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REDSIM: Approach to soil water modelling

Tools and data considerations to provide relevant soil water information for deficit irrigation

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Contents

Introduction

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.

The objective of task D of REDSIM is to assemble a tool which is able to provide soil water information at a low cost applying a soil water simulation model in a distributed way, i.e. for each plot in the study area. The model will be set up and calibrated using data from existing databases (soil, climate, land use) and monitoring campaigns. Low-cost satellite information will be assimilated into the model to update the relevant state variables.

This document summarizes the approach which is proposed to set up the tool that will provide the relevant soil water information. Chapter 2 contains a short description of different model candidates and evaluates the model against different criteria. The specifications of the selected model are described in chapter 3. Data requirements specifically relevant to this project are summarized in chapter 4. Chapter 5 lists a few critical factors that are expected for the successful building of the tool.

Model selection

Many crop simulation models are currently available, most of them developed and used within an academic context, others also used within an operational or even commercial context. This chapter summarizes and evaluates different model candidates that could be of use given the objectives of the REDSIM project.

Modeling concepts

Existing crop simulation models have all been developed with different objectives. The governing equations and underlying theory of these models as such are very divergent. According to van Ittersum (2003) water-oriented models, also called agrohydrological models, perform better and are more suitable for irrigation and water-use assessments than crop-growth oriented models, although both approaches have been used. This model selection chapter will include both models focusing on crop growth processes, as well as models that include more detailed soil water descriptions.

The mathematical formulation, structure and complexity of crop simulation models are also very different. For some models, empirical equations were sufficient to describe the processes of interest, while other models include complex mechanistic equations to capture a certain crop or soil water response. However, most models contain a mixture of empirical and mechanistic concepts.

For the crop growth components of the models, the main distinction that can be made in terms of their underlying equations, is whether they are (i) radiation (or light) use efficiency based, (ii) photosynthesis based, or (iii) water use efficiency based.

The concepts behind modeling of soil water dynamics range from the use of a simple bucket-filling model to those that solve more complex and vertically algorithms, based on the Richards´ equations. Richards' equation has a clear physical basis at a scale where the soil can be considered to be a continuum of soil, air and water. In principle, the use of numerical solutions for the Richards´ equation are better for soils below field capacity.

The impact of water stress on crop growth is normally described by either (i) a tipping bucket concept through f.e. stress response functions or can be (ii) Richards´ potential driven.

Existing model overviews

The following model overviews have been done in the past on models encompassing the soil-water-vegetation and atmosphere continuum:

- **Compendium on methods and tools to evaluate impacts of, and vulnerability and adaptation to, climate change,** by UNFCCC Secretariat, 2008**.** A summary of principle models available compared with each other based on their usefulness for climate change studies.
- **The Meta-Analysis of Crop Modelling for Climate Change and Food Security Survey,** organized by The Consultative Group on International Agricultural Research (CGAIR), 2011**.** A survey recently done to better understand the global extent of crop model development and to identify gaps in capabilities.

- **The Register of Ecological Models (REM)** is a meta-database for existing mathematical models in ecology and environmental sciences. Link: http://ecobas.org/www-server/ .
- **Ittersum et al. (2003)** describes different models from the Wageningen school.
- **Eitzinger et al. (2004)** compare the performance of three models for different soil types against soil water measurements.
- **Gandolfi et al (2006)** compare various one dimensional soil water and crop growth models
- **Bonfante et al. (2009**) compares three models two contrasting soil cropped with maize.

Model candidates

This section lists a number of models that were selected as possible candidates for the REDSIM project. Only models that have been or are used within a similar context (crop water use and irrigation scheduling) were selected as candidates

APSIM

The APSIM model is designed for on-farm decision making, and is currently being used in an operational setting for the commercial Australian decision-support system for farmers, called Yield Prophet (http://www.yieldprophet.com.au/).

Soil water dynamics

In APSIM there are modules for the two major modelling approaches that are commonly used for the soil water balance, namely bucket or cascading layer approach and a solution of the Richard's equation methods. The implementation in the APSIM model is based on the 'stand alone' SWIMv2.1 (Soil Water Infiltration and Movement). Parameterisation of the soil water properties for APSWIM requires specification of the moisture characteristic and hydraulic conductivity relationships in each soil layer. Runoff is dealt with by considering surface roughness.

Crop growth processes

Growth modules are available for crops, pasture and forests, including their interaction with soil. The plant modules simulate the key physiological processes and operate on a daily time step in response to input daily weather data, soil characteristics and crop management actions. The crop modules have evolved from early versions for focus crops such as maize.

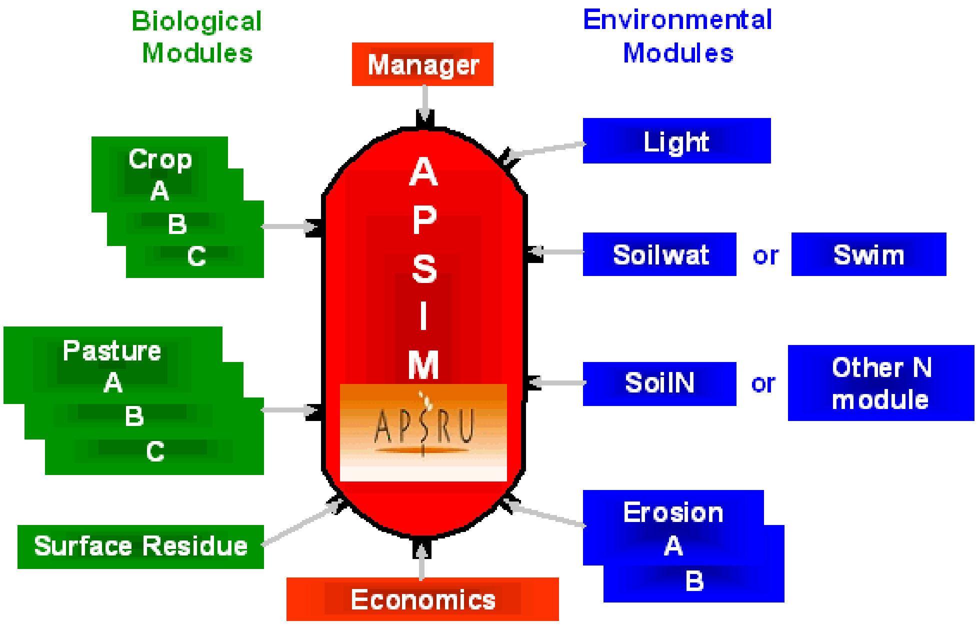

Figure 1. Diagram of APSIM with individual crop and soil modules, module interfaces and the simulation engine (Keating et al. 2003).

