Annexes

The following annexes are included:

- Annex I. – Final dissemination meetings
- Annex II. Final reporting of soil water status and water productivity predictions
- Annex III. Farmer evaluation of REDSIM Irrigation Advisory Bulletin
- Annex IV. Benchmarking indicators for the Cartagena irrigation district
- Annex V. Some examples of application of indicators to Segura River Basin
- Annex VI. Final reporting on Mapping Quantitative Precipitation Estimates
- Annex VII. Brochure: REDSIM guidelines
- Annex VIII. Layman’s report

Annex I. Final dissemination meetings

Two final dissemination meetings were organized:

- A roundtable at the Murcia Agricultural Council, for local farmers and other interested stakeholders (extension services, academics). Speakers were researcher from REDSIM and the regional councillor of Water and Agriculture.
- Co-organization a European event in Madrid, focused on water efficiency and water management solutions within the European context (legislation, funding, research, etc).

Of both events, this annex includes the programs:

Program event in Murcia

REDSIM

Mesa Redonda

SOLUCIONES PARA MEJORAR LA PRODUCTIVIDAD DEL AGUA
RESULTADOS DEL PROYECTO EUROPEO *"REMOTE-SENSING BASED DSS FOR SUSTAINABLE DROUGHT-ADAPTED IRRIGATION MANAGEMENT" (REDSIM)*

Fecha: **Jueves 3 de Mayo, 2012**

Lugar: Salón de Actos de la **Consejería de Agricultura y Agua de la Región de Murcia**

En esta mesa redonda, se presentarán los resultados más relevantes del proyecto europeo REDSIM (www.redsim.net) que coordina la Universidad Politécnica de Cartagena (UPCT), con la participación del IMIDA, CSIC-CEBAS, Universidad de Córdoba y AFRE. El objetivo de REDSIM es desarrollar técnicas y herramientas de asesoramiento al riego deficitario, principalmente a través de Internet.

Agenda

17.30 – 17.45 Acto inaugural (Excmo. Sr. Consejero de Agricultura y Agua, D. Antonio Cerdá Cerdá), Rector de la UPCT y el Director de la Escuela Técnica Superior de Ingeniería Agronómica de la UPCT)

17.45 – 18.45 Mesa redonda. Moderada por Alain Baille (UPCT), coordinador de REDSIM:

- Alejandro Pérez Pastor, UPCT – Riego deficitario controlado en frutales
- Juan José Alarcón, CEBAS - Riego deficitario controlado en cítricos
- Manuel Erena, IMIDA – Sistema de información web REDSIM
- Gonzalo Gonzales Barbera, CEBAS – ¿Cuánto ha llovido en mi parcela?
- Johannes Hunink, UPCT – Boletín semanal de riego

18.40 -18.45 Conclusiones

Organiza:

ETSIa Cartagena
Universidad Politécnica de Cartagena
CAMPUS MARE NOSTRUM
Región de Murcia

Program event in Madrid

PROGRAM

II EUROPEAN $\Sigma H_2 0$ FORUM

WATER INNOVATION. CONSTRUCTING A SUSTAINABLE HYDROLOGIC FUTURE

MADRID

8th - 9th OF MAY, 2012

Tuesday, May 8

08,00-09,00 h. Accreditations and documentation.

09,00-10,00 h. Presentation and official opening of the European Commission intervention, the Ministry of Agriculture, Food and Environment, Ministry of Economy and Competitiveness, CSIC and PTEA.

Presenter: ***Mr. Sergi Martí.*** *Vice PTEA Communication.*

10,00-10,20 h. Session under "The PTEA and its contribution to R & D + i and the Spanish and European competitiveness in water" PTEA balance for first year since its official establishment and presentation of the strategic guidelines for 2012/13.

Mr. Miquel Vila. *President of the PTEA.*
Mr. Miguel Lopez Estebaranz. *Secretary General of PTEA*

10,20-11,30 h. Session 1. Scientific-technological discussion "innovation in water, water planning and financing" with keynote presentations from the Ministry of Agriculture, Food and Environment, Ministry of Economy and Competitiveness and PTEA with plenary discussion.

Presenter and moderator: ***Mr. Angel Cajigas Delgado.*** *PTEA International Vice President.*

Invited Speakers:
"Rules and guidelines for a new water planning." *Mr. Juan Urbano Lopez de Meneses. Director General of Water. Ministry of Agriculture, Food and Environment.* *
"Taxation of R & D+i and purchase innovative". *Mr. Luis Cueto. ADG Business Innovation Development of the Ministry of Economy and Competitiveness.*
"Framework Programme and water." *Mrs. Carolina Rodriguez. CDTI.*
"The EIP Water" *Mr. Robert Schroeder. DG Environment of the European Commission. EIP Responsible Water.* *
"Fund R&D+i in water: 1 st proposal on funding opportunities" *Mr. Antolin Aldonza. Technical Vice PTEA*

Plenary discussion "R & D+i in water planning and financing instruments to debate."

12,00-13,15 h. **Session 2. Scientific and technological discussion"Treatment of wastewater and desalination"** with presentations by experts on the issues to be resolved, innovative solutions and projects tractors "I + D + i" all with a broad plenary discussion moderated and energized representatives from the Ministry of Agriculture, Food and Environment and the PTEA.

Presenter and moderator: ***Ms. Rosa Xuclá Lerma.*** *Deputy Director of Infrastructure and Technology Water Directorate of the Ministry of Agriculture, Food and Environment. **

Short presentation "State of the art in technological innovation in water treatment and desalination"
"Regeneration and reuse of water." *Mr. Valentin Garcia. Isolux Corsan.*
"Wastewater treatment in small populations." *Mr. Fernando Hortigüela. IDEO.*
"Renewable energy and desalination." *Mr. Arturo Buenaventura. Befesa Water.*

Presentation "project / axle tractor R & D + i":
"Systems and advanced techniques in treatment and water quality." *Mr. Mario Diaz. GT Coordinator " Treatment and Water Quality "PTEA.*

Plenary discussion "Technology and R & D+i in water treatment debate."

13,15-14,30 h. **Session 3. Scientific and technological debate "Irrigation efficiency"** presentations by experts on the issues to be resolved, innovative solutions and projects tractors "I + D + i" all with a broad plenary discussion moderated and energized by representatives of the Ministry of agriculture, Food and Environment and the PTEA.

Presenter and moderator: ***Mr. Joaquin Rodriguez Chaparro.*** *Deputy Director General of Irrigation Water Directorate of the Ministry of Agriculture, Food and Environment.*

Short presentation "State of the art irrigation technology innovation":
"Irrigation Networks." *Mr. Richard Abbey. University Miguel Hernández.*
"Irrigation Systems". *Mr. Diego Intrigliolo. Valencian Institute of Agricultural Research.*
"Irrigation in greenhouses." *Mr. Santiago Bonachela. University of Almería.*

Presentation "project / axle tractor R & D + i":
"Systems and advanced irrigation techniques efficiently." *Mr. Juan José Alarcón. GT Coordinator "Irrigation Efficiency" PTEA.*

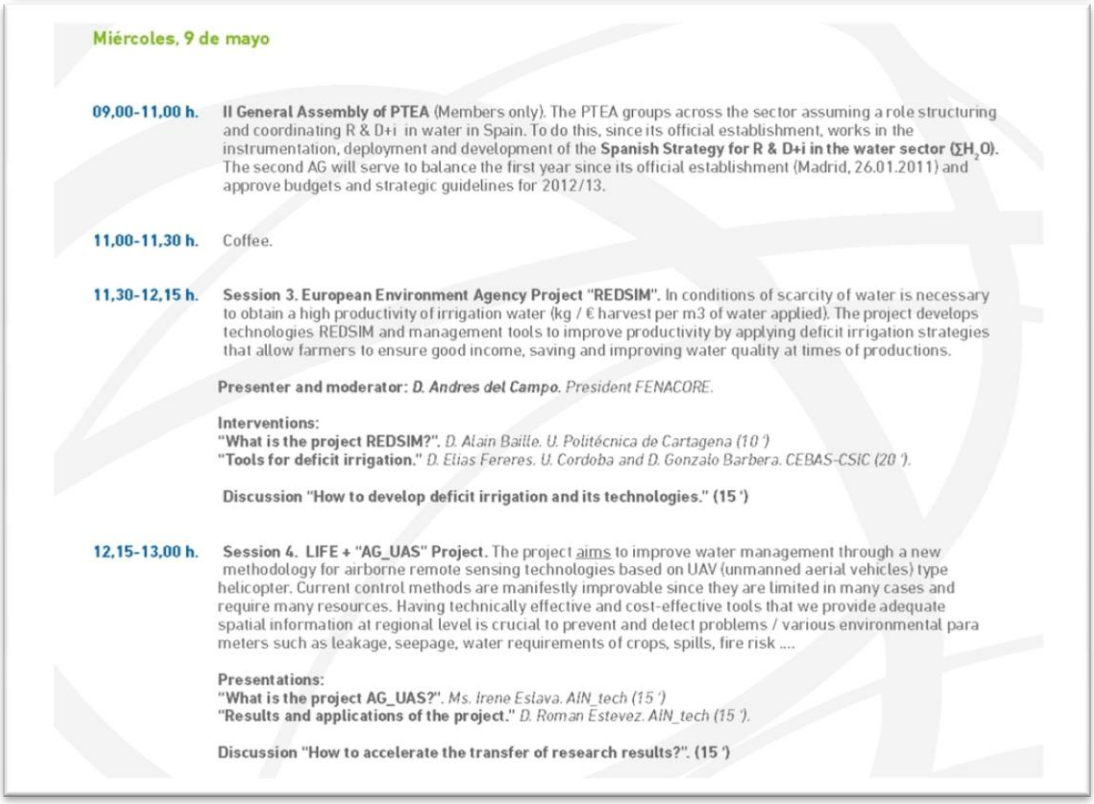
Plenary discussion "Technology and R & D+i in irrigation debate."

14,30-16,00 h. Cocktail-lunch.

16,00-17,30 h. **Workshop of European R + D + i.** Flash Presentations (5 minutes) of ideas / proposals for R + D + i for presentation at upcoming calls seeking officers and employees.

Presenter and moderator: ***Ms. Francisca Gomez.*** *Technical Secretary of the PTEA.*

17,30-19,00 h. **Bilateral meetings.** Sort encounters (10 minutes) among participants who have requested previously.



Miércoles, 9 de mayo

09,00-11,00 h. **II General Assembly of PTEA** (Members only). The PTEA groups across the sector assuming a role structuring and coordinating R & D+i in water in Spain. To do this, since its official establishment, works in the instrumentation, deployment and development of the **Spanish Strategy for R & D+i in the water sector (ΣH_2O).** The second AG will serve to balance the first year since its official establishment (Madrid, 26.01.2011) and approve budgets and strategic guidelines for 2012/13.

11,00-11,30 h. Coffee.

11,30-12,15 h. **Session 3. European Environment Agency Project "REDSIM".** In conditions of scarcity of water is necessary to obtain a high productivity of irrigation water (kg / € harvest per m3 of water applied). The project develops technologies REDSIM and management tools to improve productivity by applying deficit irrigation strategies that allow farmers to ensure good income, saving and improving water quality at times of productions.

Presenter and moderator: ***D. Andres del Campo.*** *President FENACORE.*

Interventions:
"What is the project REDSIM?". *D. Alain Baille. U. Politécnica de Cartagena (10 ')*
"Tools for deficit irrigation." *D. Elias Fereres. U. Cordoba and D. Gonzalo Barbera. CEBAS-CSIC (20 ').*

Discussion "How to develop deficit irrigation and its technologies." (15 ')

12,15-13,00 h. **Session 4. LIFE + "AG_UAS" Project.** The project aims to improve water management through a new methodology for airborne remote sensing technologies based on UAV (unmanned aerial vehicles) type helicopter. Current control methods are manifestly improvable since they are limited in many cases and require many resources. Having technically effective and cost-effective tools that we provide adequate spatial information at regional level is crucial to prevent and detect problems / various environmental para meters such as leakage, seepage, water requirements of crops, spills, fire risk ....

Presentations:
"What is the project AG_UAS?". *Ms. Irene Estava. AIN_tech (15 ')*
"Results and applications of the project." *D. Roman Estevez. AIN_tech (15 ').*

Discussion "How to accelerate the transfer of research results?". (15 ')

Annex II. Final reporting of soil water status and water productivity predictions

Authors: Johannes Hunink, Marga García Vila, Gonzalo González Barberá, Oussama Mounzer, Alain Baille

1-Introduction

Background

Optimal irrigation water management relies on accurate knowledge of plant water consumption, water flows and soil moisture dynamics throughout the growing season. The decision-supporting tools should therefore capture well the temporal and spatial variability of rainfall, soils, and crops. This cannot be reconstructed fully from field measurements or remote sensing, so dynamic simulation models are deemed necessary to describe soil physical processes, the surface water balance and crop growth in order to provide this information to the stakeholder and finally derive water productivity estimates.

In the past decades researchers devoted much effort to develop and calibrate field scale simulation models for water flow, salt transport and crop growth. Many calibration procedures were developed to extend the applicability of these integrated simulation models. Gradually these simulation models grew beyond the laboratory and plot scale and are now sufficiently mature that they can be usefully applied in an operational context.

During the last decade, several studies and projects aimed at delivering up-to-date soil water information to farmers to support them in their day-to-day irrigation scheduling. Most of them are however rather demanding in terms of resources as they require either detailed ground-based measurements or high-resolution satellite information.

Objectives

The objective is to provide the REDSIM toolbox components that allow the prediction of soil water status, crop production, water consumption and water productivity, combining generic crop process models (SWAP and AquaCrop), remote sensing information and data from existing databases (soil, climate, land use) and monitoring campaigns.

This annex summarizes the approach that was followed to set up the toolbox components that provide the relevant information on soil, crop and water needs. Chapter 2 contains the specifications of the selected models. A description of the datasets used can be found in chapter 3. Chapter 4 shows results on the calibration of the toolbox components using data that was gathered at the REDSIM pilot sites. Chapter 5 shows how the toolbox components were used within the REDSIM information and advisory tools.

2-Modeling concepts

Definitions

Total Available soil Water

The total available water (TAW) or plant extractable water is the amount of water a crop can theoretically extract from the root zone (Fig. 3.1b). Since (i) the water content above field capacity cannot be retained in the soil and will be lost by drainage, and (ii) the water content below permanent wilting point is so strongly attached to the soil matrix that it cannot be extracted by plant roots, the Total Available soil Water is the amount of water held in the root zone between field capacity (FC) and permanent wilting point (WP):

$$TAW = FC - WP \qquad (1)$$

Field capacity is normally defined as the water with a matric potential of -33 kPa, although higher values have been suggested for very coarse soils. Wilting is usually defined as the water held by the soil with a potential of -1.5MPa.

Readily Available Water

Readily available water (RAW) is the water that a plant can easily extract from the soil. RAW is the soil moisture held between field capacity and a nominated refill point for unrestricted growth. In this range of soil moisture, plants are neither waterlogged nor water-stressed. In fact, RAW is the maximum amount of water that a crop can extract from its root zone without inducing stomatal closure and reduction in crop transpiration.

Relative available water content

The relative available water content refers to the available soil water in the root zone expressed as a fraction of TAW, i.e.:

WCr = (WC -WP)/(FC-WP)

Soil moisture and water uptake

For the objectives of REDSIM, it is necessary to simulate the interaction between soil water availability and crop transpiration to estimate with a reasonable precision the water stress experienced by the crop. This is done by modeling the water uptake by plant roots. Depending on the model chosen, there are different ways to simulate root water uptake in function of the available soil water.

For REDSIM, detailed crop-growth oriented models are not useful as they require many input data that are not available or very costly to collect. Water-oriented crop simulation models (also called agrohydrolgoical models) perform better and are more suitable for irrigation and water-use assessments than crop-growth oriented models, although both approaches have been used (van Ittersum, 2003). SWAP and AquaCrop can be considered to fall in this category. They use simple conceptual approaches to simulate water uptake through roots and the consecutive transpiration loss. AquaCrop also includes different interactions that simulate the consequences for crop yields.

In most existing crop simulation models, root distribution is somehow taken into account in the potential of the plant to extract water from the soil. This potential has been either fully based on root distribution (see, e.g., Feddes et al. 1978) or on both root distribution and soil water availability (Li et al. 2001a). Various linear and nonlinear root distribution functions (e.g.Tiktak and Bouten 1992; Vrugt et al. 2001a) have been used in the rootwater uptake conceptualization.

Three water stress response functions, proposed respectively by Feddes et al. (Feddes et al. 1978), Van Genuchten (Van Genuchten 1987) who extended the Feddes formulation with osmotic stress, and Tiktak and Bouten (Tiktak and Bouten 1992), are commonly used in the soil–plant–water modeling community. All three functions contain empirically determined reduction point parameters and therefore require calibration and validation if no appropriate values can be found in the literature. Also several models have been proposed for water stress compensatory effects due to partial wetting and drying.

For studies in which there is a certain degree of uncertainty in the estimation of the principal fluxes that determine the water balances, the choice of the root-water uptake conceptualization and the water stress function may be arbitrary (Braud et al. 2005).

Van den Berg and Driessen, 2002 conclude that for the empirical approaches normally used in these type of models to use for example “soil water depletion fraction” or “soil water potential” to indicate the limit of readily available water is an arbitrary choice. They give a thorough review of the different approaches used to model water uptake. They come to the conclusion that a simple approach, estimating the relation Ta/Tm as a function of soil water contents seems most indicated but warn that uncertainties remain with respect to the assessment of critical soil water contents and the true importance of compensatory effects.

SWAP uses the methods proposed by Feddes (1978) as in Figure 1, while AquaCrop uses the concept of ´relative available water content´, illustrated in Figure 2.

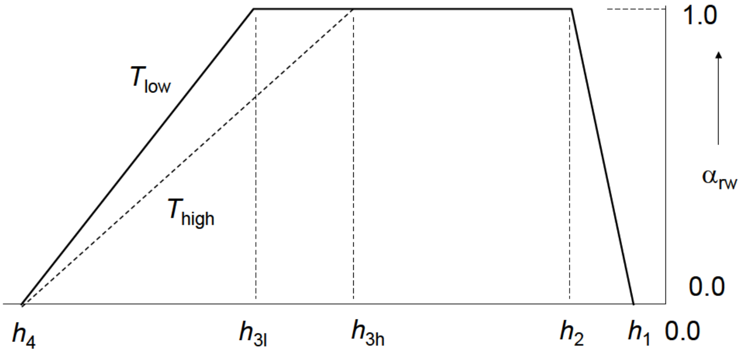


Figure 1. Reduction coefficient for root water uptake, αrw, equal to Ks, as a function of soil water pressure head h and potential transpiration rate Tp (after Feddes et al., 1978).

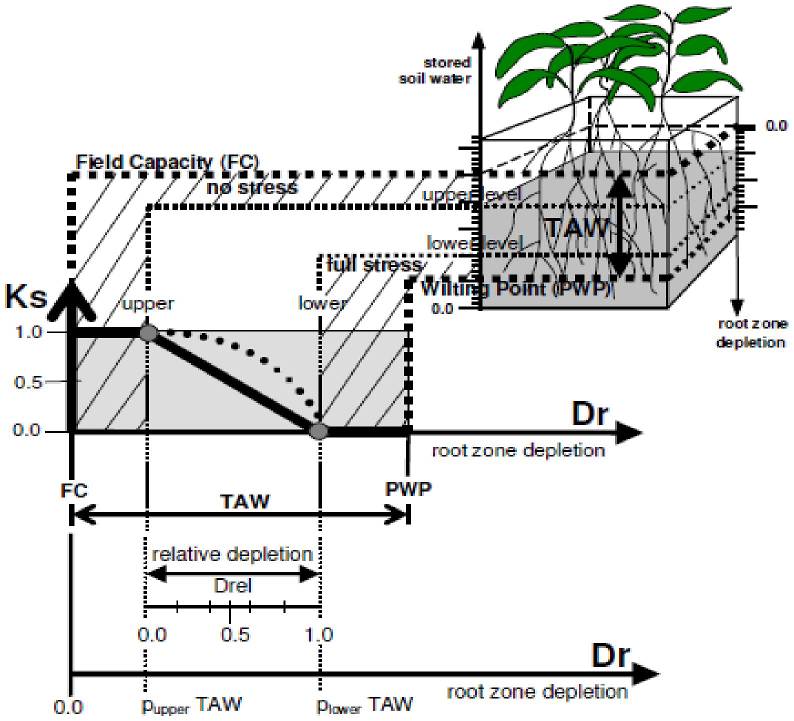


Figure 2. Stress coefficients for root water uptake used in FAO-AquaCrop.

Model selection

In the model selection procedure, different model candidates were evaluated and ranked (see Annex REDSIM Progress report #1). Ten indicators were defined to evaluate the models and compare them. The model with the highest score was SWAP. The relative high score is due to the fact that this particular model has been applied very frequently within similar contexts and much research has been done on the assimilation of remote sensing data. Besides, source code and support from the developers is assured, which makes the successful integration of the model into the REDSIM components more likely.

An additional advantage is that it has a simple crop growth module which allows straightforward testing and tailoring, while it can also be coupled with the more mechanistic and complex crop model WOFOST, offering future possibilities to extend the applicability of the tool. Another strength of the model is that it has been applied already several times within a distributed context as a decision support tool, which means that the required efforts within REDSIM for the upscaling from plot to regional scales can be based on previous experiences and literature.

AquaCrop is the selected model to be applied in the Guadiana River Basin. Although the model is relatively straight-forward (relatively small number of explicit and mostly-intuitive parameters and input variables), it emphasizes the fundamental processes involved in crop productivity and in the responses to water deficits, both from a physiological and an agronomic perspective. For these reasons, the model has been reported to perform well for deficit irrigation conditions, compared to other models. The insufficient transparency and simplicity of other model structures were considered strong constraints for their adoption. Therefore, AquaCrop is a useful tool to achieve the overall objective of REDSIM: improve irrigation water productivity in water-stressed watersheds by developing an Information Decission Support System.

The disadvantages of moderated support from developers and code unavailability are saved by the fact that a lot of expertise was built up during the last years in the team of the University of Cordoba, participating actively in the process of model development. This experience will enable to make tools that facilitate the assimilation of EO data, and make easy the calibration and validation of the model for the area crops.

SWAP

SWAP (Soil-Water-Atmosphere-Plant) is an integrated physically based simulation model for water, solute and heat transport in the saturated-unsaturated zone in relation to crop growth. A detailed description of the model and all its components is beyond the scope of this paper, but can be found in Van Dam et al. (1997), Kroes et al. (1999), and Van Dam (2000). For this study, the water transport module and both the simple crop growth as well as the module WOFOST will be used. The first version of the SWAP dates back to 1978 (Feddes et al., 1978) and since then the model went through various phases. The version used for this study is SWAP 3 and has been described by Van Dam et al. (2008).

The SWAP model has been applied and tested for many different conditions and locations and has been proven to produce reliable and accurate results (SWAP, 2003). The package used commonly for calibration of the SWAP model is PEST ((http://www.sspa.com/pest/). Several studies have been done so far in which SWAP is applied within a distributed context and several data assimilation techniques have been tested using SWAP, sometimes coupled with WOFOST:

- Inverse modeling approach and distributed, in Droogers, P., et al, 2010.
- Updating approach, Kalman filter, in Vazidefoust, 2007
- Distributed approach with SEBAL output, Minacapilli et al. 2009
- Different assimilation methods (forcing, updating and calibration) in Singh, 2005
- Used as a reference to compare different models for irrigation planning, in Jhorar, 2009

The next two sections describe the soil water and crop growth modules in the SWAP model relevant to this study.

Soil Water Module

The core part of the soil water module is the vertical flow of water in the unsaturated-saturated zone, which can be described by the well-known Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right)-S(h)\right] \qquad (1)$$

where, θ denotes the soil water content ($cm^3 cm^{-3}$), t is time (d), h (cm) the soil matric head, z (cm) the vertical coordinate, taken positive upwards, K the hydraulic conductivity as a function of water content (cm d^{-1}). S (d^{-1}) represents the water uptake by plant roots (Feddes et al., 1978), defined for the case of a uniform root distribution as:

$$S(h) = \alpha(h)\frac{T_{pot}}{|z_r|} \tag{2}$$

where, T_{pot} is potential transpiration (cm d^{-1}), z_r is rooting depth (cm), and α (-) is a reduction factor as function of h and accounts for water deficit and oxygen deficit. Total actual transpiration, T_{act}, was calculated as the depth integral of the water uptake function S.

The partitioning of potential evapotranspiration into potential soil evaporation and crop transpiration is based on the leaf area index (LAI) or soil cover. Actual crop transpiration and soil evaporation are obtained as a function of the available soil water in the top layer or the root zone, respectively. Actual crop transpiration is also reduced when salinity levels in the soil water are beyond a crop specific threshold value.

Actual soil evaporation can be estimated by the Richards' equation using the potential evaporation as the upper boundary condition. However, this requires information about the soil hydraulic properties of the first few centimeters of the soil, which are hardly measurable and are highly variable in time as a consequence of rain, crust and crack formation, and cultivation (Van Dam et al., 1997). All these processes reduce the real actual evaporation in comparison with the values obtained by applying Richards' equation. Therefore, the additional soil reduction function option from SWAP was implied, whereby the actual evaporation is a function of the potential evaporation, the soil moisture content of the top soil, an empirical soil-specific parameter, and the time since the last significant rainfall. Details of this procedure are given by Boesten & Stroosnijder (1986).

Irrigation processes can be modeled as well and irrigation applications can be prescribed at fixed times, scheduled according to different criteria, or by using a combination of both.

As mentioned earlier, SWAP contains three crop growth routines: a simple module, a detailed module, and the detailed module attuned to simulate grass growth. Independent of external stress factors, the simple model prescribes the length of the crop growth phases, leaf area, rooting depth and height development. The detailed crop module is based on WOFOST 6.0 (Supit et al., 1994; Spitters et al., 1989).

