SOFTWARE FOR ON-FARM IRRIGATION SCHEDULING OF STONE FRUIT ORCHARDS UNDER WATER LIMITATIONS

by

Zapata, N.[1]*, Chalgaf, I.[2], Nerilli, E.[3], Latorre, B.[1],

López, C.[1], Martínez-Cob, A.[1], Girona, J.[4] and Playán, E.[1]

Abstract

This paper presents a real-time, on-farm irrigation scheduling software (RIDECO). The software was been designed for stone fruit orchards in the semiarid conditions of Spain. The characterization of stone fruit crop water requirements for the local conditions and under different irrigation strategies is presented. Meteorological data in the study area is collected daily from the SIAR public network of weather stations in an automated fashion. Subsequently, values of cumulative degree-days are computed to identify the stages of fruit growth and crop development. The software allows performing weekly irrigation schedules under standard, regulated deficit irrigation and water restriction conditions. The irrigation scheduling software stands as a valuable tool for on-farm water resources allocation planning. It can be used to forecast the irrigation water

[1] Dept. Soil and Water. EEAD-CSIC. Zaragoza. Spain.

[2] Dept. Soils and Irrigation. CITA-DGA. Zaragoza. Spain.

[3] IAMB-CIHEAM. Bari. Italy

* Corresponding author. v.zapata@csic.es

[4] IRTA-Lleida. Spain.

required to meet seasonal meteorological, agronomical and managerial scenarios in stone fruit orchards. RIDECO can also be used to plan deficit irrigation strategies in cases of severe water restrictions. The software can be parameterized to adjust to specific varieties and local farming conditions. A variety of graphs assist irrigation managers in their decisions.

Keywords

Irrigation scheduling software, Regulated Deficit Irrigation, Fruit Trees, Growing Degree-Days, Crop Stages, Fruit Growth, Crop Coefficients.

1. Introduction

In semi-arid areas, as in most of Spain, the productivity of stone fruit orchards heavily depends on irrigation. The area devoted to stone fruits in Spain is 215,500 ha (MARM, 2010). 86% of this area is irrigated, with a total production of 2.9 million tons. Advanced irrigation techniques (such as Regulated Deficit Irrigation, RDI) offer to this productive sector the opportunity to conserve irrigation water, improve fruit quality and reduce the cost of pruning (Fereres and Soriano, 2007).

The application of advanced irrigation techniques requires previous knowledge of standard irrigation techniques, which are based on crop water requirements. Recommendations on crop coefficients (Kc) are often site and year specific, and have been reported to depend on local reference evapotranspiration (ET_o), rainfall, and crop management practices (Allen et al., 1998). Several authors have compared the results obtained using the standard FAO 56 approach (Allen et al., 1998) with measured evapotranspiration using various approaches (Casa et al., 2000; Allen, 2000; Lascano, 2000; Dragoni et al., 2004). These comparisons have often shown a significant overestimation of basal crop coefficients when the FAO 56 method was used, as compared to evapotranspiration measurements (Paco et al., 2006). Therefore, local adaptation of the standard approach seems to be required before advanced irrigation management can be implemented in fruit orchards.

Regulated deficit irrigation (RDI) has been documented in the literature as a successful strategy for water conservation in fruit orchards. RDI has enjoyed more success in tree crops and vines than in field crops (Fereres and Soriano, 2007). This technique is based on: 1) plant sensitivity to water stress varies among phenological stages; and 2) water stress at specific phenological periods can help control growth and vegetative-fruit competition (Chalmers et al., 1981; Mitchell and Chalmers, 1982; Cameron et al., 2006).

Relevant scientific efforts have been devoted in the last decades to the classification of phenological stages as sensitive or non sensitive to water stress. These efforts have targeted different fruit species and even varieties (Torrecillas et al., 2000; Ebel et al., 2001; Goldhamer et al., 2002; Gelly et al., 2004; Intrigliolo and Castel, 2005; and Lopez et al., 2008). Other authors have analyzed the effect of different levels of irrigation deficit at the non sensitive stages (Girona et al., 2005; Antunez-Barria 2006; Marsal et al., 2009; Ballester et al., 2011). Results suggest that crop coefficients and RDI parameters depend on a number of variables (meteorology, irrigation system, variety, rootstock, planting density, training system, crop level and crop load), which show large variations among orchards.

Growing degree-days (GDD) have long been used to model the effect of temperature on biological processes. This technique was applied in the 1960s to model the phenology of orchards (Rom and Arringto, 1966). The duration of the phenological stages and the resulting irrigation schedule adapt to the meteorological characteristics of a given year when using thermal time (Vaughn, 2005). Each species is adapted to grow over a certain minimum (base) temperature, and decline in growth at a maximum temperature. Thermal models have been applied to fruit tree orchards to determine the chilling units needed to break dormancy, and the cumulative heat requirements to bloom for different species and varieties (Anderson et al., 1986; Topp et al., 1989; Boonprakob et al., 1992; Muñoz et al., 1986; Valentini et al., 2004). These data provide information about the adaptive success of species and cultivars to different meteorological conditions. Thermal models have also been applied to forecast harvest time in orchards (Pailly et al., 1999). Normand and Léchaudel (2006) reported that the predictive capacity of those models heavily depends on the value of the temperature threshold, and highlighted that the base temperature for a given species can vary depending on altitude and fruit load. On the other hand, Bonhomme (2000), working with corn, indicated that the temperature threshold only has a slight influence on phenological estimates if average temperatures are well above threshold level. For peach trees, Marra et al. (2002) reported a base temperature of 7 ºC and a critical temperature of 35 ºC, while Rageau et al. (1998) and Mounzer et al. (2008) used base temperatures of 4.5 ºC and 4.0 ºC, respectively, and a critical temperature of 36 ºC. The date used to start accumulating degree-days, known as the biofix date, varies with the species and is usually based on specific biological events. Growing degree-hours (GDH) provide a more reliable way to assess the effect of air temperature on the plant development stages than GDD (Mimoun and DeJong, 1999). These authors documented that GDH for 30 days after bloom are highly correlated with yearly differences in harvest date for peach, plum and nectarine cultivars.

The application of irrigation scheduling techniques to a commercial orchard requires consideration of a number of additional factors. Zapata et al. (201Xa, 201Xb) reported on the effect of the variability orchard environmental factors (soils, meteorology, species and cultivars), crop water status, and the limitations imposed by the irrigation system on orchard water requirements and irrigation performance. These authors concluded that individual irrigation schedules need to be produced for each irrigation subunit (the area irrigated by a valve). Undesirable reactive irrigation management will be required to continuously correct for water excesses and shortages if all these variables are not taken into consideration.

One of the first software applications exploiting data from on-line open agrometeorological servers to produce irrigation scheduling was the WISE system

(Washington Irrigation Scheduling Expert), reported by Leib et al. (2001) and Leib et al. (2002). The software was designed to perform standard irrigation scheduling for a large variety of crops and irrigation systems. One of the principles of WISE was to create a tool that producers could use without the aid of professional consultants (Leib et al., 2001). Leib et al. (2002) reported that producers of high-value crops, such as deciduous orchards, are more willing to rely on irrigation scheduling software than producers of field crops.