AquaCrop

AquaCrop is a crop water productivity model developed by FAO, through consultation with experts from major scientific and academic institutions and governmental organizations worldwide. It simulates yield response to water of herbaceous crops, and is particularly suited to address conditions where water is a key limiting factor in crop production. The AquaCrop model is still under development. Different pre-calibrated crops are available. The model has not been used yet within an operational context, as far as known. Recently a plugin became available that allows easy incorporation of the model other systems and apply it in a distributed way.

Soil water dynamics

The soil component of AquaCrop is configured as a dispersed system of a variable depth allowing up to 5 horizons of different texture composition along the profile. As default, the model includes all the classical textural classes present in the USDA triangle but the user can input its own specific value. For each texture class, the model associates a few hydraulic characteristics which can be estimated them from soil texture through pedotransfer functions. The hydraulic characteristics include the hydraulic conductivity at saturation, and the volumetric water content at saturation, field capacity, and wilting point.
For the soil profile explored by the root system, the model performs a water balance that includes the processes of runoff (through the curve number), infiltration, redistribution or internal drainage, deep percolation, capillary rise, uptake, evaporation, and transpiration. A daily step soil water balance keeps track of the incoming and outgoing water fluxes at the boundaries of the root zone and of the stored soil water retained in the root zone. A distinctive feature of the water balance in AquaCrop is the separation of soil evaporation (E) from crop transpiration (Tr) based on a modification of the Ritchie's approach. Soil salinity and capillary rise from shallow water tables are not yet implemented in AquaCrop 3.1+

Crop growth processes

AquaCrop is a water-driven model, meaning that the crop growth and production are driven by the amount of water transpired, relying on the conservative behaviour of biomass water productivity (or biomass water use efficiency). The model does not simulate lower hierarchical processes expressing the intermediary steps involved in the accumulation of biomass. The underlying processes are "summarized" and synthetically incorporated into one single coefficient defined biomass water productivity (WP). The final yield is expressed as the product of biomass and harvest index.

In AquaCrop, the crop system has five major components and associated dynamic responses (see Fig. 1.2): phenology, aerial canopy, rooting depth, biomass production and harvestable yield. In stead of leaf area index AquaCrop uses green canopy cover to express foliage development. The crop grows and develops over its cycle by expanding its canopy and deepening its rooting system while at the same time the main developmental stages are established. It accounts for three levels of water-stress responses (canopy expansion rate, stomatal closure, senescence acceleration, water logging effects, and harvest index), and for fertility status. Its application encompasses rain fed as well as supplementary, deficit and full irrigation.

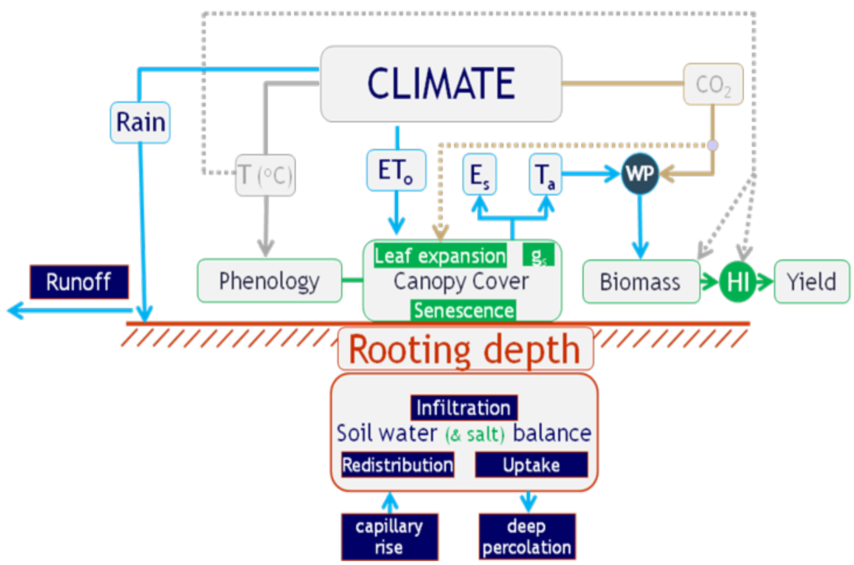

Figure 2. Diagram of the modeling components of AquaCrop (Steduto et al. 2009)

CROPSYST

The CropSyst is very much crop growth oriented and contains modules for deciduous trees that many other models lack. Recently, the model was applied to pear trees for real-time deficit irrigation decision support (Marsal and Stockle, 2011), focusing on stem water potential.

Soil water dynamics

Water redistribution in the soil can be simulated by a simple cascading approach or a numerical solution of the Richard's soil flow equation. CropSyst, due to its internal numerical constraints in the parameterization of the retention and conductivity functions is reported to need considerable calibration (Bonfante et al. 2009).

Crop growth processes

The simulation of crop development is based on thermal time, which is the required daily accumulation of average air temperature above a base temperature and below a cutoff temperature to reach given growth stages. The accumulation of thermal time may be accelerated by water stress. This can be conceptualized as a response to increased crop temperature. The core of biomass accumulation calculations is the determination of unstressed (potential) biomass growth based on crop potential transpiration and on crop intercepted PAR. LAI is calculated as a function of biomass accumulation.