Simple growth module

Crop yields can be computed using a simple crop-growth algorithm based on Doorenbos & Kassam (1979) or by using a detailed crop-growth simulation module that partitions the carbohydrates produced between the different parts of the plant, as a function of the different phenological stages of the plant (Van Diepen et al. 1989). The basic assumption of the simplified crop production function is that actual yield is a function of potential yields and water stress:

$$\frac{Y_{act,i}}{Y_{pot,i}} = \frac{T_{act,i}}{T_{pot,i}} \tag{3}$$

where $Y_{pot,i}$ en $Y_{act,i}$ are the potential and actual yield for a specific year i, and $T_{pot,i}$ en $T_{act,i}$ the potential en actual transpiration for year i. Sometimes evapotranspiration is considered in stead of only transpiration, since determination of only crop transpiration is difficult. Doorenbos & Kassam (1979) expanded this approach by including that the sensitivity of the crop to water stress during subsequent growing periods is not constant:

$$1 - \frac{Y_{act}}{Y_{pot}} = K_y\left(1 - \frac{T_{act}}{T_{pot}}\right) \tag{4}$$

where K_y is yield reduction factor (-) indicating whether a crop is sensitive (>1) or less sensitive (<1) to water stress. K_y can have different values for different growing periods y.

A main drawback of this approach is the determination of the potential yield Y_{pot}. For practical reasons we have used here the approach that the potential yield for a certain year is a linear function of the real maximum potential yield as obtained during very favorable climate conditions and optimal farm management:

$$\frac{Y_{act,i}}{Y_{pot,\max}} = \frac{T_{act,i}}{T_{pot,i}} \frac{T_{pot,i}}{T_{pot,\max}} \qquad (5)$$

where $Y_{\text{pot,max}}$ en $T_{\text{pot,max}}$ are the maximum crop yield and maximum transpiration during the period of 30 years as considered in this study.

Obviously, the option to use the detailed crop modeling approach would be preferred, but for the first prototype of REDSIM we will use the simplified approach as indicated in order to allow smooth and fast coupling with the other components of the system. Extension with the detailed crop growth module will be considered if successful, and when limitations of the simple approach for this particular purpose become clear. In any case, it has to be stressed that the model will be used most of all for soil water status and crop stress information, for which yield calculations are in principle of less importance.

AquaCrop

AquaCrop is the FAO crop-model to simulate yield response to water. It is designed to balance simplicity, accuracy and robustness. AquaCrop is a companion tool for a wide range of users and applications including yield prediction under climate change scenarios. AquaCrop is a completely revised version of the successful CropWat model. The main difference between CropWat and AquaCrop is that the latter includes more advanced crop growth routines.

AquaCrop includes the following sub-model components: the soil, with its water balance; the crop, with its development, growth and yield; the atmosphere, with its thermal regime, rainfall, evaporative demand and CO2 concentration; and the management, with its major agronomic practice such as irrigation and fertilization. AquaCrop flowchart is shown in **Error! Reference source not found.**3.

The particular features that distinguishes AquaCrop from other crop models is its focus on water, the use of ground canopy cover instead of leaf area index, and the use of water productivity values normalized for atmospheric evaporative demand and of carbon dioxide concentration. This enables the model with the extrapolation capacity to diverse locations and seasons, including future climate scenarios.

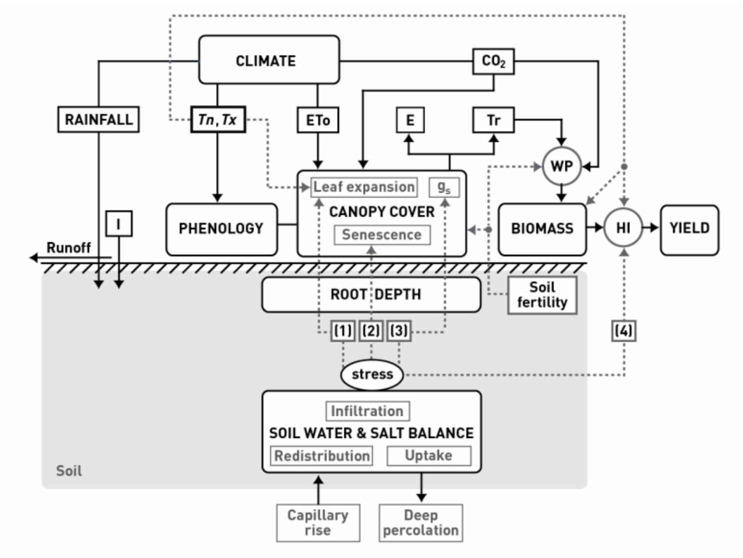


Figure 3. Main processes included in AquaCrop.

Theoretical basis

The complexity of crop responses to water deficits led to the use of empirical production functions as the most practical option to assess crop yield response to water. Among the empirical function approaches, FAO Irrigation & Drainage Paper nr 33 (Doorenbos and Kassam, 1979) represented an important source to determine the yield response to water of field, vegetable and tree crops, through the following equation:

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y \left(\frac{ET_x - ET_a}{ET_x}\right) \qquad \text{Eq. 1}$$

where Y_x and Y_a are the maximum and actual yield, ET_x and ET_a are the maximum and actual evapotranspiration, and k_y is the proportionality factor between relative yield loss and relative reduction in evapotranspiration.

AquaCrop evolves from the previous Doorenbos and Kassam (1979) approach by separating (i) the ET into soil evaporation (E) and crop transpiration (Tr) and (ii) the final yield (Y) into biomass (B) and harvest index (HI). The separation of ET into E and Tr avoids the confounding effect of the non-productive consumptive use of water (E). This is important especially during incomplete ground cover. The separation of Y into B and HI allows the distinction of the basic functional relations between environment and B from those between environment and HI. These relations are in fact fundamentally different and their use avoids the confounding effects of water stress on B and on HI. The changes described led to the following equation at the core of the AquaCrop growth engine:

$$B = WP \cdot \Sigma Tr \qquad \text{Eq. 2}$$

where Tr is the crop transpiration (in mm) and WP is the water productivity parameter (kg of biomass per m^2 and per mm of cumulated water transpired over the time period in which the biomass is produced). This step from Eq. 1.1 to Eq. 1.2 has a fundamental implication for the robustness of the model due to the conservative behavior of WP (Steduto et al., 2007). It is worth noticing, though, that both equations are different expressions of a *water-driven growth-engine* in terms of crop modeling design (Steduto, 2003). The other main change from Eq. 1.1 to AquaCrop is in the time scale used for each one. In the case of Eq. 1.1, the relationship is used seasonally or for long periods (of the order of months), while in the case of Eq. 1.2 the relationship is used for daily time steps, a period that is closer to the time scale of crop responses to water deficits.

The main components included in AquaCrop to calculate crop growth are **Error! Reference source not found.**:

- Atmosphere
- Crop
- Soil
- Field management
- Irrigation management

These five components will be discussed here shortly in the following sections. More details can be found in the AquaCrop documentation (Raes et al., 2009)

Climate — File: (None) — Specify climatic data when Running AquaCrop

Growing cycle: Day 1 after sowing: 22 March - Harvest: 24 July

Crop — DEFAULT.CRO — a generic crop

Irrigation — (None) — Rainfed cropping

Field — (None) — No specific field management

Soil — DEFAULT.SOL — Deep loamy soil

Period — From: 22 March - To: 24 July

Initial conditions — (None) — Soil water profile at Field Capacity

Off-season — Simulation period linked to cropping period

Project — (None) — No specific project

Figure 4. Overview of AuqaCrop showing the most relevant components.

Atmosphere

The minimum weather data requirements of AquaCrop include the following five parameters:

- daily minimum air temperatures
- daily maximum air temperatures
- daily rainfall
- daily evaporative demand of the atmosphere expressed as reference evapotranspiration (ET_0)
- mean annual carbon dioxide concentration in the bulk atmosphere

The reference evapotranspiration (ET_0) is, in contrast to CropWat, not calculated by AquaCrop itself, but is a required input parameter. This enables the user to apply whatever ETo method based on common practice in a certain region and/or availability of data. From the various options to calculate ETo reference is made to the Penman-Monteith method as described by FAO (Allen *et al.*, 1998). The same publication makes also reference to the Hargreaves method in case of data shortage.

A companion software program (ETo calculator) based on the FAO56 publication might be used if preference is given to the Penman-Monteith method. A few additional parameters were used for a more reliable estimate of the reference evapotranspiration. Besides the minimum and maximum temperature, measured dewpoint temperature and windspeed were used for the calculation.

AquaCrop calculations are performed always at a daily time-step. However, input is not required at a daily time-step, but can also be provided at 10-daily or monthly intervals. The model itself interpolates these data to daily time steps. The only exception is the CO_2 levels which should be provided at annual time-step and are considered to be constant during the year.

Crop

AquaCrop considers five major components and associated dynamic responses which are used to simulate crop growth and yield development:

- phenology
- aerial canopy
- rooting depth
- biomass production
- harvestable yield

As mentioned earlier, AquaCrop strengths are on the crop responses to water stress. If water is limiting this will have an impact on the following three crop growth processes:

- reduction of the canopy expansion rate (typically during initial growth)
- acceleration of senescence (typically during completed and late growth)
- closure of stomata (typically during completed growth)

Finally, the model has two options for crop growth and development processes:

- calendar based: the user has to specify planting/sowing data
- thermal based on Growing Degree Days (GDD): the model determines when planting-sowing starts.

Soil

AquaCrop is flexible in terms of description of the soil system. Special features:

- Up to five horizons
- Hydraulic characteristics:
    - hydraulic conductivity at saturation
    - volumetric water content at saturation
    - field capacity
    - wilting point
- Soil fertility can be defined as additional stress on crop growth influenced by:
    - water productivity parameter
    - the canopy growth development

  - maximum canopy cover
  - rate of decline in green canopy during senescence.

AquaCrop separates soil evaporation (E) from crop transpiration (Tr). The simulation of Tr is based on:

- Reference evapotranspiration
- Soil moisture content
- Rooting depth
- Canopy cover

Simulation of soil evaporation depends on:

- Reference evapotranspiration
- Soil moisture content
- Mulching
- Canopy cover
- Partial wetting by localized irrigation
- Shading of the ground by the canopy

Irrigation management

Simulation of irrigation management is one of the strengths of AquaCrop with the following options:

- rainfed-agriculture (no irrigation)
- sprinkler irrigation
- drip irrigation
- surface irrigation by basin
- surface irrigation by border
- surface irrigation by furrow

Scheduling of irrigation can be simulated as

- Fixed timing
- Depletion of soil water

Irrigation application amount can be defined as:

- Fixed depth
- Back to field capacity

3-Pilot sites and data

Pilot sites in Segura basin

Regional soil maps

Soil properties determine to a large extent the water available to the plant. Agrohydrological models require therefore different soil hydraulic (physical or empirical) parameters that should be measured or derived. To derive reasonable estimates of these parameters so-called pedo-transfer functions can be used (Saxton et al. 1986, Jabro et al. 1992 and Schaap et al 2001). These functions related soil hydraulic parameters with easily measurable quantities in the field, mainly soil texture.

Soil samples were taken to measurements soil texture of the pilot plots involved in the REDSIM project to allow determination of the soil hydraulic properties using pedotransfer functions. These parameters were further fine-tuned by calibration using measured soil moisture data of the experimental plots where this data was available from installed soil moisture sensors.

The following sources are available that provide some level of soil information of several points in the area:

- Mapa de Suelos de Espana. (Soil Map of Spain); Author: Gomez-Miguel, V.; Publisher: Instituto Geografico Nacional. The scale of this map is 1 : 1,000,000. Publication year 2005.
- Digital Soil Map of Murcia Region (*Mapa Digital de Suelos de la Región de Murcia)* published in 1999 by the LUCDEME project, provides GIS layers with the soil classification units according to FAO classification. For the major part of Murcia, tables with soil hydraulic and texture measurements from sampling are included, however, precisely of the main arable areas in Murcia, no relevant quantitative information is available.
- Jiménez-Martínez (2009) shows soil data of one extensively monitored plot of which soil samples were taken and different characteristics were measured

Due to the lack of information on soil properties in the irrigated areas of the Segura Basin, one of the key activities within REDSIM was to generate soil texture maps, using the existing databases on soil profiles in the region and advanced spatial interpolation techniques.

The regional map of soil texture and organic carbon content to be used as an input for hydrologic components of crop models is produced by establishing statistical relationships of key soil variables (texture and organic matter) to environmental variables. This way, point estimates of soil variables are upscaled to the regional scale by using several environmental variables as proxy-variables and which are available for the entire region.

Soil data of the Segura basin were taken from LUCDEME maps and data base. The LUCDEME project intended to create soil cartography for SE Spain in order to be used in combating desertification. Documentation is composed of two soil data bases and soil cartography. One soil data base is the tillage layer while the other one is the profile data base. The profile database contains detailed quantitative descriptions of soil profiles while the tillage layer documents only some variables and does not take into account vertical profile variability. However, the number of samples of the tillage layer data base is much higher which mains that it contains valuable information on the spatial variability of the soils. Therefore, this database was used as the principal dataset to upscale the soil data and generate a map covering the entire basin.

The following environmental variables were introduced to produce geospatial models and to generate maps of soil properties:

- Topographical variables: slope gradient, curvature, orientation.
- Microclimatic variables: Total incoming solar radiation (under assumption of clear atmospheric conditions and taking into account topographic effects).
- Climatic variables: Average annual temperature and precipitation.
- Soil class according to LUCDEME cartography.
- Land use as recorded in CORINE.

Textural information provided by LUCDEME data base is quite complete and first it was summarized to 3 soil texture classes: (i) clay, 0-2 µ; (ii) silt 2-20 µ; and (iii) sand 20 µ-2 mm. A error checking procedure was implemented adding up the three fractions. They have to add up 100 as they are expressed as percentage. All the samples with data <98.5 or >101.5 were deleted. The rest were rescaled to add up exactly 100. In total, close to 1000 were available.

The strategy to estimate soil texture consisted of developing statistical models relating soil texture in the sample with environmental attributes and remote sensing information. In Table 1 they are shown the different layers prepared and the source of data.

Table 1

Atributos	Descripción
(1) Soil Map (LUCDEME) [SLu]	Soil Map. World Soil Classification (FAO). E. 1:100.000
(2) Saline Phase (LUCDEME) [SPLu]	Soil Map. World Soil Classification (FAO). E. 1:100.000
(3) Lithological map (MAGNA) [LM]	Interpreted from the National Geological Map MAGNA, E. 1:50.000
(4) Digital Elevation Model (ASTER GDEM) [DEM]	ASTER satellite, spatial resolution 30m.
(5) Slope Gra dient [Slo]	Calculated from ASTER GDEM.
(6) Profile curvature [CuP]	Calculated from ASTER GDEM.
(7) Perpendicular curvature [CuPP]	Calculated from ASTER GDEM.
(8) Global Radiation [RaG]	Calculated from ASTER GDEM.
(9) Direct Radiation [RaDr]	Calculated from ASTER GDEM.
(10) Diffuse radiation [RaDi]	Calculated from ASTER GDEM.
(11) Radiation duration [RaDu]	Calculated from ASTER GDEM.
(12) Flow accumulation [FAc]	Calculated from ASTER GDEM.
(13) Annual rainfall [Pr]	National map by Laboratorio de Biogeografia Informática (LBI) CSIC
(14) Mean annual temperature [Tmp]	National map by Laboratorio de Biogeografia Informática (LBI) CSIC
(15) Normalized Vegetation Difference Index (NDVI). February [NDVIfeb]	Calcualted from Landsat 5
(16) Normalized Vegetation Difference Index (NDVI). July 24/07/2009 [NDVIjul]	Calcualted from Landsat 5
(17) Remote sensing index for Clay Minerals. February [CMIfeb]	Calcualted from Landsat 5
(18) Remote sensing index for Ferrous Minerals February [FMIfeb]	Calcualted from Landsat 5
(19) Remote sensing index for Iron Oxides. February [IOIfeb]	Calcualted from Landsat 5
(20) Remote sensing index for Clay Minerals. July [CMIjul]	Calcualted from Landsat 5
(21) Remote sensing index for Ferrous Minerals. July [FMIjul]	Calcualted from Landsat 5
(22) Remote sensing index for Clay Minerals.July [IOIjul]	Calcualted from Landsat 5

The underlying idea of the procedure is that soil texture is controlled by climatic, microclimatic, geomorphic, geological and biological processes reflected at some extent in the layers. Additionally, information from soil maps (soil taxonomy) and remote sensing indicators of mineral composition can refine that information.

Statistical models were built by stepwise regression but using minimization of Akaike's Information Criteria (AIC) as the objective function. One model was developed by each one of the soil texture components: clay, silt, sand.

Processes controlling soil texture may be scale-dependent. Therefore the modeling was carried out at 5 resolutions 25, 50, 100, 200 and 400 m. Data were recalculated at each resolution by appropriate methods. Moreover, it may be that some processes controlling soil texture were more evident to one spatial scale and other processes equally relevant may be more evident at a different spatial scale. Consequently multi-scale models were also created.

Statistical models were built by stepwise regression but using minimization of Akaike's Information Criteria (AIC) as the objective function. One model was developed by each one of the soil texture components: clay, silt, sand. The advantage of using AIC metrics in this context is that models of completely different structure (e.g. models at different spatial scales) can be directly compared. Standard techniques for formal inference like log-likelhood ratios do not it.

The best models were always an very clearly according to AIC values the multiscale models. For the sake of brevity the structure of the models is not shown here but they are the regional maps of texture. In spite of the models being sound from the modeling point of view their predictive power is not high and should the results should be use carefully.

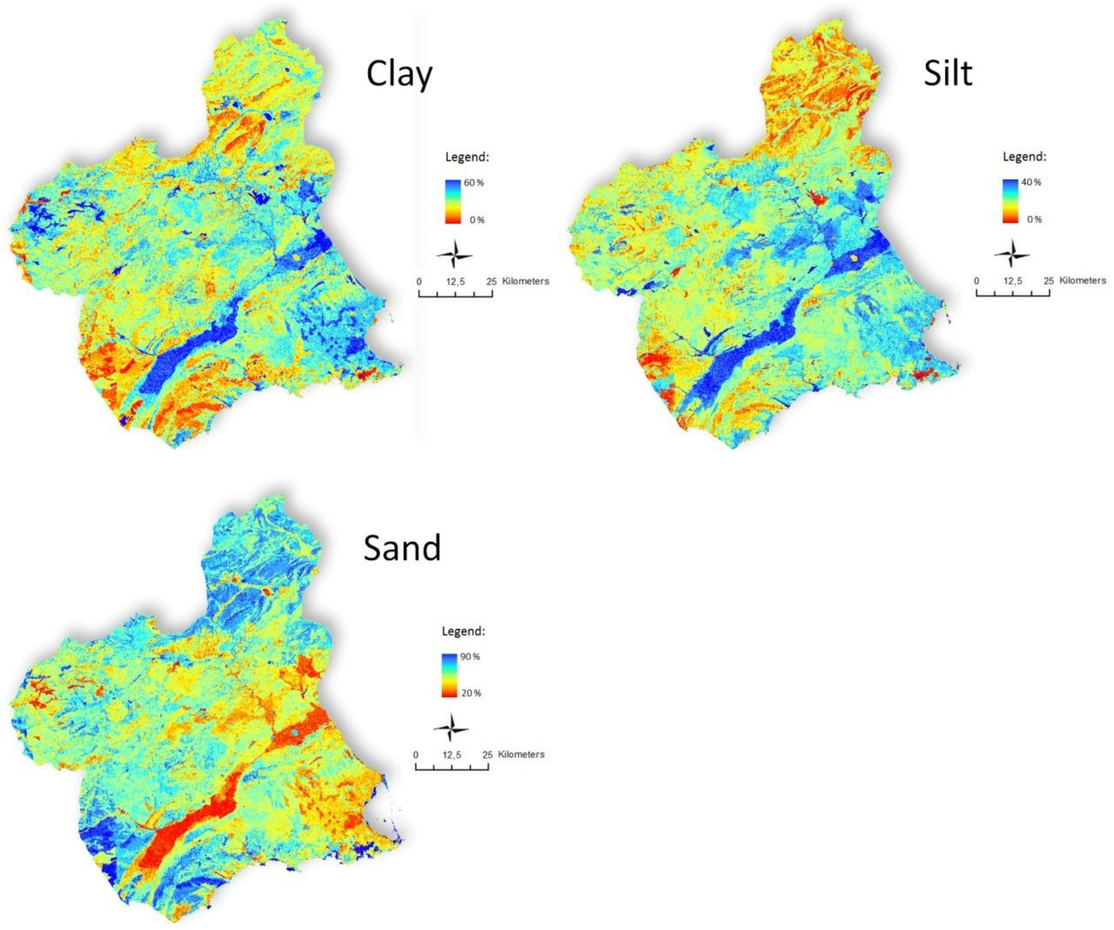


Figure 1. Regional soil texture maps, used for REDSIM soil water modeling.

Other Data

Of the pilot plots, the following table summarizes the data available for the model setup and calibration.

Pilot plot	**Irrigation**	**Evapotranspiration**	**Soil moisture**	**Soil properties**
Orange – 2 Eddy station sites	Continuous	ETa, measured continuously	Continuous, 3 sensors at each site	Texture
Orange – other 5 sites	Continuous	Estimated ETc – from FAO and RS-based vegetation fraction	No	Texture
Mandarine, FI and DI sites	Continuous	Estimated ETc – from FAO and RS-based vegetation fraction	Weekly, multiple sensors	Texture
Nectarine	Continuous	Estimated ETc – from FAO and RS-based vegetation fraction	Continuous, 2 sensors	Texture

Other data sources that are required for the setup and calibration of the model are:

- Weather data
  - Rainfall and meteorological variables required to calculate FAO reference evapotranspiration (ETref). Weather stations of the local network SIAM were used for the daily meteorological input of the model. ETref is estimated using these data and the Penman-Monteith method.
  - Weather predictions provided by the national weather agency (AEMET) that provide 7-day forecasts are used and converted to quantitative estimates of precipitation and evapotranspiration (see Annex VI)
- Crop data
  - Crop coefficients are calculated using the values proposed by FAO, dependent on the vegetation cover, estimated in the field and by using remote sensing imagery
- Initial and Boundary Conditions
  - Soil water content will be assumed at Field Capacity a few days after the last rainfall event in each plot.
  - Free drainage will be assumed at the bottom layer
  - Lateral drainage will not be modeled as this can be assumed negligible with drip irrigation
- Water and Crop Management
  - Data of the irrigation infrastructure (drippers, etc)
  - Nutrient-limited-stress and fertilization effects will be neglected.

Pilot sites in Guadiana basin

AquaCrop uses a relative small number of explicit parameters and largely intuitive input variables, either widely used or requiring simple methods for their determination. Input consists of weather data, crop and soil characteristics, and management practices that define the environment in which the crop will develop (Fig. 12). The inputs are stored in climate, crop, soil and management files and can be easily adjusted through the user interface.

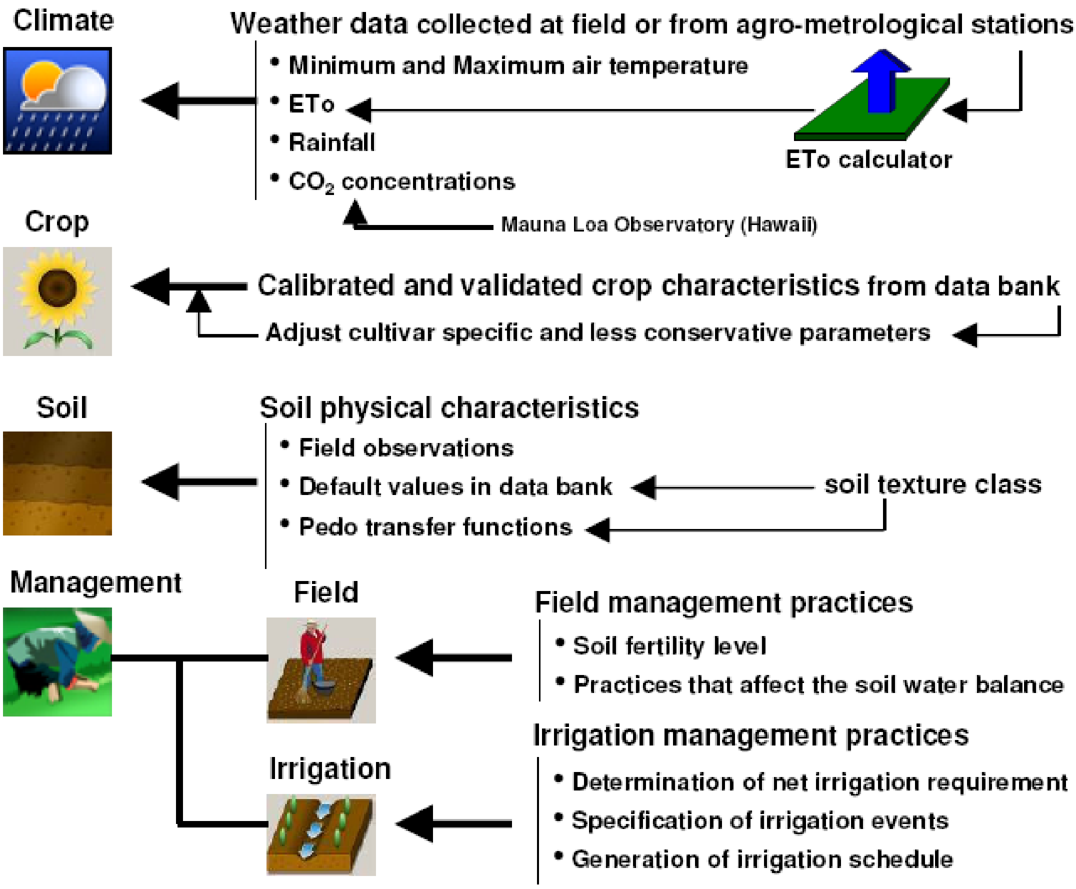


Figure 2. Input data defining the environment in which the crop will develop

AquaCrop will be included in the first prototype of REDSIM, simulating the evolution of the soil water content, yield, and water productivity for melon in the Guadiana River Basin. The experimental fields and pilot plots participating in the project are located in the Aquifer 23 (farmer' plot) and in the agricultural experiment station 'Las Tiesas' (Aquifer 29).