In this research, we report on a specific software application for irrigation scheduling of stone fruit orchards under different irrigation strategies (standard and regulated deficit irrigation) and under water restrictions. This software summarizes current knowledge on advanced irrigation techniques for stone fruit orchards. The design goal was to develop a practical tool for farmers and technicians in the semi-arid stone fruit production areas of Spain. As a consequence, secondary objectives were:

1. To take advantage of current developments in on-line agrometeorological servers;
2. To allow average users to quickly develop irrigation schedules adapted to local conditions in an intuitive, practical fashion;
3. To permit advanced users full software parameterization;
4. To disseminate RDI and to adapt to dynamic water restrictions.

2. Methodology

2.1. Target geographical areas

The real-time, on-farm irrigation scheduling software for stone fruit orchards (RIDECO) targets the major stone fruit production areas of Spain. RIDECO stands for

"RIego DEficitario COntrolado", RDI in Spanish. Three criteria were used to select the target geographical areas: 1) stone fruit production above 30,000 tons (MARM, 2010); 2) stone fruit irrigated area above 500 ha (MARM, 2010); and 3) coverage by an on-line, open access meteorological network. The SIAR network of agricultural weather stations (http://www.magrama.gob.es/siar/), created in 1998 by the Spanish Ministry of Agriculture (MARM) in cooperation with regional governments, was selected to satisfy the third criterion above. The goals of that network include dissemination of irrigation requirements and promotion of irrigation scheduling. The SIAR network covers most irrigated areas in Spain, adapting the density of observations to the local intensity of irrigation developments. Each agricultural weather station (AWS) in the network records half-hour averages of air temperature and relative humidity, wind speed and direction, incoming solar radiation and cumulative precipitation. A web page publishes daily-updated agrometeorological information for each AWS of the SIAR network. Published information includes standardized reference evapotranspiration values estimated by the FAO Penman-Monteith method (Allen et al., 1998). Fig. 1 presents the ten provinces, located in the south and north-east of Spain, finally selected for the software, as well as the location of each AWS of the SIAR network. A total of 153 weather stations were considered in the RIDECO software. The average length of the meteorological data series in 2011 was 8 years, with a minimum of 6 years. Fig. 2 presents shaded contour maps of average annual precipitation (Fig. 2a) and reference evapotranspiration (ET_o) (Fig. 2b) in the target area. All complete data years were used to determine these average values. About 89 % of the average precipitation values fell in the range of 300 to 600 mm year^{-1}. The areas with lowest annual precipitation corresponded to the central Ebro Valley (Zaragoza, Huesca and Teruel), Murcia and Badajoz. About 57 % of the long-term average ET_o values fell in the range of 1,000 -

1,300 mm $year^{-1}$. The areas with highest ET_o roughly corresponded to the areas with lowest precipitation. As a consequence, these areas resulted in maximum crop water requirements.

2.2. Definition of the farm and the irrigation subunit

The software addresses the needs of an irrigation professional, managing a number of farms in different locations. Farms are declared in the software and associated to a certain AWS. Farms are divided in subunits, each irrigated from a control valve. Each of these valves is the subject of irrigation scheduling. As a consequence, information is required on the natural environment, the agronomic traits and the irrigation system in the subunit. The subunit area characteristics, the crop species and variety are recorded in the database. The RIDECO software includes complete information for three crops: cherry, apricot and four cycles of peach (extra-early, early, medium and late maturing). Soil depth and fruit load are qualitatively assessed. The tree spacing, the number of emitters per tree, the emitter discharge and the irrigation efficiency are required to convert irrigation schedules from irrigation depth to irrigation time.

2.3. Crop phenology

García-Vera and Martínez-Cob (2004) proposed the following crop stages for stone fruits, adapted from the four crop stages defined in the FAO 56 manual (Allen et al., 1998): 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.

In addition to the crop stages above, fruit growth stages are commonly used to select the timing appropriate for RDI practices (Goodwin and Boland, 2000). The fruit growth stage delimitation used in this work was proposed by 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). FIV was further 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 and deficit irrigation coefficients.

Fig. 3 presents the relationships between FAO stages and fruit growth stages. These stages are used in the RIDECO software to establish standard crop water requirements and the timing of RDI. The initial FAO stage starts with bud swelling, while the initial fruit growth stage starts with blooming. The dates for bud swelling and blooming are manually set for each subunit; default values are provided for each crop and crop cycle.

2.4. Crop and deficit irrigation coefficients

Complete Kc data sets are not available for all the target geographical areas, with the exception of the recommendations reported by García-Vera and Martínez-Cob (2004) for the Ebro Valley (NE Spain, provinces of Huesca, Zaragoza and part of Teruel). García-Vera and Martínez-Cob (2004) adapted the FAO 56 crop coefficients (single Kc approach) to the local conditions for a number of crops, including stone fruits, and were adopted in the RIDECO software as default values (Table 1). Users can replace these default values by local, more accurate estimates; new crops and varieties can also be added to the database. The tree canopy diameter is used in the software to estimate the percent shaded area and to determine whether evapotranspiration needs to be adjusted (decreased). The approach by Fereres and Castel (1981) was used for this purpose.

Crop evapotranspiration under RDI was estimated by reducing water requirements at the fruit development stages least sensible to water stress. This was accomplished by multiplying crop evapotranspiration (ETc) by a RDI coefficient (Kr_{RDI}) adopting values [0 - 1]. For cherry, apricot, and extra-early and early maturing peaches, the RDI strategy only reduced water application at postharvest stage (FIV). For medium and late maturing peaches, the RDI strategy reduced water application at fruit growth stages FII and FIV (pit hardening and postharvest, respectively). Values of Kr_{RDI} for each species and cycle were adapted from the literature (Chalmers et al., 1981; Johnson et al., 1992; Torrecillas et al., 2000; Goldhamer et al., 2002; Gelly et al., 2004; Girona et al., 2005; Dichio et al., 2007; Marsal et al., 2009). These values can be manually adjusted to local conditions by the users. Table 2 presents the minimum and maximum Kr_{RDI} for cherry, apricot and the four peach trees cycles used in this work. These coefficients are presented as a function of qualitative estimations of fruit load and soil depth following Girona et al. (2003, 2005) for peaches, Marsal et al. (2009) for cherries, and Perez-Pastor et al. (2009) and Perez-Sarmiento et al. (2010) for apricots. Table 2 has simplified those research works to obtain practical guidelines for farmers. Differences on Kr_{RDI} for different soil depths were reported by Girona et al. (2005) for peaches. These authors stated that in shallow soils fruit trees respond faster to water replacement than in deep soils. This different behavior leads to larger values of Kr_{RDI} for shallow soils than for deep soils. If the RDI strategy is chosen, the average of the maximum and minimum coefficients is selected.

2.5. Thermal time modeling

The cumulative growing degree-days model (Winkler et al., 1962) was used in the RIDECO software to model thermal time:

$$GDD = \sum_{Biofix\_date}^{leaf\_fall} \left(T_{av} - T_{base} \right) \qquad \text{(Eq.1)}$$

GDD thresholds separate the abovementioned phenological stages. Despite the fact that GDH models have been documented to be more precise than GDD models to assess crop and fruit development (Mimoun and DeJong, 1999), GDD was used in this research because it accommodates the information available at the SIAR network. The biofix date for deciduous fruit trees was defined in this work as the bloom date. The base temperatures adopted in this research were 4.0 ºC for the four peach cycles (Rageau et al., 1998; Mounzer et al., 2008) and cherries (Zavalloni et al., 2006), and 4.4 ºC for apricots (Valentini et al., 2004 and 2006). Critical temperatures of 36 ºC for peach trees (Rageau et al., 1998; Mounzer et al., 2008), and 25 ºC for cherries (Chung et al., 2009) and apricots (Guerriero and Monteleone, 2006) were adopted. These temperature parameters can be modified by the users.

