

Hydro-tech: An integrated decision support system for sustainable irrigation management (I): Main algorithms and field testing

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Abstract: In the framework of a specific project supported by the EC-ERDF programme in the Apulia Region (Italy), a local consortium of private ICT companies and Research institutions is currently developing and testing a Decision Support System called 'HydroTech' (HT-DSS), which aims to integrate the latest scientific knowledge on crop water requirements and irrigation scheduling with the more advanced technological solutions for the continuous sensor-based monitoring in the soil-plant-atmosphere system, as well as the remote and automated control of irrigation supply networks. The 'core' algorithm of Hydrotech-DSS is based on the well-established FAO-56 methodology (Allen *et al.*, 1998), further improved in order to allow the application of different models for ETo estimation, to apply the heat unit concept for the simulation of crop development, to customize irrigation strategies options according to a complete set of priorities (including deficit irrigation), and finally to allow the further improvement of the Kc curve according to crop/variety specific biometric and phenological measurements. An additional 'multi-plot/crop management module' has been created for the real-time simulation of the crop water balance, as well as to simulate a 3 to 7-days projected scenario using the high-resolution weather forecasting data, in order to forward a day-by-day irrigation planning. Then, a 'dynamic optimizer' supports the optimal setting of the irrigation priorities at the farm scale by taking into account water availability at the source (e.g. well, reservoir), the level of water stress reached by each crop type and the economic parameters including the cost of applied management practices and expected market price. At plot scale, the continuous monitoring of soil water status by capacitance soil water sensors enables the HT-DSS to further support the application of 'closed-loop' irrigation control strategies by setting irrigation timing and amount in order to reach a specific soil moisture content and/or to avoid/control plant water stress. Finally, HT-DSS integrates a set of flexible solutions for partially or completely automated irrigation management, by means of real-time and remote monitoring in the water supply network (volumes, discharges, pressures, etc.) and control of actuators (at the level of pumping station, hydrants, electro-valves, etc.) to support farm operational management, as described in the companion paper (Riezzo *et al.*, 2013; this issue). The preliminary results of the DSS implementation are presented in relation to the on-going experimental and demonstration activities established in different local farms, and an example of application for a peach orchard is briefly introduced.

Keywords: Irrigation, decision support system, water balance model, capacitance sensor, optimization.

1. INTRODUCTION

In southern EU Member States, 'sustainable' water management in agriculture has been identified as the major issue in the implementation of the Water Framework Directive (2000/60/EC) and several related national and local legislations. Accordingly, the Common Agricultural Policy (CAP) has subjected the direct financial support to farmers to the mandatory respect of related EU environmental legislation (cross-compliance), and in the framework of the new CAP program (2014-2020) the 'sustainable management of natural resources' will gain more and more importance among the priorities and objectives of rural development policies, with a special emphasis on water resources management at farm level and research-innovation transfer into practice (Dwyer, 2013).

Additionally, the EU Commission initiative 'European Innovation Partnership on Water' (EIP-Water) has pointed out that appropriate policies are required to support the development of innovative technologies for water management and to facilitate their dissemination at local scale. Among the 'priorities' suggested

by the EIP-Water, there is the need to develop ‘decision support systems’ (DSS) to further improve water management, especially at the ‘demand’ side. Innovative DSS should be based on the effective integration of the new technologies available in computer science, modeling, electronics, sensor technology and wireless communication.

With specific reference to irrigated agriculture, the application of new technologies to the control and automation of irrigation is becoming a very relevant issue in the last decade, and especially the automatic irrigation scheduling is receiving growing attention. Several international projects have been recently founded by the Sixth and Seventh EU Research Framework Program following the goal to develop and to apply advanced technologies in decision support systems for irrigation management at farm scale (e.g. IRIQUAL, FLOW-AID, FIGARO, WATERBEE; for more examples, see STREAM online).

The ‘sustainable’ irrigation management requires reliable and easy-to-use methods to support real-time scheduling, which is a ‘decision process’ to determine ‘when’ to irrigate and ‘how much’ water to supply, with respect to the specific crop response to stress (Steduto *et al.*, 2012), and with respect to the need to save water and increase its productivity (Fererer and Soriano, 2007). On-farm irrigation scheduling can be supported by means of several technical and scientific methods based on the evaluation of soil/plant water status and/or on the simulation of crop-soil water balance, although for all basic approaches both advantages and disadvantages are normally found, as briefly summarized in Table 1 (Jones, 2004). It is possible, and often convenient, to combine more than one of these approaches to arrive at the desired procedure.

Scheduling methods can be also characterized in terms of: a) type of information given (timing and/or depth of water application); b) accuracy of the equipment and the method as a whole; c) resolution (desired at field level); d) timeliness (the information must be given before unacceptable damage is done); e) nature and distribution of errors; f) reliability (fitness to fluctuating environmental conditions, wide application range); h) simplicity and practicality (rugged instruments, easy to repair and replace); i) suitability for computerized and/or automated irrigation (Cavazza, 1988).

Table 1. Summary of the main classes of irrigation scheduling approaches with their advantages/disadvantages (from Jones, 2004).

Irrigation scheduling approach	Advantages	Disadvantages
Soil water measurements (e.g. capacitance/TDR sensors)	Easy to apply in practice; quite precise; give information on ‘how much’ water to supply; many commercial systems available; some sensors readily automated; telemetry can give instantaneous data	Soil heterogeneity requires many sensors or extensive monitoring programs; selecting representative positions is difficult; take no account of evaporative demand, so do not indicate plant stress
Soil water balance calculations	information widely available; easy to apply in principle; indicate ‘how much’ water to supply	not as accurate as direct measurements; need accurate local estimate of precipitation; evapotranspiration estimates require good estimates of crop coefficients; regular calibration is needed (errors are cumulative)
Plant stress ‘sensing’ (e.g. pressure chamber, thermal sensing)	measure the plant response directly; integrates environmental effects; potentially very sensitive	does not indicate ‘how much’ water to supply; calibration required to determine control thresholds; still largely at research/development stage and little used yet for routine agronomy

In the Apulia Region (Southern Italy), a local consortium of private ICT companies and Research institutions is currently carrying out a project called ‘Hydro-Tech’ (‘Advanced technologies for sustainable irrigation management’) supported in the framework of the EC European Regional Development Found (ERDF) programme, with the aim to develop and test a specific DSS (hereafter referred as ‘HT-DSS’) by integrating some of the latest scientific advances in crop water requirements and modelling with the

available technological solutions for the continuous sensor-based monitoring in the soil-plant-atmosphere system, as well as the remote and automated control of irrigation supply networks.

Among the main objectives of the project, the following are here highlighted: i) to test and validate at farm level the effectiveness and reliability of HT-DSS simulations for different vegetables, fruit trees and grapevine crops, under different agronomic, management and pedo-climatic conditions; ii) to test the effective integration of different technologies; iii) to design of ‘simple and practical’, user-friendly computer/mobile-based DSS, by considering also the end-user feedbacks and specific requirements; iv) to evaluate the most cost-effective solutions. The main algorithms of the model are briefly introduced in this paper, together with a description of the on-going experimental activity at farm level.