Soil Data

In AquaCrop, the extent of water limitation is expressed as a fraction of the total available water (TAW) in the root zone, with TAW defined as the water held in the soil between its field capacity (FC) and permanent wilting point (PWP). Accurate FC and PWP are important to specify the local conditions if water is a significant limiting factor.

The soil hydraulic characteristics of the study plots will be derived from soil texture with the help of pedo-transfer functions (Saxton et al., 1986; 'Soil Water Characteristics' software package). Thus, soil texture measurements have been made in the pilot plots, and the derived soil hydraulic parameters are presented in Table 1.

Table 1. Soil hydraulic characteristics of the study plots. Volumetric soil water content at: permanent wilting point (PWP); field capacity (FC); and saturation (SAT). Ks: hydraulic conductivity at saturation

Depth (cm)	PWP (vol %)	FC (vol %)	SAT (vol %)	Ks (mm h^{-1})
Aquifer 23				
0 - 15	13.5	24.9	44.7	20.52
15 - 30	13.7	25.0	44.6	19.82
Aquifer 29				
0 - 40	20.5	33.5	45.2	5.21

Other Data

Other data that are required for the calibration and validation of the model are:

- Weather data
    - Rainfall, maximum and minimum temperature, and FAO reference evapotranspiration (FAO Penman-Monteith equation). Daily meteorological data from the weather stations of the local network SIAR (irrigation advisory service of Castilla-La Mancha) will be used for the daily meteorological input of the model. Also, data from a local station located in experimental station 'Las Tiesas' will be used.
- Crop data
    - The pilot farm and the experimental plot 'Las Tiesas' will be used to parameterize AquaCrop for melon. The conservative and cultivar specific crop parameters will be adjusted using this information.
    - The selected cultivar was 'Ibérico' (type 'Piel de Sapo'). Planting density, growing period, phenology, canopy cover, final biomass and crop yields have been reported.
- Initial and Boundary Conditions
    - Initial and final soil water content were determined gravimetrically in each plot.
- Water and Crop Management
    - The soil was covered with transparent plastic mulch, and the irrigation system consisted of one drip line per crop row.
    - The farmer (Aquifer 23) provided information on his daily irrigation practices, and also water meters were installed in all sub-plots of each irrigation treatments.
    - Nutrient-limited-stress and fertilization effects were neglected.

4-Tool calibration

SWAP

Active root zone

To apply agro-hydrological models to drip-irrigated systems, special attention has to be paid to the strong spatial variability in soil moisture. Especially for drip-irrigated trees, large differences exist within a plot as the water is only applied through the emitters, which means that a significant part of the soil surface remains fully dry, except during rainfall events. The infiltration process occurs within a very small area as compared to the total soil surface. The infiltration is thus three dimensional in this case as compared to one dimensional for most other irrigation methods.

Also root development in these systems occurs normally purely around the emitters, thus root water extraction only occurs in the wetted bulb surrounding the emitters. For this reason, and to describe correctly the fluxes in the soil-water-plant-atmosphere domain, a distinction needs to be made between the rooted versus the non-roote areas.

Figure 3 shows a schematic view of the two-dimensional domain. It shows the area Z1 related with the area where most of the roots are present (´active root zone´), principally in the direct surrounding and under the emitters. And secondly the area which is usually dry, except during rainfall events (Z2).

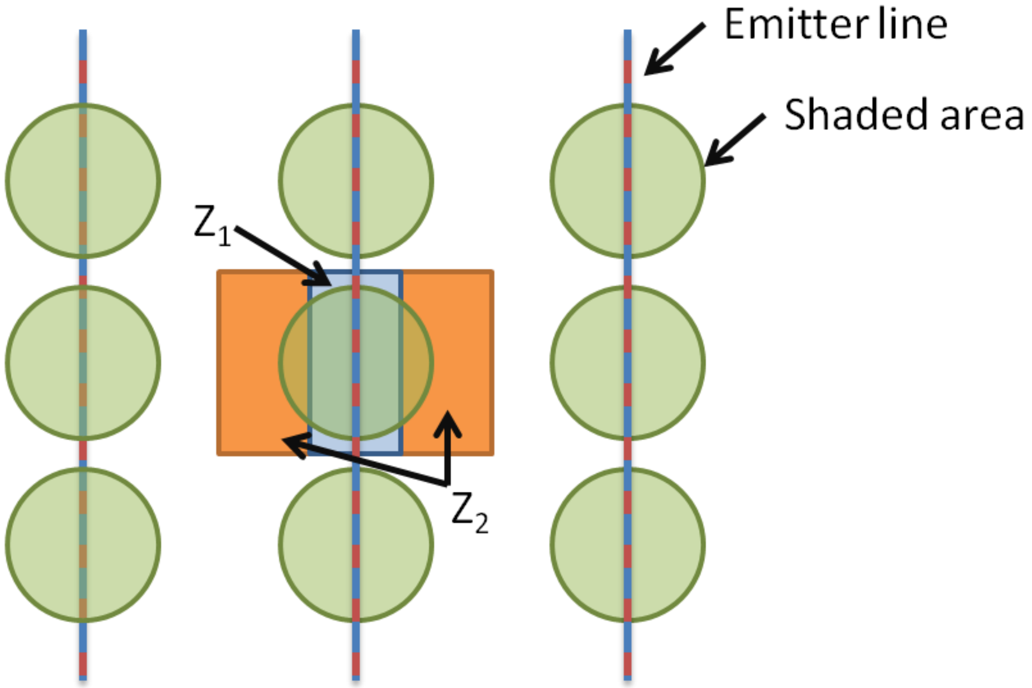


Figure 3. Schematic overview of modeling domain

We define the proportion between Z1 (active root zone) and the total area as: *fr*. Thus,

$fr = Z1 / (Z1 + Z2)$

This parameter depends on the number of emitter lines, emitters per line, emitter type, the shaded area, the soil hydraulic properties and root development. This proportion can be roughly estimated in the field by delimiting the wet bulb around the emitters.

To estimate or simulate the soil water balance, two separate calculations can be made for the Z1 and Z2 domain. However, the corresponding evapotranspiration flux cannot be delimited to one these domains, as the transpiration from the crop covers a larger area as Z1. Therefore, it is recommendable to calculate the evapotranspiration fluxes over the entire domain (Z1 and Z2). The *fr* factor can be used to scale the water balance correctly. Thus, the water balance equations of both areas can be described as (see also Figure 4):

$$ET_{wetted} = fr*(I_1 + P_1 - \Delta S_1 + D_1)$$

$$ET_{dry} = (1-fr)*(P_2 - \Delta S_2 + D_2)$$

$$ET_{total} = ET_{wetted} + ET_{dry}$$

where the subscripts 1 and 2 refer to the areas Z1 and Z2, respectively, ET_{wetted} represents the sum of the crop transpiration and the soil evaporation from the potentially wetted and rooted surface, and ET_{dry} =represents the soil evaporation from the surface not affected by the emitters.

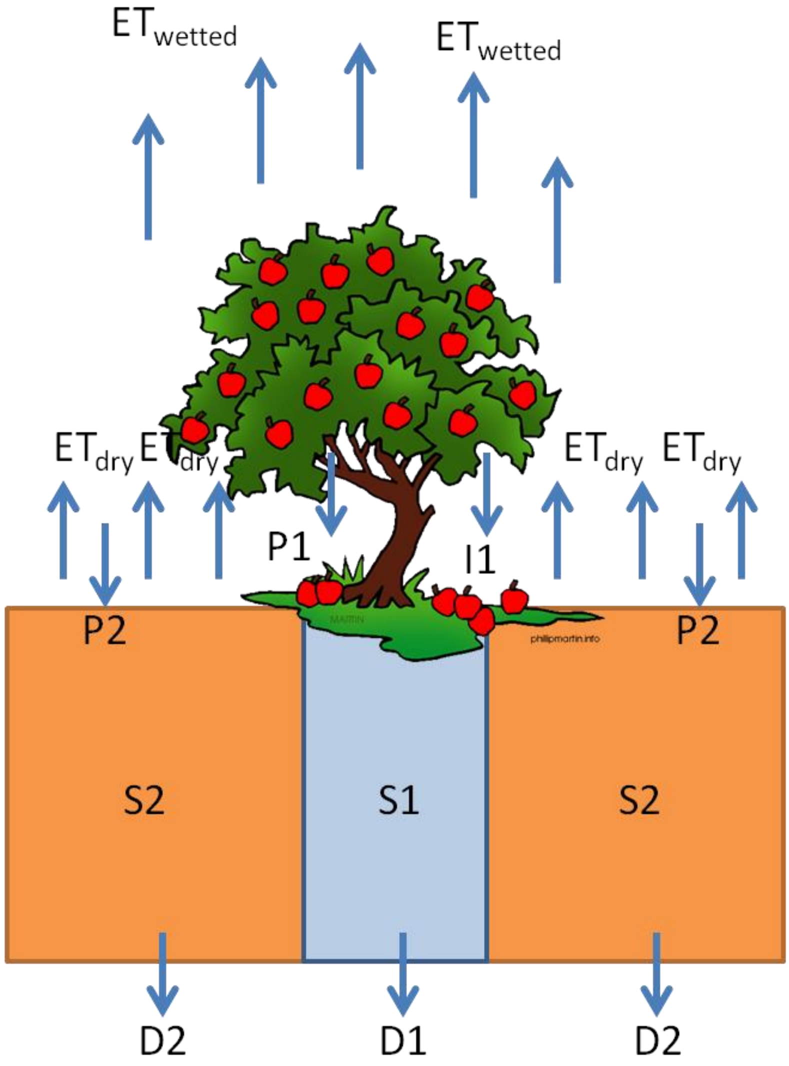


Figure 4. Schematic overview of water balance for the two modeling domains Z1 and Z2 as in Figure 3.

The agro-hydrological models that are suitable for water management decision support are not designed to incorporate this dual approach between wet and rooted versus dry and non-rooted areas. For research purposes, normally more complex two-dimensional or three-dimensional models are used (f.e. Hydrus) but these models are not fit for regional decision support applications and are too data demanding.

Inverse modeling

To test the validity of this dual approach in the SWAP agro-hydrological model, a comparison was performed for different assumptions on the rooted vs the non-rooted area (*fr)*. The goodness-of-fit for the models obtained for each of the *fr* values was evaluated to see whether the *fr* value of the fittest model was close to value that can be expected based on the field observations at the study site. The inverse modeling approach was applied to fit the soil hydraulic parameters for different values of *fr*. Then, the fitness of these different models was compared to see which value of *fr* produced the 'fittest' model.

The inverse modeling approach consists in this case in fitting soil hydraulic parameters, provided that root water uptake function and potential evapotranspiration rates are known. The accuracy level of the fitted parameters has been found to be suitable for water management decisions based on simple soil water balance computations (f.e. Jhorar et al., 2002).

As explained before, the inverse modeling approach was applied for different values of *fr*. This parameter was changed between the maximum of 1 and the assumed minimum value of 0.05. Data was available of one site for different irrigation treatments (full irrigation and deficit irrigation). Several performance indicators were assessed to compare the observed soil moisture values with the simulated ones at this site, and give insight in the prediction uncertainty of the inversely obtained models.

To obtain first estimates of the soil hydraulic functions based on soil texture data, pedotransfer functions can be used. The most commonly used are those described by Saxton et al. (1986), Jabro et al. (1992) and Schaap et al (2001). The equations described by Schaap et al (2001) are included in a software package called Rosetta which is commonly used for this purpose.

Goodness-of-fit measures

The model performance was evaluated using the following statistics of goodness-of-fit.

Sum of Squares Due to Error: this statistic is used for calibration and measures the total deviation of the response values from the fit to the response values. It is also called the summed square of residuals and is usually labeled as *SSE.*

$$SSE = \sum_{i=1}^{n} w_i \left(y_i - \hat{y}_i \right)^2$$

A value closer to 0 indicates that the model has a smaller random error component, and that the fit will be more useful for prediction.

Another goodness-of-fit parameter used to evaluate the prediction error is the **Root Mean Squared Error**. This statistic is also known as the fit standard error and the standard error of the regression. It is an estimate of the standard deviation of the random component in the data, and is defined as

$$RMSE = s = \sqrt{MSE}$$

where *MSE* is the mean square error or the **Residual mean square**

$$MSE = \frac{SSE}{v}$$

This statistic adjusts the SSE based on the residual degrees of freedom. The residual degrees of freedom is defined as the number of response values n minus the number of fitted coefficients m estimated from the response values, i.e.: $v = n - m$

Results

The analysis was carried out using data from the mandarin experimental plot, using soil moisture profile data, obtained weekly starting in 2009, to 2011. This data was available both for full irrigation (FI) as for deficit irrigation (DI) treatments. The following table and figure show the relationship between the selected *fr* values and the goodness-of-fit measures.

Table 2. Selected *fr* values against the goodness-of-fit values for the inversely obtained models

fr	**SSE**	**MSE**	**RMSE**
0.05	0.058	0.0018	0.042
0.08	0.040	0.0012	0.035
0.1	0.037	0.0011	0.034
0.2	0.039	0.0012	0.035
0.5	0.039	0.0012	0.035
1	0.048	0.0015	0.039

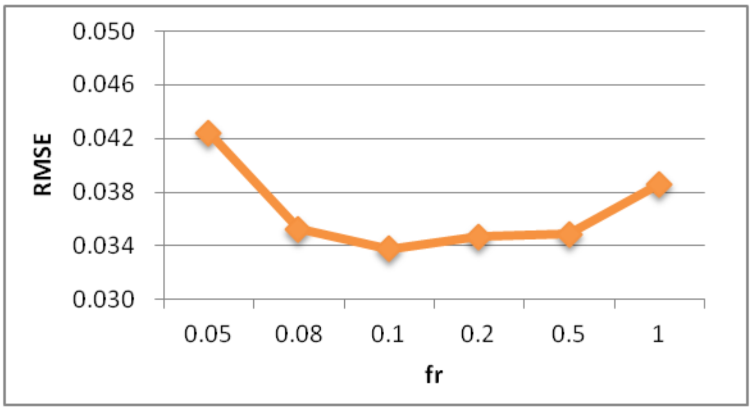


Figure 5. The *fr* values against the goodness-of-fit values for the inversely obtained models

The above table and figure indicate that the model with *fr* = 0.1 has the lowest prediction error. The prediction uncertainty gets notably larger when *fr* approaches 1 or comes close to the assumed minimum (0.05).

This methodology to test the validity of the dual approach as shown in Figure 3, shows the model obtained with an effective active root zone (Z1) of around 10% is the most adequate. This value corresponds with local field observations of this site in which the radius of the wet bulb was delimited using soil samples. During irrigation, a wetted radius of around 0.5m was observed. This leads to an approximate wetted area of 11% (3 drippers per tree; Z1+Z2 = 17.5 m^2), close to the minimum value of 10% obtained in the analysis.

This optimal value of 10% is also in the same order of magnitude as the design guidelines on drip irrigation infrastructure. Generally, it is recommended that the wetted area should cover around 30% of the shaded area. The shaded area for this particular site is 57%. This would give a wetted area for this site of around 15%.

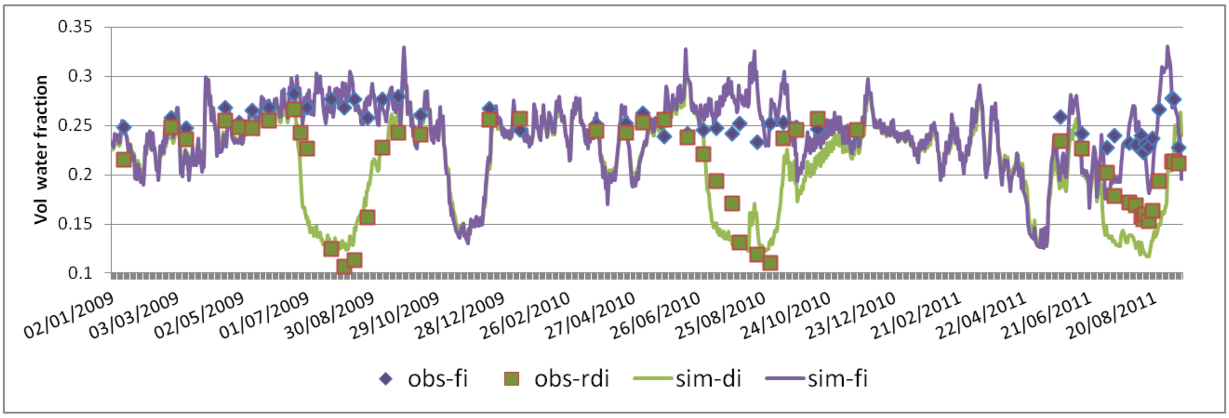


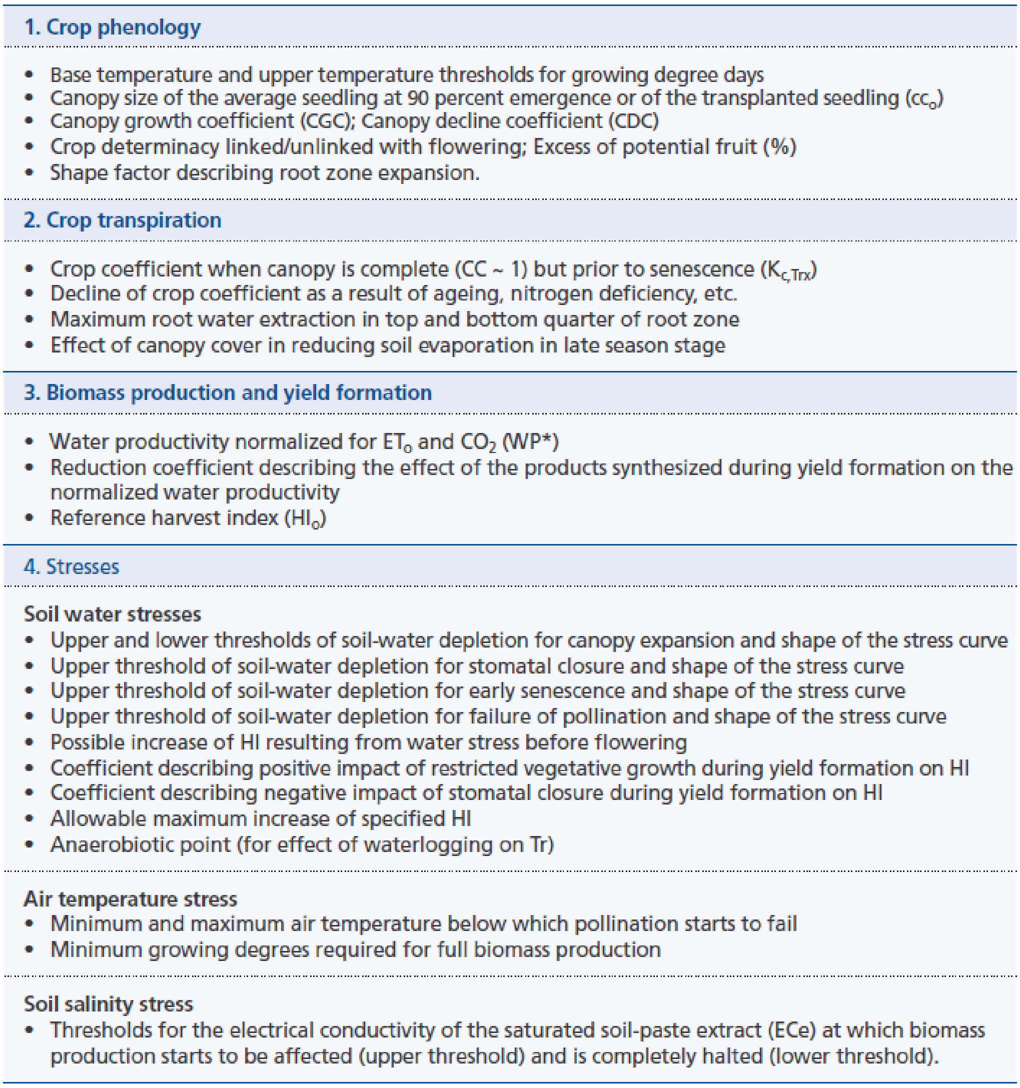
Figure 6. Observed total soil water content (%) against simulated, for the full irrigation (FI) and deficit irrigation (DI) treatment.

AquaCrop

Conservative parameters

AquaCrop is constructed with parameters falling into two groups. One group is considered conservative (Table 3), in that the parameters should remain basically constant under different growing conditions and water regimes. The other group encompasses parameters that are dependent on location, crop cultivar, and management practices, and must be specified by the user. Nevertheless, some of the parameters assigned to the conservative group may vary within small limits for different cultivars of the crop species.

Table 3. Conservative crop parameters (FAO, 2012).



1. Crop phenology

- Base temperature and upper temperature thresholds for growing degree days
- Canopy size of the average seedling at 90 percent emergence or of the transplanted seedling (cc_o)
- Canopy growth coefficient (CGC); Canopy decline coefficient (CDC)
- Crop determinacy linked/unlinked with flowering; Excess of potential fruit (%)
- Shape factor describing root zone expansion.

2. Crop transpiration

- Crop coefficient when canopy is complete (CC ~ 1) but prior to senescence ($K_{c,Trx}$)
- Decline of crop coefficient as a result of ageing, nitrogen deficiency, etc.
- Maximum root water extraction in top and bottom quarter of root zone
- Effect of canopy cover in reducing soil evaporation in late season stage

3. Biomass production and yield formation

- Water productivity normalized for ET_0 and CO_2 (WP*)
- Reduction coefficient describing the effect of the products synthesized during yield formation on the normalized water productivity
- Reference harvest index (HI_o)

4. Stresses

Soil water stresses
- Upper and lower thresholds of soil-water depletion for canopy expansion and shape of the stress curve
- Upper threshold of soil-water depletion for stomatal closure and shape of the stress curve
- Upper threshold of soil-water depletion for early senescence and shape of the stress curve
- Upper threshold of soil-water depletion for failure of pollination and shape of the stress curve
- Possible increase of HI resulting from water stress before flowering
- Coefficient describing positive impact of restricted vegetative growth during yield formation on HI
- Coefficient describing negative impact of stomatal closure during yield formation on HI
- Allowable maximum increase of specified HI
- Anaerobiotic point (for effect of waterlogging on Tr)

Air temperature stress
- Minimum and maximum air temperature below which pollination starts to fail
- Minimum growing degrees required for full biomass production

Soil salinity stress
- Thresholds for the electrical conductivity of the saturated soil-paste extract (ECe) at which biomass production starts to be affected (upper threshold) and is completely halted (lower threshold).

For the calibration of these conservative parameters, diverse data sets are necessary to cover a wide-range of climate and soil conditions, and more cultivars. Particularly crucial are data sets for water-deficient conditions, on which the calibration of the water-stress parameters depends. With time, calibration of the melon will be improved based on additional data sets. Therefore, in principle, the calibrated conservative parameters require no adjustment to the local conditions or for the common cultivars, and can be used as such in simulations.

Trial-and-error iterations

Trial-and-error iterations are the heart of the parameterization process. The procedure was to run simulations with the model starting with estimated or guessed parameter values and than compare the output with the measured experimental data, then adjust the parameters and run the simulation and compare again. To make the adjustments of the conservative parameters, observed green canopy development and biomass and yield production data, obtained at different irrigation levels, were used. The measured data were differentiated according to their reliability and exactness, and make rational adjustment to the vague estimates of input first to see if the simulated results better match the measured results, before changing the model parameters.

During trial-and-error runs of AquaCrop to calibrate the parameters, attention was paid equally to how well the simulated results (green canopy cover) agree with the measured values as time progresses through the season, as well as the total biomass, yield and consumptive water use at crop maturity.

Goodness-of-fit measures

To evaluate AquaCrop performance, a linear regression was determined between the observed and simulated values of green canopy cover, yield and biomass. The following statistics specifically designed for model goodness of fit were used: root mean square error (RMSE), Willmott's Index of Agreement or *d* statistic (Willmott, 1982), and modeling efficiency (EF) (Loague and Green, 1991). The model fit improves as d and EF approach unity, and as RMSE approach zero.

Results

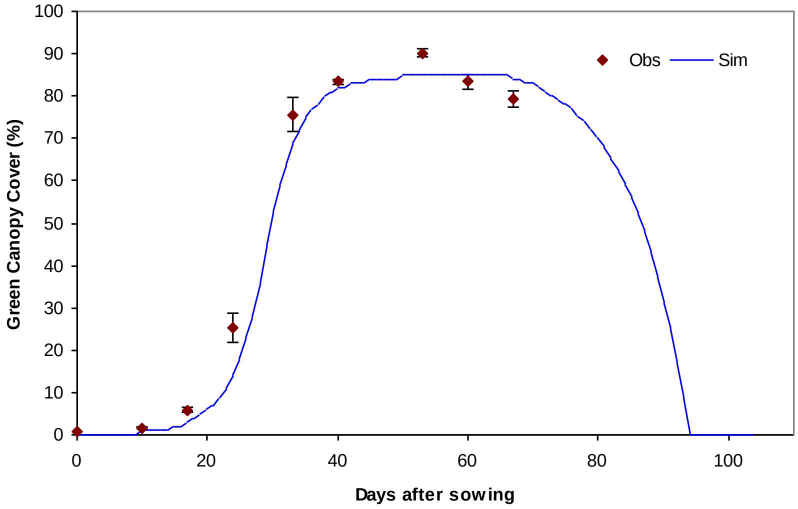
The conservative crop parameters were varied until satisfactory results for all treatments were achieved. The model was calibrated in terms of comparing aboveground biomass, yield, and green canopy cover. Table 4 presents some of the results of the parameterization of AquaCrop for melon using the experiments performed in the Guadiana River Basin.

Table 4. Preliminary values of goodness-of-fit: Root Mean Square Error (RMSE), index of agreement (d), and modeling efficiency (EF) for seasonal progression of green canopy cover (GCC), biomass, and yield of all the treatments.

