Portfolio of methods developed in OPERA to improve irrigation

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OPERA consortium members

	OPERA Consortium partners	Short name
1	Wageningen Environmental Research (Alterra), The Netherlands	WENR
2	Stellenbosch University (SU), South Africa	SU
3	Evenor Tech (Evenor), Spain	Evenor
4	Instituto de Recursos Naturales y Agrobiologia de Sevilla (IRNAS – CSIC), Spain	IRNAS
5	French National Institute for Agricultural Research (INRA – EMMAH), France	INRA
6	University of Florence (UNIFI – DISPAA), Italy	UNIFI
7	Council for Agricultural Research and Economics (CREA) – Research Centre for Policies and Bioeconomy (CREA-PB), Italy	CREA
8	Institute of Technology and Life Sciences (ITP), Poland	ITP

Table Content

Summary

One of the challenges encountered in European agriculture is to improve the efficiency of water use in irrigation and to cope with increased water demand and a decline in (or more variable) water resources. In OPERA we aim at developing improved approaches based on different levels of innovation such as using models to better assess soil water content, remote sensing to characterize the vegetation status and take profit of the new capabilities of the recent satellite missions, and ensemble weather forecasts to account for uncertainties of this meteorological forecast. Six methods are developed in OPERA:

1. *Agroclimatic and remote sensing based Indices* developed by EVENOR Spain and implemented in the case of olive trees. The aim is to improve their characterisation and propose indices combinations to improve irrigation recommendations.
2. *Plant-based irrigation method* developed by IRNAS-CSIC Spain implemented for olive trees. The irrigation needs are assessed using stomata conductance modelling and thus better take into account the plant control of the transpiration.
3. *The APSoMoCo method* (Accurate Predicted Soil Moisture Content) based on soil-crop modelling developed by WENR (the Netherlands) implemented for a field crop (potatoes). It is based on the use of a soil-crop model and ensemble weather forecast to provide soil moisture forecast and associated uncertainties.
4. *The CROPIRR method* based on crop modelling developed by ITP Poland implemented for a field crop. It is based on the use of a crop model and meteorological forecast to provide soil moisture.
5. *The IRRICROP method* based on remote sensing and the crop model developed by UNIFI on field crop (tomato, corn). The method intends to improve the IRRISAT tool, already operated for commercial application, by adding an assessment of the soil moisture using the AquaCrop model and ensemble meteorological forecast to address uncertainties in the forecasts.
6. *Irrigation requirements at the territory level* method based on a crop model and remote sensing developed by INRA on a large variety of irrigated crops (grass, orchard, gardening, field crop, vineyard, olive trees). The method aims at mapping actual irrigation water needs at the level of an irrigated sector.

These methods are mostly designed for farmers, but they can be up-scaled and thus be of interest to a wider range of users as administration and water association.

The objectives of this deliverable are i) to identify the methods developed by specifying their context of use, the principle of the method and the innovation targeted, the conditions of implementation and ii) put in place a shared approach to evaluate the relevance of the methods produced.

1 Introduction

One of the challenges encountered in the territories is to improve the efficiency of water use in irrigation to cope with growing needs and a declining or more variable water resource. Such a situation is accentuated in the context of global changes with a stronger demographic pressure and climate change. Improving irrigation can be done either by playing on the water application techniques or by optimizing its use and reducing losses. In OPERA it is essentially on this second axis of improvement that we have focused.

Methods for scheduling irrigation have been the subject of much research and innovation in the past. Beyond the farmer's expertise, we can consider that the current standard is to control irrigation based on an estimate of the climatic demand (ET_0) and the development of the vegetation cover. Many service companies have invested in this field. Some estimation methods rely on sensors that characterize the water status of the soil (tensiometer, watermark probe, capacitive probes) or vegetation (diameter of fruits). If the ideas of using such sensors are old, their implementations in an agricultural context, the analysis of the signals and the formalization of the decisions remain a difficulty not always mastered, which would explain the absence of generalization of their use.