The dates corresponding to crop and fruit growth stages are determined for every AWS and year by the GDD model, following the thresholds presented in Table 3. Threshold values were obtained for the extra-early maturing peach from phenological observation in an orchard at the Murcia region (Mounzer et al., 2008). For the rest of crops and crop cycles, phenological observations reported in an orchard of the Ebro Valley were used (Zapata et al., 201Xa and 201Xb). Default parameters governing thermal time can be specifically edited for each subunit in order to facilitate local adaptation of the irrigation schedules.

As an alternative to thermal time, the software allows simulation of crop phenology based on user-entered dates limiting phenological stages.

2.6. Irrigation scheduling strategies

Three irrigation strategies responding to common practical situations can be executed in the RIDECO software:

1. **Standard irrigation**. Application of 100% of the estimated crop water requirements. This strategy corresponds to non water-stressed areas. Even in these areas, deficit irrigation is becoming a common practice (Salvador et al., 2011) owing to fruit quality restrictions and to the cost of irrigation water and pruning operations.
2. **RDI strategy**. Reduction of irrigation water application during periods not sensitive to water stress. The scientific community has identified relevant benefits from the adoption of this strategy. However, its widespread implementation is limited by the spatial variability of environmental factors and by irrigation performance (Zapata et al. 201Xa; Zapata et al. 201Xb). The plot-specific irrigation scheduling produced by our software is expected to contribute to its practical implementation.
3. **Water restrictions**. The RIDECO software has been programmed to adapt to water restrictions, proposing the irrigation schedules resulting in minimum yield affection. If available irrigation water (m^3 ha^{-1}) does not suffice to satisfy crop water requirements, the first step is to adopt the RDI strategy. The second step is to adopt a minimum RDI strategy, based on using the minimum Kr_{RDI} coefficients reported in the literature and stored in the RIDECO database. If this was not enough, a homogeneous and global reduction from minimum RDI would be adopted to make irrigation application match available water, introducing a reduction coefficient. The homogeneous and global reduction coefficient was computed as the ratio between the total available water and the crop water requirements for the minimum RDI strategy. The software can adapt to restrictions rising at the beginning or during the season or even to different, successive restrictions applied during the season.

2.7. Types of simulation

The next step in the process is to decide among three different types of simulation:

1. **Real time simulation**. The software produces an irrigation schedule (irrigation hours) for the following week based on the meteorology of the past week. This type of simulation is designed to control the irrigation system at real time.
2. **Historical simulation**. This simulation can be applied using all complete annual meteorological series or user-selected meteorological subsets. Historical simulation was designed for seasonal water allocation planning under a variety of hypotheses on evapotranspiration, precipitation, soil, crop and irrigation factors, and restrictions in water allocation.
3. **Complete the current irrigation season**. This simulation is a mix of the two cases above. Real time scheduling is performed till the present day, and the hypothesis characterizing historical simulations can be adopted to simulate the remaining irrigation weeks. Expected contingencies affecting water availability towards the end of the season can be tackled through the planning of conservative irrigation schedules.

2.8. Output

The model provides both tabular and graphical output, and a number of export options. The critical software output is the Weekly Irrigation Time (WIT, hr week^{-1}). Additional information for advanced users includes the time evolution of selected variables under standard irrigation, RDI conditions, minimum RDI and under water restrictions. The variables of interest are Kc and the gross and net irrigation requirements (weekly and cumulative). Gross irrigation requirement is the total amount of water that needs to be withdrawn from the source to satisfy crop water requirements. Net irrigation requirement is the difference between crop evapotranspiration and effective precipitation (Smith et al. 1991). The percentage of net to gross irrigation requirements is irrigation efficiency.

3. RIDECO software implementation

3.1. Programming tools

The RIDECO software has been developed in the object-oriented programming language C# using .Net technology (Visual Studio 2008). This programming language provides an intuitive and user friendly interface in Windows environment. The Extreme Programming methodology was used to develop this application. Objects were designed using the CRC (class, responsibility and collaboration) methodology. Two types of classes were defined: 1) those bound to the tables of the database; and 2) those that execute specific operations. Classes are formed by attributes and consult methods specializing on information management. Specific libraries (DLL ActiveX Open source) programmed in C# facilitate 2D graphical representation in .Net.

The selected database manager was PostgreSQL, providing the power and flexibility to manage the software data requirements. The data manager receives the information provided by the client and stores it in the database. Information can be also recovered and presented in the correspondent forms. A specific application was developed in the Phyton programming language to improve efficiency in data flow.

The software interface was developed in Spanish since was designed for technicians of the Spanish fruit sector. The software is technical by nature but it has been designed to provide generic answers with minimum input and very site-specific answers with detail input. The main software form gives the user access to all software functionalities.

Object-oriented programming has led to the development of a general purpose irrigation scheduling code, specifically adapted to the generation of irrigation schedules in the area covered by the SIAR network of Spain. The code will find application in the current efforts to develop automatic ET_o-based irrigation controllers (Zapata et al., 2009). A generalization of the communication module will permit unattended connection to additional public access agrometeorological networks.

3.2. Software and database interaction

Fig. 4 provides a schematic diagram of the interaction between the RIDECO software, the SIAR network, the RIDECO database and the users. The RIDECO software communicates with the SIAR network using a standard HTTP protocol (transfer protocol of hypertext between a navigator and a Web server). The selection of an AWS in the software automatically connects with the SIAR server and updates meteorological data in the RIDECO database from the last download to the current date. Specific meteorological updating can also be performed for selected time periods. The RIDECO database has a bidirectional relation with the software: data from the database can be required by the software, while software-managed data (such as downloaded meteorological data, parameters or the results) can be stored in the database.

Two types of users have been defined: standard and advanced. The standard user can interact with the software using the graphic interface. The advanced user can also manage three specific files (Fig. 4): the configuration file (App.config), the event log file (App.log) and the backup file (App.backup). The configuration file (XML format) stores information about the access to the SIAR server, the location of the events log and backup files and about the properties and attributes of the different classes. The event log file provides detailed information about the software execution errors. Finally, the backup file is automatically created to secure all application data when the application is closed.

The data flow chart of the RIDECO software is presented in Fig. 5. The selection of the farm location leads to the selection of the AWS best representing the meteorology of the farm. The software connects to the SIAR server and the selected meteorological data series is updated into the software database. The description of soil, crop and irrigation parameters for each irrigated subunit of the farm is input by the user through specific data forms. The user needs to select the type of simulation to perform (real time, historical or completing a season), as well as an irrigation strategy (standard, RDI or water restriction). Default values for the crop and deficit coefficients (Kc, Kr_{RDI} and Kr_{RDImin}) for the different species, cycles and irrigation strategies are stored in the application, and can be modified by the user. The software simulates the crop development stages and produces a weekly irrigation schedule for each irrigated subunit of the farm.