Parameters	**RMSE**	***d***	**EF**
GCC	9.63 (%)	0.934	0.889
Biomass	1.55 (t ha^{-1})	0.912	0.873
Yield	0.68 (t ha^{-1})	0.976	0.941

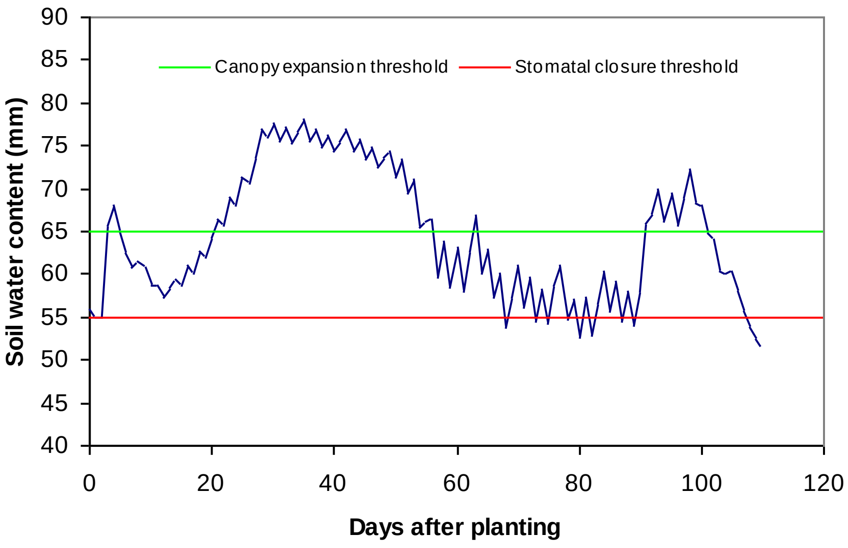
Comparison of observed and simulated time-trends of GCC for the two pilot sites shows that there was an acceptable matching. As an example, Figure 7 shows the evolution of GCC for T1 of the Aquifer 29 pilot site, with an adequate match between the simulated values and the observations. The satisfactory performance in the simulation of GCC led to a reasonably fit in biomass accumulation and final yield, as indicated by the high values of *d*, and EF. We must take into account that the proper adjustment of crop stress parameters enabled the accurate simulation of biomass and yield in the deficit irrigation treatments.

Figure 7. Observed and simulated seasonal evolution of melon green canopy cover for T1 of the Aquifer 29 pilot site.



In summary, the results of calibration of the model for melon reported in Table 4 shows that the model is able to simulate satisfactorily the response of the crop to different levels of water stress, and thus provides grounds for confidence in its performance. However, more efforts are needed to improve the calibration of the crop parameters, using data from different studies in different parts of the world. Nevertheless, AquaCrop has proved to be an useful tool for soil water content (Figure 8) and WP simulations.

Figure 8. Simulation of the seasonal evolution of the soil water content for RDI treatment of the Aquifer 23 pilot site.

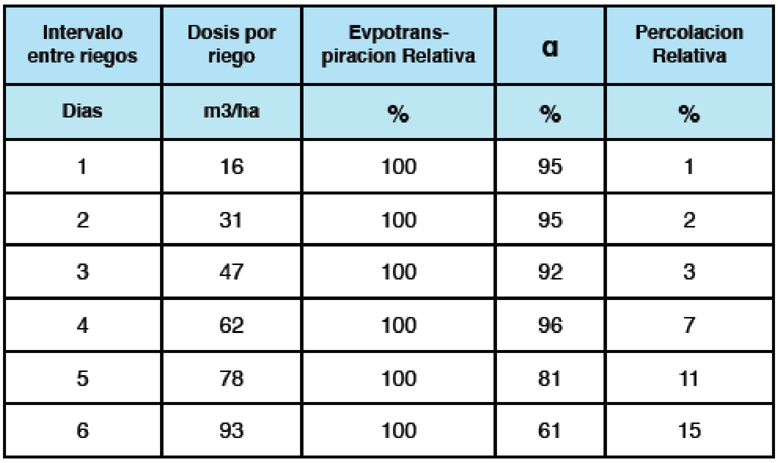


5-Tool output in REDSIM

REDSIM Irrigation Advisory Bulletin

One of the principal components of the REDSIM Irrigation Advisory Bulletin is obtained from output using the approach and model SWAP as described in the previous sections. This component provides information on how different irrigation scheduling options could affect two parameters of interest: (i) the amount of water percolating to the aquifer, and (ii) the minimum available water capacity that would occur for the 7-day forecasted period. The latter - that could be considered as an indicator of crop water stress – is calculated using SWAP.

Soil texture for each site involved in the REDSIM evaluation activities were extracted from the regional soil texture maps produced within REDSIM, as presented before. The different parameterized models for each site were run iteratively with different scheduling options, i.e. with different irrigation intervals and doses. A table is included in the bulletin with synthesized output of the SWAP model, including an estimate of the relative evapotranspiration.



Intervalo entre riegos	Dosis por riego	Evpotrans-piracion Relativa	α	Percolacion Relativa
Dias	m3/ha	%	%	%
1	16	100	95	1
2	31	100	95	2
3	47	100	92	3
4	62	100	96	7
5	78	100	81	11
6	93	100	61	15

Table 5. Example the table presented in the irrigation advisory bulletin indicating how the chosen irrigation scheduling option affects relative evapotranspiration, soil moisture (alpha) and percolation

The outputs of the model were used to generate so-called surface plots that indicate how the irrigation options affect the selected indicator. The two key indicators are visually represented as shown in the following figures. Relative percolation (Fig. 9) was calculated as the average percolation rate divided by the water input (irrigation + rainfall) for the 7-day forecasted period. This graph should give the farmer an indication how

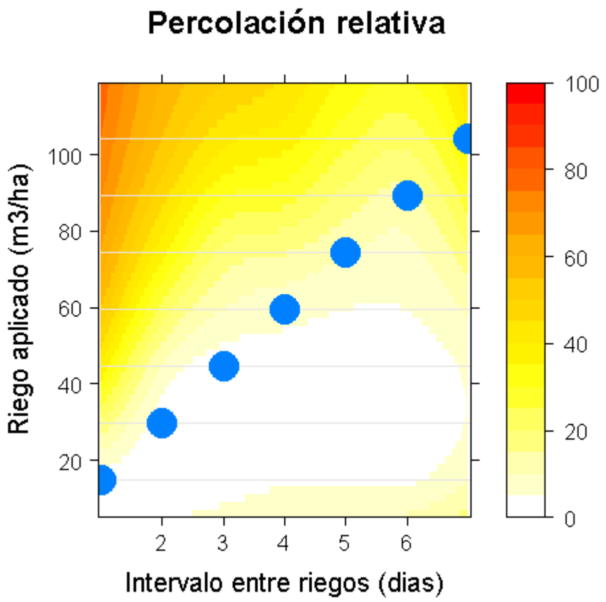


Figure 9 showing how the irrigation scheduling affects the losses through percolation in the forecasted period

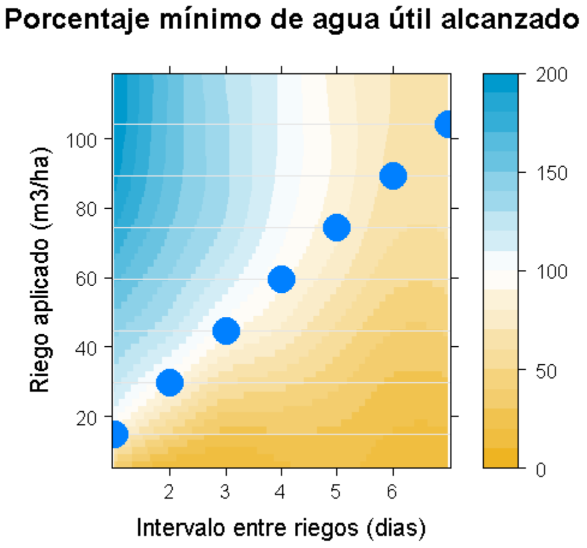


Figure 10 showing how the irrigation scheduling affects the soil water content during the forecasted period

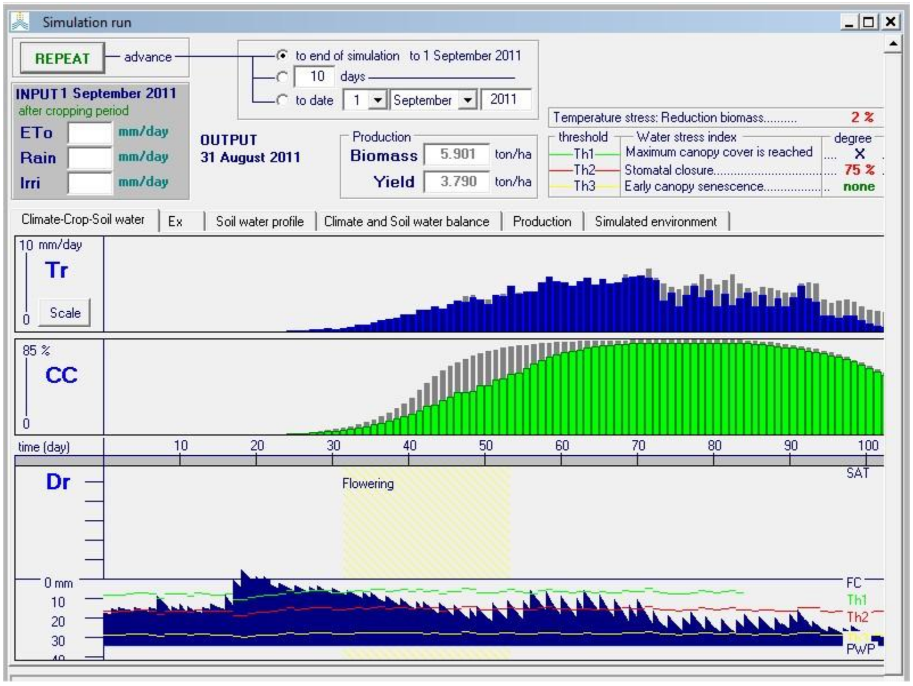
Irrigation planning and Water productivity

The goal of irrigation scheduling is to determine how to supply the crop with the correct amount of water at the appropriate time. Most growers make irrigation decisions based on their practical experience and consider the practical limitations of their systems. AquaCrop can provide guidelines for efficient irrigation management, giving specific crop responses to water and covering the following key items: crop water requirements, yield response to water supply, and recommended strategies for deficit irrigation.

The calibration of AquaCrop for melon allows the development of optimal irrigation schedules. There are options to asses the net irrigation requirement and to generate irrigation schedules based on specified time and depth criteria. Since the criteria may change during the season, the programme provides the means to test deficit irrigation strategies by applying chosen amounts of water at various stages of crop development. Yield response to water stress differs largely depending on the stage the water stress occurs. In Melon, flowering and yield formation stages are sensitive to stress, while stress occurring during the ripening phases has a limited impact, as in the vegetative phase, provided the crop is able to recover from stress in subsequent stages. In situations where water resources are very limited, deficit irrigation is frequently practiced. Scheduling for full irrigation can follow general guidelines, but deficit irrigation will require adjustments for local conditions.

The optimal irrigation scheduling (either full, deficit or supplementary) derived from AquaCrop enhances management strategies for increased water productivity and water savings. Also, the outputs of the model are useful for benchmarking, and for studying the effect of water management practices on crop yield and water productivity. The figure below shows the seasonal evolution of soil water under deficit irrigation schedule generated by AquaCrop for melon, and its impact on production.

Figure 11. Output of deficit irrigation schedule generated by AquaCrop model for melon


● to end of simulation to 1 September 2011
○ 10 days
○ to date 1 September 2011

INPUT 1 September 2011
after cropping period
ETo mm/day
Rain mm/day
Irri mm/day

OUTPUT
31 August 2011

Production
Biomass 5.901 ton/ha
Yield 3.790 ton/ha

Temperature stress: Reduction biomass.......... 2 %

threshold	Water stress index	degree
Th1	Maximum canopy cover is reached	X
Th2	Stomatal closure	75 %
Th3	Early canopy senescence	none

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Annex III. Farmer evaluation of REDSIM Irrigation Advisory Bulletin

By: Sorada Tapsuwan, Johannes Hunink, Francisco Alcon, Aafke Mertens and Alain Baille

Introduction

The increased level of water scarcity in the Mediterranean region in the last decade has forced policy-makers to focus their attention on measures and tools that promote the sustainable use of water resources. This is one of the goals that the European Water Framework Directive (WFD) pursues: a good ecological status of all water bodies in Europe and the development of a River Management Plan that ensures its sustainable use.

Particularly in the Segura River Basin, south east of Spain, the demand for water exceeds its availability resulting in the region having the highest water exploitation index in Europe (EEA, 2009). Water is used mainly in agricultural production with the irrigation sector consuming 89% of the overall demand in the region (PHCS, 1998).

To reduce the imbalance between water supply and demand, policymakers and stakeholders in this area seek for new sources of supply, water saving techniques and decision supporting tools to optimize water use. On the supply side, measures to increase water availability in this water scarce area currently focus on reuse of water and desalination. On the demand side, various management options and water saving technologies are being considered and in some cases implemented. Drip irrigation for example has already been widely adopted in this area (Alcon et al., 2011). The adoption of this type of technologies to increase Irrigation Water Productivity (economic output produced per applied irrigation unit) could be the key to managing scarce water resources in arid and drought-prone areas (Cason and Uhlaner 1991).

Although high investments have been done in modern irrigation infrastructure (storage, pressurized systems, drip irrigation, etc), it is recognized that there are still important water losses due to overirrigation and non-optimal timing and dosing of irrigation. Also emerging irrigation strategies, such as Regulated Deficit Irrigation, can help farmers to achieve significant water savings but require additional information on soil and crop to be available to the farmer to control risks (e.g. Geerts and Raes 2009). This can be obtained by implementing measurement and control systems that monitor soil or crop responses on irrigation (precision irrigation) but should be complemented by more up-to-date and guiding information including weather and crop demand predictions versus irrigation scheduling options. (e.g. Rao et al 1992). Simple soil water balance models have been reported to be successfully used within irrigation advisory tools by various authors, in some cases with weather forecast information (e.g. Rao 1987; Cabelguenne et al, 1997; Cai et al 2009; Rossi 2011). (Varshneya, Kale, Vaidya, Pandey, & Karande, 2011). In Italy, Rossi (2011) reports a successful implementation of an advisory service which aims to facilitate the operation and management of irrigation systems by offering personalized forecasting to farmers through a website, using also simple soil water balance models.

Although the potential for using simulation models to schedule irrigation has been recognized for many years (e.g. Jensen, 1969), the use of computer simulation models to support irrigation scheduling is still limited. For example in the US, only around 2% of irrigated farms used these types of tools (USDA, 2009). Coupling agro-hydrological models with real-time plant based measurements has been demonstrated to be effective (e.g. Rogers and Elliot, 1989; Thomson and Ross, 1996; Steppe et al., 2008) but the lack of parameter values for different crops is a serious limitation at present. A promising tool in this sense is the FAO AquaCrop model which is currently being calibrated for various crops in different parts of the world (Steduto et al., 2009).

The application of short-term weather forecasts for irrigation scheduling have been demonstrated by several authors to benefit crop production (Hashemi and Decker, 1969; Gowing and Ejieji, 2001; Wang and Cai, 2009). Weather information is also used for the timing of other farming operations, such as the application of pesticides and fertilizers and to control salinity risks (e.g. Wang 2001; Lascano and Li 2003). In Spain, agrometeorological information is made accessible by government agencies, agricultural extension services and research institutions. Currently, farmers in the Murcia region can access geo-referenced information on irrigation water needs provided by the regional agrometeorological public service, called SIAM (Erena et al., 2000). This information is based on historical weather data from a network of agrometeorological weather stations throughout the region. Surveys in the area have shown that a considerable part of the farmers in this region use this advisory service to some extent for their irrigation scheduling.

Traditional development of advisory services is a top down process, giving little consideration to the farmers' preferences for the type of information required and the ease of interpreting instructional information provided. In recent years, several authors have stressed the importance of a participatory approach during the development of decision support tools for farmers to improve the functionality of the design in relation to the objectives and conduct evaluative activities early in the process, integrated with design activities (e.g. Vanclay and Lawrence, 1994; Tessmer, 1994, Walker 2002). Such an approach could limit the risks of non-adoption because the design fails to meet the actual user requirements. A proper needs analysis is not sufficient to ensure that the tool meets the requirements as the developers will always give their own interpretation to some extent.

This paper describes the participatory approach used for the design and implementation of an irrigation advisory service that has been developed to provide farmers with specific information by means of a bulletin sent each week to the farmer. Specifically, the main objective was to enhance the design of an irrigation advisory bulletin by involving innovative farmers in the tool development process in order to meet better their requirements. This was done by obtaining farmers' feedback before and after they have used the advisory bulletin and assessing the usefulness, clarity and acceptance of the tool components during the design process to obtain useful information on how to adjust the tool better to the user and foster uptake.

Weekly Irrigation Advisory Bulletin

The weekly irrigation advisory bulletin joins different pieces of up-to-date information into a single document to support farmers in their weekly decisions on irrigation planning. The bulletin contains (i) 7-day weather forecast information, including forecasted crop water demand, (ii) options for irrigation dose and frequency to meet the forecasted demand, and their impact on percolation and available soil water, and (iii) past information (last year and last week) on irrigated amounts compared to theoretical computed local crop water requirements.

This synthesized information source should enable farmers to consider various factors jointly when making decisions on the appropriate amount of irrigation water applied each week. An updated version of this bulletin is provided every week by email to the farmer. The farmer is asked to send back each week the irrigation schedule he applied.

The principal considerations for the design of the bulletin were to provide clear-cut and uncomplicated information using concepts the farmer is supposed to be familiar with and tailored to the corresponding plot, satisfying local needs. The objective was to include information that could be synthesized based on existing datasets, in order make it easily transferable to other regions. The methodological procedures for these components are explained in the following sections.

Weather and crop water demand forecasts

Weather forecasts are extracted weekly from the Spanish National Meteorological Agency (AEMET). The following 7-day forecasted information is used for the bulletin: (i) rainfall amounts, (ii) minimum and maximum temperatures, (iii) cloudiness and (iv) wind speed. Forecasted rainfall amounts and cloudiness are represented in the bulletin visually (see Figure XX). Temperature forecasts are used for the calculation of the reference evapotranspiration (ET_o) for each day of the following week.

The most common and precise method to estimate ET_o is using the Penman Monteith FAO-56 formula, proposed by Allen et al, (1998), in the following $ET_{o,PM}$:

$$ET_o = \frac{0.408\Delta(R_n - G) + g\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature at 2m height (°C), u_2 is the wind speed at 2m height (m s^{-1}), is the vapour pressure of the air at saturation (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the saturation vapour pressure curve (kPa $°C^{-1}$) and γ is the psychrometric constant (kPa $°C^{-1}$). A complete set of equations is proposed by Allen et al. (1998) to compute the parameters of Eq. (1) according to the available weather data and the time step computation, which constitute the so-called FAO-PM method. G may be ignored for daily time step computations. This method was followed to calculate ET_o for each agro-meteorological weather station in the area with daily data from the years 2002-2011.

The disadvantage of using this method for the purpose of forecasting evapotranspiration rates is that it requires many input variables with relatively large prediction errors. A more straightforward method for ET_o estimation is the Hargreaves (HG) ETo equation:

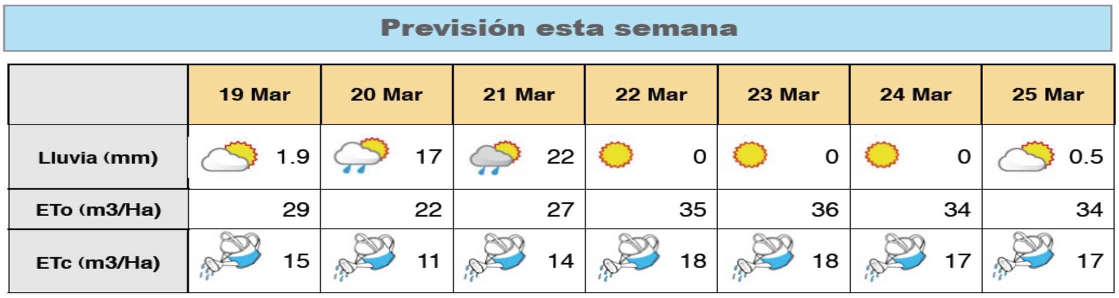
$$ET_{o.HG} = 0.0023\,(T_{avg} + 17.8)(T_{max} - T_{min})^{0.5} R_{ext} \qquad (2)$$

where T_{avg} is the mean air temperature, T_{min} is the minimum air temperature and T_{max} is the maximum temperature [°C], and R_{ext} is the extraterrestrial solar radiation [MJ m^{-2} d^{-1}]. This estimate can be locally adjusted with ET_o estimates using the Penman Monteith equation. Allen et al. (1998) recommends performing a linear regression with the Penman Monteith (PM) ETo as follows:

$$ET_{o,PM} = a + b\, ET_{o,HG} \qquad (3)$$

This linear regression was performed for all the weather stations in the area, with daily data over the period 2002-2011. The identified values of the parameters a and b allowed calculating $ET_{o,HG}$ (Eq. 2), which represents the farm-adjusted estimate of the daily forecasted ET_o to be included in the bulletin.

The following step was to calculate the standard crop evapotranspiration for a specific crop (ET_c) by multiplying ET_o by a crop coefficient, K_c, which is an empirical parameter that accounts for the physiological and structural differences between the actual crop and the grass-like reference surface assumed in Eq.(1). For operational applications, this approach is often preferred because it only requires phenological and standard meteorological data while providing acceptable ET_c estimates compared to physically-based modeling and field measurements. The crop coefficients used are the recommended values by Allen et al. (1998). The daily forecasted ET_c is represented also visually by means of a watering can, filled according to its value.



Previsión esta semana

	19 Mar	20 Mar	21 Mar	22 Mar	23 Mar	24 Mar	25 Mar
Lluvia (mm)	1.9	17	22	0	0	0	0.5
ETo (m3/Ha)	29	22	27	35	36	34	34
ETc (m3/Ha)	15	11	14	18	18	17	17

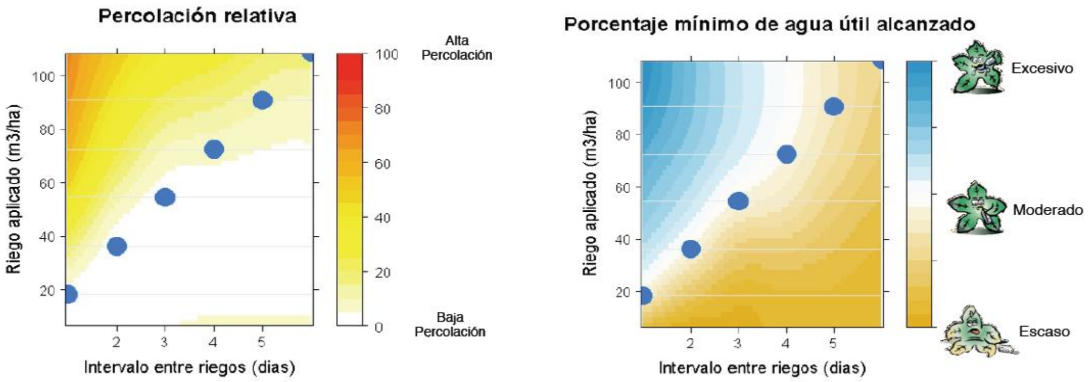
Figure 3 Visual representation in bulletin of daily weather and evapotranspiration forecasts

Impact of irrigation scheduling options

In addition to the prevision of the crop water demand of the following week, the bulletin provides information on how different irrigation scheduling options could affect two parameters of interest: (i) the amount of water percolating to the aquifer, and (ii) the minimum available water capacity that would occur for the 7-day forecasted period. The latter - that could be considered as an indicator of crop water stress - was calculated using the agro-hydrological Soil–Water–Atmosphere–Plant (SWAP) model (Kroes and Van Dam, 2003). The SWAP model simulates the transport of water, solutes and heat in unsaturated and saturated soils. The model is designed to simulate flow and transport processes at the field scale level, during growing seasons and for long term time series.

Water movement simulation in the SWAP model is based on Richards equation which requires the definition of initial, upper and lower boundary conditions, as well as the knowledge of the soil hydraulic properties, i.e. the soil water retention curve, and the soil hydraulic conductivity function, K(h). These functions are usually expressed by using the parametric relationships of Van Genuchten (1980) and Mualem (1976). The related soil hydraulic parameters were derived using the pedo-transfer functions proposed by Schaap et al. (2001) based on soil texture. Soil texture for each site was extracted from regional maps produced by using different environmental and spatial variables as proxy-variables in the spatial interpolation of point samples of soil texture (Pérez-Cutillas and Barberá, 2012). For three sites in the area, detailed soil profile and hydraulic data was available to verify that this regional approach to estimate soil hydraulic parameters is valid, given the type of output required for the bulletin.

The different parameterized models for each site were run iteratively with different scheduling options, i.e. with different irrigation intervals and doses. The three output parameters of interest are visually represented as shown in Figure 4 (a) and (b.) Relative percolation (Fig. 2a) was calculated as the average percolation rate divided by the water input (irrigation + rainfall) for the 7-day forecasted period. To show the impact on soil moisture (Fig. 2b), the minimum is taken of the readily available water (FC-WP in the rootzone) of the forecasted period.



(a) (b)

Figure 4 Visual representation of the impact of different irrigation scheduling options (dose and frequency) on minimum available soil water (a) and the mean relative percolation (b)

Comparison of irrigated versus crop water demand

The following component of the bulletin consists of a representation by means of tables and graphs on how the applied irrigation amounts of the particular farmer compare with the crop water requirements calculated based on the closest weather station data and the local crop coefficients. This comparison is given both for the last week and for the last 12 months. Both monthly and weekly information can be of use to the farmer to allow him to plan irrigation for the entire season while at the same time being responsive to current weather conditions using up-to-date information. In this way, the farmer is able to revise the decisions he made each week and adjust if needed the irrigation schedule for the subsequent weeks, while keeping under consideration the full planning horizon.