In OPERA, we aim at developing improved approaches based on different the following levers of innovation as developed in the initial proposal:

- Integration of different sources of information and models. Methods will integrate different sources of information and models (T2.2)
- Coupling RS (remote sensing) data and models. Use of high resolution satellite images (Sentinel and Landsat 8) with crop model (data assimilation, model input, model calibration) to provide spatial soil water content, plant requirements and assess the quality of irrigation implementation (T2.3)
- Use of in situ sensors to monitor vegetation status and development of upscaling strategies to account for heterogeneities at the field and the farm scale using models and remote sensing (T2.4)
- Implementation of ensemble weather forecast in crop models and errors assessments. (T2.5)

The definition of irrigation scheduling methods is very dependent on the context of application, which takes into account the cropping systems, the organization of the sectors and the management of the water resource and the tensions on the uses of water. In OPERA, the methods that have been developed are based on concrete cases from the pilot sites and the skills of the teams in charge of the developments. Note that the methods developed are not intended solely for irrigation management by the farmers at the plot scale, but also targets other levels of decision-making, such as water resources administrations and managers. The objectives of this deliverable are:

- To clearly identify the methods developed by specifying their context of use, the principle of the method and the innovation targeted, the conditions of implementation. Each model is presented in the form of a factsheet that allows internally and externally to clearly define the outline of the technical innovations in OPERA that falls under WP2.
- Put in place a shared approach to evaluate the relevance of the methods produced. This amounts to determining performance indicators and defining a benchmark representing the state of the art, against which the results will be compared.
- The methods formulated in this deliverable are currently being tested in the pilot areas / case studies under Work package 3.

2 Methods developed in OPERA

Six methods are developed by the partners of the project:

- M1 : Agroclimatic and remote sensing based Indices developed by EVENOR Spain and implemented Olive trees
- M2 : Stomata conductance modelling developed by IRNAS-CSIC Spain implemented on Olive trees
- M3 : APSoMoCo based on crop modelling developed by WENR the Netherlands implemented on field crop (potatoes)
- M4 : CROPIRR based on crop modelling developed by ITP Poland implemented on field crop
- M5 – IRRICROP based on Remote sensing and a crop model developed by UNIFI on field crop (Tomato, corn)
- M6 - Irrigation requirements at the territory level based on crop model and remote sensing developed by INRA on large variety of irrigated crops (grass, orchard, gardening, field crop, vineyard, olive trees).

The main characteristics of the methods are given in Table 1.

Table 1 Summary of the main characteristics of the methods applied in OPERA.

Method ID	Users	Model	RS*	Field Sensors **	EF***	Crops in OPERA and limitation
M1	Farmers, public administration		X			Olive (OPERA) should be calibrated for other crops
M2	Farmers, public administration	X	X			Olive (OPERA) should be calibrated for other tree production
M3	Farmers, water distributor	X		(x)	X	Potatoes (OPERA) all crops being modelled by SWAP-WOFOST
M4	Farmers, advisory services	X				Sugar beet, Parsley (OPERA) Can be applied to any crops
M5	Farmers, farmer's association, public administration	X	X		X	Tomato and Corn (OPERA) Limited to crop modelled by the AquaCrop model
M6	Irrigation association, public administration	X	X			Orchard, Grass land, gardening, Olive, Vineyard, field crop (OPERA) can be applied to any crop simulated by STICS or AquaCrop models

* Remote sensing
** Field sensors to assess crop water stress status involved in the method implementation
*** Ensemble Weather Forecast

2.1 Model

In irrigation scheduling it is important to take the water content of soils into account. Indeed, the only climatic demand does not take into account the available water quantity for the plant. To facilitate the organization of work and avoid over-irrigations leading to losses of water and nitrogen or under irrigation impacting the plant development, it is important to integrate the buffering capacity of the soil to establish an irrigation schedule and fix the doses. The water content of the soil can be measured directly but, as we have seen, the implementation of moisture measurements remains delicate in an operational context. The implementation of models representing the soil water balance is therefore an alternative.