2. BRIEF DESCRIPTION OF HT-DSS

2.1. General overview of the system

HT-DSS is based on the integration of the following series of software and hardware components: a) a crop-soil water balance model, to compute the daily balance for each single irrigated plot; b) a specific software ‘module’ elaborating the weather data collected from a meteo station close to the area of interest and the short-time (3-7 days) weather forecast to compute a sort of ‘predicted’ crop water balance for incoming days, in order to support the decision process; c) a specific ‘multi-plot and multi-crop management module’ for the optimal water allocation considering all farm’s irrigated plots, water availability and economic parameters of cultivation; e) capacitance sensors, for the real-time monitoring of soil water content; f) modern information and communication technologies for data-cloud computing; g) specific software applications for both ‘desk’ computers and ‘mobile’ devices (tablet, smartphone); h) field data-loggers, connected with weather and/or soil moisture sensors; i) remote monitoring in the water supply network (volumes, discharges, pressures, etc.) and control of actuators (at the level of pumping station, hydrants, electro-valves, etc.) to support farm operational management. In this paragraph, the main algorithms and sensors developed and/or tested (a-e) are briefly described; for additional technical details on other software-hardware components (f-i) see the companion paper (Riezzo *et al.*, 2013, this issue).

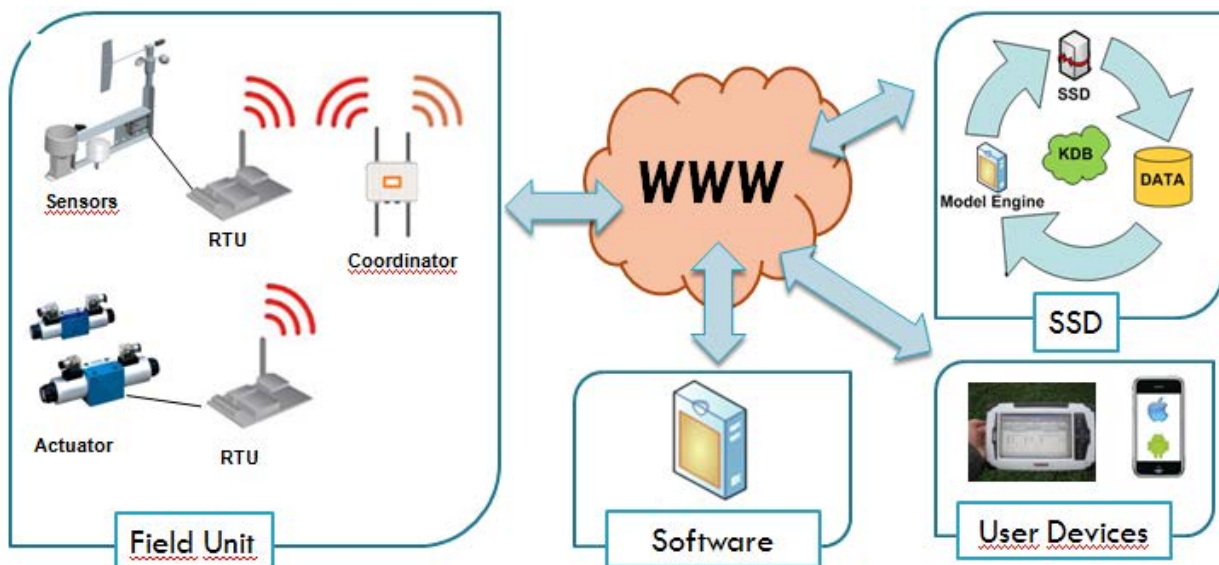


Fig. 1. General overview of the HydroTech decision support system (from Riezzo *et al.*, 2013; this issue).

2.2. Irrigation scheduling: the water balance method

2.2.1 Crop-soil water balance model (at plot scale)

The 'core' algorithm of HT-DSS is designed to run simulations at the scale of a single 'irrigated plot', defined as 'the field-unit cultivated with the same crop (also in terms of variety type, planting date, density, etc.), with relatively homogeneous soil characteristics (average depth, texture, soil water holding capacity, etc.) and receiving the same irrigation applications (in terms of timing and amount)'. Crop-soil water balance and irrigation scheduling are computed by means of a specific model, originally written in the MS Excel® programming language and previously tested and applied for similar applications (Todorovic, 2006). The model estimates crop evapotranspiration, irrigation water requirements and relative yield through the standard procedure proposed by the FAO 56 Paper (Allen et al., 1998), and it is composed of three main calculation 'modules' (Fig. 2): the 'ETo module', the 'water balance module' and the 'management module'.

Additionally, the following three databases are provided: 1) the 'climate database', created with the aim to store historical climate data (for a specific year or as multi-year averages) coming from the public meteorological services and/or as recorded from a specific station; 2) the 'soil database', containing the basic hydrological properties as required for the model for several typical soil types, and connected to a specific pedo-transfer function (PTF) allowing to create and store new types according to site-specific soil analysis; 3) the 'crop database', containing the 'default' standard parameters for a wide number of crop types, as suggested by literature (Allen et al., 1998; Allen and Pereira, 2009).

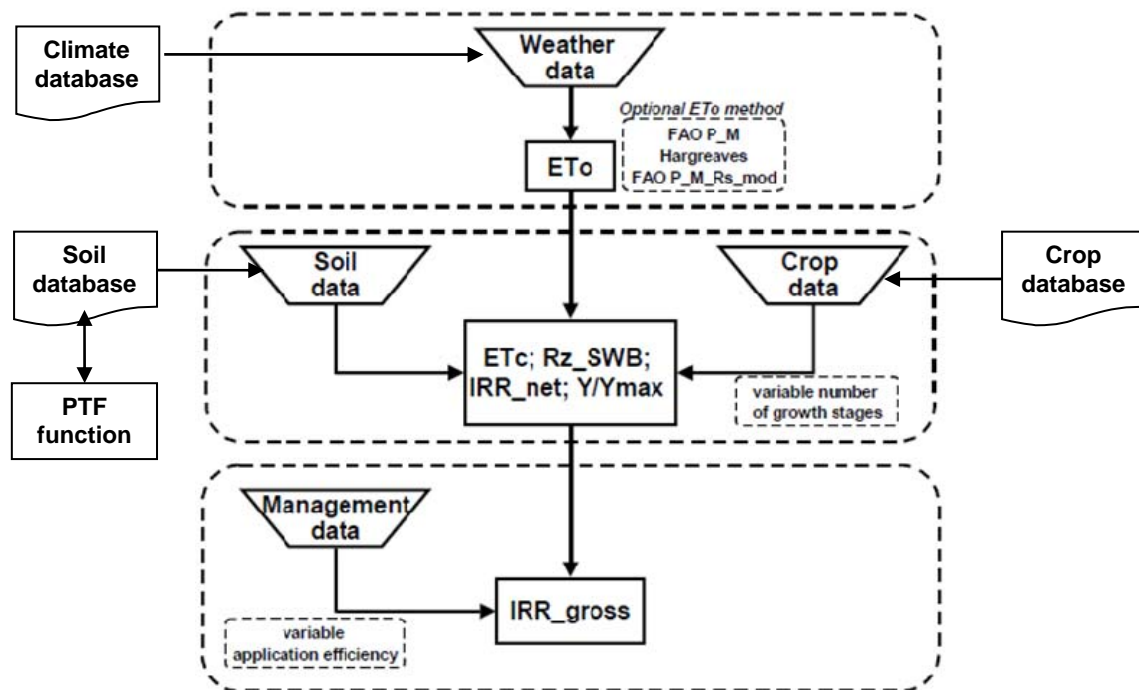


Fig. 2. Main calculation modules and databases of the irrigation scheduling model (modified from Todorovic, 2006).