The interaction between the main tables of the RIDECO database is presented in Fig. 6. Tables are presented in four groups according to their contents: meteorological, farm physical parameters, crop parameter and simulation results. Relations between tables are coded using standard symbols to specify one or n table elements. For instance, the relationship between the weather station table and the farm table is of the type “one to n”, indicating that a farm is represented by only one weather station, while a weather station can be representative of several farms. Meteorological tables include the regions of the SIAR territory, the provinces of each region, the AWS available at each province and the meteorological parameters stored by each AWS. The Farm table relates to the table containing its Subunits, which in turn relates to the Soil characteristics, the Irrigation system, the Fruit load and the Crop tables. The Crop table connects to the Variety, Species and Cycle, Kc, Kr_{RDI} and Fruit stage tables. The fourth group of tables corresponds with the simulation results tables. The Simulation Parameter table relates with the Subunit table, since the Subunit is the simulation unit. This group stores data related to the simulation types, the irrigation strategies, the simulation dates and the simulation results.

The RIDECO software is available for free download at the following URL: http://digital.csic.es/handle/10261/45608. A software manual is included.

4. Software application

4.1. Input and output sample forms

Fig. 7 presents a screen shot of the Parameters software form applied to a real time simulation. The selected AWS (in this particular case, Caspe) is displayed at the upper right side of the form, above the logos. The availability of meteorological data in the selected AWS (in this example, from 2005 to 2010) is displayed at the lower right side of the screen. The types of simulation and the options for results formatting are listed at the upper-left side of the screen. A real time simulation was selected in this particular example, as indicated below the logos. A summary of the farm parameters (name, area and selected meteorological data series) is displayed at the upper part of this section. The subunits of the farm and their main characteristics are listed bellow the farm name. The parameters of the highlighted subunit (in this example, “Sector temprano”) are listed at the lower half part of the form. The simulation and save buttons are displayed at the right side of the section.

Fig. 8 presents scheduling results for weekly irrigation time (hours) corresponding to a historical simulation. The upper part of the screen is similar to the input screen (Fig. 7), while the central part of the screen is divided in the graphic part on the left and the results table on the right. Weekly irrigation time for all irrigation strategies (standard, RDI and RDI_{min}) are presented in both graphical and tabular formats.

4.2. Study cases

Two examples of water restrictions (fixed and variable along the season) are presented in this section. The simulated farm (a late maturing peach orchard) was located in Caspe (Zaragoza). Fig. 9 presents the results of the fixed water restriction case, while Fig. 10 presents the variable water restriction case. Figs. 9a and 10a present the evolution of the crop coefficient along the season for the standard, RDI, and minimum RDI strategies, and for the analyzed water restriction case. Figs. 9b and 10b present gross irrigation requirements (GIR) under the same four irrigation strategies, Figs. 9c and 10c present cumulative gross irrigation requirements (CGIR). Finally, Figs. 9d and 10d present the weekly irrigation time for each of the studied strategies.

In the case of fixed water restrictions, irrigation scheduling is adjusted to an allocation of 4,000 m^3 ha^{-1}. This is a very low allocation, since the gross water requirements would be 10,161, 8,202 and 7,978 m^3 ha^{-1} for standard, RDI and minimum RDI conditions, respectively. In order to adjust to this very low limitation, all crop coefficients were adjusted to values below the minimum. The solution proposed by the software allocates the existing water using proportional adequacy criteria, but does not guarantee neither full yield (yield will be affected for sure) nor the agronomic sustainability of this operation (trees will be affected by this severe drought and salinity may build up in the soil).

For the variable water restriction case, the water restriction started with 4,000 m^3 ha^{-1} and on July 15th, the restriction was updated to 5,000 m^3 ha^{-1}. The new scenario still falls below minimum RDI conditions, but leads to a substantial increase in the compound crop coefficient, in the gross water requirements and in the number of irrigation hours.

Zapata et al 201Xa and 201Xb presented a comparison between the irrigation volume applied in a commercial orchard and the irrigation volume resulting from the application of an RDI strategy (following the methodology of the RIDECO software). The study concluded that the orchard’s irrigation practices did not correspond to an RDI strategy: crop water stress was detected during fruit stages which have been reported to be highly sensitive to water stress, while some periods of recommended RDI were not water stressed

5. Conclusions

Most of the fruit producing areas in Spain and all over the word need to improve irrigation water management to meet the goals of water conservation, standards on fruit quality, reduction of the production cost (minimizing pruning needs) and maintain environmental quality. The RIDECO software was designed to perform irrigation scheduling under standard, regulated deficit and water restriction irrigation strategies, optimizing the irrigation water management at farm level. The software summarizes current scientific knowledge on advanced irrigation techniques for stone fruit orchards. Software design ensures that irrigation managers not specifically acquainted with current developments in irrigation science can use this tool. The graphic interface provides an easy and practical way of exploiting the developments of on-line agrometeorological servers and facilitates the adaptation of irrigation schedules to local conditions. The irrigation scheduling software stands as a valuable tool for on-farm water allocation planning, since it permits to forecast the seasonal volumes of water that will be required under specific scenarios. The RIDECO software also permits to analyse deficit irrigation strategies required to meet severe water restrictions.

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restriction started at 4,000 m^3 ha^{-1}, and was updated to 5,000 m^3 ha^{-1} in July 15. Results include: a) crop coefficients; b) gross irrigation requirements; c) cumulative gross irrigation requirements; and d) irrigation time (hr $week^{-1}$).

Table 1. . Crop Coefficients (Kc) as reported in Garcia-Vera and Martinez-Cob 2004, for the different species and peach cycles in the FAO phases: initial, medium and final.

Crop coefficient	**K_c**		
	$K_{c\ initial}$	$K_{c\ medium}$	$K_{c\ final}$
Cherry	0.36	0.98	0.20
Apricot	0.36	0.98	0.20
Extra-early Mat. Peach	0.44	0.93	0.24
Early Mat. Peach	0.44	0.93	0.24
Medium Mat. Peach	0.38	0.94	0.26
Late Mat. Peach	0.36	0.94	0.31

Table 2. Maximum and minimum reduction coefficients for the RDI strategy (Kr_{RDI}) at the non sensitive fruit stages for several stones fruits species (cherry, apricot, extra-early maturing peach, early maturing peach, medium maturing peach and late maturing peach).

Soil Depth	**Crop**	**K_{rRDI} High fruit load** FII	FIV$_{initial}$	FIV$_{final}$	**K_{rRDI} Low fruit load** FII	FIV$_{initial}$	FIV$_{final}$
Deep	Cherry	-	0.40-0.60	0.40-0.60	-	0.40-0.60	0.40-0.60
	Apricot	-	0.30-0.50	0.30-0.50	-	0.30-0.50	0.30-0.50
	Extra-early Mat. Peach	-	0.30-0.50	0.50-0.70	-	0.30-0.50	0.50-0.70
	Early Mat. Peach	-	0.30-0.50	0.50-0.70	-	0.30-0.50	0.50-0.70
	Medium Mat. Peach	0.00-0.50	0.00-0.30	0.50-0.70	0.00-0.50	0.00-0.30	0.50-0.70
	Late Mat. Peach	0.00-0.50	0.00-0.50	0.00-0.50	0.00-0.50	0.00-0.50	0.00-0.50
Shallow	Cherry	-	0.50-0.70	0.70-0.80	-	0.50-0.70	0.70-0.80
	Apricot	-	0.50-0.70	0.70-0.80	-	0.50-0.70	0.70-0.80
	Extra-early Mat. Peach	-	0.50-0.70	0.70-0.80	-	0.50-0.70	0.70-0.80
	Early Mat. Peach	-	0.50-0.70	0.70-0.80	-	0.50-0.70	0.70-0.80
	Medium Mat. Peach	0.40-0.70	0.20-0.50	0.70-0.80	0.40-0.50	0.20-0.50	0.70-0.80
	Late Mat. Peach	0.40-0.70	0.50-0.70	0.50-0.70	0.40-0.50	0.50-0.70	0.50-0.70

Table 3. Growing degree-days necessary to reach the specific phenological stages determined with the GDD model, meteorological data and phenological observations.