The simplest models are limited to a soil water balance using a soil water balance including an representation of the evapotranspiration. In this case the vegetation status is an input data of the model that can be either estimated with remote sensing (M5, M6) or tabulated from reference on crops in a regional context (M4). This is the case of the approaches based on a crop coefficient (Kc) which links the crop water demand to the climatic reference ET0. The synthesis made by the FAO (Allen et al., 1998) provides an excellent basis to infer Kc and its dynamics for a wide variety of crops and climatic regions. The disadvantage of the Kc approach is that the tabulation of Kc lead to a plant development schedule that does not take into account the climate actually encountered. For example, the plant development is governed more by the sum of temperatures than the time elapsed. With regard to the use of remote sensing, the methods must rely on workflows ranging from image recovery, processing and incorporation into the models. With recent progress it can be considered that these operations are now facilitated. However, in some areas cloud cover does not allow enough images and the use of remote sensing is based on vegetation development proxies introducing uncertainties.

More advanced versions of crop models can simulate plant growth and development in interactions with water, nitrogen and carbon cycles. This is the case in OPERA with the use of the SWAP-WOFOST (Kroes et al., 2017; Boogaard et al., 2011) models used in M3 and STICS (Brisson et al., 1998; 2008) used in M6. The interest of these models is to be able to take into account feedback on production under irrigation and therefore work on strategies to optimize the efficiency of water use. The disadvantage of these approaches lies in the large number of parameters that are not accessible in an operational framework at the level of each agricultural parcel.

We therefore see that in the OPERA project, four of the six methods (M3 to M6) rely on the models to evaluate the soil water reserve, but with different models and implementation conditions. All methods share a common challenge that is the quality of the estimates of the soil water reserve in a context of strong uncertainty about the parameters, especially those linked to soil water balance, which have a strong impact on the results. The question will be whether the information provided by the model simulations, at least on the relative level, remains relevant for decision-making.

The M2 method also relies on modelling to represent more finely the evapotranspiration process by simulating the stomatal conductance by an ecophysiological approach. This makes it possible to better take into account the interaction with the climate. In addition, the method represents the coupling with photosynthesis to link irrigation strategies to production.

2.2 Remote Sensing

The use of remote sensing in agriculture is boosted by the Sentinel 2 mission that provides a real breakthrough. As a matter of facts, the frequent acquisition of the images (each 5 days), the high resolution (10 m), the global coverage and the spectral content of the measurements opens new avenues in the design of services to farmer. In addition, the traditional images processing, which in the past required skills in remote sensing, are now taken in charge by data centre and thus condition of remote sensing use democratisation is on the way. In OPERA, 4 methods are implemented with remote sensing to characterize the vegetation, either through a vegetation proxy (i.e. the normalized difference index (NDVI)) as done in

M1 or the leaf area index (LAI) used in M2, M5 and M6. In M6, satellite image are also used to localise irrigated crop identify them.

2.3 Sensors

A single approach in OPERA plans to rely on field sensors (M3). The challenge is to see if a measurement of the soil moisture would improve the prediction made by the model. Such sensors make it possible to readjust the level of the measured soil moisture and thus to have absolute values. However, soil moisture sensors needs field calibration and the representativeness of a measurement point is not always easy to grasp.

In M2, LAI measurement with a smartphone application is proposed as an alternative to remote sensing determinations.

If in other methods their implementation is not strictly dependent on field measurements, the acquisition of references to determine critical relationships may be necessary to specify them in relation to the crops concerned and the local environmental conditions. This is particularly the case in the M2 method or the calibration of the models is desirable. Such a calibration requires measurements in the field. For the other methods we can expect that uncertainties obtained on the simulated results would suggest to better handle key relationships.

2.4 Ensemble weather forecast

Using ensemble forecast approaches make it possible to address uncertainties on the climate forecasts. These are produced by meteorological models whose results vary according to the model, its initialization, the parameterization of the surface and methods of regionalization. It is therefore customary in the community of climatologists to work on a set of simulations to represent the future climate. This leads to simulate climate variables and uncertainties. In the case of applications and in particular those in the agricultural field, this climate variability is not taken into account. The goal in OPERA is therefore to propagate climate uncertainties in crop simulation models (M3, M5 and M6). The challenge will then be to develop recommendations that take advantage of knowledge of such a variability.

3 Evaluation

The evaluation of the methods developed in the OPERA project requires defining the performance criteria and a benchmark against which we want to compare our results.