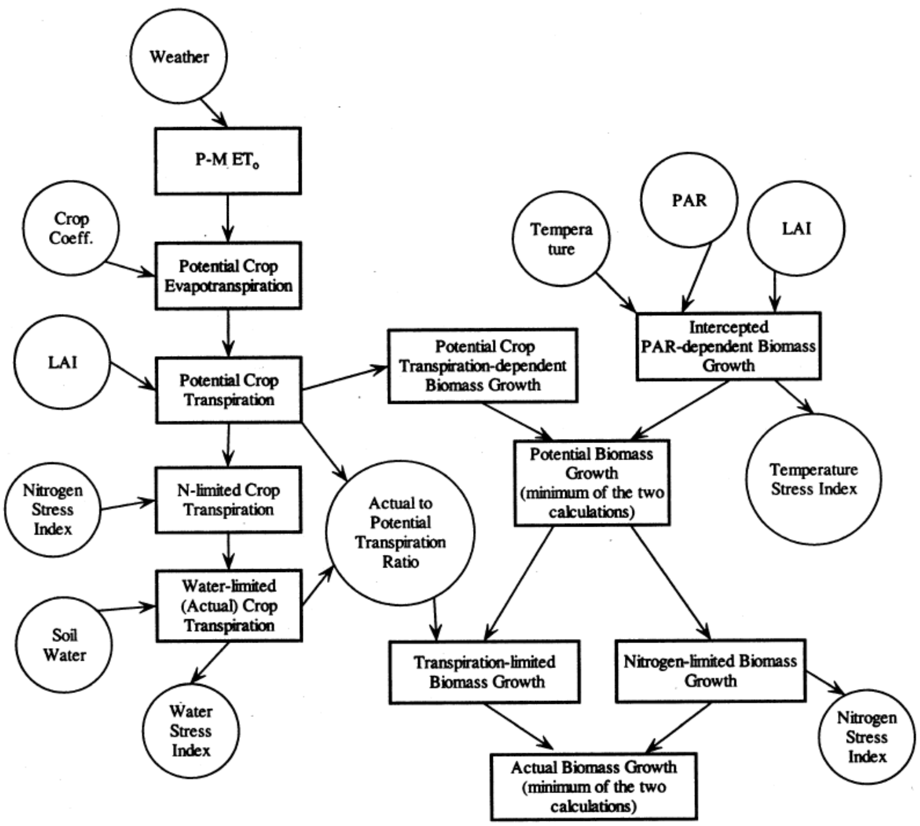

Figure 3. Flow chart of biomass calculations of CropSyst

DSSAT

DSSAT is used very frequently within academic and applied research to study all type of crop responses. The modeling system is very much focused on crop processes, and less on soil water related processes, but applications exist in which the model is used for precision agriculture (e.g. Thorp et al. 2008).

Soil water dynamics

The soil water balance module in the crop growth models of DSSAT computes one-dimensional soil water balance of a stratified profile in a daily time step, as described by Ritchie (1998). Soil characteristics, climate parameters, and crop management practices are standard inputs to the model (IBSNAT,1990). Values of plant growth variables estimated by other modules are also input to SWBM. Water from either precipitation or irrigation infiltrates into the top layer after subtraction of runoff. Empirical procedures are used to calculate soil water flow upwards and downwards through the profile. Drainage flow is calculated by a 'cascading' approach, in which excess water above field capacity of a layer is passed directly to the layer below. Drainage does not occur when soil moisture is below field capacity. A normalized soil water diffusion equation, parameterized for general soil types of different textures, is used to simulate upwards flux.

Crop growth processes

DSSAT has a modular structure and includes many mechanistic crop models (CERES, CROPGRO, etc), each of them applicable to one or more crops. They simulate daily phenological development and growth in response to environmental factors (soil and climate) and management (crop variety, planting conditions, nitrogen fertilisation, and irrigation). Crop yield simulations are used to derive statistical production functions that are the inputs of the economic model. Generally these models are quite demanding in terms of data and require substantial calibration.