Phenological stages	Cherry	Apricot	Extra-early Mat. Peach	Early Mat. Peach	Medium Mat. Peach	Late Mat. Peach
Beginning of pit hardening	169	183	370	568	531	515
Finish of pit hardening	371	466	450	671	1004	1406
Fruit ripenning	703	1123	920	1262	1979	2956
Leaf fall	3336	3362	3862	3547	3511	3494

Fig. 1. Location of the target geographical areas and the agrometeorological stations of the SIAR network.

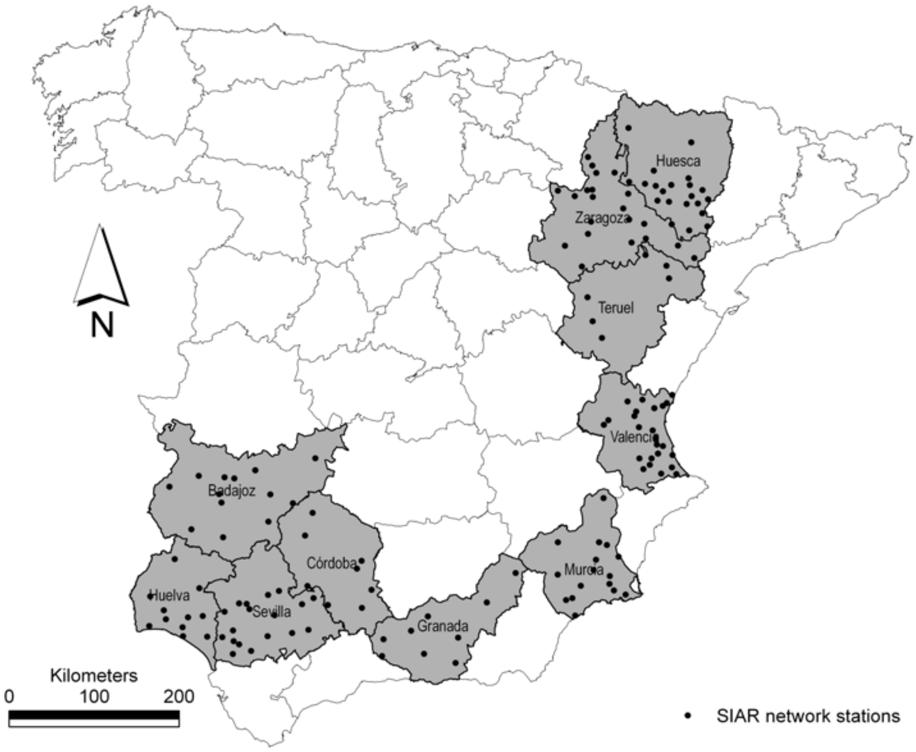

Fig. 2. Shaded contour maps of long-term average annual precipitation (mm yr^{-1}, Fig 2a) and reference evapotranspiration (ETo, mm yr^{-1}, Fig 2b) in the target stone fruit production areas.

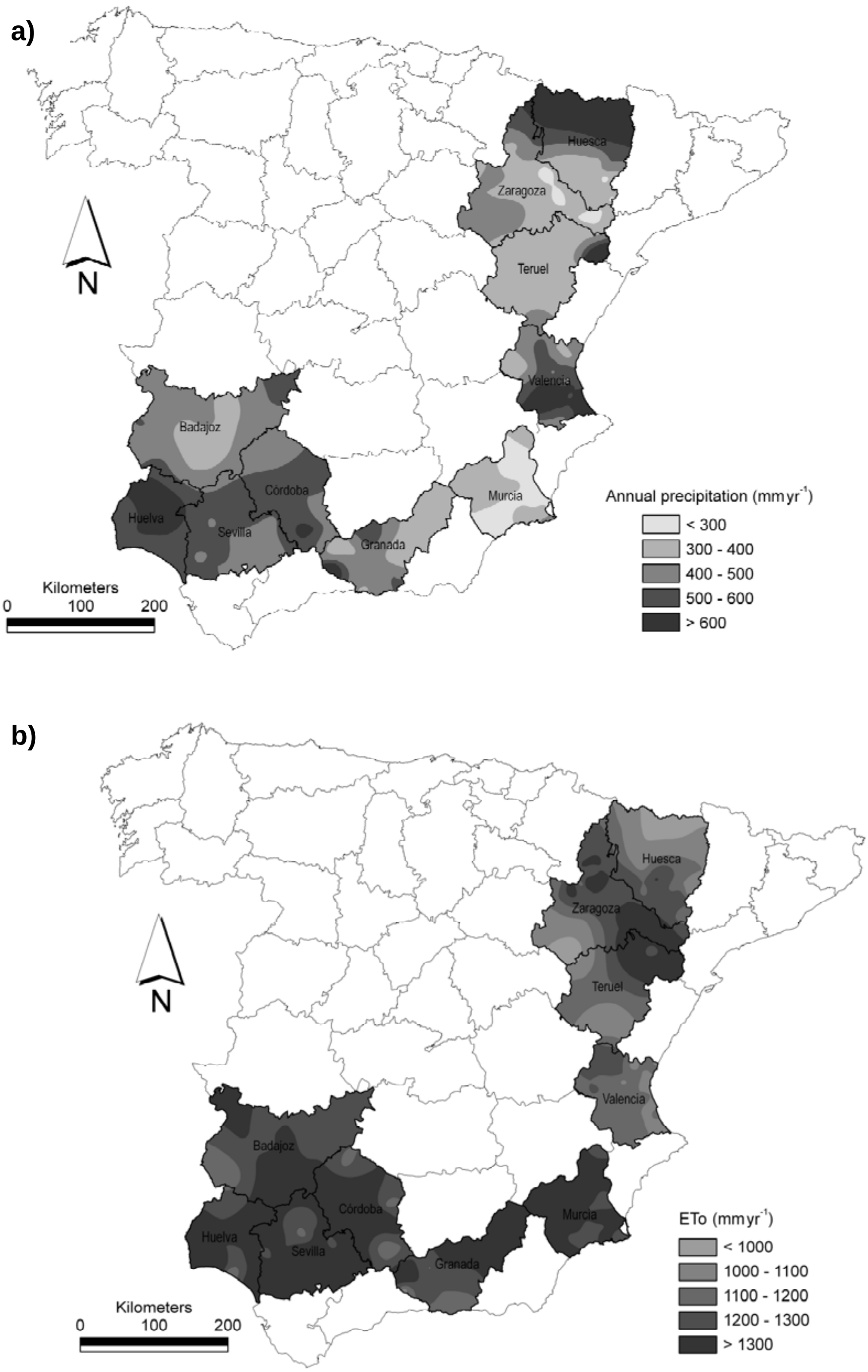

Fig. 3. Correspondence between the phenological events defining the FAO crop development stages (as proposed in García-Vera and Martínez-Cob 2004) and the fruit growth stages.