The benchmark should represent the current practices followed by farmers in making their irrigation decision, but also the more elaborate methods currently available on the market. On this point, there is a consensus in the OPERA community to consider that the use of climate demand forecasting (ET0) combined with a characterization of crop specificity via parameter Kc has now reached a stage of maturity that has helped develop services currently available to farmers. The success of this method has been reinforced by FAO's publication (Allen et al., 1998), which offers many references for implementing it in a variety of contexts. Regarding farmers' practices, work will have to be done on each of the sites to formalize in the comparisons the decision taken by the farmer.

In the performance criteria we can distinguish the technical criteria related to the method that relies on quantities to make the decision and agronomic performance criteria. Concerning the technical criteria one can for example give the case of soil moisture in methods M3, M4 and M5, which is the information sought to help the farmer in his decision. These quantities, generally measurable, will be confronted with observations on the experimental sites implemented in the various pilot sites. Other variables such as stomatal transpiration and conductance measurements could be collected to evaluate M2.

The agronomic criteria cover gains in water consumption and yields, which remains the main objective of the farmer. The concept of Water Use Efficiency, defined as the yield divided by the quantity of water supplied, allows synthesizing the two types of criteria (yield, water consumption).

In M6, the goal is to address water consumption at the territory level. The identification of irrigated areas is a first step, which accuracy can be checked by field visits. Evaluation of the water needs can be assessed using record water flows at different level (channel, field).

Finally, end-user feedback (farmers, water resources managers …) remains an important point of the evaluation. It will have to report on the nature of the recommendations and their reliability.

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Appendix - Factsheets presenting the different methods

Summary

The developed method aims at providing irrigation requirement at the field scale to provide an objective assessment of the actual water need for olive orchards. The method is based on three approaches to estimate the water requirement at plot level using meteorological station and satellite image through agroclimatic indices. The method will be implemented in 8 commercial plots with the possibility to scale up the results.

Objective of the method

Implementation context: the surface water distribution is regulated by administration authorities or farmer associations following management rules and being distributed by hydraulic infrastructure. According to the expected increments in the atmospheric demand and decreases in the precipitation due to climate change, the use of deficit irrigation strategies is becoming an interesting solution to adapt to climate change while making agriculture more productive. The goal of the method to be implemented in OPERA is to provide calculation of tree water use for applying precision irrigation in crops to optimize water management based on three different approaches.

The water efficiency in agriculture has been highly studied. Traditionally, the use of agroclimatic indicators of climatic data provided by meteorological stations allows estimating the water requirements for the crop target. However, the recent studies by the satellite missions applied in agriculture allow estimations more accurate and specific for our plot and crop.

Irrigation system: The irrigation system is drip in a super-high-density olive orchard (*Olea europaea* L., cv. Arbequina), and the irrigation strategies depend of the water availability for the farmers. However, the soil infiltration characteristics, the stress level of the tree and climatic variables allow identifying critical periods and water requirements in different areas of our plot. These advances could allow the management of water more efficiency and reduce the cost for the farmers.

Users : The final outcome is a protocol of irrigation for farmers and managers at the farm level and a tool which can be used by public administration in relation to the regional water management. The expected actors involved in the implementation of the method are initially the farmers and orchard managers, but the information at the regional scale would be potentially useful for public administrations in the area of agriculture.

Method description

The method is based on the calculation of a set of indices derived from climatic data and remote sensing. Decision will be elaborated by combining the different indices, the combination methodology being part of the development work.

- *The "Traditional" approach* use meteorological data with several indices to estimate the water requirements (ET_0 = potential evapotranspiration) In addition, as added value, other variables will be calculated for the irrigation schedule (HUI= Humidity Index, IFM= Modified Fournier

Index, ICP= Precipitation Concentration Index, ARi= Index of Aridity; AKI= Arkley Index and LPC= Length of the Growth Period).