Input weather data include location information and measured daily values of the main weather variables. The 'ETo module' is designed for the calculation of daily reference evapotranspiration by several methods: 1) the standard FAO Penman-Monteith approach (Allen et al., 1998), provided that a complete set of weather data is available (either with solar radiation or eliophany data); 2) the well-known Hargreaves-Samani equation (Hargreaves and Samani, 1985) which uses only maximum (T_{max}) and minimum (T_{min}) temperature measurements for ETo estimate; and 3) the Penman-Monteith-Temperature

approach (PMT) where T_{min} and T_{max} are measured and other weather parameters (solar radiation, vapour pressure deficit and wind-speed) are estimated using the method described in Allen et al. (1998) and Todorovic et al. (2013). The 'water balance module' contains soil and crop data and uses the ET_0 data estimated in the previous module. The software allows up to three soil layers, each characterized by soil texture, depth, field capacity, wilting point and related soil water holding capacity. The basic crop model inputs data are 'base' (T_b) and 'cut-off' (T_{co}) temperatures for the simulation of crop development, initial and maximum rooting depth (R_d), length (L_i) of the four main crop growth stages (initial, development, mid season and late season) together with the corresponding values of crop coefficient (K_c), yield reduction coefficient (K_y), depletion fraction threshold for optimum yield (p), and management allowable depletion (irrigation threshold).

The length of the growing stages depends mainly on variety and climatic conditions, first of all temperature. Instead of fixed stage lengths, a linear crop growth model based on the 'growing degree days' (GDD) approach can be used to compute the length of the stages for a given variety type and under the average daily thermal conditions (Raes *et al.* 2009). In mathematical terms:

$$GDD = \begin{cases} T_{avg} - T_b, & \text{if } T_{avg} < T_{co} \\ T_{co} - T_b, & \text{if } T_{avg} \geq T_{co} \\ 0, & \text{if } T_{avg} \leq T_b \end{cases} \text{ with } T_{avg} = (T_{max} + T_{min})/2 \quad (1)$$

The daily crop evapotranspiration (ET_c) is calculated from ET_0 by means of the 'single- K_c approach', where the effects of both crop transpiration and soil evaporation are integrated in a single crop coefficient (K_c). The effect of soil water stress is considered by multiplying ET_c by the water stress coefficient (K_s), resulting in the 'actual' or 'adjusted' or 'effective' ET_c value ($ET_{c,eff}$) as:

$$ET_{c,eff} = K_s K_c ET_0 = K_s ET_{c,max} \quad (2)$$

where $ET_{c,max}$ is the daily maximum crop evapotranspiration (under non water stress conditions), and K_s (≤ 1) is a dimensionless coefficient, following a linear decrease (from 1 to zero) when soil water depletion (D) falls below RAW:

$$K_s = (TAW - D) / (TAW - RAW) \quad (\text{for } D > RAW) \quad (3)$$

where total available water (TAW, mm) in the root zone is calculated by multiplying the soil water holding capacity by the rooting depth (R_d), and the readily available water (RAW, mm) by taking into account the specific crop depletion coefficient (p).

The soil water balance is computed on a daily basis, according to the following equation:

$$D_i = D_{i-1} - P_i - IRR_i - CR_i + ET_{c,i} + RO_i + DP_i \quad (4)$$

where IRR is the net irrigation requirement (calculated by the model or inserted as an input), P is effective rainfall, DP is deep percolation, CR is the capillary rise and RO is surface runoff (all variables expressed on a daily basis, in mm). Both RO and CR were assumed to be negligible, respectively because the field was flat and irrigated with low intensity, and because of the of the karstic soil features and the very deep water table. DP is calculated as the excess of water in the root zone as caused by excessive precipitation and/or irrigation. Relative yield reduction (YR) due to soil moisture stress is expressed as a percentage of the maximum production achievable under optimal conditions. The coefficient K_y can be set for each specific growth stage. YR is computed by means of a multiplicative approach as described in Rao et al. (1988), based on the following formula:

$$YR = \frac{Y_a}{Y_m} = \prod_{i=1}^N \left[1 - K_{y,i} \left(1 - \frac{ET_{c,eff,i}}{ET_{c,max,i}} \right) \right] \quad (5)$$

where Y_a and Y_m are respectively the actual and the maximum expected crop yield with and without water stress, while $ET_{c,eff}$ and $ET_{c,max}$ are daily crop evapotranspiration with and without water stress. K_y values are crop specific and may vary over the growing season.

In the ‘management module’, several irrigation strategies options can be set according to the specific user priorities (including the application of deficit irrigation strategies, see paragraph 2.3.3). In order to simulate different irrigation strategies and thus to control the timing and quantity of irrigation to apply, two basic parameters have been included in the model: i) the ‘management allowable depletion’ (MAD), a threshold value that can be taken respectively higher, equal or lower than p , in order to modify the irrigation timing according to the level of water stress allowed; ii) an ‘irrigation application coefficient’, which allows to modify the scheduled quantity of water to apply at any irrigation event. These coefficients can be set with different specific values under the various growth stages.

2.2.2 Multi-plot/crop management module (at farm scale)

The decision process must take into account different equipment, resource and regulatory or human constraints: i) ‘equipment constraints’, such as maximum flow rate available due to pumping capacity or the maximum and minimum amount of water per irrigation cycle allowed; ii) ‘resource constraints’, such as a limited total amount of water for irrigation or a decreased flow rate during the irrigation period; iii) ‘regulatory or human constraints’, such as irrigation bans and/or fixed/flexible irrigation intervals to observe during the week, or farmer reluctance to work for all or part of certain days, etc. Additionally, the choice of whether or not to irrigate is improved by taking advantage of short-term weather forecast information.

In HT-DSS, a specific ‘multi-plot and multi-crop management module’ has been created for the contemporary simulation of the crop water balance for all the ‘irrigated plots’, as dependent to the same water source (e.g. hydrant), and by considering available short-time weather forecasts. Once the complete set of model parameters have been chosen, measured climate data are used for daily computation of the crop water balance for each plot, while high-resolution weather forecasts allow to simulate a 3 to 7-days projected scenario, in order to put forward the day-by-day soil water balance. Then, a specific ‘dynamic optimizer’ (based on non-linear optimization models) supports the optimal setting of the irrigation priorities at the ‘multi-plot’ scale by taking into account water availability at the source and the level of water requirements and stress reached by each crop type, as well as the projected level of stress for the following days. The general conceptual structure of the ‘dynamic optimizer’ is described in the following Fig. 3 (Riezzo *et al.*, 2013; this issue).

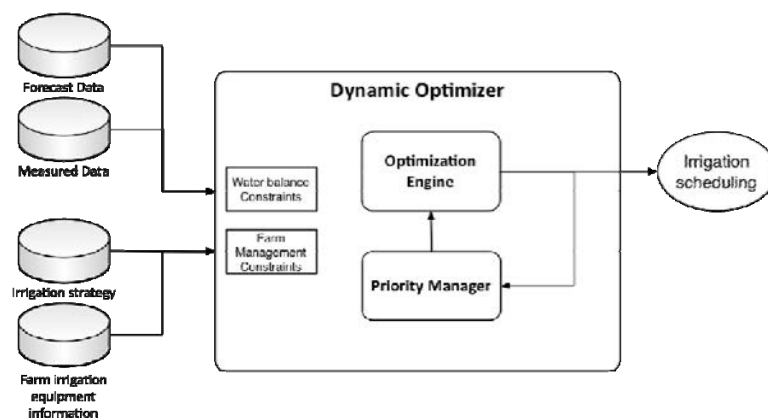


Fig. 3. Main structure of the dynamic optimizer’ module (from Riezzo *et al.*, 2013; this issue).