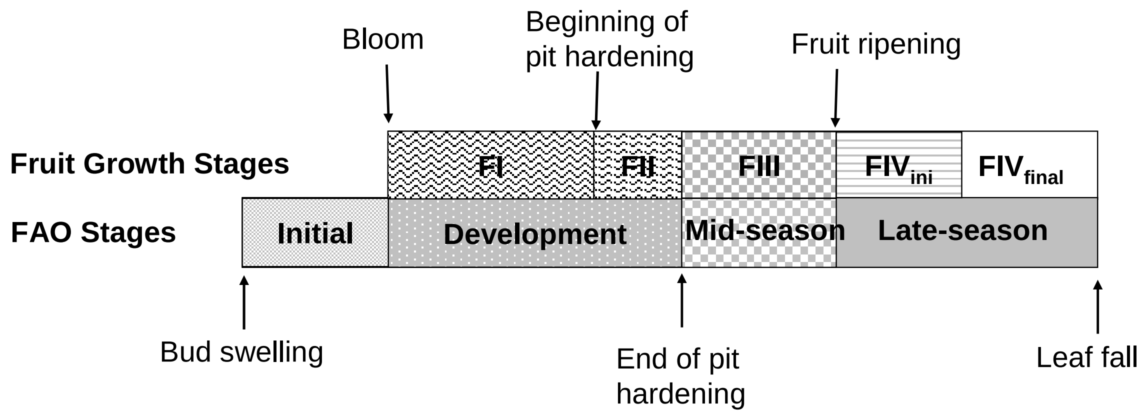

Fig. 4. Interaction between the RIDECO software, the Internet-based SIAR agrometeorological data, the RIDECO database and the users.

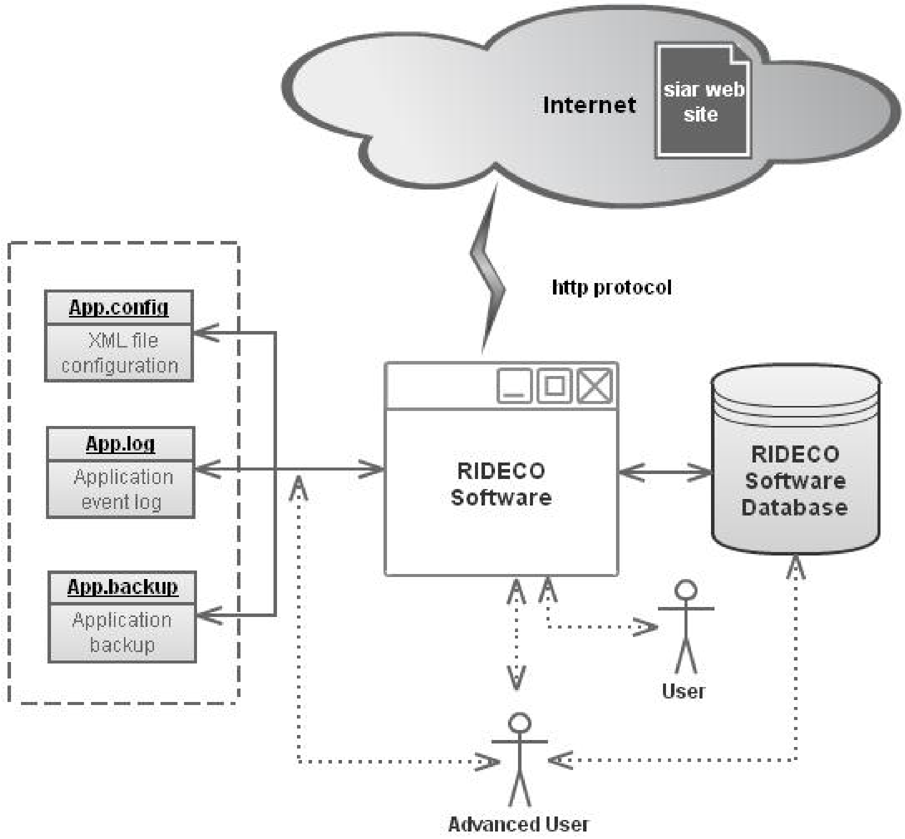

Fig. 5. Flow chart of the RIDECO software: elaboration of a weekly irrigation schedule.

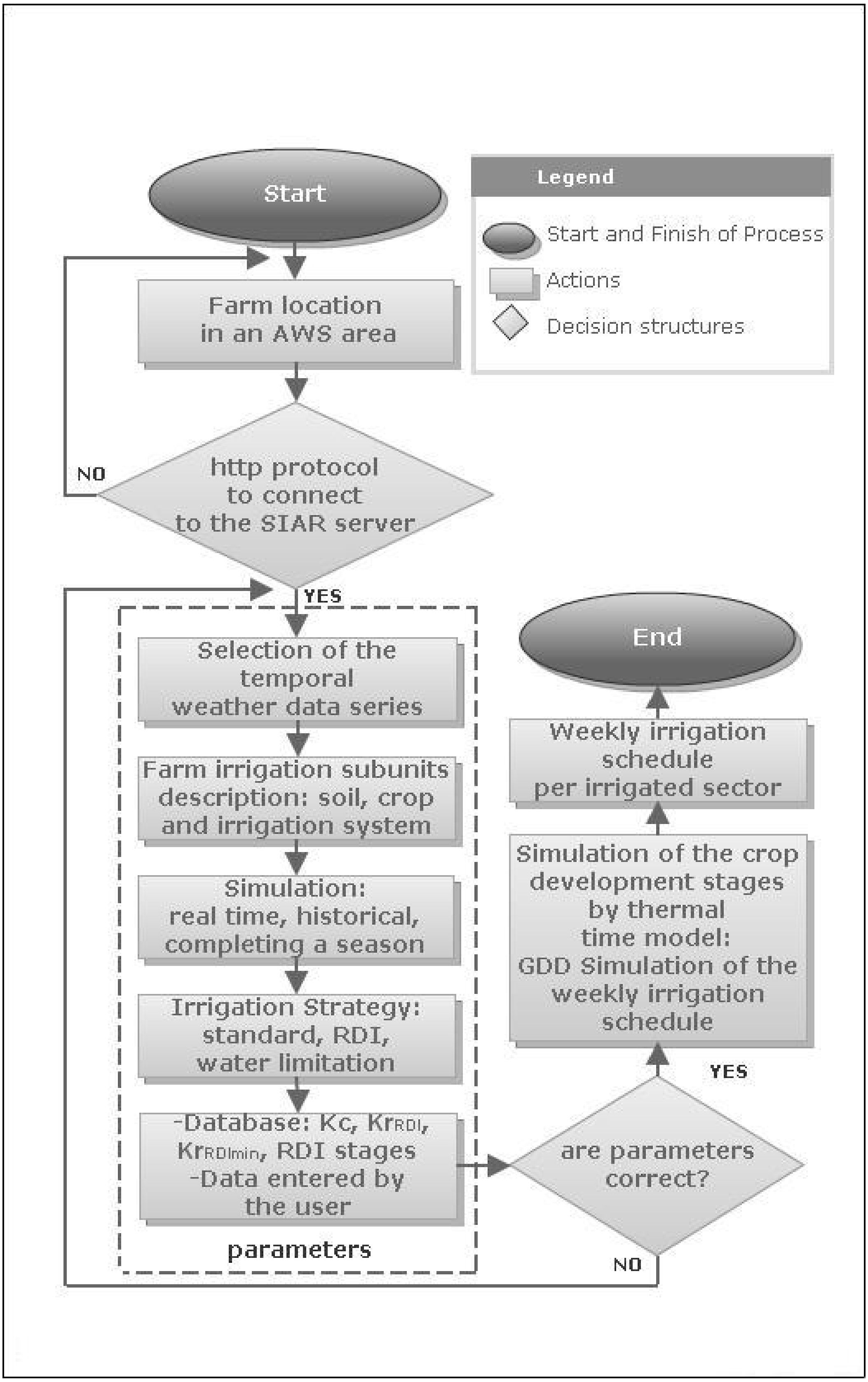

Fig. 6. RIDECO database design, showing the relations between the main database tables.