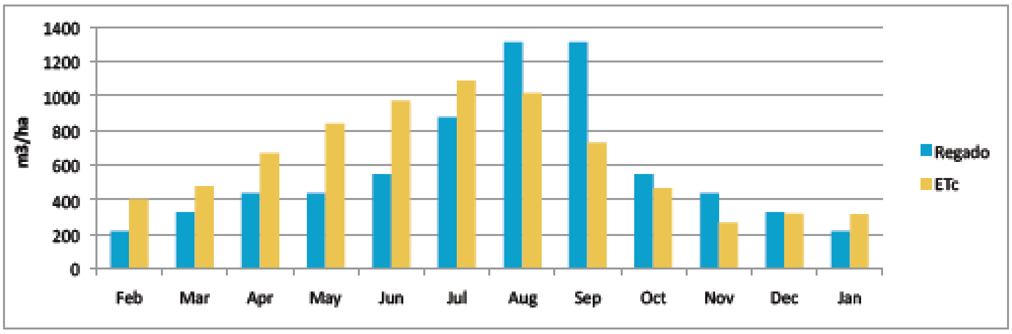


Figure 5 Graph in bulletin showing irrigated amounts versus crop water requirements of the last 12 months

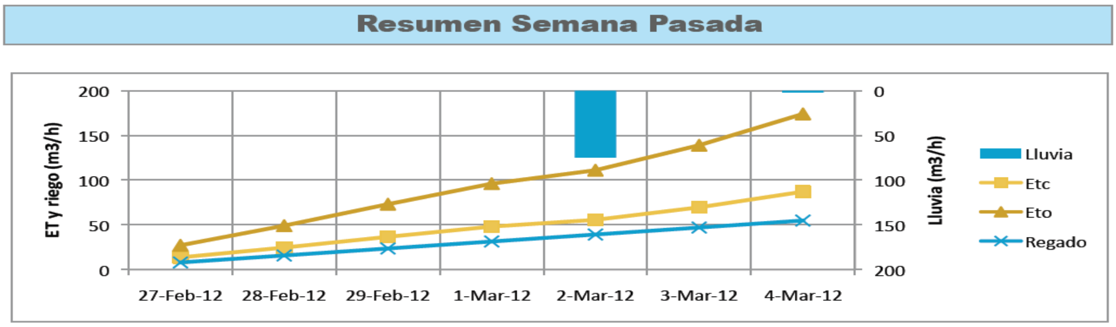


Figure 4 Graph in bulletin showing irrigated amounts versus crop water requirements of last week

Bulletin evaluation methodology

The criteria used to evaluate the success of decision support tools in agriculture are often stated in technical terms (Lynch et al. 2000). However, good scientific knowledge that is poorly communicated, unable to reach the target end-user or not easily understood is unlikely to be useful (Keogh et al. 2004). Formative evaluation framework is commonly used to improve the design of the instructional materials, such as textbooks, by means of identification and remediation of problematic aspects, through a consultative process with experts and end-users. It is typically conducted during the development and improvement stage of the instructional material (Scriven 1991). Empirical studies, over a thirty-year span that has applied the formative evaluation framework to revise student instructional material, shows that student performance increases in comparison to unrevised instructional material (Tessmer 1994).

In order to maximise the acceptability of the irrigation advisory bulletin amongst farmers in the Murcia region, a formative evaluation framework was conducted in the form of individual and small group interviews and field test survey. The aim is to measure the usefulness, comprehensibility and acceptability of the irrigation advisory bulletin. Results from the evaluation allows researcher to have a better understanding of farmers' information requirements and the form in which the information is best communicated.

Sample selection and recruitment

A number of citrus farmers in the Murcia region were selected to participate in the group interviews. These farmers were selected, with the advice from an extension service agent, because they were considered innovative farmers or early adopters compared to other farmers in the region. According to Rogers (2003), innovators have the ability to understand and apply complex technical knowledge, are able to cope with a high degree of uncertainty about innovation, are risk-takers and enjoy the rush from risk-taking. Also innovators are willing to accept setback when innovations are not successful playing the gate keeping role in the flow of new techniques into the system. The selected farmers have demonstrated their keenness to learn and apply new farming techniques that have been shown scientifically to improve productivity or minimise productions costs.

During the recruitment phase, some farmers expressed their interests to participate in the group interview but were not able to attend. As such, these farmers were contacted later for a personal interview. In addition to farmers, a number of agricultural engineer, who are advisors to farmers on how much irrigation should be applied were also contacted for the group interview. In the Murcia region, some farmers rely on these irrigation experts for advice on crop irrigation schedule. Hence, it was relevant to include the opinions of these irrigation experts in the research.

Pre-trial run interviews

The personal and group interviews were conducted in January 2012. The group interview was organised in the Extension Services Office in Murcia. A total of eight farmers and three irrigation experts, from here onwards are called irrigators, participated. Each interview lasted approximately one hour. At the beginning of each interview, experts from the REDSIM program explained the functionality and benefits of RDI to the irrigators. This is to ensure that the irrigators have a basic understanding of how the bulletin works and where the technical information comes from. The experts showed what the bulletin would look like, what type of information it would convey and how farmers can interpret and make use of the information to help with their irrigation decision making each week. After the discussion, the floor was opened to the irrigators for questions and feedback. The questions and feedback were noted and used to remediate the issues in the weekly bulletin that were identified problematic by the irrigators.

Pre-trial run survey design

Before the commencement of bulletin trial run, the irrigators were asked to complete a short survey to assess how much they believed the information in the weekly bulletin would be useful to them and how the bulletin could help improve their productivity. This is the pre-trial run survey and it consisted of three sections. Each section contained 7 point Likert scale questions (rating 1 = not useful at all, to rating 7 = very useful). The first section was designed to assess the irrigators' opinion about the usefulness of the information that is presented in the weekly bulletin. The second section contained questions aimed at measuring their agreement towards the benefits of adopting the bulletin, such as benefits associated with increased tree performance and fruit quality. The third section contained questions to determine whether they were already using other sources of information such as that provided by SIAM, and whether they would use the information in the bulletin to assist in their irrigation decision making process.

Post-trial run survey design

At the end of the bulletin trial run ended, participating irrigators in the trial run were sent a follow up survey about the bulletin. The objective of the follow up survey was to assess whether they found the information in the bulletin useful, how frequently the information was actually used to influence support their irrigation decision and whether they would like to use the bulletin in the future. As these irrigators were considered early adopters of irrigation technology, it was important to find out whether their experiences in using the bulletin would lead them to use the bulletin in the future and recommend it to other irrigators.

For consistency, the format of the follow up survey mimicked the post-trial run survey with some minor variations. The first section contained questions that would assess on the irrigators' opinion about the usefulness of the information provided by the bulletin, how frequently they used the information for decision making and whether they found the information difficult to understand. Additionally, farmers were asked to give us their opinion on how the information can be improved in open-ended questions. The second section contained 7 point Likert scale questions to assess the factors that may have influence the irrigators' decision to use the bulletin's information in the future.

Results

A total of 8 irrigators participated in the bulletin trial run. The most relevant results were on the usefulness of the bulletin, how easy the information was to understand, and the general rating of acceptance for future use. Responses from these irrigators before and after the trial run were collated and compared. A number of statements from the open-ended section of the follow-up survey are also presented.

Usefulness of the information

Responses pre and post the bulletin trial run suggest that irrigators' expectations of the type of information they would require differed from what they found useful and used most often. In general, irrigators expected that all the information provided in the bulletin would be useful, as indicated by the average rating of 5 or greater for every type of information in the pre-trial run results (see Table 1). Irrigators gave a particularly high score to FORECAST and COMPARISON. However, after their exposure to the bulletin for four weeks, irrigators rated that SUMMARY information was the most useful. Every All farmers also stated that they used SUMMARY information every week during the trial run, as compared to other types of information that were not used every week.

Table 1 Usefulness rating of the bulletin information pre and post the bulletin trial run

	Before the trial		**After the trial**		**Frequency of use**		**Difficult to under stand (No=0)**
Rate how useful (will) was the following information (be) to you	**Mean**	**Std Dev**	**Mean**	**Std Dev**	**Mean**	**Std Dev**	
Summary of annual irrigation levels (HISTORIAL)	5.3	0.8	5.1	1.0	3.6	0.5	0
Comparison of irrigated amounts and crop water requirements (COMPARISON)	6.3	0.5	5.1	1.0	3.5	0.5	0
Irrigation summary and crop water requirements of last week (SUMMARY)	5.7	0.5	5.4	0.7	3.9	0.4	0
Daily weather and evapotranspiration forecasts (FORECAST)	6.4	1.0	4.6	1.7	2.9	1.4	1
Table of irrigation scheduling options (OPTION)	5.1	1.2	3.9	1.5	3.4	1.2	2
The impact of different irrigation scheduling options (dose and frequency) on minimum available soil water (WATER)	5.6	1.3	4.0	1.1	3.5	0.5	1

The impact of different irrigation scheduling options (dose and frequency) on the mean relative percolation (PERCOLATION)	5.6	1.4	4.0	1.2	3.1	0.8	1

Noteworthy, usefulness ratings for FORECAST, OPTION, WATER and PERCOLATION were lower than for HISTORIAL, COMPARISON and SUMMARY, despite being the area of the bulletin where recommended irrigation scheduling in the future is provided. Two irrigators provided their justifications for the reluctance to use the predicted information as follow:

"The last part where it talks about percolations I think it is too general and the information is not adapted to the specific farm. Water quality should be an important factor. The crop cycles and the periods of harvest are not taken in account."

"The recommended irrigation level does not seem to be realistic for this area. At times in the past when humidity level is high and irrigation should be cut back to control for diseases stemming from excess humidity, however, the bulletin recommends a high irrigation level.

Despite having reservations about the recommended irrigation level presented by the bulletin, one farmer admitted that he still followed the recommended schedule.

"It [the bulletin] asks me to lower my irrigation use to a 60% of what I use today. I don't know if this will work for my crops, but I have already lowered 90m3/ha in a week, when I normally use 300m3/ha."

In addition to these questions, irrigators were also asked before and after the trial run whether the bulletin will help (has helped) them adjust their irrigation levels to match crop water requirements; implement deficit irrigation on their farms; and save water. They were also asked to give a general usefulness rating of the bulletin. A summary of response ratings of pre and post the trial run are presented in Table 2, indicating that irrigators had relatively high expectations for the bulletin to help them improve their irrigation scheduling and save water. However, after trialling the bulletin, the irrigators did not find the bulletin to be as useful as they had expected. Their ratings regarding the bulletin helping them to support to implement deficit irrigation on their farms was particularly low compared to other items ratings. One irrigator indicated that the information should have considered crop life cycle and periods of harvest into the recommended irrigation schedule. Specifically, his suggestion was

"It is necessary to continue the evaluation of this information for the whole crop cycle, since winter months are the ones with less water requirements."

This same farmer also mentioned that water quality is also an important factor to account for in irrigation scheduling, but was not covered by the information in the bulletin.

Table 2 Perception of the benefits of the bulletin to irrigation and farming

Rate how useful will the following information be to you	**Before the trial**				**After the trial**			
	Mean	**Std Dev**	**Min**	**Max**	**Mean**	**Std Dev**	**Min**	**Max**
In general, the information provided in the bulletin is very useful	5.4	0.5	5	6	4.6	1.5	1	6

The information permits me to create an irrigation program that is adjustable to the needs of my crops	6.0	0.8	5	6	4.8	0.9	3	6
The information permits me to implement regulated deficit irrigation	5.0	1.2	5	7	3.8	1.7	1	6
The information helps me save water	5.3	1.4	4	7	4.6	1.4	3	7

Comprehensibility of the information

When asked on the comprehensibility/ambiguity of the information, none of the irrigators found information related to HISTORIAL, COMPARISON and SUMMARY confusing. One irrigator found information in PREVISION ambiguous, expressing his doubts in relation to ET_o, ET_c and rainfall in the following way:

"I don't understand the relationship between ET_o and ET_c. For example, for the 21st and 23rd of March you have to irrigate almost the same (ET_c are almost the same) but on the 21st it rained a lot (22mm) and on the 23rd nothing. Why?"

To this irrigator, the information was counter-intuitive and did not appear to produce consistent correlations from week to week. Two irrigators confessed that they struggled with interpreting the alpha value and the relative percolation. One irrigator complained about the PERCOLATION diagram in that the interaction with soil type and water salinity was missing as follow:

"I understand that percolation depends on the type of soil, but I miss a graph which would tell me if the salinity influences the irrigation water as salinity is a crucial factor to deal with in my plot, given the poor irrigation water quality"

Acceptability of the bulletin

In the follow up survey, the irrigators were asked to rate their level of agreement on whether they would recommend the bulletin to other irrigators; change their irrigation schedule based on the bulletin information; access the bulletin if it were available on the internet; and pay for the bulletin in the future. A summary of their responses is presented in Table 3. In general, respondents were positive towards recommending the bulletin to other irrigators, accessing future information from the internet and using the information to adjust their irrigation schedule (Table 3). One farmer, who earlier mentioned his doubts about the recommended irrigation level, stated in the bulletin that his irrigation behaviour has changed since receiving the bulletin, as follow:

"I'm scared of using less irrigation water because I don't know what will happen. I have never worked with low levels of water, but with the bulletin I have been able to make some changes to my irrigation patterns."

One irrigator in particular, provided positive feedback to the trial run as follows:

"Most of the bulletin is very interesting .... Congratulations with the effort, it would be interesting if this information does not get lost, and it should get to other farmers and technicians."

The statement above suggests that this particular farmer found the information valuable and would like to see others adopt the bulletin as well, which is one of the objectives of this exercise, to have early adopters help spread the word. Another farmer, however, cautioned that the bulletin may not be 'for everyone' and that only certain farmers might benefit from using it: . His comments were

"I think most of the farmers will not find this information useful. I would recommend it only to certain farmers.

In terms of willingness to pay, respondents were less supportive of paying for the information. This is not surprising as one of the farmers interviewed mentioned the current economic crisis in Europe and having limited funding to spend on this type of investment. The same farmer also confessed that water was relatively abundant this year, so he does not need such information be too careful with using his water.

Table 3 Acceptability rating of the bulletin

	Mean	**Std Dev**	**Min**	**Max**
I will recommend the bulletin to other farmers	5.0	0.8	4	6
I will use this information to adjust my irrigation level in the future	4.6	1.5	2	7
I will try to access this information if it were available on the internet	4.9	1.9	1	7
I would be willing to pay for this information	3.4	1.9	1	7

Discussion and recommended revisions

Despite being early adopters of irrigation technology, not all irrigators have a good grasp of scientific terms such as ET_o, ET_c and the minimum available water capacity. When the information presented was counterintuitive, despite being technically correct, irrigators became sceptical and chose a conservative option because not too follow the recommended irrigation schedule as they did not fully understand the rationale behind the recommended scheduling and numbers. Amongst the respondents, one chose to adjust his irrigation amounts to values close to those recommended by the bulletin, levels, despite he kept some doubts about the recommended figures closer to the recommended levels in the bulletin. This suggests a certain degree of trust that the farmers have in the science behind the information, or the institution that provides the information. This trust can be increased if the information is better explained and the doubts are removed, particularly when counter-intuitive facts are presented. , the doubt could be removed.

It was observed that irrigators utilised the part of the bulletin (HISTORIAL, COMPARISON and SUMMARY) where actual irrigation level is compared with recommended irrigation level more frequently than other parts of the bulletin. Hence, these irrigators are utilising the bulletin to reflect 'backwards' on how they have performed, instead of looking forward on what they should be irrigating. To produce these diagrams, the irrigators would have to report their irrigation level on a weekly basis. Hence, irrigators may give these parts particular attention due their involvement in the data collection process. Additionally, these diagrams allow them to compare and validate their actual performance against experts' recommendations. The most useful diagram was the one in which actual and recommended irrigation level were compared on a weekly basis.

Irrigators also prefer that the information provided is more specific or tailored to each farm. This type of data is ideal but is generally more labour intensive and costly. Hence, the benefit should outweigh the cost to pursue more detail in the data given. The irrigators may increase their level of willingness to pay for the information if it they are more tailored to their specific situation. This can be evaluated using non-market techniques such as the contingent valuation method or choice experiments.

Due to the brief duration of the trial runs it was difficult to compare how irrigation behaviour may have changed between wet and dry months. In addition, during the trial run Murcia experienced more than usual rainfall this season. Consequently, the plants were not under severe water stress. It is recommended that the bulletin should be trailed over a period of one year, or at least during the dry and wet seasons in order to control for the impact of rainfall and temperature variation.

Conclusion

The purpose of this study is to develop a better understanding of how farmers and irrigators perceive and use climate, plant growth and soil information to assist in their irrigation schedule decision making. A formative evaluation framework was conducted to capture and record feedback from irrigators on how and why each type of information provided was found to be useful, understandable and acceptable and what aspects of the bulletin need further improvement. This is to ensure that when scientific information is provided to assist irrigators, it is presented in such a way this is useful and encourages uptake. The benefit is to both the irrigators and the service providers as maximum benefit is being gained from such services. Early adopters of irrigation technologies were asked to participate in the bulletin trial run.

In conclusion, the bulletin pre and post trial run surveys have revealed that there are many factors that influence the acceptance of better irrigation information by early adopters. Some factors can be improved or modified by the scientists providing the information. These factors include how easy the information is to understand, how realistic it appears to be, how specific is the information to each farm and how integrated is the information (water quality, quantity, climate, soil, land use, etc) with each other. Other factors, which are external to the bulletin but have shown to have an impact on acceptance or the bulletin, include the current financial stress driven by the economic situation in Europe and the level of water availability.

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Annex IV. Benchmarking indicators for the Cartagena irrigation district

By: Soto García, M., Martínez Alvarez, V., Martín Górriz, B., Nicolas Aleman, E

Summary

The irrigable area of the Irrigation Community of Campo de Cartagena (CRCC) has been characterized by deriving benchmarking indicators from data over a 10-year period (2002-11). During this period, around 85% of the area has been equipped with modern irrigation infrastructure, including pressurized drip irrigation (between 2006 and 2009). Periods of drought have taken place with around 25% of lower water availability as usual (between 2006 and 2008). The benchmarking indicators used were based on those proposed by Malano and Burton (2001). Other indicators considered were those proposed by authors who have previously applied benchmarking techniques in Spain (Rodriguez, 2003; Córcoles, 2009, Abbey et al., 2010.) The study shows that the water shortage causes a decrease in the distribution efficiency, increases costs and energy consumption per volume of supplied water. A comparison with other irrigation districts in Spain shows that this irrigation district has a high temporal variability, a relatively low water availability, a high distribution efficiency, a low energy consumption per volume of water and the value of agricultural production is very high. The study highlights the importance of studying benchmarking indicators over time because factors such as drought can significantly affect the values obtained.

Introduction and objectives

In the coming decades, increasing water demand, environmental constraints and climate change will reduce the available water resources for agricultural production. Especially in semiarid regions such as southeastern Spain, this water shortage is predicted to form a serious threat to the sustainability of the agricultural sector (IPCC 2007, IPCC 2008). In Spain, around 70% of water demand corresponds to irrigated agriculture. The so-called Irrigation Communities (CR) that unite the irrigators in a certain district play an key role in the management of these water resources. According to the Spanish National Irrigation Plan of 2008, Spain counted 7,196 census irrigation communities in 2001.

The irrigation area of the Irrigation Community of Campo de Cartagena (CRCC) is located in southeastern Spain, the Autonomous Community of Murcia. It covers an irrigable area of 41,063 ha and has 9,462 community members, both small-holders as well as larger farmer corporations. The predominant crops in the irrigation area are vegetables (lettuce, melons, artichokes and broccoli), citrus (lemon and orange) and greenhouse crops (pepper). The theoretically allocated water resources to this district are 142 hm3/yr, but in reality the available surface water is much lower in most years. The CRCC is subject to a high variability in the water available for the distribution to its members. Critical situations have occurred as for example in 1995 when the CRCC was only able to distribute a total amount 18 hm3.

Currently the whole process of distribution of irrigation water is regulated automatically with real-time control of the distribution network through a mobile phone (Del Amor, 2006). This allows the irrigator to verify in real time (CRCC, 2012) the water allocated and distributed through Internet and his mobile device. To support this service, remote stations have been installed that control the hydraulic valves and pumping stations and collect data from the counters located in the 1.000 km pipeline distribution network.

The analysis and monitoring of the district performance through benchmarking techniques is one of the tools to optimize water use and efficiency in the district. The use of benchmarking has traditionally been used in business organizations but is now also being used in other areas of specialization. Malano and Burton (2001) defines benchmarking as "a process of learning from your own past performance and the performance of others in the pursuit of continuous improvement." The application of benchmarking techniques to improve the functioning of the irrigation communities is a relatively recent phenomenon (Rodriguez et al., 2008).

Rodriguez (2003) conducted a study of irrigation water management and application of benchmarking techniques to the irrigated areas of Andalusia, which includes 9 communities of irrigators in Andalusia during the years 1996-2002. Córcoles (2009) studied water management and energy use with irrigation benchmarking techniques, by analyzing 7 irrigation communities of Castilla-La Mancha during the period 2006-2008. Another comparative study of energy saving measures and economic irrigation communities was carried out by Abbey et al. (2010), in which the energy use of 22 irrigation communities were analyzed throughout Spain .

The objective of this paper is to analyze the effects of modernization and periods of water shortage within the irrigation area of the CRCC by means of benchmarking indicators. This evaluation should show the temporal dynamics of these indicators over time and allow a comparison with other districts.

Materials and Methods

The study period is 10 years, ranging from 2002 to 2011. During this period, around 85% of the area has been equipped with modern irrigation infrastructure, including pressurized drip irrigation (between 2006 and 2009). Periods of drought have taken place with around 25% of lower water availability as usual (between 2006 and 2008). The benchmarking indicators used were based on those proposed by Malano and Burton (2001). Other indicators considered were those proposed by authors who have previously applied benchmarking techniques in Spain (Rodriguez, 2003; Córcoles, 2009, Abbey et al., 2010.). The factors considered are those related with water use (performance indicators), with the economic (financial indicators), with energy (energy indicators) and with agricultural production (productivity indicators).

This summary report has made a selection of these indicators, as presented in the following table:

Indicator	**Code**	**Unit**
Total annual volume of irrigation water delivery per unit irrigated area	VsSr	m3 ha−1
Consumed active energy per unit irrigation delivery	EacVs	kWhm−3
Water price	PA,	€
Main system water delivery efficiency	ED	%

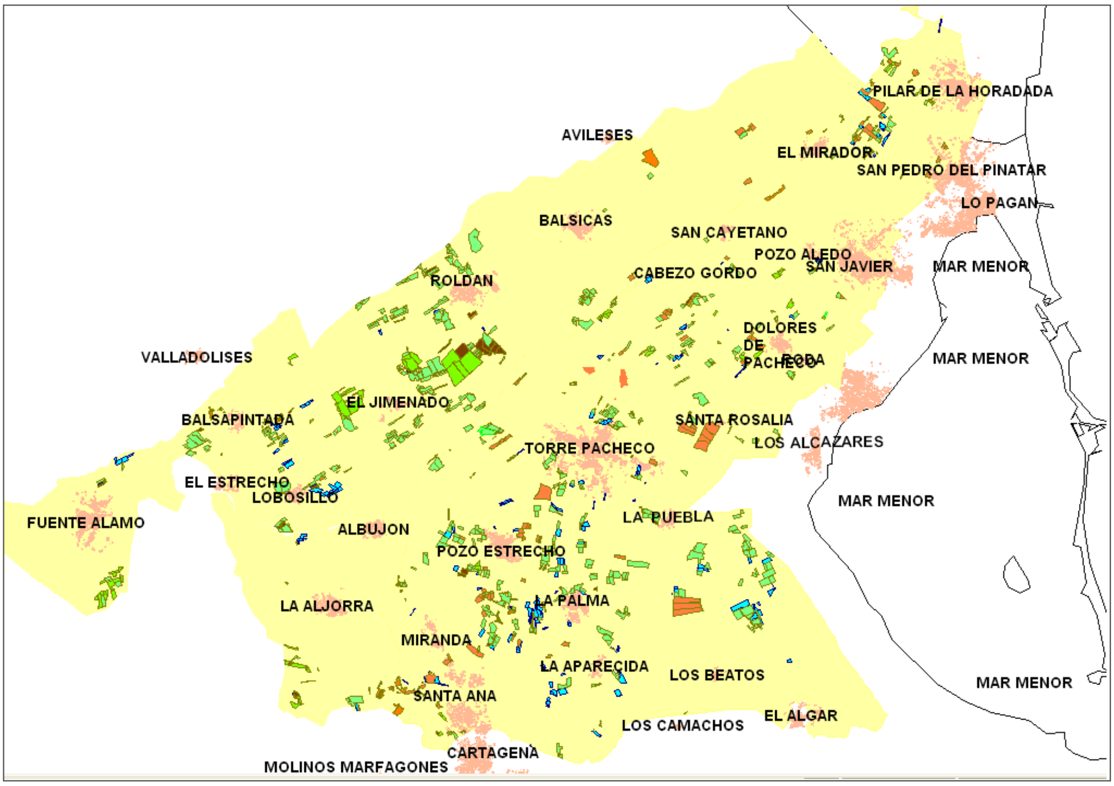

Figura 1. Surveyed plots of the irrigation district.

Results and Discussion

The indicators show a high temporal variability during the period 2002-11. The key indicator “Total annual volume of irrigation water delivery per unit irrigated area” varies between 3,086 m3ha-1 in 2004 and 558 m3ha-1 in 2006. These values are comparable (Figure 2) with the SLV (2), SC (3) and SOR (4) irrigation communities studied by Córcoles (2009), with values between 5,200 and 6,778 m3ha-1, and those derived in studies of Rodriguez (2003) for the CRFP (5), CRGC (6) and CRPG (7), which vary between 1,661 and 4,491 m3ha-1.