The model works by considering the number of plots irrigated from the same source and the number of forthcoming days for which climate forecasts are available. The specific irrigation planning is first elaborated for each plot separately. Then, the non-linear optimization model is considering the available timing of irrigation applications and amount of water to supply. The system of equations is based on the 'objective function' (Z) that has to be optimized under some specific 'constraints' (which define the field of activity of the optimizer). As an example, if the selected strategy is to reduce the overall amount of water applications to a minimum, the mathematical model is solved as:

$$\left\{ \begin{array}{l} \text{Minimize} \quad Z = \sum_{ij} t_{ij} x_{ij} \\ \text{subject to} \quad q_{ij}^{\min} \leq x_{ij} \leq q_{ij}^{\max} \\ \text{and} \quad D_{ij} \leq \beta_{ij} \text{RAW}_{ij} \end{array} \right. \quad (6)$$

where t is the time variable and x is the irrigation amount, and the sum refers to each i -th 'irrigated plot/crop' and to each j -th forecast day. Some 'physical constrains' can be considered, such as the possible fixed/flexible irrigation interval and/or the daily maximum (q^{\max}) and minimum (q^{\min}) amount of water available at the source. A second type of constrains are the 'farm management constrains', to take into consideration the level of water stress allowable for each crop; in its simpler form, if D is the depletion and RAW is the readily available water, the parameter β_{ij} could be lower or higher than 1, introducing a sort of MAD (Management Allowable Depletion) to consider the different sensitivity of crop response to water stress, depending on the phenological stages, as well as the possible economic consequence of yield loss. Physical and management constraints have the role to define respectively the 'upper' and the 'lower' limit of the water that could be supplied.

A 'flexible' model parameterization is allowed by the number of variables and equations that could be selected, in order to define a specific system of equations for each farm case. The system has been designed to consider also the case in which the 'optimal solution' cannot be found (for example for an excess in daily crop water requirements with respect to the effective water availability). In this case, the priorities among plots are established as a function of the different sensitivity or level of water stress between crops/plots, the day of the last irrigation and the amount of water to supply. Then, the optimizer is able to find 'sub-optimal' solutions, ensuring the planning in all conditions.

2.3. Further on-going improvements of the model

2.3.1 Correction of the K_c values in relation to local climate and crop characteristics

The 'single- K_c ' approach as applied by the HT-DSS (paragraph 2.2.1) provides a simple, convenient and reproducible way to estimate E_{Tc} , and tabular values of K_c have been reported for a wide variety of agricultural crops. The standard values of K_c and length of stages are inserted in the HT-DSS 'crop database'. Nevertheless, further adjustments of mid and late-season K_c values to local climate conditions can be considered as a function of humidity, wind speed and crop height, according to the following equation (Allen *et al.*, 1998):

$$K_{c_{\text{mid/end}}} = K_{c_{\text{tab}}} + [0.04(u_2 - 2) - 0.004(\text{RH}_{\min} - 45)](h/3)^{0.3} \quad (7)$$

where $K_{c_{\text{tab}}}$ is the corresponding tabular value, u_2 and RH_{\min} are respectively the average wind speed and minimum relative humidity during the period, and h is the height of the crop.

Additionally, the crop specific vegetation amount is highly variable depending on the local cropping system (variety, planting density, pruning system, etc.), so that substantial uncertainties still exist for using K_c tabular values. For this reason, a density factor (K_d) has been introduced by Allen and Pereira (2009) that allows for adjusting K_c by a physical description of the vegetation based upon the fraction of ground covered by vegetation and its height, as:

$$K_d = \min \left(1, M_L f_{\text{eff}}, f_{\text{eff}}^{\left(\frac{1}{1+h}\right)} \right) \quad (8)$$

where f_{eff} is the effective fraction of ground covered or shaded by vegetation near solar noon (dependent on specific canopy shape, plant height and solar angle above the horizon), h is crop height and the M_L parameter is a multiplier (1.5-2) that can be used to simulate the physical constraints imposed to evapotranspiration by some restrictive conditions, and it is modified to fit crop specific conditions.

Because both the fraction of effective ground cover and plant height are relatively easy to estimate in the field, the methodology seems to be effective in order to improve the reliability of K_c values used for each specific cropping system. Allen and Pereira (2009) presented a comparison of crop coefficients computed from K_d with those reported in the literature for measurements in orchards and grapes, showing a satisfactory agreement. Other approaches are available in literature using ground cover data to estimate K_{cb} or K_c (e.g. Ayars *et al.* 2003; Goodwin *et al.* 2006; Villalobos *et al.* 2009) confirming the linear correlation with f_{eff} . Thus, a similar methodology is currently under implementation in the HT-DSS, in order to allow 'adjustments' of K_c values with local biometric measurements.

2.3.2 Detailed phenological stages and sensitivity to water stress

For a further improvement of the K_c curve and to consider the variable sensitivity to water stress of different phenological stages (PS), the following modifications are currently under evaluation: i) the increase in the number of crop stages and, thus, of K_c , to allow a better correspondence to the most relevant PS for each specific crop; ii) the integration of a 'phenological model' allowing to predict the timing of the occurrence (start and duration) of each PS, based either on the GDD model (equation 1, if crop/variety specific information are available) or on standard 'tabular values' (that can be further modified by the user by inserting local observations); iii) the definition of the relative sensitivity to water stress for each PS according to existing scientific literature (e.g. Steduto *et al.*, 2012) and by setting the most appropriate values of parameters K_y (equation 5) and/or β (equation 6) for model simulation.

Variable number of crop growth stages have been yet suggested by Raes *et al.* (2006) when modeling K_c variation or considering sensitivity to water stress in different stages. As an example, for annual grain crops Todorovic (2006) extended the number of growth stages up to seven distinguishing between pre- and post-emergence stage, early and late vegetative stage, flowering, yield formation and senescence (Fig. 4). Once the crop specific 'key' phenological stages have been modelled, it is possible to consider more accurately the stronger/weaker sensitivity to stress with an easier application of the variable β factors for a more detailed application of the MAD threshold (equation 6) in irrigation scheduling, as well as the multiplicative approach (equation 5) to predict the impact of water stress on yield (FAO Water, on-line).