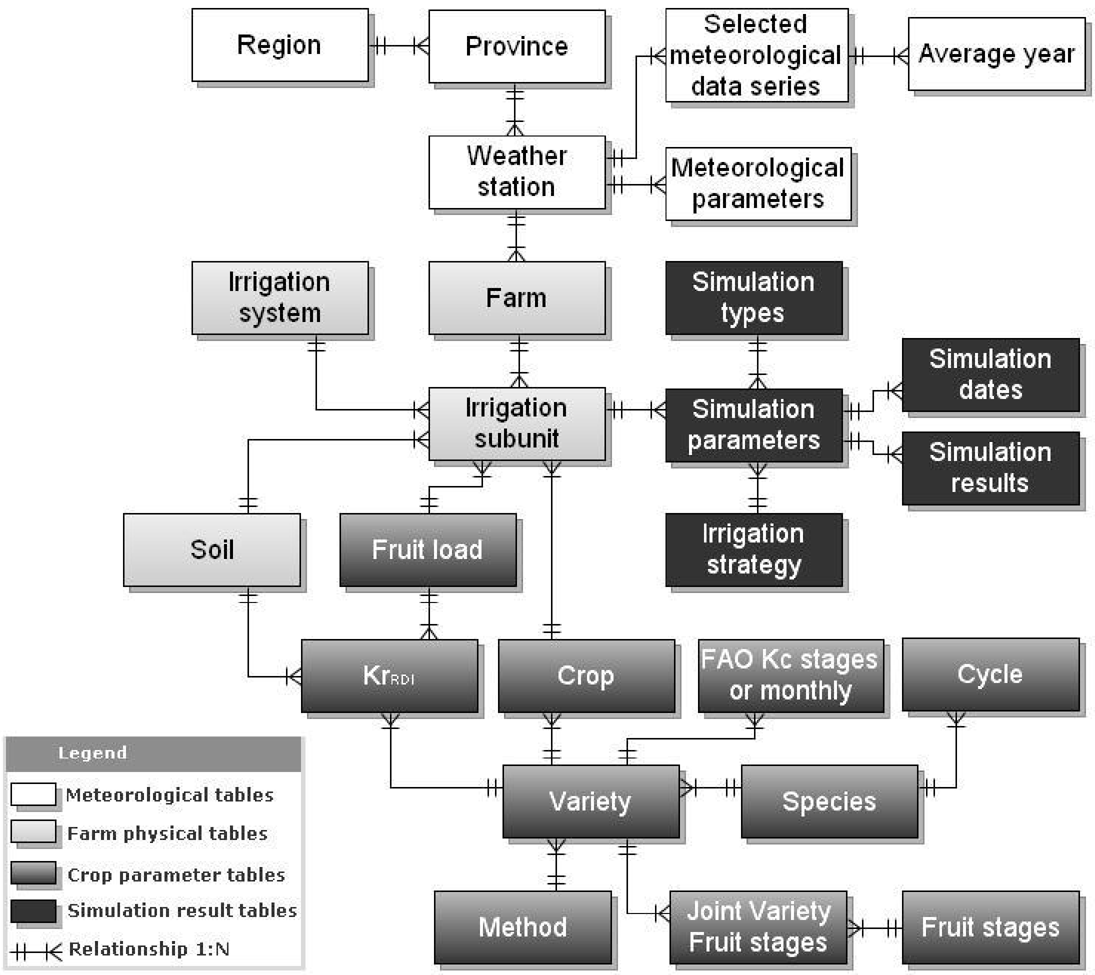

Fig. 7. A typical RIDECO data input form: farm and simulation parameters. The original version of the software windows is in Spanish.

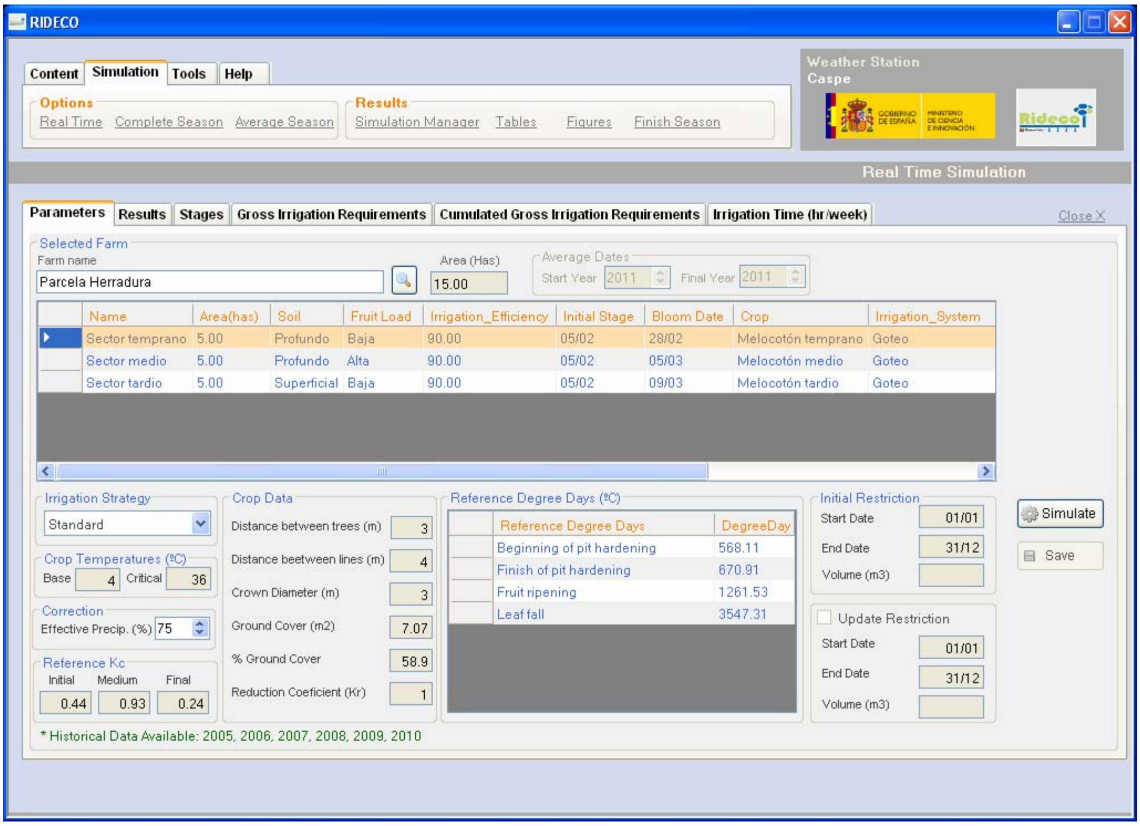

Fig. 8. A typical RIDECO results form: Weekly Irrigation Time. The original version of RIDECO windows is in Spanish.