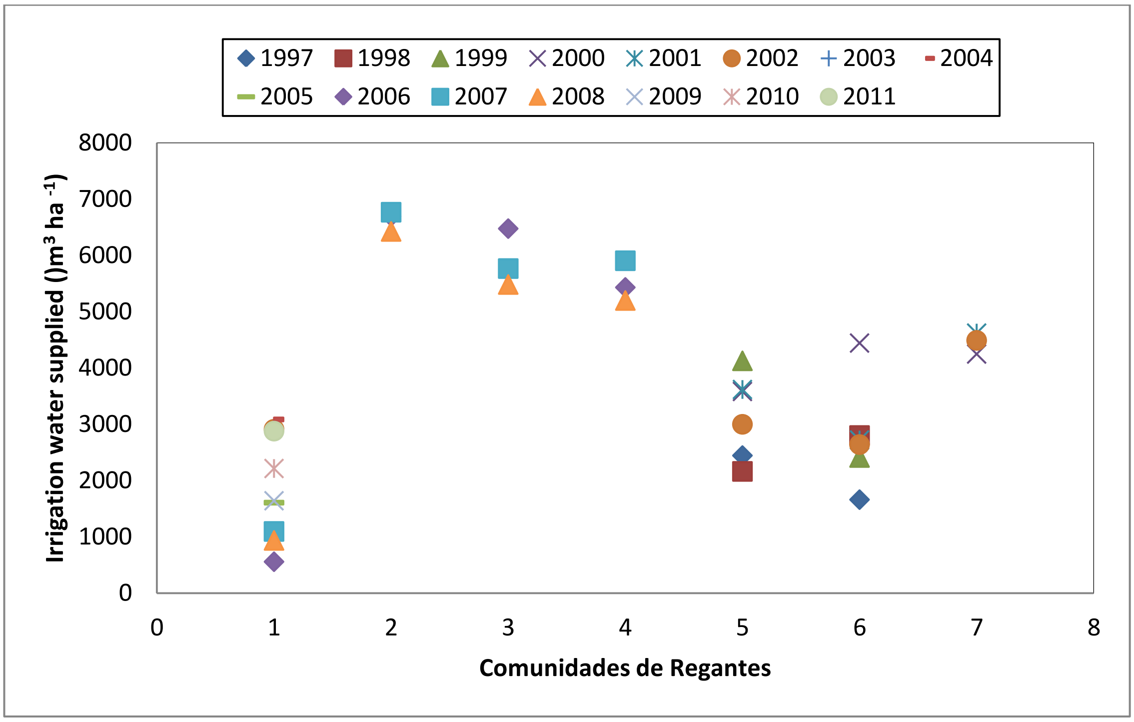

Figura 2. Comparative of supplied irrigation water between irrigation districts CR. 1=CRCC, 2=SLV, 3=SC, 4=SOR, 5=CRFP, 6=CRGC y 7=CRPG

The Main system water delivery efficiency (ED) has a minimum of 84% in 2006, when the Irrigation water supplied reached its lowest value in the study period (Figure 3). A very high efficiency was obtained in 99% in 2004, 2009, 2010 and 2011 when the irrigation water supplied was much higher. The high distribution efficiency during the latest years is because of the modernization while the low value of the ED appears related with the low amount of supplied irrigation water. In the irrigation communities studied in Andalusia the values range between 78 and 97%, while in Castilla-La Mancha ED varies between 85 and 100%.

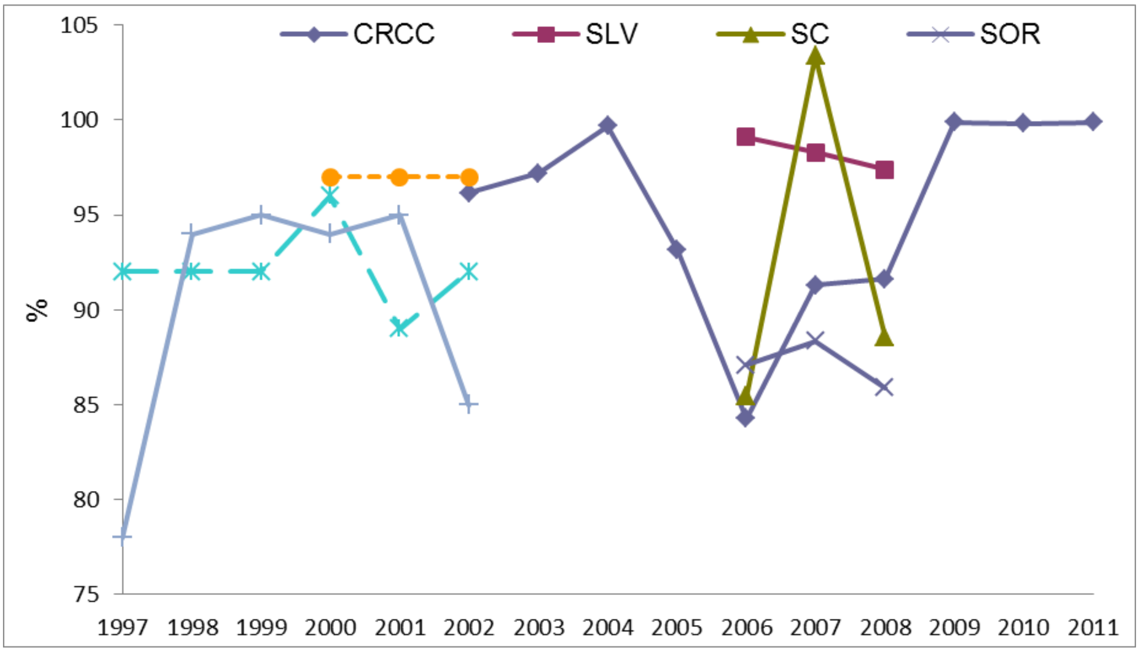

Figura 3. Evolution of *ED* in the district and comparison with other districts.

The Water Price (PA) (Figure 4) of the CRCC shows large variations over the years, which can be explained by the variability of the available water supply and the increased price level of the Tagus-Segura water transfer (regulated by law 52/80 and subsequent amended law 24/2001). The PA in the CRCC has ranged from € 0.139 m-3 in 2002 and € 0.257 m-3 in 2007. To compare the WP with the CR of Castilla-La Mancha and Andalusia, the average unit returns of irrigation water supplied were taken into consideration. The values range between 0.068 and € 0.161 m-3 for Castilla-La Mancha and between 0.070 and 0.216 € m-3 for Andalusia.

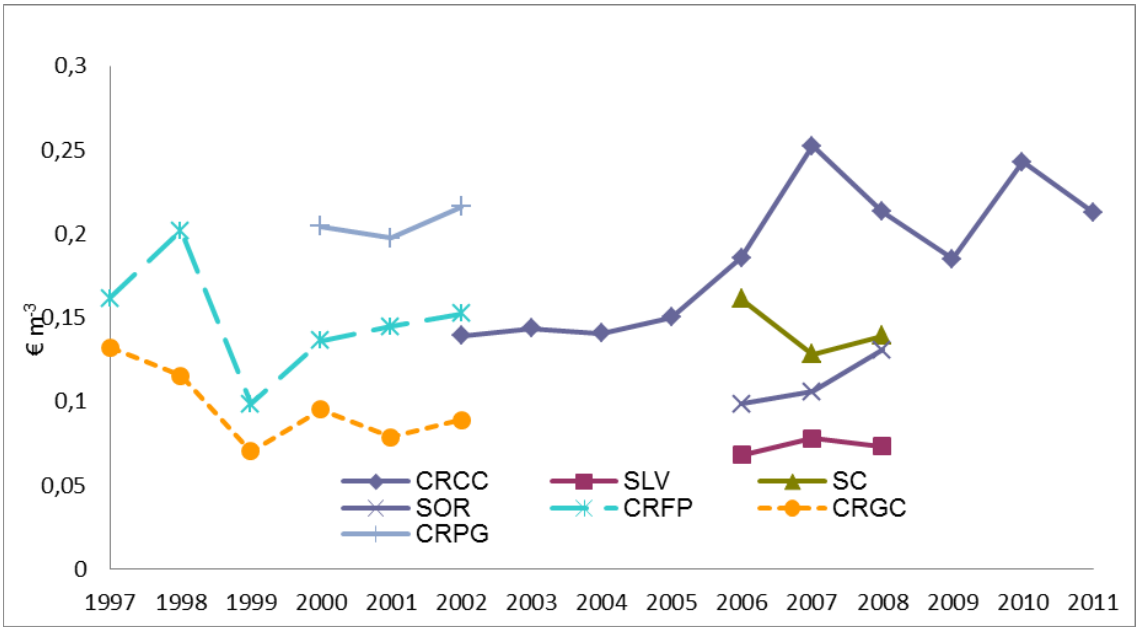

Figura 4. Evolution of *PA* in CRCC district and comparison with other districts.

Figure 5 shows the relationship between the Active Energy Consumption per volume of water supplied compared with the Total Irrigation Water Supply. As can be seen, this relation suggests that periods of water shortages cause an increase in energy consumption per m3 CRCC supplied to irrigators.

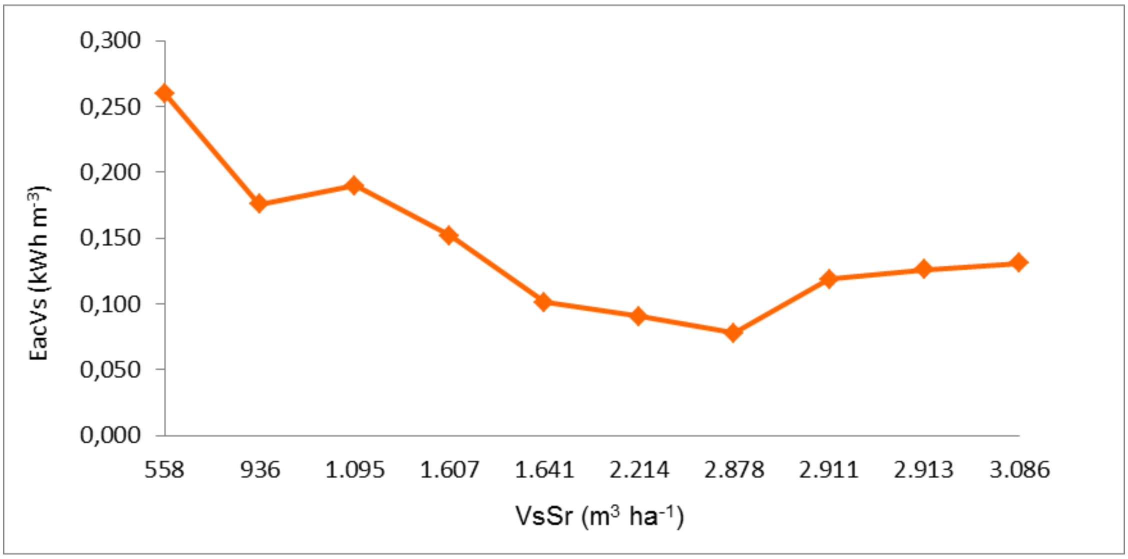

Figura 5. Relationship between *EacVs* and *VsSR* in the CRCC district.

The Active Energy Consumption per volume of water supplied (Figure 6) in the CRCC is between 0.078 kWhm-3 at 2011 and 0.260 kWhm-3 in 2006. In the study by Abbey (2010) the average value of 0.8776 was analyzed CR-3 and kWhm in Castilla La Mancha varies between 0.573 and 1.303 kWhm-3.

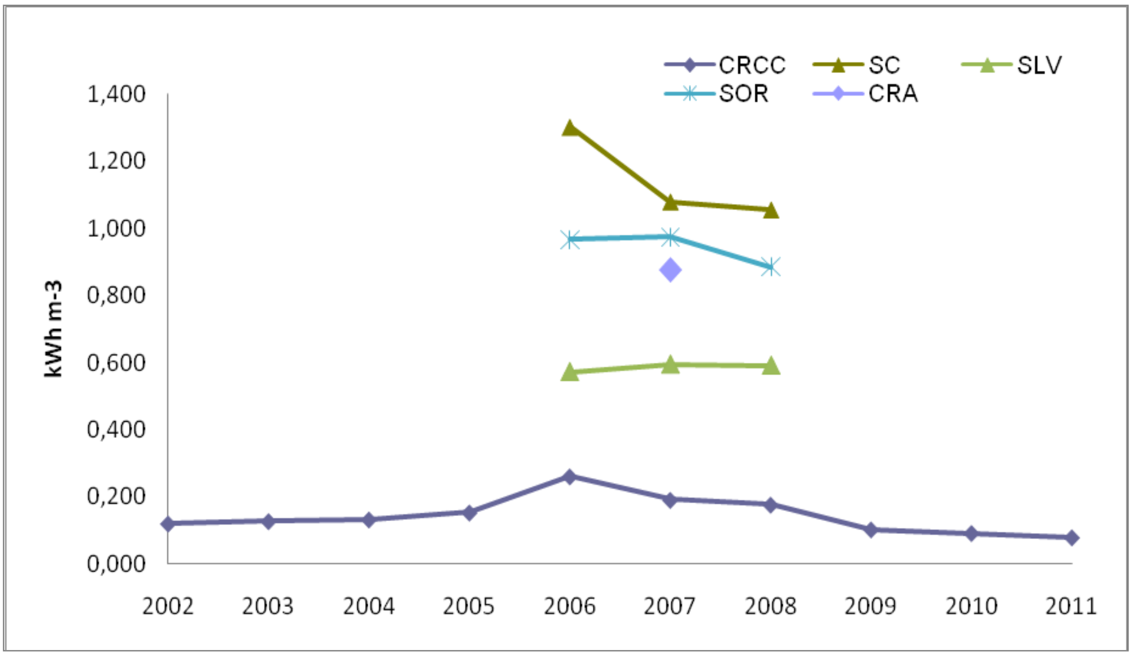

Figura 6. Evolution of *EacVs* in the CRCC district and comparison with other districts.

The Agricultural production value per unit of irrigated area (Figure 7) depends on the prices of agricultural products produced by farmers through time. The values for the CRCC range between € 16,835 ha-1 in 2003 and € 9,552 ha-1 in 2011. The Agricultural production value per unit of irrigated area obtained from surveys with farmers in the CRCC was for 2011 of € 9,088 has -1. A clear downward trend in this indicator was observed during the period analyzed. In Andalusia varies between 17,719 and € 2,843 ha-1 and those of Castilla-La Mancha between 6,990 and € 1,874 ha-1.

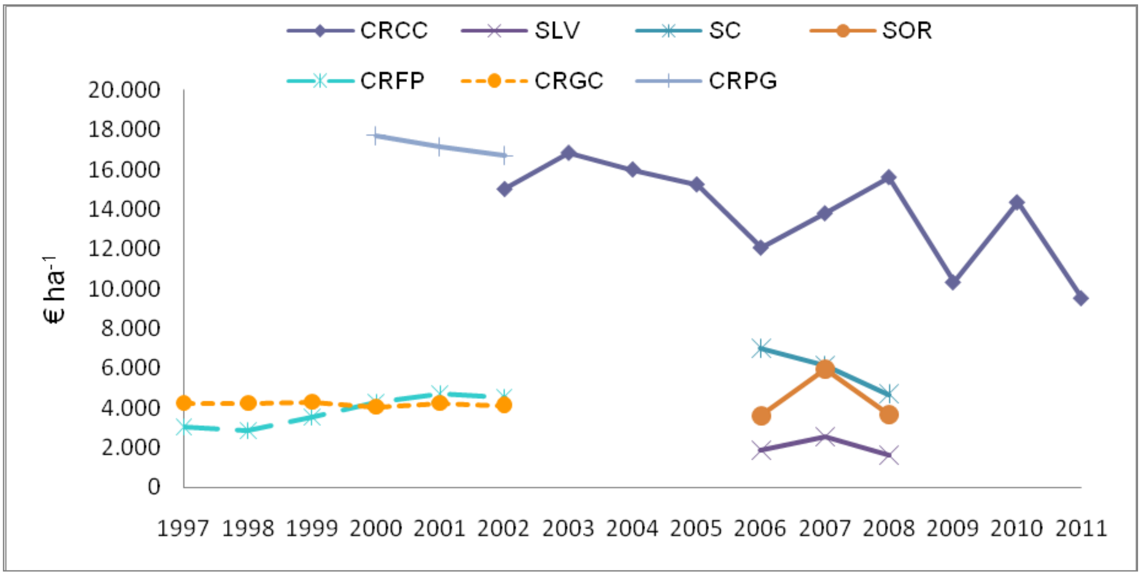

Figura 7. Evolution of *VPSr* in the CRCC district and comparison with others.

Concusions

By analyzing the benchmarking indicators in the CRCC irrigation district over a period of ten years it was shown that the Total Supplied Irrigation Water suffers great annual variation. During years with a high water shortage the distribution efficiency decreases due to the evaporation and infiltration losses in the conveyance and distribtuion network. This indicator is low because the losses remain more or less the same in absolute terms which means that during dry years this loss is relatively more significant. Furthermore, in years with low water availability, the economical indicators that depend on the irrigation supply increase considerably. Also it was confirmed that the modernization works that were carried out during the latest years have increased the energy and distribution efficiency. The Agricultural production value per unit of irrigated area shows a downward trend in the period analyzed.

From the comparative study with other irrigation districts it follows that: (a) the CRCC district has the highest temporal variability in available irrigation water, (b) the distribution efficiency is relatively high, except during periods of water shortages, (c) the CRCC irrigators pay a relatively high price for the water, (d) the Active Energy Consumption per volume of water supplied can be considered low, and (e) the Agricultural production value per unit of irrigated area is relatively high.

This study shows that benchmarking indicators should be analyzed over time since factors such as drought, can significantly affect the results of one year to another. On the other hand the temporal monitoring of them and their comparison with other CR allows to evaulatue the functioning of the Irrigation districts and support the optimization the planning and management of the available water resources.

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Annex V. Some examples of application of indicators to Segura River Basin

Standardized Runoff Index (SRI)

The Standardized Runoff Index (SRI) can be computed the same way as the Standardized Precipitation Index (SPI), except for being based on the monthly-mean runoff time series (Shukla and Wood, 2008). The SRI is used to classify hydrological drought. We also employ an index framework based on a combination of reservoir storage and annual runoff (CHS index), to demonstrate the coherence of SRI.

The data are provided by Water Agencies, considering relevant and selected stream gauges. At regional level, an aggregation for the data could be considered, according water resources management concerns.

The behaviour of SRI and the State Index (or CHS index) of Segura River Basin (SRB), was assessed for the time period 2004-2009, showing a good agreement (Figure 1). SRI was estimated for time period 1980-2010, from natural runoff of the basin. CHS Index is derived from annual runoff and reservoir storage, at basin scale. Considering selected CHS Index thresholds (Table 1), pro-active measures are applied in the framework of Drought Contingency Plan in order to mitigate negative effects of droughts.

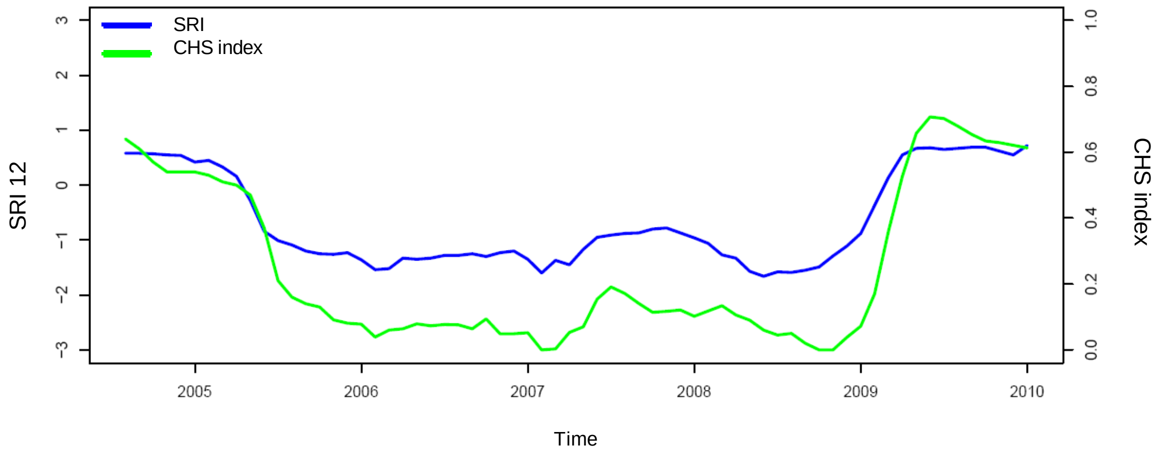


Fig. 1. SRI 12 versus CHS index. 2004-2009 time period, for SRB.

Table 1. Thresholds of CHS Index.

Condition	CHS Index
Emergency	< 0.2
Alert	0.2-0.35
Pre-alert	0.35-0.5
Normal	>= 0.5

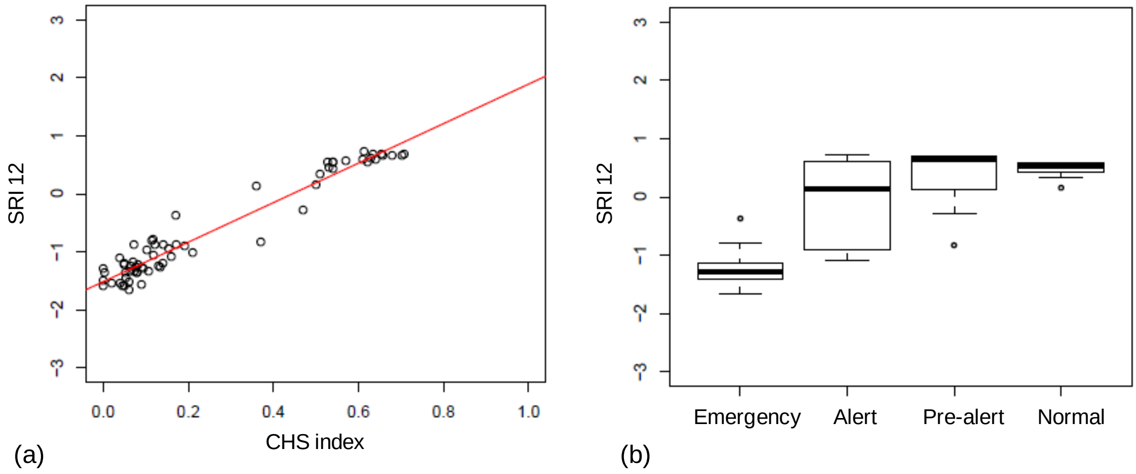


Fig. 2. CHS index versus SRI: (a) Dispersion plot and lineal regression, and (b) boxplot for each CHS Index threshold.

A high correlation coefficient (r2=0.941) between SRI 12 and CHS index, is observed (Figure 2 (a)). From Fig. 2 (b), the variability of SRI for each CHS index threshold is presented. Alert situation presents the highest variability, however a general good correspondence between SRI and CHS index situations is observed. A positive trend in SRI is detected, according the situation is changing from emergence to normal, for the time period analyzed. The lineal regression is SRI = -1.514 + 3.407 * CHS Index.

Indicators based on remote sensing

The indicators estimated from remote sensing, include ratios of two or more bands in the visible and NIR wavelengths (such as NDVI, etc.), and those obtained from the interpretation of LST-NDVI trapezoid (Vegetation Index/Temperature Trapezoid).

TVDI index

For deriving information regarding with content of surface soil moisture, Sandholt et al. (2002) proposed an index of aridity (TVDI), that takes values of 1 for the dry edge (limited water availability) and 0 for the wet edge (maximum evapotranspiration and thereby unlimited water availability).

The TVDI is related to soil moisture, where high values indicate dry conditions and low values wet conditions. This is based on the fact that the LST is mainly controlled by the energy balance and thermal inertia, factors influencing moisture conditions at the surface and in the root zone (Andersen *et al.*, 2002).

Following the concept in Fig. 3, the value of TVDI for a given pixel in the LST-NDVI space, is calculated as the ratio of lines A and B, and therefore calculated using the following equation (Sandholt *et al.* 2002),

$$TVDI = \frac{A}{B} = \frac{LST - LST_{\min}}{a + bNDVI - LST_{\min}}$$

where LST_{min} is the minimum LST in the triangle, defining the wet edge, and LST corresponds to the pixel. Then, *a* and *b* are the coefficients of the regression line that define the dry edge, as follows,

$$LST_{\max} = a + bNDVI$$

where LST_{max} is the maximum LST for a certain NDVI.

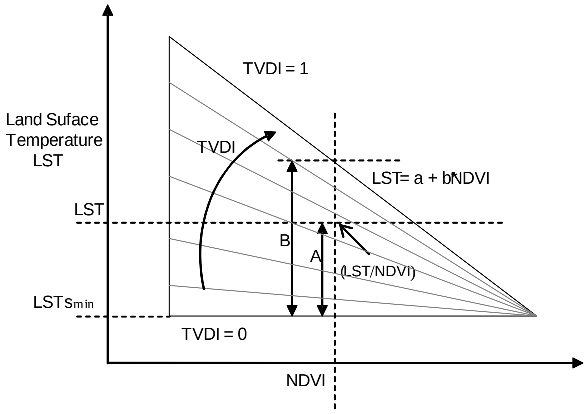


Fig. 3. Definition of TVDI index (adapted from Sandholt *et al.*, 2002).

The parameters a and b are estimated based on pixels from an large enough area to represent the full range of surface soil moisture content, from wet to dry, and from bare soil to fully vegetated surfaces.

Uncertainty about TVDI is greater in the high range of NDVI, where the TVDI isolines are grouped. The simplification of representing LST-NDVI with a triangle instead of a trapezoid (eg Moran *et al.*, 1994) may add uncertainty to TVDI estimation for high values of NDVI. The wet edge is also modeled as a horizontal line as opposed to an inclined one, as in the trapezoidal method, which can lead to an overestimation of TVDI for low NDVI.