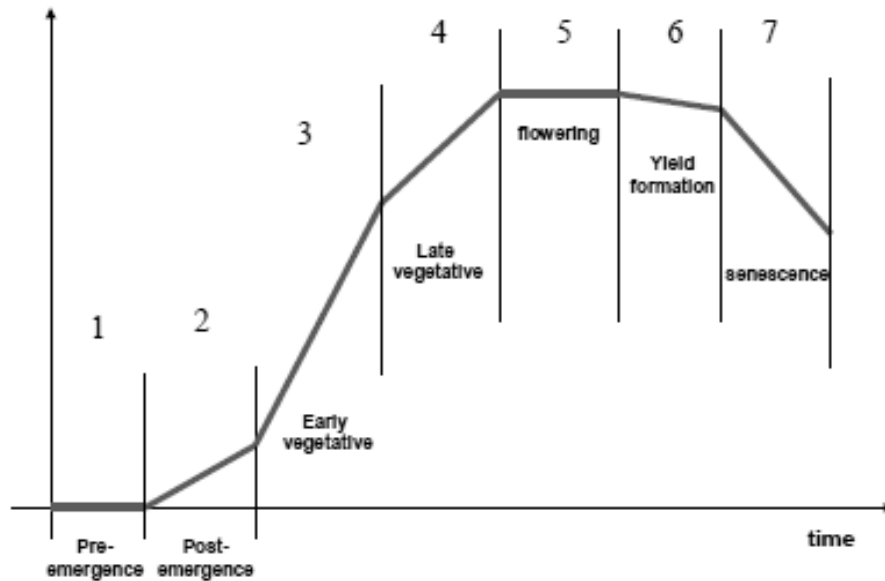


Fig. 4. K_c curve with increased number of stages, as suggested by Todorovic (2006) for a typical grain crop.

2.3.3 Deficit irrigation to support water saving

If it is not possible to supply the amounts needed to meet maximum ET_c , irrigation supplies should be planned in order to have plant water deficits during stress-tolerant periods of the season. Moreover, there are some cases where it is possible to actually exploit the positive responses to water deficits to improve fruit quality, and thus growers would profit from both higher gross revenue and reduced water costs (Ferreles *et al.*, 2012).

Under these conditions, the so-called 'deficit irrigation' (DI) technique could be applied by means of two alternative strategies: i) in the 'continuous or sustained' DI (SDI), a constant fraction of the crop ET is applied at regular intervals, the soil is progressively depleted and the water deficits increase with time in the absence of rainfall; ii) in the 'regulated' DI (RDI), water stress is confined at specific developmental stages that are considered to be the least sensitive to water deficits, with the goal to have little negative impact on the yield of marketable products and on gross profits (Ferreles and Soriano, 2007).

Both SDI and RDI strategies are currently under implementation and testing in the HT-DSS, through an appropriate configuration of the 'management parameters' of the model (par. 2.2.1 and 2.2.2) together with a detailed description of the phenological crop development (par. 2.3.2).

2.3.4 Pedo-transfer function for soil parameters estimation

The amount of water remaining in the soil at saturation and field capacity varies with the soil texture, organic matter content and structure. The clay and organic matter content of a soil horizon predominantly define its soil water content at permanent wilting point. The user can make use of indicative values provided by HT-DSS for various soil textural classes, or import locally determined or derived data from soil texture with the help of pedo-transfer functions (e.g. Saxton and Rawls, 2006); the indicative values for the soil hydraulic characteristics can be updated and soil types can be added or removed from the 'soil database'.

2.3.5 Additional model functions

Additional model functions (not described in detail in this paper) are under further development, in order to: i) allow to simulate the use of saline water for irrigation; ii) estimate crop 'eco-efficiency' as the ratio between the product added value and its relative water, nutrient and energy consumption; iii)

integrate a 'nutrient management module', for the management of fertilization/fertigation and to estimate the risk of nutrient leaching below the root zone.

2.4. Soil moisture monitoring with 'capacitance' sensors

At 'plot' scale, the continuous monitoring of soil moisture enables the HT-DSS to further support the application of 'closed-loop' irrigation control strategies by setting irrigation timing and amount in order to reach a specific soil moisture content (McCarthy *et al.*, 2011). Additionally, soil moisture readings are also useful to support the site-specific calibration of model parameters, in order to reduce the differences between simulated (model) and measured (sensor) data.

Instruments to determine either the soil water content or tension were developed long ago (e.g. tensiometers, gypsum block), although in the last decade techniques have become more sophisticated with the improvements in electronics. Sensors based on measuring the dielectric properties of the soil to infer the volumetric water content (VWC) are currently becoming popular for both research and practical applications, and they are based on two main approaches, the time domain reflectometry (TDR) and the frequency domain reflectometry (FDR) (Evelt *et al.*, 2012; Pardossi *et al.*, 2009).

For HT-DSS application, two types of FDR (or 'capacitance') sensors have been chosen for integration and field testing: i) the sensors of Decagon's ECH2O series (Decagon Devices Inc., USA), and more specifically the 10-HS type (measuring VWC) and the 5TE (measuring VWC, temperature and electrical conductivity), that have been connected by specific data-loggers (Riezzo *et al.*, 2013; this issue) for the continuous remote monitoring of soil moisture at different soil depths (Fig. 5, left); ii) the PR2 profile probe (DeltaT Devices Ltd, UK), for the use by technicians and end-users for periodic monitoring of the soil water content along the profile (Fig. 5, centre).

HT-DSS allows to display the real-time soil water content as measured by sensors, in order to support the irrigation decision process by also considering the water extraction trends. As suggested by Fereres *et al.* (2012) (Fig. 5, right) if a sensor is positioned at the shallow depth (20-30 cm deep) while another one deeper (50-60 cm or more, depending on root system depth), the soil water fluctuations in the shallow depth (dotted line) will show the typical responses to irrigation applications followed by fast extraction; instead, for the deeper sensor (solid line): i) the top example indicates insufficient water application based on the decline of soil water content (deficit irrigation); ii) the graph in the middle shows an increase in soil water which indicates excessive applications; iii) the third graph at the bottom represents a pattern indicative of adequate irrigation applications.

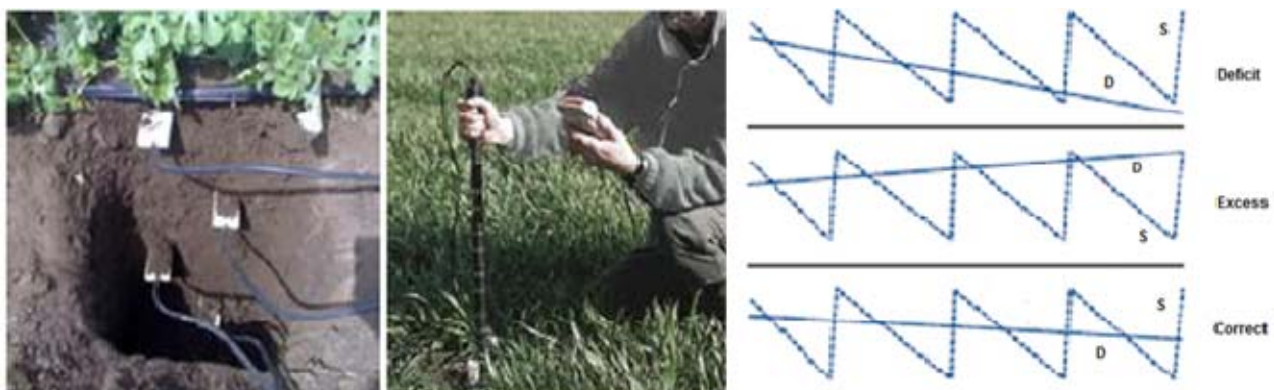


Fig. 5. Left: an example of the positioning of ECH2O Decagon sensors at different soil depth along the profile. Centre: DeltaT PR2 probe inserted in appropriate access tubes for recurrent soil moisture profile readings. Right: schematic representation of the soil moisture content at the shallow (S) and deeper (D) sensor position, respectively under deficit (top) or excess (middle) or correct (bottom) water applications (from Fereres *et al.*, 2012).