- METRIC (Evapotranspiration Mapping with High Resolution and Internal Calibration) is an evapotranspiration (ET) estimation model developed by the University of Idaho, USA. UU Allen et al. (2007a) and based on the SEBAL (Surface Energy Balance Algorithms for Land) model by Bastiaanssen et al. (1998). *The METRIC approach* use Landsat or Sentinel satellite and meteorological data providing Specific Evapotranspiration of crop target. Following the methodology of other works carried out (Allen et al., 2005, Allen et al. 2007a., Lorite et al. 2004a, Santos et al. 2007), through a geographic information system, the data of meteorological stations are introduced and are related to the satellite image. The relation is produced with the band that shows thermal information of the satellite image. Each pixel of the thermal band is assigned the values of the climatic stations.
  The final result is daily values of ET measured in mm / day, and that have been obtained by combining climatic data of meteorological stations and data from satellite images.
- The NDVI-Csw method is useful for managing the water resources of Mediterranean olive groves but the spatially fragmented and two-layer nature of the olive groves requires a separate estimate of NDVI for trees and grasses, which can be obtained by applying appropriate statistical operations to images satellites with different space-time properties. The crops coefficients (Kc) can be obtained from data obtained by remote sensing and combined with daily potential evapotranspiration estimates for the operational prediction of real evapotranspiration (ETA). Calculation of actual transpiration (TrA) and evaporation (EvA).

  TrA = ET0 x FVC x Kc veg x Cws
  EvA= ET0 x (1 – FVC) x Kc soil x AW

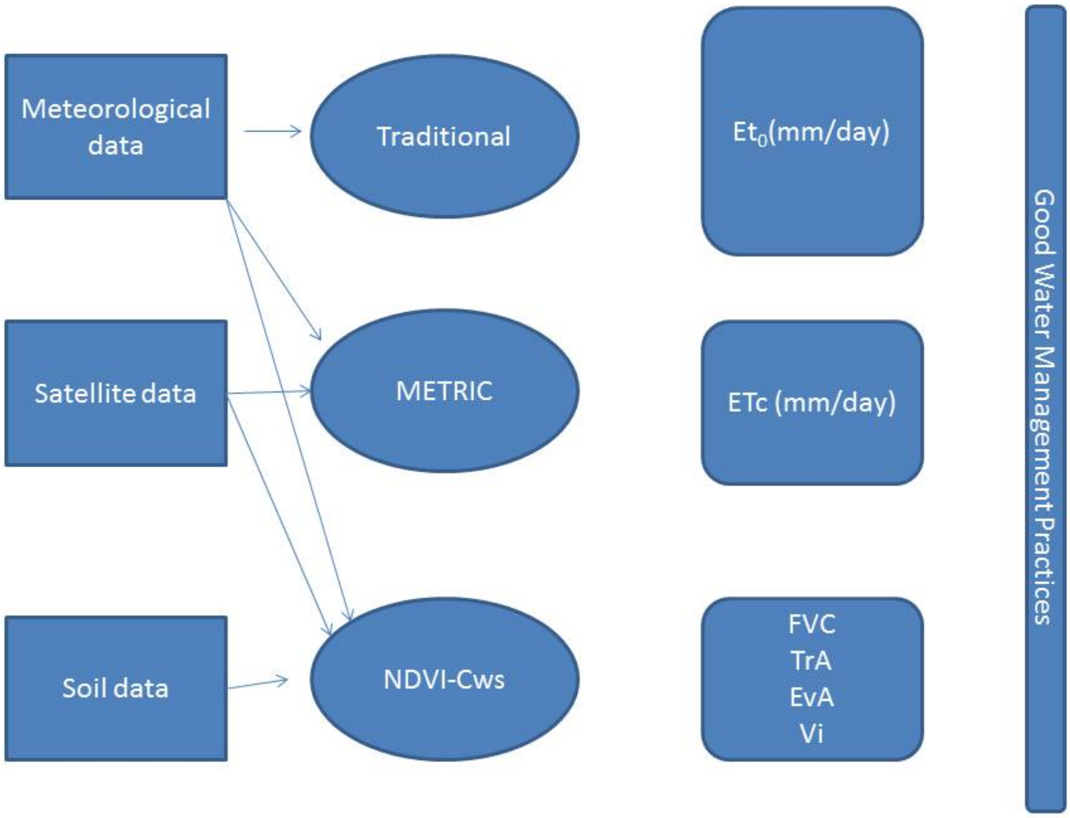
  Where:
  - FVC= Fractional green vegetation cover derived from NDVI data
  - Cws= Short term water stress factor, is defined for woody and non-woody plants according to Maselli et al. (2009, 2013): Cws = 0.5 + 0.5AW (AW, the water available, is the relationship between precipitation and potential evapotranspiration, both accumulated for two months for trees and one month for pastures.) As AW is established when the precipitation exceeds ET0, Cws can vary between 0.5 (when there is maximum water scarce) and 1 (when there is no water scarce).
  - KcSoil= maximum Kc of the soil, variable according to soil properties and humidity (Allen et al., 2005). A low value of KcSoil (0.2) can be used to guarantee the general applicability of the method.