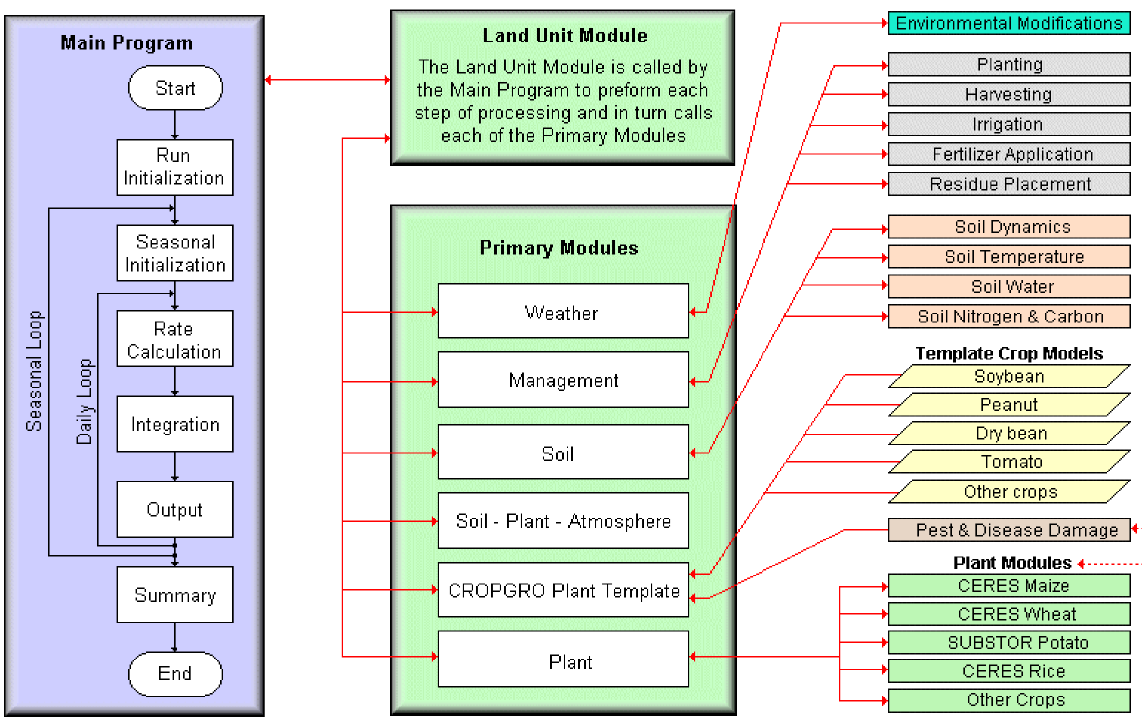

Figure 4. Overview of the components and modular structure of the DSSAT cropping system model (Jones et al. 2003)

STICS

STICS is a model that has been developed at INRA (France) since 1996. It simulates crop growth as well as soil water and nitrogen balances driven by daily climatic data. It calculates both agricultural variables (yield, input consumption) and environmental variables (water and nitrogen losses). The assimilation of remote sensing data with the STICS model has been investigated and described by several authors (Weiss et al. 2010; Hadria et al. 2006, etc). Also a specific calibration package for STICS has come out, developed in Matlab, called OptimiSTICS (Wallach et al. 2010)

Soil water dynamics

The description of soil includes four compartments: microporosity (or textural porosity), macroporosity (or structural porosity), fissures (in the case of swelling clay soils) and stones. The soil is divided in 5 horizons but calculations in the microporosity are done per 1 cm layer. The macroporosity and the fissure compartments play a role in drainage and run-off processes. The macroporosity functioning is simulated at the level of the horizon (not per cm) whereas the fissures are supposed to be independent of the layer/horizon soil partitioning.

Crop growth processes

Crop growth is driven by the plant carbon accumulation: solar radiation intercepted by the foliage and then transformed into aboveground biomass that is directed to the harvested organs during the final phase of the crop cycle. The crop nitrogen content depends on the carbon accumulation and on the nitrogen availability in the soil. According to the plant type, crop development is driven either by a thermal index (degree-days), a photothermal index or a photothermal index taking into account vernalisation. The development module is used to (i) make the leaf area index evolve and (ii) define the harvested organ filling phase. Water stress and nitrogen stress, if any, reduce leaf growth and biomass accumulation, based on stress indices that are calculated in water and nitrogen balance modules.

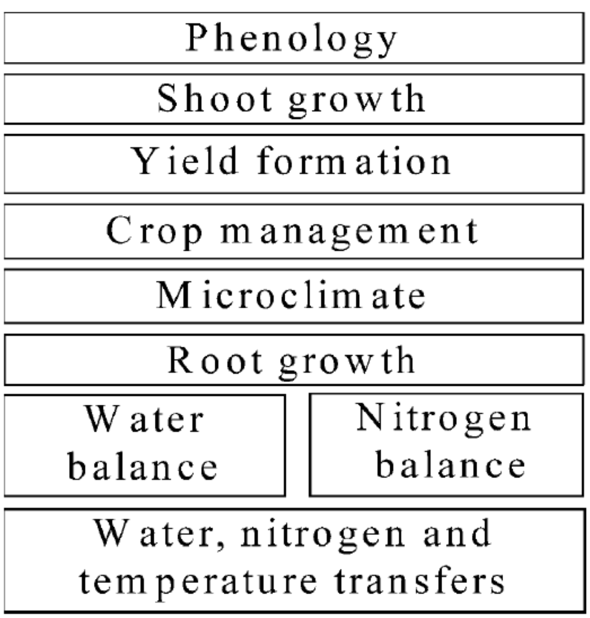

Figure 5. The various modules of the STICS model (Brisson et al. 2003)

SWAP

SWAP (Soil, Water, Atmosphere and Plant) simulates transport of water, solutes and heat in unsaturated/saturated soils. The model is designed to simulate flow and transport processes at field scale level, during growing seasons and for long term time series. The developers are from Alterra, Wageningen based in the Netherlands.

Soil water balance

Water movement simulation in SWAP is based on Richards' equation. The numerical solution of Eq. (16) 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). SWAP applies Richards' equation integrally for the unsaturated-saturated zone, including possible transient and perched groundwater levels.

Crop growth processes

SWAP includes both simple and detailed crop growth modules. In the simple crop module, crop growth is forced by the measured leaf area index, crop height and rooting depth as a function of crop development stage. The simple crop module does not simulate any interaction between the crop growth and the water and salt stress conditions. However, the detailed crop module has the advantage of giving a feedback between crop growth and water and salt stress conditions. The detailed crop growth module is based on the World Food STudies (WOFOST) model, which simulates the crop growth and its production based on the incoming photosynthetically active radiation (PAR) absorbed by the crop canopy, its photosynthetic leaf characteristics, and accounting for water and salt stress on the crop. The effects of nutrient supply, pests, weeds, and diseases on the crop growth and its production are not implemented in the present version of WOFOST. The above described both simple and detailed crop growth simulation approaches are included in the present version SWAP 3.03 model (Kroes and Van Dam, 2003).