3. FIELD TESTING AT FARM LEVEL

In this chapter, a general overview is presented about the on-going experimental and demonstration activities of the HT-DSS in different farms of the Apulia Region (Italy), and examples of application include typical fruit orchards, olive groves, vineyards and vegetable crops grown under semi-arid Mediterranean environments. Preliminary results are also briefly introduced for the case-study of an intensive peach orchard.

3.1. Setting up the experimental activities at farm scale

As summarized in Table 2 and Fig. 6, nine farms have been selected in the Apulia Region to host the project experimental activities (for a total of 10 crop types and 20 'irrigated plots') and these farms are significantly different in terms of pedo-climatic conditions, crops, total surface, level of organization and technical assistance, in order to test the HT-DSS under different environmental and management conditions.

In each farm, a weather station has been installed for the site-specific acquisition of climate variables as required by the model to estimate reference evapotranspiration. Additional climate data are also automatically acquired by the HT-DSS from the public agro-meteorological service, based on a wide-spread regional network of field stations, by which the HT-DSS automatically 'compensate' some possible failures in data records by the on-farm station (Fig. 6).

After the preliminary selection of the 'irrigated plots' where the experimental activities have to be carried out, the basic information on farm configuration have been acquired, to describe the irrigation system design (hydrant discharge, number of irrigated plots and areas, sprinkler/drippers spacing and discharge, etc.) and the possible physical constraints (maximum and minimum volumes for each irrigation, fixed/flexible intervals) and management constraints (according to farmers' objectives).

Table 2. List of farms and crops considered for the project experimental activity (2013).

N.	Farm name	Crop	Plot n.	Observational period
1	Cantine Due Palme	Grapevine (wine)	DP1, DP2, DP3	Spring - Summer
2	Soc. Agr. Amastuola	Grapevine (wine)	AM1, AM2, AM3	Spring – Summer
		Citrus (mandarin)	AM4, AM5	Autumn – Winter
3	Az. Agr. Caliandro	Grapevine (wine)	CA1, CA2	Spring – Summer
4	Az. Agr. Boccuzzi	Grapevine (table)	BO1	Spring - Summer
5	Soc. Agr. Moccari	Peach	AB1, AB2	Spring - Summer
		Artichokes	AB3	Autumn - Winter
6	Soc. Agr. Frasca	Olive	FR1, FR2	Spring - Autumn
7	Soc. Agr. Sempreverde	Potato	SV1	Winter – Spring
		Watermelon	SV2	Spring – Summer
		Vegetables	SV3	Autumn - Winter
8	Az. Agr. Gigante	Cherry	GG1	Spring – Summer
		Vegetables	GG2	Autumn - Winter

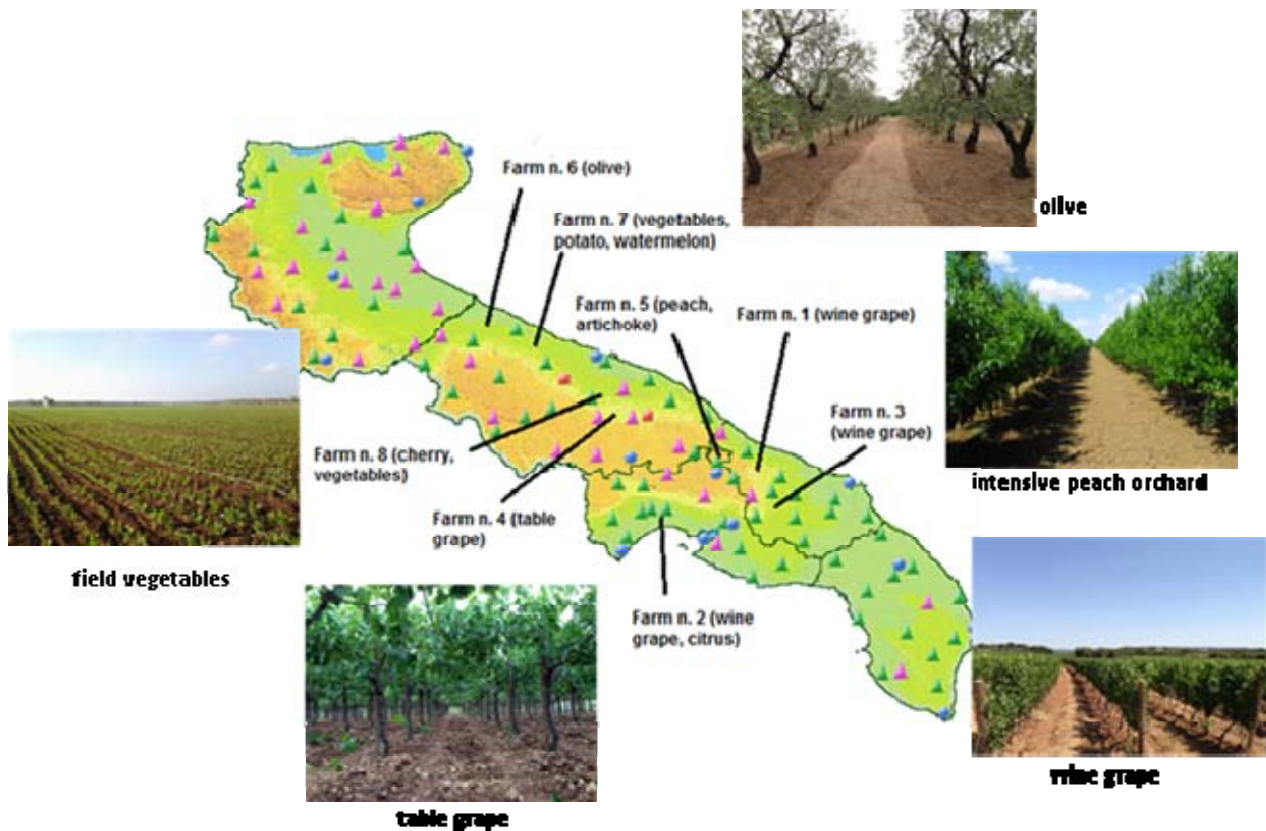


Fig. 6. Geographical location of selected experimental farms together with some representative pictures of different cropping system. In the map, the symbols refer to the network of the stations of the regional agro-meteorological service.

Soil samples have been taken in order to evaluate the basic physical soil characteristics as required by the model for the soil water balance simulation. The soil texture has been determined by the ‘pipette method’ and the corresponding texture class has been referred to the USDA classification. The soil retention curve has been determined for each plot on ‘undisturbed’ soil samples collected on the top soil layer (0.1-0.3 m), by means of the ‘suction plate’ method (Stakman *et al.*, 1969). Additionally, the basic soil hydrological properties have been estimated from basic soil data (texture, organic matter, gravel content, etc.) by means of the pedo-transfer function suggested by Saxton and Rawls (2006) (Table 3). According to the results, it is clear that the selected plots significantly differ in terms of textural class, percentage of gravel content, field capacity (ranging from 0.37 to 0.21), wilting point (from 0.23 to 0.06) and soil water holding capacity (from 0.10 to 0.19).

The following crop types have been considered: table and wine grapes, olive, peach, cherry, citrus, potato, vegetables, artichoke, watermelon. Specific crop parameters have been selected to run the model in each site. For each crop type, the most suitable planting dates, the values of depletion fraction (p), initial and maximum rooting depth, crop coefficient (K_c), length of development stages (L), maximum height (h) and yield response factor (K_y), have been done by considering FAO reference values (Allen *et al.*, 1998; FAO Water, online). The basic crop parameters for the model were initially set according to Allen *et al.* (1998) and Allen and Pereira (2009) as reported in Table 4.