  Total ETA of the olive grove is obtained by adding TrA and the corresponding EvA estimates.
  Using the ETA value, the water content in the soil is predicted from the following equation (Gardin et al., 2014):

  $Vi = Vi_{-1} + Prec\ i – ETAi –Dpi$

  Where:
  - Vi = water content of water in the soil
  - Preci = Precipitation

- ETAi = Real Evapotranspiration
- Dpi = Deep percolation or runoff (assumed equal to the output that occurs when the water exceeds the maximum water retention capacity in the soil)



Innovation : the main innovation of the proposed methodology is the combination of different approach using image satellite, soil data and meteorological data. If the farmers need more precision for their crops, the combination is necessary to downscale of information provided by satellite and drone images. With this methodology we will provide different approaches according to the needs and requirements for the farmers. The use of different methodology provides data updated every three days, according to the satellite data, at plot level.

Requirements :

Input Type	Variable identification and metric	Temporal and spatial scale	source of data
Climate	Precipitation (mm), Air temperature min and max (°C), Wind speed (m/s), Vapor pressures (mbar), Solar radiation (MJ/m^2) PET (mm)	Hour and Daily – spatial unit	Regional Agricultural Government and National Environmental Government
Soil	% Clay % Sand Field capacity Dry Bulk density Permanent wilting point	Spatial unit	Soil map of Andalusia 1:400.000 and soil samples

Vegetation	NDVI, NDWI	Spatial unit	Landsat 7 and 8 Sentinel 2A and 2B
Agricultural practices	Crop type and variety Irrigation (rules or calendar)	l/h	Local expertise

Frequent remote sensing images in the optical domain and other spectral domain are mandatory (Sentinel and Landsat).

Maturity : Every approach is supported by previous works applied in different areas and crops. The traditional approach has been very extensive used and, in the OPERA project, we will build on the methodology published by Bautista et. al, (2014) in the development of CLIC-MD. According to the others approaches, METRIC has been applied in the Andalusia region (Allen et. al, 2007a; Glenn et. al. 2010; Lorite et.al. 2004a; Santos et. al. 2007) with other crops and there are similar works with olive orchard and NDVI-Cws has been applied with olive orchard in the Mediterranean area (Maselli et. al. 2009; Maselli et. al. 2013; Maselli et. al. 2014). The goal in OPERA is to refine every methodology in our case study and identify key variables to scale the results to European level.

Method Evaluation

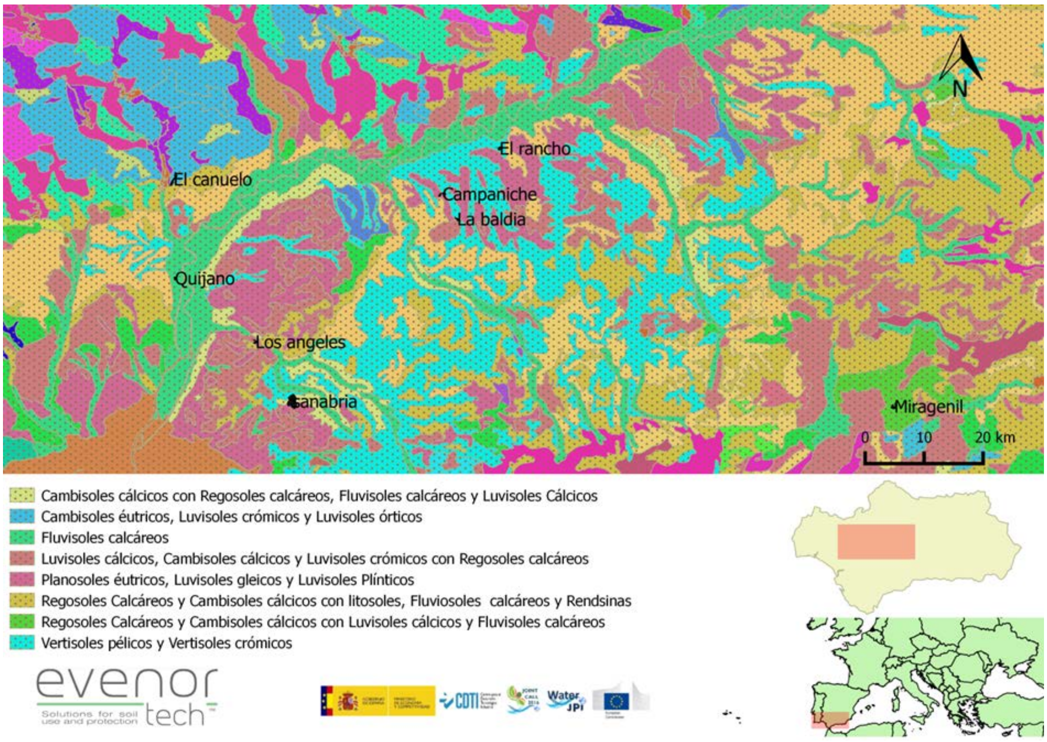
Performance indicator: The main output will be the evaluation of irrigation needs. This can be evaluated at the field level using farmer records by using the monitoring data collected of satellite image.