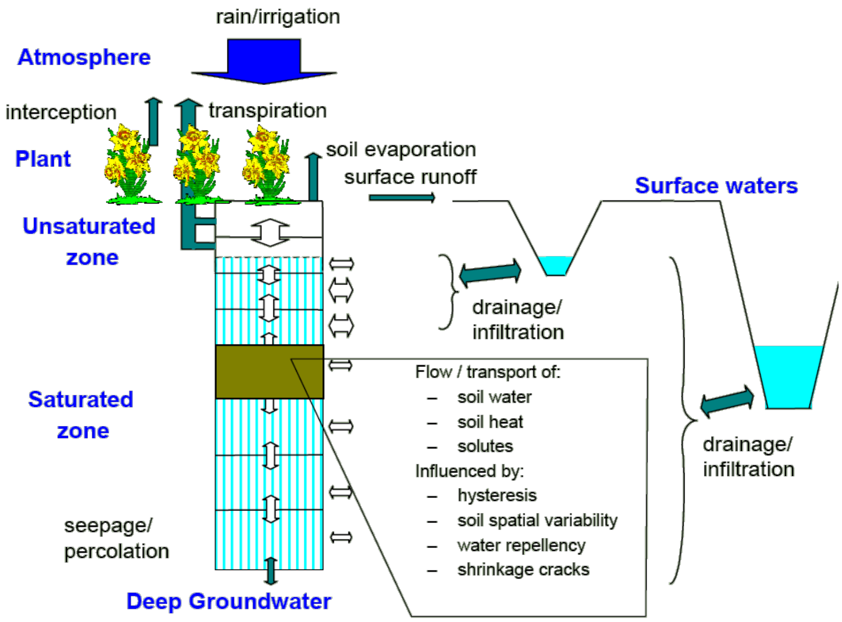

Figure 6. Schematization of processes of SWAP (from documentation)

SWAT

SWAT was developed primarily by the United States Department of Agriculture (USDA) to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time.

Soil water dynamics

SWAT uses a cascading approach to simulate the dynamics of soil water content. It computes infiltration using either the Curve Number (CN) method at daily intervals or the Green-Ampt method when hourly precipitation data are available. A routing module is used to simulate flow of soil water through each soil layer in the root zone. Downward movement or percolation occurs when field capacity of a soil layer is exceeded and the underlying layer is not saturated.SWAT simulates the movement of saturated flow between soil layers and assumes the uniform distribution of soil moisture within a given layer. Unsaturated flow between soil layers is indirectly estimated by the distributions of plant water uptake and soil water evaporation through two parameters: the soil evaporation compensation coefficient, ESCO and the plant uptake compensation factor, EPCO, respectively. Although these two parameters relate directly to crop water stress, determination of their values is not documented in SWAT.

Crop growth processes

Crop growth simulation in SWAT is based on the EPIC model, using daily accumulated heat units, harvest yield, biomass from solar radiation and water and temperature stress adjustments. It provides a general description of the growth of a vegetative canopy using deterministic relation-ships based on physiological or physical processes.

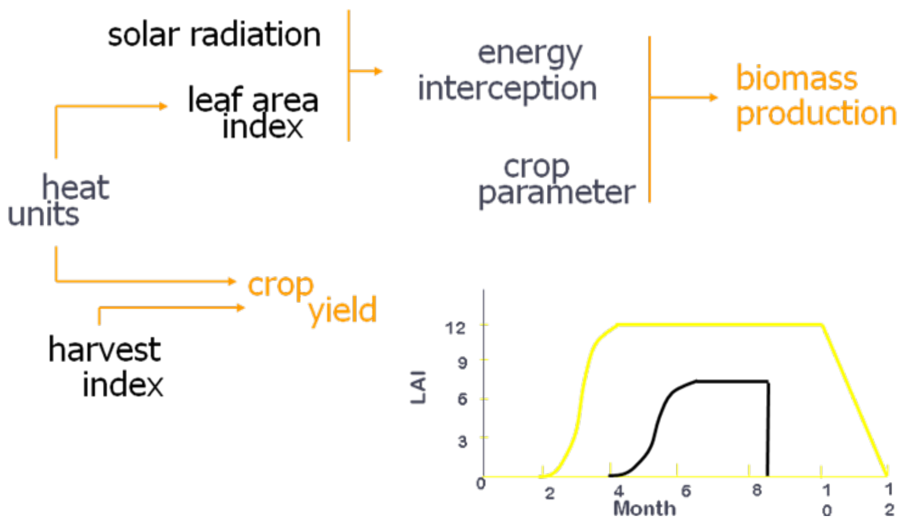

Figure 7. Crop growth modeling in SWAT (Neitsch et al. 2005)

WOFOST

The World Food STudies (WOFOST) model is a simulation model for the quantitative analysis of the growth and production of annual field crops, developed by Alterra, Wageningen, Netherlands. It can be coupled with the soil water model SWAP.

Soil water dynamics

In WOFOST three different soil water sub models are distinguished (depending on the implementation). The first and most simple soil water balance applies to the potential production situation. Assuming a continuously moist soil, the crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

The second water balance in the water-limited production situation applies to a freely draining soil, where groundwater is so deep that it can not have influence on the soil moisture content in the rooting zone. The soil profile is divided in two compartments, the rooted zone and the lower zone between actual rooting depth and maximum rooting depth. The subsoil below rooting depth rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper.

The third water balance is for water-limited production on soils having influence of shallow groundwater in the rooting zone. The principles are similar to the freely draining situation. Different is that the soil moisture retention capacity is determined by the depth of the groundwater, as is the percolation rate. There is capillary rise if the rooted soil dries out. The groundwater level can be controlled by artificial drainage and the moisture content within the root zone does not vary with depth.

Crop growth processes

The WOFOST model simulates the crop growth and its production based on the incoming photosynthetically active radiation (PAR) absorbed by the crop canopy, its photosynthetic leaf characteristics, and accounting for water and salt stress on the crop. The effects of nutrient supply, pests, weeds, and diseases on the crop growth and its production are not implemented in the present version of

WOFOST. The above described both simple and detailed crop growth simulation approaches are included in the present version SWAP 3.03 model (Kroes and Van Dam, 2003).