Table 3. Textural classification and corresponding basic hydrological properties of some plots as determined by the pedo-transfer function method suggested by Saxton and Rawls (2006) (WP= wilting point, FC = field capacity, SAT = saturation, SWHC = soil water holding capacity).

Plot n.	USDA textural class	Silt	Sand	Clay	Gravels	WP (1500 kPa)	FC (33 kPa)	SAT (0 kPa)	SWHC
		(%w)	(%w)	(%w)	(%w)	(%v)	(%v)	(%v)	(%v)
BO1	silty clay loam	0,42	0,20	0,37	0,34	0,23	0,37	0,48	0,12
DP1	silty loam	0,50	0,32	0,18	0,20	0,13	0,29	0,46	0,14
DP2	clay loam	0,28	0,37	0,34	0,24	0,21	0,34	0,46	0,11
DP3	sandy loam	0,47	0,47	0,06	0,20	0,06	0,21	0,48	0,13
CA1	clay loam	0,44	0,23	0,33	0,11	0,20	0,35	0,47	0,14
CA2	loam	0,38	0,43	0,20	0,24	0,13	0,26	0,43	0,11
AM1	silty clay loam	0,51	0,20	0,29	0,53	0,18	0,34	0,47	0,10
AM2	clay loam	0,42	0,29	0,29	0,40	0,18	0,33	0,45	0,11
AM3	silty clay loam	0,51	0,16	0,33	0,10	0,20	0,36	0,48	0,15
AB1	loam	0,44	0,46	0,10	0,00	0,10	0,24	0,43	0,14
FR1	loam	0,47	0,32	0,21	0,01	0,14	0,29	0,44	0,15
SV1	silty loam	0,62	0,12	0,26	0,02	0,16	0,35	0,47	0,18
SV2	silty loam	0,68	0,06	0,26	0,03	0,16	0,36	0,48	0,19
GG1	silty clay loam	0,55	0,14	0,32	0,04	0,20	0,36	0,48	0,16
GG2	silty clay loam	0,59	0,13	0,28	0,03	0,18	0,35	0,47	0,17

In each plot, soil moisture has been measured by means of 4-6 Decagon's ECH2O sensors (10-HS and 5TE types), placed respectively in 2-3 positions in the field and at two depths (0.25 m and 0.50 m below the soil surface), and connected to specific data-loggers for the continuous remote data acquisition. Additionally, the DeltaTPR2 probe has been used by farm technicians for the weekly evaluation of the soil water content along soil profile in several access tubes (6-10) placed randomly in the plot.

In order to collect detailed data for the possible correction of the K_c values (par. 2.3.1) and the site-specific definition of the 'phenological stages' for the given crop/variety, both biometric measurements (crop height, percentage of effective ground cover) and phenological survey (according to the standard BBCH scale) have been done on a weekly basis, together with the acquisition of the basic agronomic information (e.g. planting density, pruning system, etc.).

Table 4. Crop parameters initially set in the model according to standard values suggested by Allen et al.(1998) and Allen and Pereira (2009).

n.	Croptype	Kc				h (m)	L (days)				planting date	Ky				Rd (m)		p
		ini	dev	mid	late		ini	dev	mid	late		ini	dev	mid	late	min	max	
1	grape (wine) (med. dens.; no ground cover)	0.3	0.7	0.7	0.45	2	20	50	75	60	Mar	0.2	0.7	0.85	0.4	1	1	0.45
2	grape (table) (high dens.; no ground cover)	0.3	1.1	1.1	0.85	2	20	50	75	60	Mar	0.4	1.1	0.8	0.4	1	1	0.35
3	olive (med. density; no ground cover)	0.6	0.6	0.6	0.55	3-5	30	90	60	90	Mar					1.2	1.2	0.65
4	peach (intensive; active ground cover)	0.8	1.2	1.2	0.85	3	30	60	120	30	Mar	0.4	0.9	0.8	0.4	1	1	0.5
5	Peach (super-int.; active ground cover)	0.8	1.25	1.25	0.85	3	30	60	120	30	Mar	0.4	0.9	0.8	0.4	1	1	0.5
6	cherries (med. density; no ground cover)	0.5	1.05	1.05	0.75	4	20	70	120	60	Mar					1	1	0.5
7	citrus (high density; no ground cover)	0.95	0.9	0.9	0.9	3	60	90	120	95	Jan					1.2	1.2	0.5
8	potato	0.5	1.15	1.15	0.75	0.6	25	30	45	30	Jan	0.2	0.8	0.8	1	0.2	0.6	0.35
9	vegetables (lettuce)	0.7	1	1	0.95	0.3	25	35	30	10	Oct					0.2	0.5	0.3
10	artichokes	0.5	1	1	0.95	0.7	20	25	250	30	May					0.2	0.9	0.45
11	watermelon	0.4	1	1	0.75	0.4	20	30	30	30	Apr					0.2	0.8	0.4

3.2. Preliminary results on intensive peach orchard

As an example of preliminary results, the case of the peach orchard (Farm n. 5) is considered. The farm is located in Mesagne (BR), with latitude 40.56, longitude 17.84 and altitude a.s.l. 52 m. The selected plot (AB1) is of about 3 ha, cultivated with an intensive 7-years old peach orchard, medium-late maturing variety, with planting spacing of about 4.5 x 4 m, and an average plant height of 3 m. The soil is a loamy textured type, without gravels, with a maximum depth of 0.70 m (from soil survey). In the top layer (0-0.3 m), volumetric water content at saturation, field capacity and wilting point are respectively of 0.43, 0.24 and 0.10, with a corresponding estimated holding capacity of 140 mm m⁻¹. The plot is irrigated as a whole, connected to an hydrant with a discharge of 50 m³ h⁻¹, by means of two drip lines for each row, with a correspondent calculated irrigation intensity of about 1.67 mm h⁻¹.

Crop parameters have been set as reported in Table 3, and specifically as suggested by Allen and Pereira (2009) for a 'high density' orchard with an effective ground cover of 0.7 (that corresponds to the maximum f_{eff} as determined in the field during our surveys). The phenological calendar has been established for the specific variety according to the information provided by the farmer and adjusted according to field weekly observations. The simulation has been done considering the climate data as recorded by the on-farm weather station up to the 24th of August (in Fig. 7, the successive days refer to the historical series as provided by the regional agro-meteorological service). A specific regulated deficit irrigation (RDI) strategy has been planned with the HT-DSS following the suggestions for peach by Girona and Fereres (2012), through an appropriate selection of model parameters in relation to the specific sensitivity to water stress

for each stage (Fig. 7, top). In the case of stone fruits (like peach), it is well known that periods of floral development and fruit set are very sensitive to water deficits, and thus damaging water stress should be avoided during ‘flowering’ and stages I and III of fruit development (respectively early fruit development and late fruit enlargement), while some moderate stress could be allowed during stage II (intensive vegetative growth, stage of pit hardening for fruit), that could be also useful to control an excessive vegetative growth and to improve fruit quality without a yield penalty. Some additional water savings could be also obtained during the postharvest period, provided that severe water stress is avoided.