Benchmark: At present, the farmers use weather forecast and recommendations of agricultural cooperatives for irrigation schedules.

Evaluation framework implemented in OPERA: The methods will be implemented and evaluated in commercial plots in the Andalusian area. The selection was made on super-high-density olive orchard in Andalusia according to soil type, lithology, climate and management. A total of 8 commercial plots have been selected. One of them located 25 km to the south-east of Seville, Spain, the trees are planted in a configuration of 4 m x 1.5 m (1667 trees ha^{-1}) at the top of 0.4 m high rides oriented N-NE to S-SW where several tree and soil sensors have been installed and operated by IRNAS-CSIC. The other 7 plots have been selected and we will take soil samples in summer. The validation and calibration of models could be evaluated with Sanabria plots where tree sensors have been installed.

Name	Soil	Lithology	Management
Quijano	Calcium Fluvisol	Sands, silts, clays and edges	Super intensive (4x1.5)
Los ángeles	Calcium Fluvisol	Sands, silts, clays and edges	Intensive (8x4)
El cañuelo	Calcareous Regosols and Calcium Cambisols	Calcoesquist slates, limestone, quartzite and conglomerates	Intensive (7x7)
La baldía	Pellic Vertisols and Chromic vertisols	Conglomerates, sands, shales and limestones	Intensive (1.5x7)
Campaniche	Pellic Vertisols and Chromic vertisols	Conglomerates, sands, shales and limestones	Intensive (7x5)

El Rancho	Pellic Vertisols and Chromic vertisols	Calcarenites, sands, marls and limestones	Intensive (8x4.75)
Miragenil	Calcareous Regosols and Calcium Cambisols	Sands, silts, clays and edges	Traditional (10x10)



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Summary

This Case Study is focused on the Andalusian olive crop. To this IRNAS-CSIC, the Institute of Natural Resources and Agrobiology together with the Technology Based Company Evenor-Tech will are the responsible of the present method at the farm level and at the territory level respectively. This document is focused on the methods used at the farm level.
The goal of the method to be implemented in OPERA is to provide calculation of tree water use for applying precision irrigation in crops to optimize water management based on physiological knowledge. Irrigation is applied by drippers and we will use a regulated deficit irrigation strategy. The method is based on the estimation of stomatal conductance which is in the crossroad of CO_2 and H_2O fluxes. It allows us to estimate the accumulated photosynthesis in each individual tree which has been proven to be closely related to fruit growth and oil synthesis. A microclimatic weather forecast for our site is provided and used for programming irrigation 3 days in advance. Remote sensing data will help us to understand the spatial heterogeneity and the temporal heterogeneity of some key parameters like LAI and photosynthetic capacity. The final outcome is a protocol of irrigation for farmers and managers at the farm level and a tool which can be used by both farmers and public administration in relation to the regional water management.