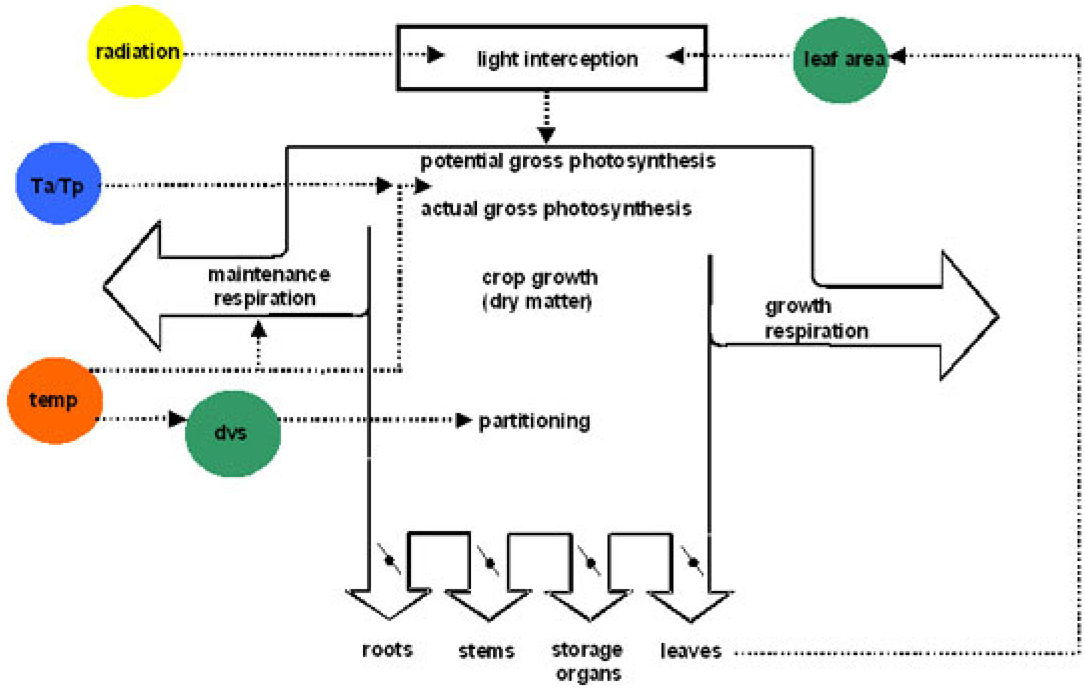

Figure 8. Crop growth processes in WOFOST

Model evaluation

An important issue in model selection is that the model should be sufficiently but not overly detailed for the question that is to be addressed. For the REDSIM project, crop information will be obtained from satellite images (LAI, evapotranspiration, crop stress). The main objective for the use of an crop simulation model is to deliver updated information on the soil water content and possible effects on crop stress, to be fed with daily meteorological data. The model structure is therefore required to be water-oriented rather than crop-growth-oriented. Given the applied and operational context, a model is required that is straightforward to use, which means that (i) empirical equations for crop growth processes are preferable and (ii) experiences should have been documented on the successful assimilation of remote sensing data into the model simulations. The availability of source code is also an important factor to allow smooth integration on the servers participating in the project.

A number of indicators were selected to value each of the model candidates (Table 1). The selection and weighting of these indicators was based on the previous considerations and taking into account the scope and objectives of the REDSIM project.

Table 1. Indicators used to evaluate the models

Indicator	Weight
Soil water balance	5
Crop growth processes	3
Pre-calibrated crops	3
Irrigation mgt	4
Data requirements	3
Relevant outputs	4
Code availability	3
Scalable for operational use	5
Support from developers	2
Assimilation EO data	3

Using these evaluation indicators, the model candidates were evaluated, distinguishing between three classes: poor, average and good (Table 2). The evaluation was based on the previous model descriptions, model documentation, scientific literature and model reviews as listed before.

Table 2. Evaluation for all indicators of the candidate models. 1 = poor, 2 = average, 3 = good.

Indicator	APSIM	AquaCrop	CROPSYST	DSSAT	STICS	SWAP	SWAT	WOFOST
Soil water balance	2	3	2	2	2	2	2	1
Crop growth processes	3	3	3	1	3	3	2	3
Pre-calibrated crops	3	1	3	2	3	2	3	2
Irrigation mgt	2	3	3	3	2	3	1	1
Data requirements	3	3	2	1	1	2	2	2
Relevant outputs	3	3	3	3	3	3	2	1
Code availability	3	1	1	3	3	3	3	2
Scalable for operational use	2	3	1	1	2	3	2	2
Support from developers	2	2	2	2	2	3	3	2
Assimilation EO data	2	1	2	2	3	3	3	3

The following step in the model evaluation was to multiply the valuations of the models against the indicators by the different weights given in Table 1. This results in a total score for each model. This total score gives a quantitative estimate of the suitability of each model within the REDSIM project.

Table 3. Evaluation table and total scores for each criterium and model

Indicator	APSIM	AquaCrop	CROPSYST	DSSAT	STICS	SWAP	SWAT	WOFOST
Soil water balance	10	15	10	10	10	10	10	5
Crop growth processes	9	9	9	3	9	9	6	9
Pre-calibrated crops	9	3	9	6	9	6	9	6
Irrigation mgt	8	12	12	12	8	12	4	4
Data requirements	9	9	6	3	3	6	6	6
Relevant outputs	12	12	12	12	12	12	8	4
Code availability	9	3	3	9	9	9	9	6
Scalable for operational use	10	15	5	5	10	15	10	10
Support from developers	4	4	4	4	4	6	6	4
Assimilation EO data	6	3	6	6	9	9	9	9
Total Score	**86**	**85**	**76**	**70**	**83**	**94**	**77**	**63**

Conclusion

In the model selection procedure, different model candidates were evaluated and ranked. Ten indicators were defined to evaluate the models and compare them. The model with the highest score is 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 simple (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.