The TVDI isolines correspond to the TVX index, proposed by Prihodko and Goward (1997), thus being able to estimate such TVDI isolines as multiple superimposed TVX lines. For drier conditions, several studies of LST-NDVI spaces present steep slopes (eg, Goetz, 1997 and Nemani *et al.*, 1993), which is consistent with TVDI. Since TVDI can be estimated for each pixel, the spatial resolution of the data is fully maintained. TVX requires an area wide enough for determination of the slope in the LST-NDVI space.

The main advantages of TVDI are: (i) its simplicity of calculation; and (ii) its derivation from satellite data alone regardless of factors such as weather, vapor pressure deficit, wind speed and surface resistance. However, this approach requires a large number of remote sensing observations to accurately define the limits of that space (Sandholt *et al.*, 2002). An example of the application of TVDI formulation, using data from MODIS sensor (Terra satellite), is presented in Fig. 4.

Water Deficit index

The Water Deficit Index (WDI, Moran *et al.* 1994), to estimate evapotranspiration in both areas completely covered by vegetation or partially covered, is based on the interpretation of the trapezoid formed by the relationship between the difference in LST and air temperature versus vegetation cover fraction (or vegetation index). The WDI quantifies the relative rate of latent heat flux, so it shows a value of 0 for fully wet surface (evapotranspiration only limited by the atmospheric demand), and 1 for dry surfaces where there is no latent heat flux.

The WDI index could be expressed as follows,

$$WDI = 1 - \frac{ET_{act}}{ET_{pot}} = 1 - \left[\frac{(LST_{\max} - T_a) - (LST - T_a)}{LST_{\max} - T_a) - (LST_{\min} - T_a)} \right]$$

where LST_{max} and LST_{min} are maximum and minimum LST respectively; ET_{act} and ET_{pot} represent actual and potential evapotranspiration respectively, found for a given vegetation cover (or vegetation index) in the left and right edges of the trapezoid VITT (Vegetation index versus difference of temperature). Then, T_a represents air temperature. Verstraeten *et al.* (2001, in Ranjan, 2006) reformulated the WDI index equation, based on the trapezoid, considering the difference of temperature on the ordinate axis and the vegetation index on the abscissa axis.

An example of the application of this methodology, considering data from MODIS sensor (Terra satellite), is presented in Fig. 5.

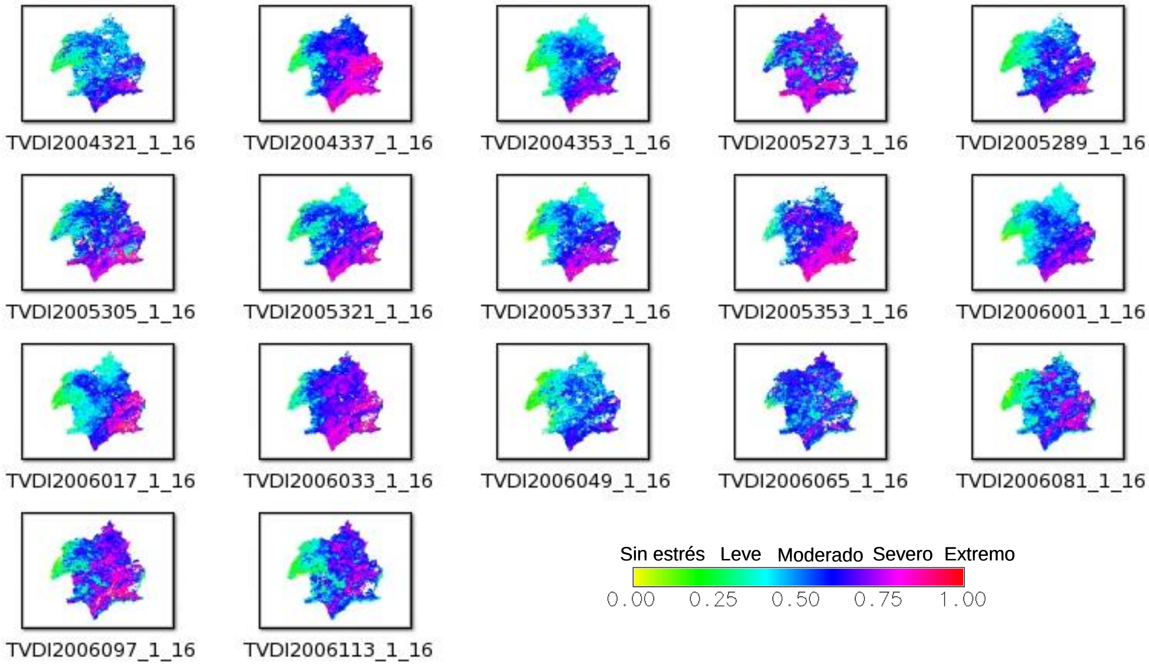


Fig. 4. Time evolution of maps of TVDI from MODIS data for the Segura River Basin

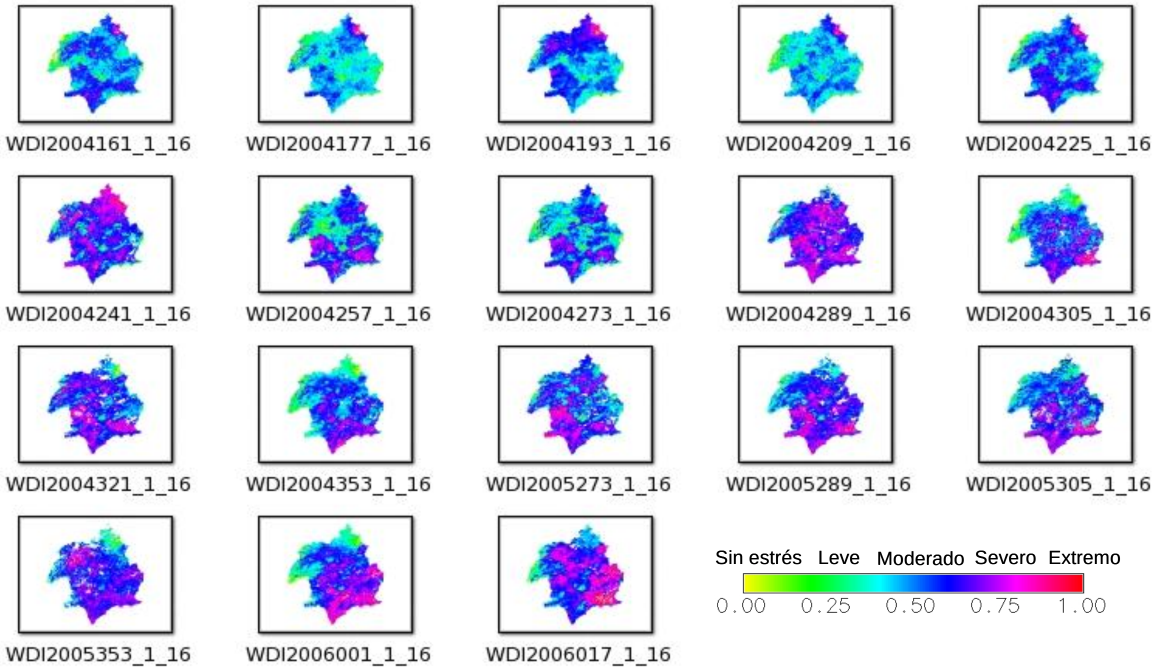


Fig. 5. Time evolution of maps of WDI for SRB from MODIS data for the Segura River Basin

Annex VI. Final reporting on Mapping Quantitative Precipitation Estimates

By: Department of Soil and Water Conservation and Management of Organic Wastes (SWC), CSIC-CEBAS

Task C1: Implementation of communication protocols between networks

The communication protocols were implemented to link the different data servers and the computational centre. Three different networks of pluviometers were integrated and the meteorological radar of the State Agency of Meteorology of Spain (AEMET). The centre for computation was the High Performance Computing centre Ben Arabi (HPC-BA) located on the Science Park of Murcia.

Rainfall data are obtained from: (i) Agroclimatic Information Service of Murcia (SIAM) embedded on the Institute of Agrifood Research and Development of Murcia (IMIDA); (ii) Automatic System of Hydrologic Information (SAIH) owned by the Water Authority of the Segura Basin (CHS); (iii) the State Agency of Meteorology of Spain (AEMET). Each network has its own server and SQL consults are carried out on them to extract data on real time.

On the HPC-BA a dedicated server was installed for the REDSIM Project. On this server all the software is installed and data base necessary for the task. The members of IMIDA and CSIC-CEBAS involved in the task access the server by remote clients.

In agreement with the owners of the basic data (pluviometers) they were defined particular protocols and policies of data sharing. Taking into account the security policy on HPC-BA the mechanism was to program local consults on the local servers, local management of the temporal files and the sending to HPC-BA by secure copy and secure FTP.

On the other hand, the data of the radar network of AEMET are managed by the IRIS software that automatically dumps data to McIDAS system. Data are exported by McIDAS to ASCII format as specific pipes of IRIS to standard formats as HDF5 were not available. The basic radar product used for REDSIM is the SRI (Surface Rainfall Intensity) that already is corrected for the bright band by the vertical profile of reflectivity (VPR). The minimal time interval of SRI provided by the radar system is 10'. Data are gathered as a tabular ASCII of reflectivity with one byte precision [0-255]. Coordinates are non-projected WGS84

Implementation of adequate data formats and a data base ready for processing

The radar data are stored on binary format with adequate coding and nomenclature. Pluviometer and radar data are integrated in a common spatiotemporal framework (geographic reference system, spatial window and hourly data aggregation). The information of initial maps and final product maps is stored on projected GeoTiff format. All these tasks are automatic and programmed by *crontask* on the dedicated server on HPC-BA. This servers send computation request to the computation nodes by the secure protocol *ssh*.

The multisensor integration is carried out on hourly intervals, on Cartesian format in order to accelerate computation times. Unfortunately, because operative problems on the processing of radar by AEMT some data sets are not available. Moreover, the SRI product received incorporate characteristic curved bands with gaps and the tabular data do not fill a rectangular mesh. Finally, some sets do include data coded as Not Available (NA) additionally to curved gap bands. Then when the SRI is received the raw ASCII data are ordered and mapped to complete meshes. It includes the conversion of the reflectivity factors [0-255] to SRI 10-min on mm h^{-1}. In order to do first the original scale is converted into decibels and then decibels are transformed into rainfall intensity by the Marshall-Palmer standard algorithm. Next gap bands are filled with an algorithm of local inverse distance (IDW). These bands are typically thin and the result is satisfactory.

Then, the complete meshes are aggregated at hourly intervals. All the available 10-min observations are integrated in each individual pixel. The protocol is able to handle the cases that one or several 10-min observations are lacking. For instance, if only observation is available it is used as the best existing estimation. Additionally, the protocol checks for corrupted data. Corrupted data are dropped from the process. The estimations of SRI [mm h^{-1}] are transformed to coordinates projected to Cartesian on the ETRS89 Zone 30N reference system (the present standard in Spain cartography) by the algorithm Lanczos. The final projected SRI hourly product (SRIH) is offered by the IMIDA as a REDSIM product on the regional Spatial Data Infrastructure (IDE) as REDSIM-IS. It is the best hourly estimation radar-only based. In order to make the product as useful as possible for other real time applications a first estimation is produced when the first 10-min interval of each hour is used to provide the estimation and then estimation are updated as other 10-min observations arrived and are processed until the full set of 6 observations is processed. The complete processing time of an hourly map is only ~20 s.

Testing of download and storage system to check proper working on operative mode without incidences and interruptions.

In this phase they are programmed a set of checks to be sure about absence of errors in the data transfer and management. Also they have been programmed backups by mechanisms implemented on HPC-BA.

Task C2: Quality Control

Quality control 1:Non automatic inspection of pluviometer network data and radar data to detect data bias. Report about pluviometric stations with quality problems

Without detriment to the own quality control (QC) mechanisms of each institution providing data the aggregation of different data sources as well as radar data let to do a crossed checking to detect not observed errors on the original sources.

In this step pluviometric networks are checked to guarantee they are free of systematic errors and the posterior multisensor estimation be successful. They are used a set of tools: cross-correlations, scatter plots, z-standardized variables, etc. Different types of errors are detected and corrected according to their characteristics.

For a static checking process it was selected and intense rainfall period of 9 days in November 2011. This period had higher precipitation and higher variability in rainfall patterns to evaluate the result of all the processes of the project. In general it was found a good agreement between radar and pluviometers. Nevertheless it was evident a high bias variable in space and time.

A general problem arose when they are compared radar and pluviometer time series. There is a time lag, pluviometer-depending, between radar and pluviometers. Cross-correlations shown that time lag is related to organism providing data (to the specific pluviometer network). SAIH network lags 2 hours in respect to radar. AEMET network is synchronous to radar. SIAM data has about half of the stations synchronous and the other half one-hour lagged. It seems that some pluviometers are working with administrative time instead UTC. Moreover, data from SAIH network look to be referred to the end of the accumulation interval while for radar the accumulated total is referred to the time at the beginning of the interval. It has been difficult to unify criteria of different organisms, therefore, it was created a table of nominal lags to correct data. This table is used as an input for the dynamic quality control. This analysis can also to propose a new time adjustment with a real-time cross-correlation analysis on a moving window. The mechanism is effective and prevents future programming failures on dataloggers or changes in the procedure of time assignment to the data in the pluviometers.

Quality Control 2: Implementation of an automatic Quality Control for preprocessing input data to the algorithm of multisensory estimation of precipitation.

With the results of the previous phase they were implemented automatic algorithms for the correction of systematic errors (into a moving window). They have been implemented on automatic mode a series of deleting rules or *cutting over a threshold* of data as a function of the statistical relations in the moving window. This procedure is similar to other already existing like TAMSAT for the combination of satellite rainfall estimates and pluviometers.

The dynamic quality control does produce a table of lags updated every hour. The table is based in the inspection of a 10-day moving window and it is used as an input for further steps on the quality control.

The data obtained after this phase are adequate for the algorithm of multisensor estimation of precipitation (MPE) pluviometer-radar, even taking into account the differences on support of the measurements of pluviometers (~0.07 m^2) and the radar (1 km^2).

Task C3: Implementation of algorithm

Implementation of CMA-OAS algorithm for the estimation of precipitation using pluviometer data filtered on the quality control and the meteorological radar, producing estimates of precipitation with hourly to daily resolution and minimal spatial resolution of 2 km^2.

In this task first the algorithm Comcurrent Multiplicative – Additive Objective Analysis Scheme (CMA-OAS) was analyzed to be adpated to real time application and they were identified the factors that control the result of the algorithm in combination with its computational efficiency. Originally the algorithm CMA-OAS requires a global optimization process that advises the parallel processing by high performance computing. This was carried out and implemented in the REDSIM project. The process was programmed for parallel execution and they were carried out the efficiency tests to determine the minimal number of processors as a function of the minimal processing speed necessary for a real time application. The original structure of the algorithm was computationally intensive. However, it was observed that a change in the order of the initial process produce a similar output and let to change the algorithm that significantly improve the computational efficiency such an extent that processing may be carried out on real time on a only one supercomputing node. This is important as the procedure may be implemented in a standard workstation without needing a high performance computing centre and parallel processing.

As a summary, first they are established the relative radii of influence of the pluviometers as function of the local density of pluviometers, and this radii are constant for the algorithm of decomposition of the local bias. Finally the radii are recalculated with a scaling parameter based on cross-validation. This procedure avoids the simultaneous estimation of influence radii (Kernel bandwidth) jointly to bias decomposition. This is theoretically suboptimal in respect to the already suboptimal original CMA-OAS procedure (García-Pintado et al., 2009) it was proofed that results are similar with the advantage that bias decomposition can be linealized and obtained by the least squares standard algorithm without iteration calculations.

Specifically, the CMA decomposes the local bias

$$g_k = \alpha_k + \beta_k r_k,$$

where g refers to observation in the pluviometer, r is the co-located radar observation and α and β are the parameters for additive and multiplicative bias, respectively. The subscript k is referred to a specific pair pluviometer and co-located radar observation.

The bias decomposition can be reordered to establish the additive bias as a restriction on function of multiplicative bias and the observations:

$$\alpha_k = g_k - \beta_k r_k.$$

In the CMA algorithm and in agreement with the algorithms of optimal interpolation the validity of an observation has a spatial decay (modelled with a complete covariance matrix when it is posible). Depending on the decay function (e.g. a Gaussian Kernel) one observation k as a weight ranging from 1 on its position to 0 at a infinte distance. The decaying function define the realtionship between the distance j to k and the weight on the point j. If the weight is λ_{jk}, the adjusted radar by pluviometer in k, on j location is:

$$r^a_{jk} = \lambda_{jk}\alpha_k + \lambda_{jk}\beta_{jk} r_j + (1-\lambda_{jk}) r_j,$$

as $(1-\lambda_{jk})$ is the remaining weight allocated to the original value of the radar in order to get a sum of weights equal to 1 and an unbiased estimation.

Introducing the additional restriction of local bias the residual between the observation in the pluviometer and the estimation by radar is

$$\rho^a_{jk} = g_j - [\lambda_{jk}(g_k - \beta_{jk} r_k + \beta_{jk} r_j - r_j) + r_j].$$

And this problema can be solved by a conventional regression with a varaible change as if we define

$$\Delta r_{jk} = r_j - r_k,$$

then we can estaimate the local multiplicative bias and then to obtain the additive one by the local restriction equation reordering the regression

$$\frac{g_j - (\lambda_{jk} g_k - \lambda_{jk} r_j + r_j)}{\lambda_{jk}} \backsim \beta_k \Delta r_{jk}.$$

solvable by ordinary least squares. This procedure forces the solution of the regression, besides of being submitted to the restriction of optimal interpolation (sum of weights equal to 0), to have a spatial effect decaying with distance and moreover has the value of the pluviometer g_k, in the location k. The combination of local regressions for the global adjustment follows then the procedure described García-Pintado et al. (2009), as from the global adjustment of the decaying parameter based on cross-validation. The order of magnitude of the global scaling parameter of bandwidth (L) is 1. Normally the values range from ~0.65 to ~1.5, indicating that the implemented local regression is really closet to the optimal, indicated by a value L=1.

Finally, the recursive part of the algorithm (the OAS part in the CMA-OAS) shows a little marginal improvement. For the real time implementation the recursive part was disregarded, improving computational efficiency. The difference in the final result is not noticeable by visual inspection. The adjustment statistics may lightly change, but the marginal improvement of the recursion does not justify the extra computation in a real-time operative context. Therefore the algorithm finally implemented in REDSIM is named Modified CMA.

The output of subtask C3 are two sets of maps in Geotiff format: (i) the Multisensor Precipitation Estimation (MPE) that combine the results of the operative implementation of the Modified CMA ; and (ii) the uncertainty maps that show the standard deviation of the estimate associated to MPE

The direct calculation of the standarad deviation resulting from cross-validation is, as well, a process requiring high computational capacity as they are calculated as many maps as pluviometers in each hourly interval. The operative implemented process, alternatively, does obtain the estimates only on the locations where are available the pair pluviometer/radar. This generate a sparse set of data interpolated by ordinary kriging to obtain the distributed estimation of uncertainty.

Additionally they were carried out a series of alternative analysis, including *Generalized Additive Models* (GAM), *Cokriging* (Cok) and *Kriging with External Drift* (KED), and other simpler algorithms like mean bias. They were evaluated the bias in fractional coverage of the precipitation fields and their influence in the product. No one of these interpolation algorithms seems to adapt to the specific characteristics of the combination radar and pluviometers (bias in fractional coverage, non-stationary spatially variable bias in the radar, etc.). Modified CMA is the most adequate product of those evaluated.

Task C4: Integration with GIS

Integration of the MPE with Geographic Information Systems for its use by farmers

The MPE were integrated on the Spatial Data Infrastructure of the Region of Murcia and at the moment can be consulted by a viewer

http://iderm.imida.es/redsim/

Elaboration of algorithms to integrate the estimation of precipitation with other components of the REDSIM project

After different meetings with other components of the project it was decided that the most appropriate format for task C is GeoTiff, a conventional spatial format selfdefined and easily integrated in any GIS system. Time series are stored on PostgreSQL that can be consulted by SQL.

Graphical information

The operative implementation of task C is producing hourly maps of precipitation and the uncertainty of the estimation. As an example they are shown here the maps produced during a rain event.

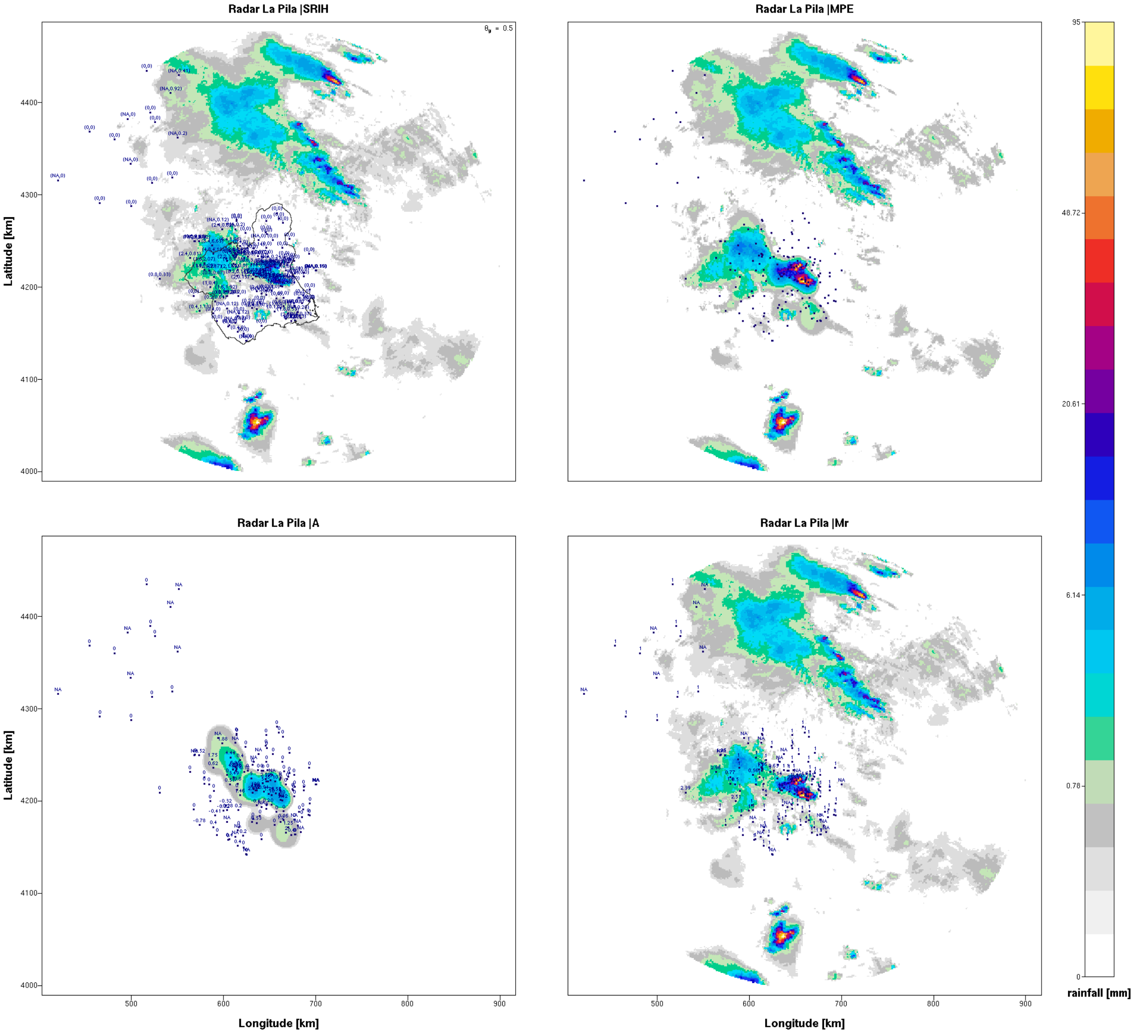
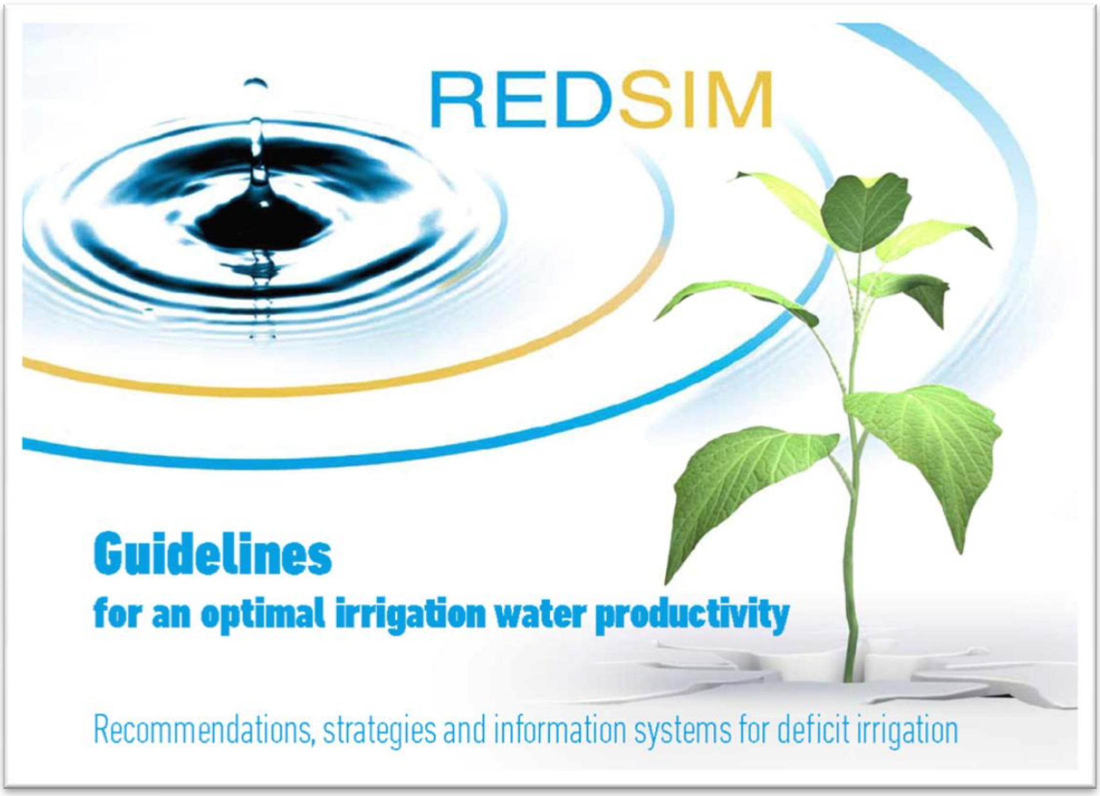


Figure 1. SRI (upper left) and MPE (upper right) estimation of one hourly interval of one event in November 2011. Additive (lower left) and multiplicative (lower right) components of MPE.

