Cob A, Cavero J, Playán E, 2011. Seasonal on-farm irrigation performance in the Ebro basin (Spain): crops and irrigation systems. Agric Water Manage 98(2011): 577-587.

Sánchez I, Zapata N, Faci JM, Martínez-Cob A, 2011. Wind spatial variability in a sprinkler irrigated district: implications for irrigation management. Biosyst Eng 109(1): 65-75.

Snyder RL, Ferreira MI, Shackel KA, 2000. A crop coefficient model for trees and vines. Proc 3rd Int Symp Irrig Hortic Crops, Leuven 1, ISHS. Vols 1 and 2, pp: 549-556.

Torrecillas A, Domingo R, Galego R, Ruiz-Sánchez MC, 2000. Apricot tree response to withholding irrigation at different phenological periods. Sci Hortic 85(3): 201-215.