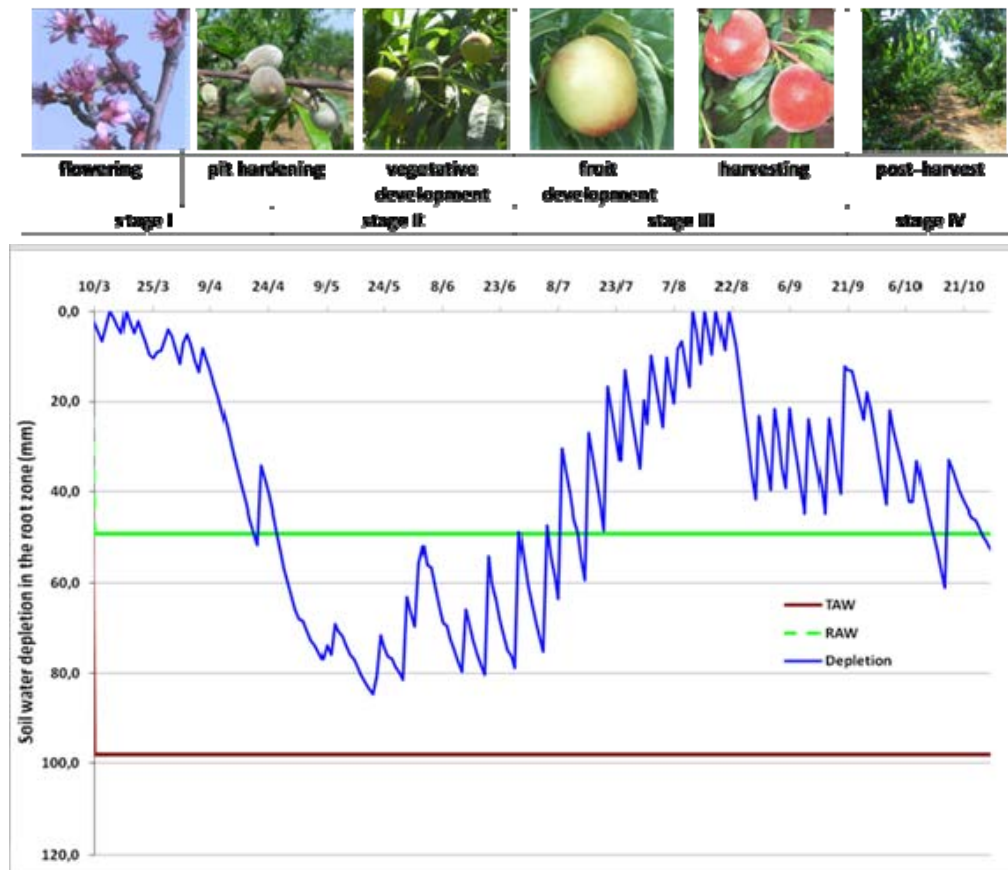


Fig. 7. Graphical representation of the main peach phenological stages (top of the figure) and corresponding trend of the soil water depletion in the root zone as simulated by the HT-DSS (bottom).

From the beginning of the cropping season and until the end of July, the farmer has irrigated constantly according to the timing and amount suggested by the HT-DSS, resulting in the following model simulations (Fig. 7): i) unstressed conditions during the flowering and early fruit development (stage I) due to the sufficient water stored in the soil profile during the winter season, so no irrigations have been required; ii) a moderate water stress during the stage II of crop development, with the start of the irrigation season scheduled at the end of May; iii) a fast recover of the unstressed conditions during the stage III, with an irrigation interval of 4-5 days and with amounts of about 30-35 mm per each application. The trend simulated by the model has been substantially confirmed by the correspondent variation in the soil water content as measured by both type of soil moisture sensors (ECH2O and PR2 probe), and resulting initially in the decrease of the water content, and then in its recovery up to a relative stability at levels of 0.20-0.24 (data not shown).

Then, during the month of August, the irrigation scheduling has been modified according to the ‘usual’ farmer’s practice, resulting in a higher frequency and amount of applications, and this over-supply has resulted in both a higher simulated deep percolation and in a steadily increase in the soil water content as

recorded by the sensors. In Fig. 8, the data recorded from the ECH2O sensors show that during the month of August there was a clear trend in increasing the soil water content in the deeper layer above the level of field capacity, thus confirming the occurrence of excessive applications.

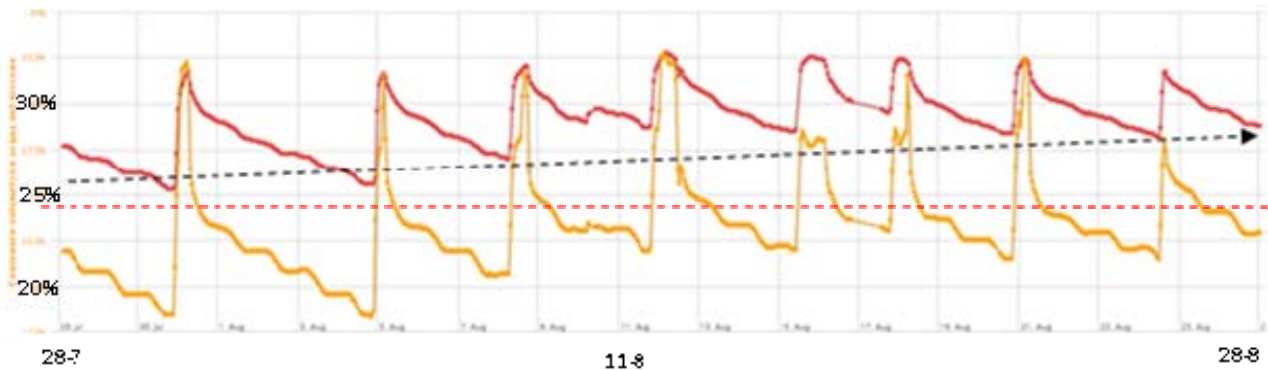


Fig. 8. Soil water content in the root zone as measured by the Decagon 5TE sensor, respectively at a depth of -0.20 m (yellow line) and -0.50 m (red line); the dotted-red line refers to the field capacity (as estimated for the top layer), while the dotted-grey line indicates the trend in increasing the average soil water content in the bottom layer under conditions of excessive water applications.

4. CONCLUSIONS AND PERSPECTIVES

The wide ‘on-going’ experimental activity of the HydroTech project is expected to provide significant experimental data and field evidence of the ‘strengths’ and the ‘weaknesses’ of the overall approach of the HT-DSS system (in relation to both software and hardware components), as well as of the ‘risks’ and ‘opportunities’ related with their application at farm level.

Nevertheless, the increasing experience gained at regional level with different type of farms, is confirming that support tools and DSS for irrigation scheduling are effectively required by growers and technicians who are looking for more precision in farm management, towards the primary objectives to achieve greater revenues (conserving water, reducing inputs and increasing net profit, in relation to water and energy costs) as well as to fulfill the mandatory regulations concerning environmental issues (e.g. limitations in groundwater extraction or protection of aquifers from nitrate pollution).

In the case of most horticultural crops (field vegetables and fruit trees), important water savings have been observed when comparing the current farmer practice with the DSS-based scheduling. In other cases (such as cherries or wine grapes), the issue of product ‘quality’ in relation to water regime seems to be of higher relevance, and the scientific knowledge should be effectively integrated with the local experience in crop water management, to design the best suited DSS according to the farmer’s perspectives.

5. ACKNOWLEDGEMENTS

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