Annex VII. Brochure: REDSIM guidelines

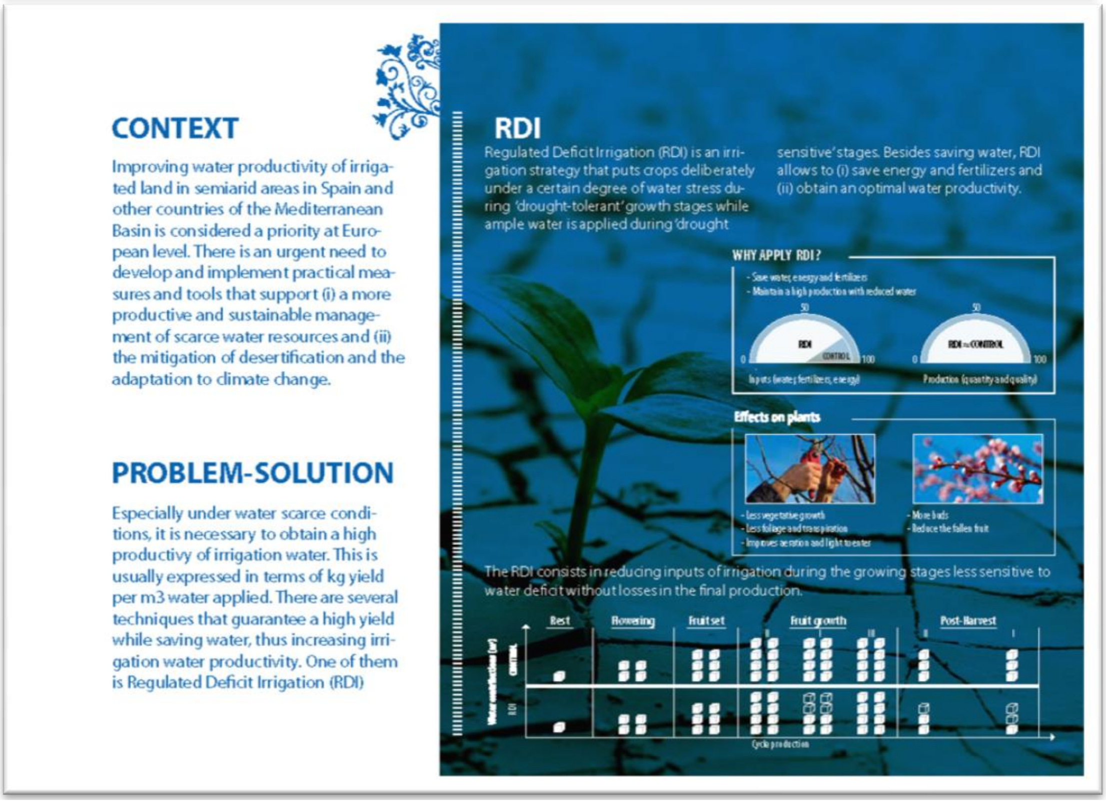


REDSIM

Guidelines

for an optimal irrigation water productivity

Recommendations, strategies and information systems for deficit irrigation



CONTEXT

Improving water productivity of irrigated land in semiarid areas in Spain and other countries of the Mediterranean Basin is considered a priority at European level. There is an urgent need to develop and implement practical measures and tools that support (i) a more productive and sustainable management of scarce water resources and (ii) the mitigation of desertification and the adaptation to climate change.

PROBLEM-SOLUTION

Especially under water scarce conditions, it is necessary to obtain a high productivy of irrigation water. This is usually expressed in terms of kg yield per m3 water applied. There are several techniques that guarantee a high yield while saving water, thus increasing irrigation water productivity. One of them is Regulated Deficit Irrigation (RDI)

RDI

Regulated Deficit Irrigation (RDI) is an irrigation strategy that puts crops deliberately under a certain degree of water stress during 'drought-tolerant' growth stages while ample water is applied during 'drought sensitive' stages. Besides saving water, RDI allows to (i) save energy and fertilizers and (ii) obtain an optimal water productivity.

WHY APPLY RDI?

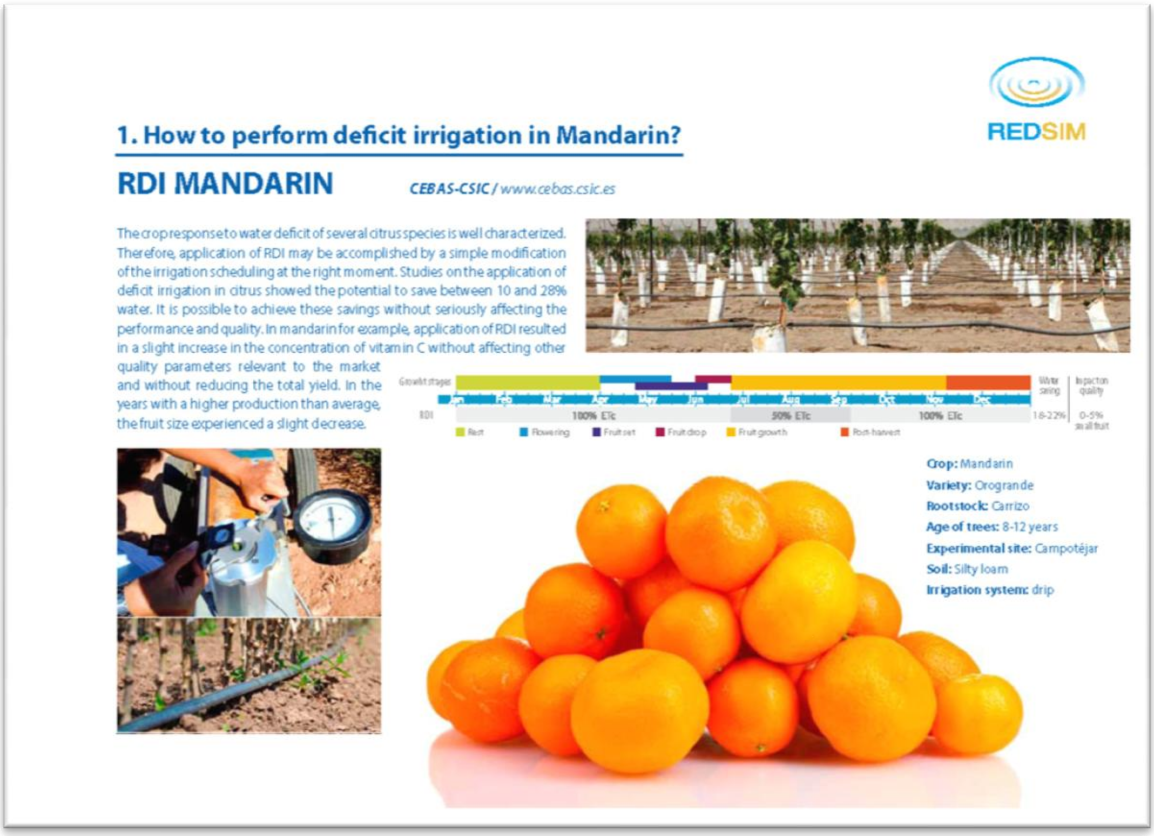
- Save water, energy and fertilizers
- Maintain a high production with reduced water

Effects on plants

- Less vegetative growth
- Less foliage and transpiration
- Improves aeration and light to enter

- More buds
- Reduce the fallen fruit

The RDI consists in reducing inputs of irrigation during the growing stages less sensitive to water deficit without losses in the final production.



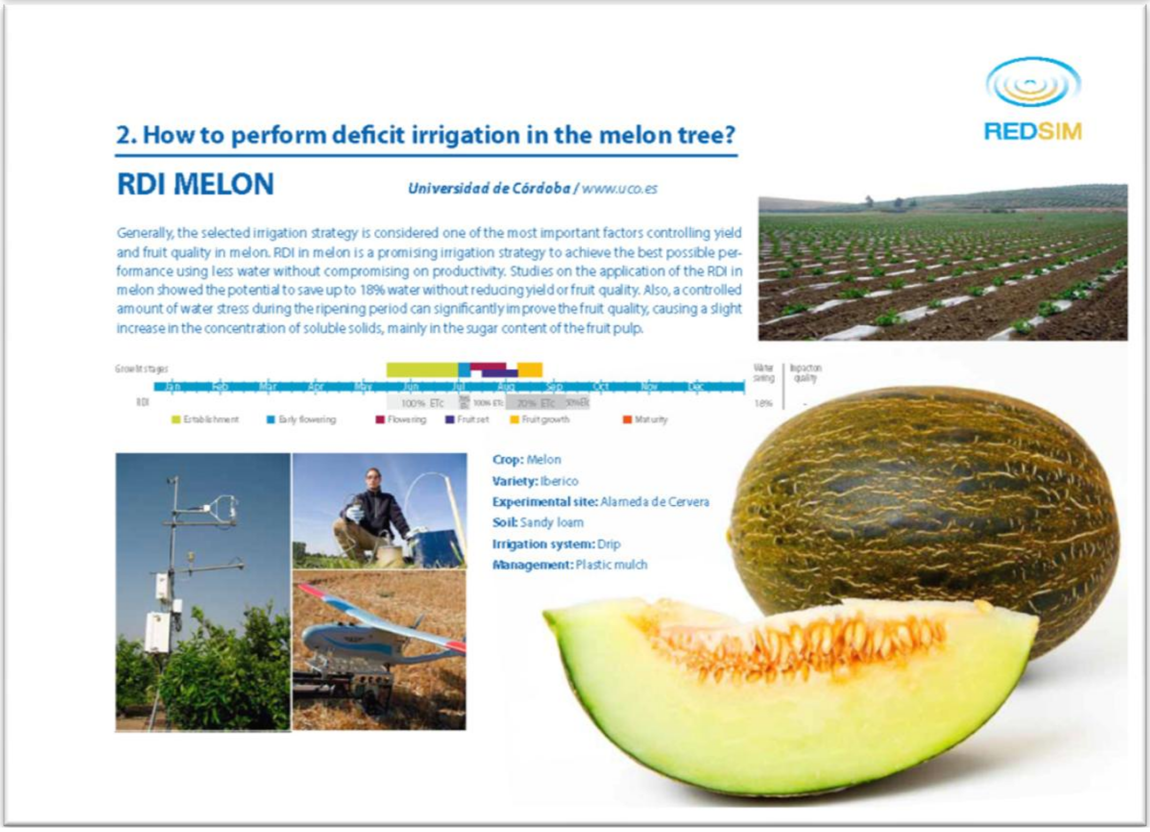
1. How to perform deficit irrigation in Mandarin?

RDI MANDARIN

CEBAS-CSIC / www.cebas.csic.es

The crop response to water deficit of several citrus species is well characterized. Therefore, application of RDI may be accomplished by a simple modification of the irrigation scheduling at the right moment. Studies on the application of deficit irrigation in citrus showed the potential to save between 10 and 28% water. It is possible to achieve these savings without seriously affecting the performance and quality. In mandarin for example, application of RDI resulted in a slight increase in the concentration of vitamin C without affecting other quality parameters relevant to the market and without reducing the total yield. In the years with a higher production than average, the fruit size experienced a slight decrease.

Crop: Mandarin
Variety: Orogrande
Rootstock: Carrizo
Age of trees: 8-12 years
Experimental site: Campotéjar
Soil: Silty loam
Irrigation system: drip



2. How to perform deficit irrigation in the melon tree?

RDI MELON

Universidad de Córdoba / www.uco.es

Generally, the selected irrigation strategy is considered one of the most important factors controlling yield and fruit quality in melon. RDI in melon is a promising irrigation strategy to achieve the best possible performance using less water without compromising on productivity. Studies on the application of the RDI in melon showed the potential to save up to 18% water without reducing yield or fruit quality. Also, a controlled amount of water stress during the ripening period can significantly improve the fruit quality, causing a slight increase in the concentration of soluble solids, mainly in the sugar content of the fruit pulp.

Crop: Melon
Variety: Iberico
Experimental site: Alameda de Cervera
Soil: Sandy loam
Irrigation system: Drip
Management: Plastic mulch

3. How to perform deficit irrigation in vineyards?

RDI VINEYARD

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The vine is one of the species best adapted to water stress conditions, so RDI is an appropriate strategy for efficient irrigation management of this crop. RDI saves water, control vegetative growth, balances production and improves the quality of the grapes (especially in red varieties). Studies on the application of deficit irrigation in vineyards showed the possibility of saving about 60% water reducing production slightly (about 5%). In turn, some quality parameters of grape (Brix, anthocyanin content, acidity and total polyphenol index) can be enhanced due to the effects of moderate stress.

Crop: Vineyard
Variety: Sauvignon, Tempranillo y Macabeo
Age of vines: 12 years
Soil: Sandy clay-loam
Irrigation system: Drip
Management: Padded saucer
Planting system: Espalier

4. How to perform deficit irrigation in nectarines?

RDI NECTARINE

***ETSIA - UPCT** / www.upct.es*

Deficit irrigation in nectarine can be applied during the post-harvest period. During this period the applied amounts can be reduced by up to 50% of crop water demand, which results in a total water saving between 15 and 25%. These savings can be achieved without affecting yield and product quality. Also during phases I and II of fruit growth the applied irrigation water can be reduced, with the aim to increase the soluble solids in the fruits, and thus increase the final product quality.

Crop: Vineyard
Variety: Viowhite
Porta-graft: Puebla de Soto 101
Age of vines: 8-12 years
Place: Molina de Segura, Murcia
Soil: Silty loam
Irrigation system: Drip

5. Supporting tools for RDI - REDSIM

WHAT DO I NEED?

To implement RDI, the farmer needs adequate information on his field, the crops and the water requirements. REDSIM provides several information and advisory tools to support the farmer in implementing this irrigation strategy. These tools join different existing information sources and simulation tools to provide up-to-date and local data and predictions.

For more info, check **www.redsim.net**

What data is available on my plot?

REDSIM-IS is a single web portal that integrates all available spatiotemporal information (meteorological networks, weather radar, satellite remote sensing, surveying, etc.) to provide updated information on soil and crops for better irrigation management, planning and scheduling by the farmer.

How much rain received my crop?

This same web portal also includes a new innovative product that uses state-of-the-art algorithms to combine information from weather station networks with rainfall radar in real time. This way, the farmer knows with high accuracy the amount of rain that received his plot during the last hours and days.

When and how to irrigate?

The REDSIM irrigation advisory bulletin is sent to the farmer by e-mail with synthesized and up-to-date information which supports decisions on irrigation planning. The bulletin includes: i) 7 days weather forecast with the forecasts of crop water needs, (ii) options in terms of dosage and frequency of irrigation to meet the predicted demand and soil water, and (iii) its impact on percolation and the a comparison between computed irrigation needs and applied amounts

How affects irrigation my productivity?

REDSIM allowed demonstrating the benefits of using the latest water productivity tool for practitioners (extension services, farmers, etc). This state-of-the-art tool "AquaCrop" is currently being developed by FAO together with researchers involved in REDSIM. It allows seasonal productivity predictions and supports the farmer in irrigation planning.

FOR MORE INFORMATION

check **www.redsim.net**

or contact the project coordinator

Alain Baille (alain.baille@upct.es)

Annex VIII. Layman’s report

The purpose of the REDSIM Layman’s report is to provide a general and brief overview of the REDSIM project and its outcomes. In particular, the following points are addressed in the Layman's report:

a) Project scope and objectives

b) Description of activities, techniques and methodologies implemented

c) Results

d) Key findings

e) Transferability of project results

REDSIM

Layman's Report

"Halting desertification in Europe"

Scope and objective

Improving water productivity of irrigated land in semiarid areas in Spain and other countries of the Mediterranean Basin is considered a priority at European level. There is an urgent need to develop and implement practical measures and tools that support (i) a more productive and sustainable management of scarce water resources and (ii) the mitigation of desertification and the adaptation to climate change.

Especially under water scarce conditions, it is necessary to obtain an optimal Irrigation Water Productivity (IWP). This indicator is usually expressed in kg yield per m3 applied water. An optimal IWP means preventing over-irrigation and applying an adequate amount of irrigation water at the most favorable moments during the growth season. Innovative techniques can even further boost IWP and guarantee a high yield while saving water. One of them is Regulated Deficit Irrigation (RDI)

Regulated Deficit Irrigation (RDI) is an irrigation strategy that puts crops deliberately under a certain degree of water stress during 'drought-tolerant' growth stages while ample water is applied during 'drought sensitive' stages. Besides saving water, RDI allows to (i) save energy and fertilizers and (ii) obtain a higher water productivity.

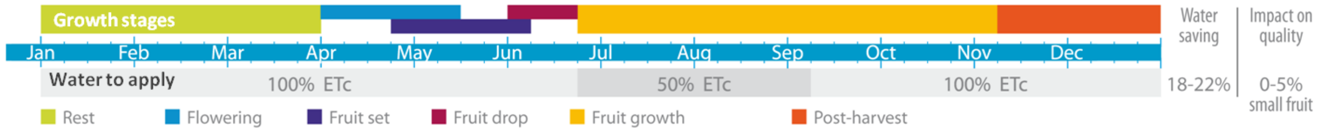
The overall objective of the REDSIM project is to improve Irrigation Water Productivity (IWP) in two Spanish water-stressed basins, by developing and validating an Information-Decision Support System (REDSIM-IS) based on Remote sensing (RS) information and simplified water balance and crop models to assist growers in implementing and managing efficiently deficit irrigation (DI) techniques.


Foto: O. Mounzer

Activities

The following activities were carried out within REDSIM to meet the objectives

1. Setting up and calibration of the REDSIM information system (REDSIM-IS) and farm advisory tools
2. Mapping and prediction of soil and crop attributes, surface fluxes, rainfall, soil water balance and WP
3. The implementation and monitoring of the deficit irrigation treatments in pilot farms, for different key crops of the Mediterranean basin (citrus, melon, nectarines, grapevine)
4. On-farm evaluation of the acceptance of the REDSIM tools, using a participatory approach
5. Dissemination through stakeholder events, and a booklet with guidelines and outcomes of REDSIM presented to the targeted users (see next Figure)



Results

Various advisory information tools may support the fine-tuning of irrigation water supply or the implementation of RDI, to optimize irrigation water productivity. These tools should join different existing spatio-temporal information sources (meteorological networks, weather radar, satellite remote sensing) to provide up-to-date information on soil and crop. This allows a more appropriate decision by the farmer on when, where and how much water to apply and may also serve as learning-tools. The REDSIM project provides the following tools to the farmer:

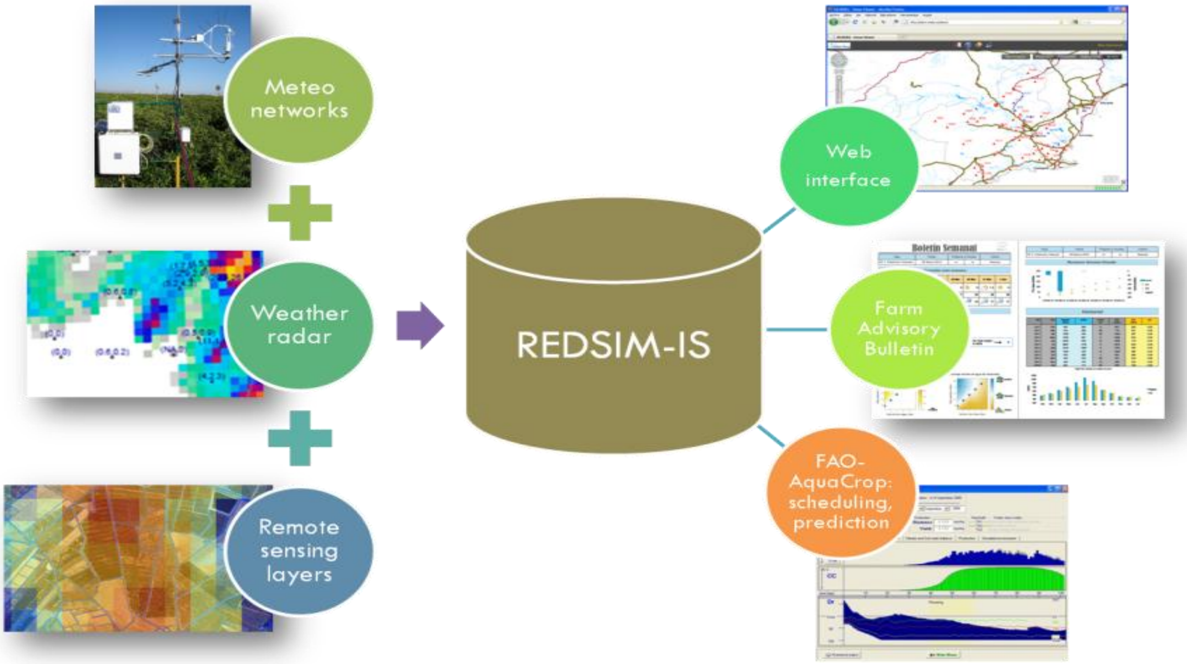
- REDSIM-IS is a single web portal that integrates all available spatiotemporal information (meteorological networks, weather radar, satellite remote sensing, surveying, etc.) to provide updated information on soil and crops for better irrigation management, planning and scheduling by the farmer.

- This same web portal also includes a new innovative product that uses state-of-the-art algorithms to combine information from weather station networks with rainfall radar in real time. This way, the farmer knows with high accuracy the amount of rain that received his plot during the last hours and days.

- The REDSIM irrigation advisory bulletin is sent to the farmer by e-mail with synthesized and up-to-date information which supports decisions on irrigation planning. The bulletin includes: i) 7 days weather forecast with the forecasts of crop water needs, (ii) options in terms of dosage and frequency of irrigation to meet the predicted demand and soil water, and (iii) its impact on percolation and the a comparison between computed irrigation needs and applied amounts

- REDSIM allowed demonstrating the benefits of using the latest water productivity tool for practitioners (extension services, farmers, etc). This state-of-the-art tool “AquaCrop” is currently being developed by FAO together with researchers involved in REDSIM. It allows seasonal productivity predictions and supports the farmer in irrigation planning.


Foto: O. Mounzer



Key findings

- The potential to increase water productivity by changing irrigation practices is substantial, even in irrigation districts equipped with modern infrastructure (e.g. Campo de Cartagena, S-E Spain) where drip irrigation is fully implemented. Over-irrigation is common and deficit irrigation techniques are hardly practised due to lack of proper crop-specific guidelines and information systems that provide the necessary information on crop water demands.

- Fine-tuned drip irrigation may, in combination with deficit irrigation techniques, ensure that these saving potentials are exploited. Water consumption can be reduced and IWP increased by up to 40% for different fruit crops. Farmer information and advisory systems are essential to support these water saving strategies.

- To this end, irrigators should become acquainted with the use of advanced irrigation management tools and become more familiar with deficit irrigation techniques, through better science communication, demonstration projects and capacity building. This is likely to have a beneficial impact on WP and sustainability of irrigated agriculture in semi-arid countries.

- Certainly, economic incentives are deemed necessary to motivate irrigators to adopt and successfully implement advanced irrigation methods and supporting tools. Also irrigators' associations can play a key role in fostering DI and its uptake by farmers.

- Combining and processing ground and RS-based spatial datasets of crop/soil indicators within integrated information/advisory systems is highly recommendable for optimizing irrigation management and increasing WP. In particular, there is scope to include radar-based rainfall mapping (QPE, quantitative precipitation mapping) in plot-level irrigation planning, especially in Mediterranean areas where rainfall is extremely variable in space and time.


Foto: O. Mounzer

Transferability

There is a potential to significantly increase irrigation water productivity in the Mediterranean basin by implementing techniques and tools studied and developed in REDSIM. No major technical barriers are foreseen for transferring the REDSIM tools to other water-scarce regions in Europe. However, the following issues are considered important for successful uptake:

- Risk-adversity and lack of knowledge of deficit irrigation techniques by farmers is a key barrier. Now, of many crops, enough knowledge is available that is yet to be communicated to farmers, though for example the REDSIM guidelines (Annex VII) and demonstration projects. Also, REDSIM confirmed that a participatory approach for the implementation of farm advisory support is recommended to adapt design to local preferences and knowledge

- Information on rainfall is currently scattered among different organizations and institutes within the same basin: in the Segura Basin, but also in several other drought-prone basins in Europe. A key outcome of REDSIM is the successful integration of all available networks, including remotely-sensed rainfall radar, providing a product that gives farmers plot-level information on the amount of rainfall during the latest hours. The key barrier to be dealt with is the institutional setting in each basin, that may limit the exchange of data for other purposes than those that are supported by the organization itself.

- Even if the investment needs are relatively low, farmers will only adopt new irrigation techniques when they find some type of economical incentive, depending on the marginal financial benefits in optimizing water use in each region.

For more information on the REDSIM project:

- contact with the project coordinator Alain Baille (alain.baille@upct.es) of the UPCT (Universidad Politécnica de Cartagena). Other partners were: IMIDA (Instituto Murciano de Investigación y Desarrollo Agrario); CEBAS-CSIC (Centro de Edafología y Biología Aplicada del Segura); UCO (Universidad de Córdoba); FutureWater; AFRE (Asociación de Fabricantes de Riego Españoles)
- or check www.redsim.net

REDSIM

Foto: O. Mounzer