Model specifications

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:

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

Error! Bookmark not defined.Error! Bookmark not defined.Error! Bookmark not defined.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:

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

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:

$$\frac{Y_{act,i}}{Y_{pot,i}} = \frac{T_{act,i}}{T_{pot,i}} \qquad (3)$$

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:

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

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 $Y_{\mathrm{pot,max}}$ en $T_{\mathrm{pot,max}}$ 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 is however seriously considered, 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.

Detailed Growth Module

A brief overview of the detailed crop growth module used to compute the maximum obtainable (=potential) yield is given here. Figure 9 shows the main processes and relations included in WOFOST (WOrld FOod STudies). The WOFOST series has been developed and applied extensively in a wide range of geographical and climatological locations, either as a stand-alone, or integrated with SWAP.

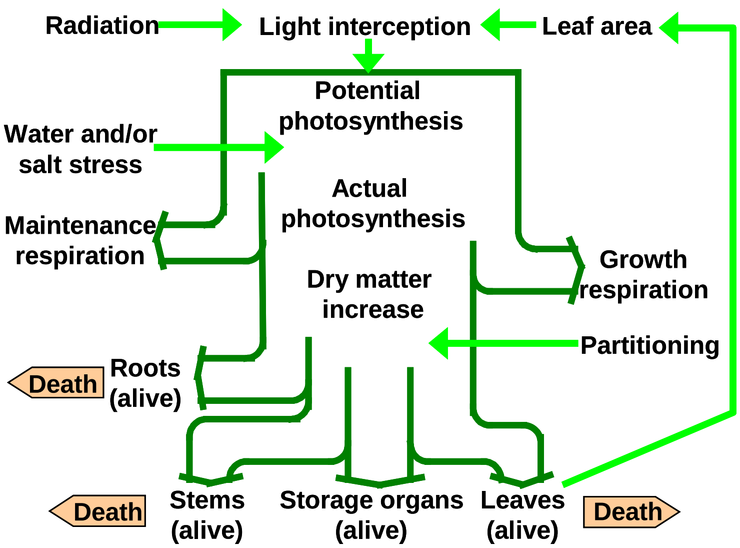

Figure 9. Overview of the main processes included in the detailed crop growth module of SWAP-WOFOST.

WOFOST computes incoming PAR just above the canopy at three selected moments of the day. Using this radiation and the photosynthetic characteristics of the crop, the potential gross assimilation is computed at three selected depths in the canopy (*Spitters et al.,* 1989). Gaussian integration of these values results in the daily rate of potential gross CO_2 assimilation (kg CO_2 ha^{-1} d^{-1}). This potential is the maximum that can be obtained given the crop variety, CO_2 concentration and nutrient status without any water stress, pest or diseases.

Part of the assimilates produced are used to provide energy for the plant maintenance processes. The rate of maintenance respiration is a function of the amount of dry matter in the various plant organs, the relative maintenance rate per organ and the ambient temperature. The remaining assimilates are partitioned among roots, leaves, stems and storage organs, depending on the phenological development stage of the crop (*Spitters et al.,* 1989). These remaining assimilate are converted into structural dry matter, and part of these assimilates are lost as growth respiration.

The net increase in leaf structural *dry matter* and the specific leaf area (ha kg^{-1}) determine leaf area development, and hence the dynamics of light interception, except for the initial stage when the rate of leaf appearance and final leaf size are constrained by temperature, rather than by the supply of assimilates. The dry weights of the plant organs are obtained by integrating their growth and death rates over time. The death rate of stems and roots is considered to be a function of development stage (DVS). Leaf senescence occurs due to water stress, shading (high LAI), and also due to life span exceedence.

Some simulated crop growth processes, such as the maximum rate of photosynthesis and the maintenance respiration are influenced by temperature. Other processes, such as the partitioning of assimilates or decay of crop tissue, are steered by the DVS. Development rates before anthesis are controlled by day length and/or temperature. After anthesis only temperature will affect development rate. The ratio of the accumulated daily effective temperatures, a function of daily average temperature, after emergence (or transplanting in rice) divided by the temperature sum (*TSUM*) from emergence to anthesis, determines the phenological development stage. A similar approach is used for the reproductive growth stage (van Dam et al., 1997).

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 Figure 10.

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.

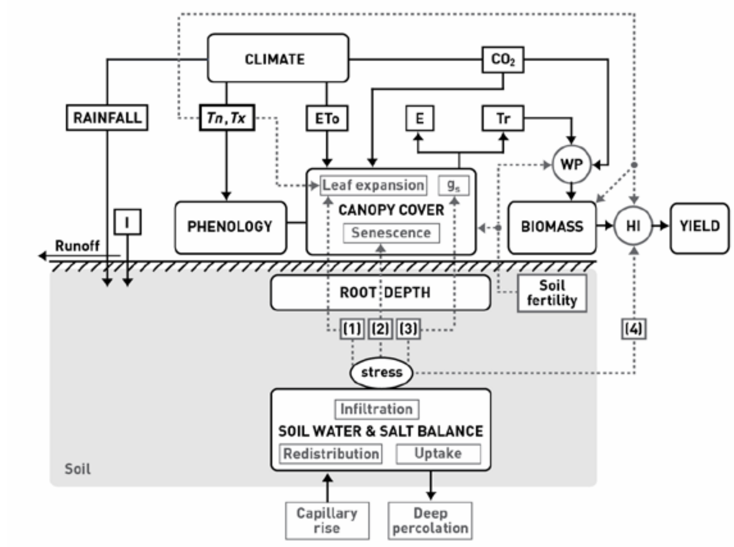

Figure 10. Main processes included in AquaCrop.