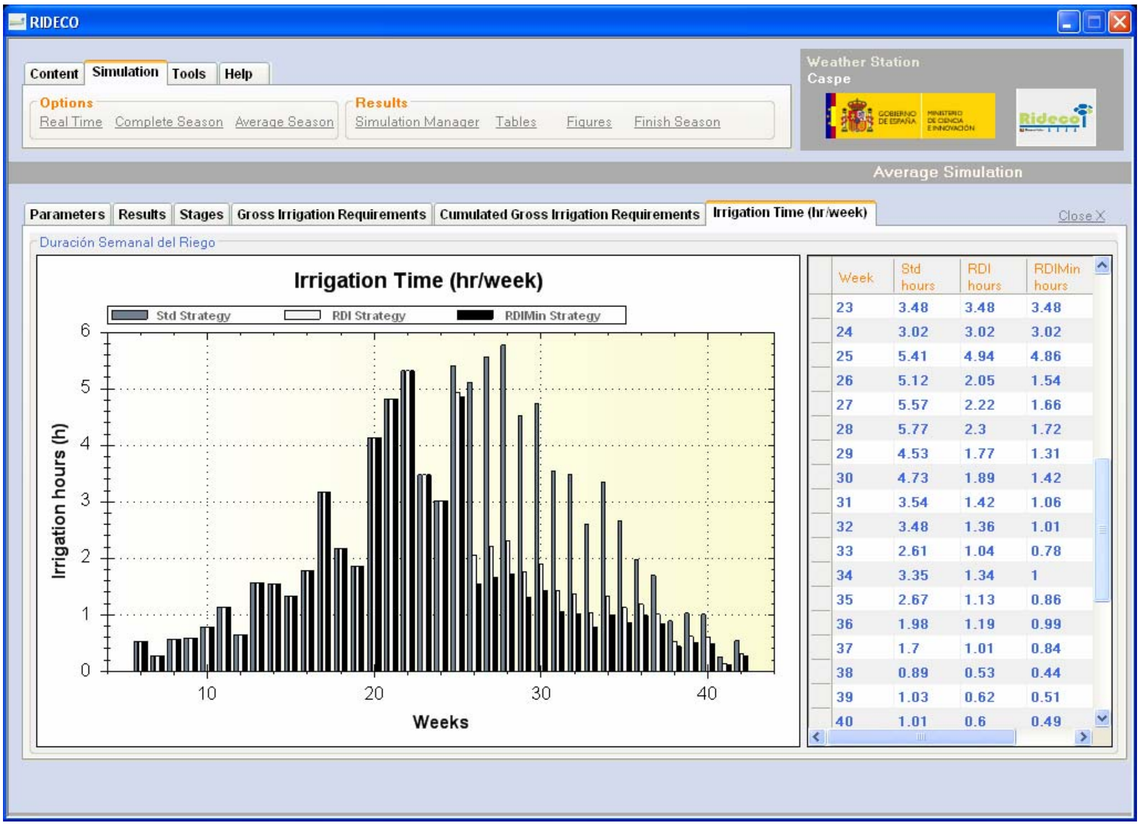

Fig. 9. Graphical results of a simulation for a late maturing peach orchard under all irrigation strategies (standard, RDI, RDImin and water restriction of 4,000 m^3 ha^{-1}): a) crop coefficients; b) gross irrigation requirements; c) cumulative gross irrigation requirements; and d) irrigation time (hr $week^{-1}$).

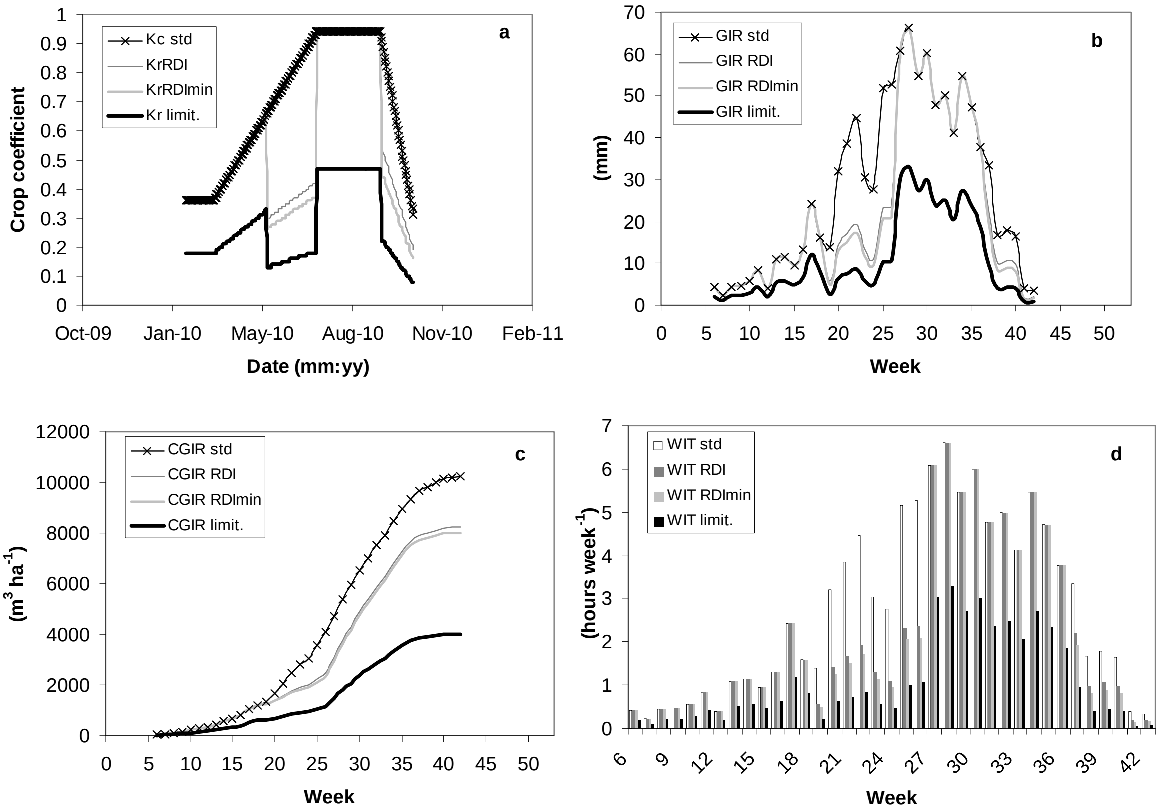

Fig. 10 Graphical results of a simulation for a late maturing peach orchard under all irrigation strategies (standard, RDI, RDImin and water restriction). Seasonal water

restriction started at 4,000 m^3 ha^{-1}, and was updated to 5,000 m^3 ha^{-1} in July 15. Results include: a) crop coefficients; b) gross irrigation requirements; c) cumulative gross irrigation requirements; and d) irrigation time (hr $week^{-1}$).