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 Ya are the maximum and actual yield, ET_x and ETa 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 m2 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 Figure 11:

- 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)

Figure 11. 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_o)
- mean annual carbon dioxide concentration in the bulk atmosphere

The reference evapotranspiration (ET_o) 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

Data Requirements

SWAP

Soil Data

The experimental fields and pilot plots participating in the first prototype of REDSIM are located in the agricultural areas around the city of Cartagena *(Campo de Cartagena)*. Soil data of this area is sparse. The following sources are available providing some level of soil information of several points in the area:

- Digital Soil Map of Murcia Region (*Mapa Digital de Suelos de la Región de Murcia)* published in 1999 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, particularly of the area of interest, 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 (Table 4)

Table 4. Soil data of experimental plot within study area (from: Jiménez-Martínez, 2010)

Depth	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm3)	Particle density (g/cm3)	Texture	Soil structure
0-30	18.7	76	3.5	1.45±0.10	2.64	silty loam	granular
30-60	13.8	80.2	6	1.52±0.11	2.65	silty loam	massive
60-90	19.5	77.2	3.3	1.58±0.05	2.67	silty loam	massive
90-150	10.8	82	6.6	1.70±0.08	2.67	silty loam	massive

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. A low-cost option to derive these parameters is calculating them using so-called pedo-transfer functions. These functions related soil hydraulic parameters with easily measurable quantities in the field, mainly soil texture.

Measurements on soil texture of the pilot plots involved in the REDSIM prototype will allow determination of the soil hydraulic properties using pedotransfer functions. Other parameters required for the model will be fine-tuned by calibration using measured soil moisture data of the experimental plots. The pedotransfer functions considered are those described by:

- Saxton et al. (1986).
- Jabro et al. (1992)
- 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.

Other Data

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. Weather stations of the local network SIAM will be used for the daily meteorological input of the model. Reference evapotranspiration is provided also, based on the daily measurements.
    - Currently is investigated how to include stations from the national weather agency (AEMET) that provide 3-day or 7-day forecasts and how to correctly convert the forecasts from probabilistic to quantitative estimates
- Crop data
    - Information on type of cultivated crop is provided by farmers. Prototype to be launched in July will include orange trees. Two experimental plots of UPCT include both adult as well as young trees, of which data will be used to parameterize the model (LAI, roots).
    - Crop yields are to be provided at the end of the season by the farmers
    - The crop factor will be based on the analysis of the measurements in the experimental orange plots, and for the other winter crops from other local sources.
- 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
    - The farmers will provide information on his daily irrigation practices through the REDSIM web-interface.
    - Nutrient-limited-stress and fertilization effects will be neglected.

AquaCrop

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.

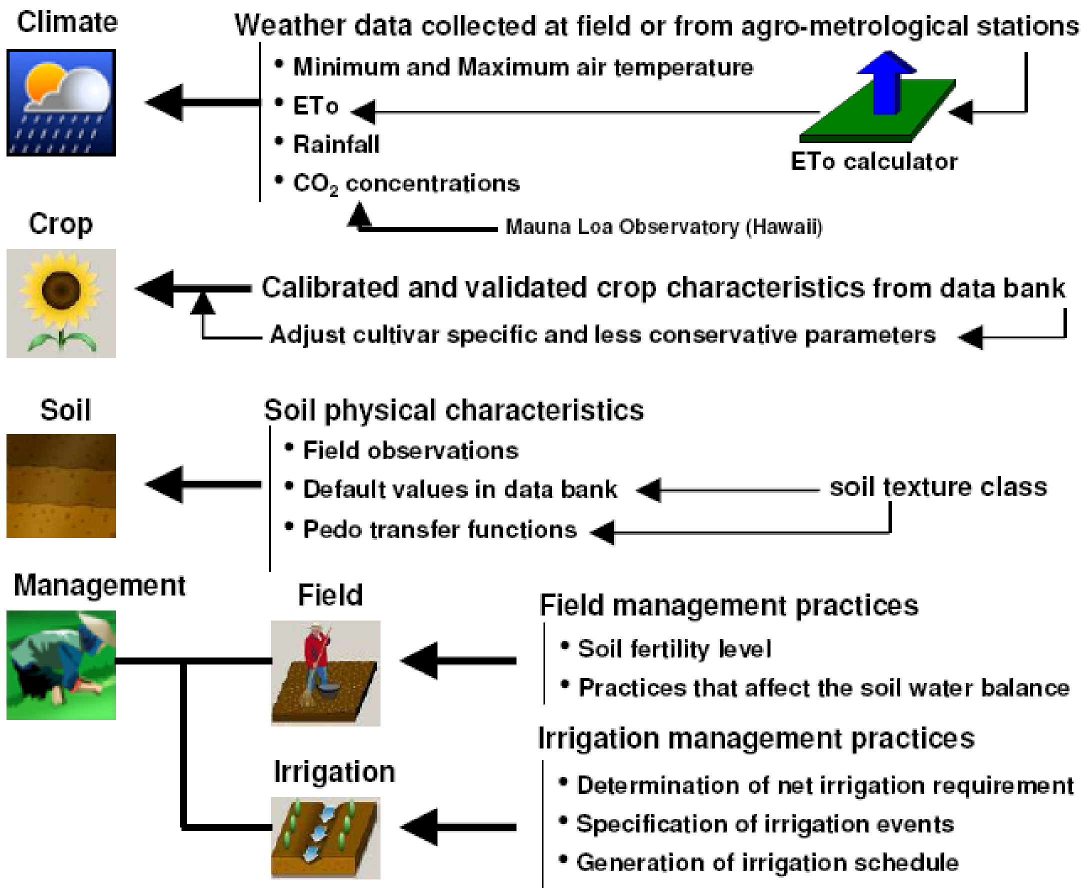

Figure 12. Input data defining the environment in which the crop will develop

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

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 will be made in the pilot plots,

Other Data

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

- Weather data
    - Rainfall, maximum and minimumtemperature, 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 will be reported.
- Initial and Boundary Conditions
    - Initial and final soil water content will be determined gravimetrically in each plot.
- Water and Crop Management
    - The soil will be covered with transparent plastic mulch, and the irrigation system will consist of one drip line per crop row.
    - The farmers will provide information on his daily irrigation practices, and also water meters will be installed.
    - Nutrient-limited-stress and fertilization effects will be neglected.

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