Objective of the method

Implementation context: In arid and semiarid regions of the world, water is a scarce resource which will become even scarcer by expected increments in the atmospheric demand and decreases in the precipitation due to climate change. However, water is central to achieve productive agricultural output. The use of deficit irrigation strategies is becoming an interesting solution to adapt to climate change while making agriculture more productive. Among the deficit irrigation strategies, regulated deficit irrigation (RDI) has proven to be really useful since it provides reduced irrigation in phenological periods in which water deficit has little effect on final yield and supplies 100% of water needs during the critical periods. This irrigation strategy reduces the amount of water used for irrigation without significantly penalizing yield. However, this strategy demands information on the water status of the trees especially during critical periods, to avoid severe stress that could affect yield negatively. Thus, the RDI strategy requires a reliable indicator to be able to accurately capture the plant response to drought. Among all the indicators of water stress in plants that have been evaluated so far in agriculture, both traditional (water potential, stomatal conductance, etc.) and those that have emerged in recent years (turgor potential, sap flow, dendrometers, etc.), one of the most suitable is the stomatal conductance (g_s). The goal of the method to be implemented in OPERA is to provide calculation of tree water use for applying precision irrigation in crops to optimize water management based on g_s simulations, which is a well suited water stress indicator and directly related to growth and yield, through its effect on tree water relation and photosynthesis. The recent progress on modelling g_s and on studying its drivers allows us to schedule a RDI strategy based on modelled g_s. We used a simplified version of g_s model tested for olive by Diaz-Espejo et al. (2012). Remote sensing information will help us to assess spatial heterogeneity in the orchard.

Irrigation system: The method will be implemented in a super-high-density olive orchard (*Olea europaea* L., cv. Arbequina) equipped with drip irrigation, but could be applied to any fruit tree orchard with a canopy well coupled to the atmosphere. The irrigation strategy used is a regulated deficit irrigation (RDI) with the aim of optimise the use of water. Each treatment involves three 12 m × 6 m plots in a randomized block design. Each plot has 24 trees, and measurements are made in the central 8 trees to avoid border effects. The control trees ($100C_{Kc}$ and $100C_{gs}$) were irrigated daily to replace 100% of the irrigation needs (IN). The irrigation system consists of a single pipe per tree row with three 2 L h^{-1} drippers per tree, spaced 0.5 m apart.

Users : the expected actors involved in the implementation of the method are initially the farmers and orchard managers, but the information at the regional scale would be potentially useful for public administrations in the area of agriculture.

Method description

Rationale of the method: We applied a regulated deficit irrigation. This strategy considers three periods over the course of the olive growing cycle during which the crop is highly sensitive to water stress. During these periods, irrigation replaces the crop water needs. Period 1 extends from the final stages of floral development to full bloom (second fortnight of April); period 2 takes place at the end of the first phase of fruit development (June); and period 3 is related to a period of approximately three weeks prior to ripening, after the midsummer period of high atmospheric demand (from late August to mid-September). Between periods 2 and 3 (late June-late August), the olive tree is highly resistant to drought (Alegre et al., 2002; Moriana et al., 2003; Iniesta et al., 2009; Fernández et al., 2013), such that irrigation is only applied twice per week, amounting to a total of ca. 20% IN for that period. From the end of period 3 to harvesting (end of October) ca. 40% of IN is supplied. Further details on RDI can be found in Fernández et al. (2013) and Hernandez-Santana et al. (2017).

The irrigation needs (IN) in the method implemented in OPERA are based on g_s measurements ($100C_{gs}$) and calculated daily based on a simplified version of the g_s model tested by Diaz-Espejo et al. (2012). Following this model, the diurnal dynamics of g_s is described by a hydraulic model in which the main drivers are the vapour pressure deficit (D), solar radiation (R_s) and tree leaf area. Assuming a perfect coupling between canopy and atmosphere, tree water consumption (E_p) is calculated as

$$E_p = g_{s,sun} \cdot A_{sun} + g_{s,shade} \cdot A_{shade} \qquad \text{(eq. 1)}$$

Where $g_{s,sun}$ is the stomatal conductance estimated for new, well-exposed leaves and $g_{s,shade}$, for those old leaves, more shaded ones. A_{sun} and A_{shade} are the leaf area of sun and shade leaves, respectively.

Stomatal conductance. The $100C_{gs}$ treatment is assumed to have a soil water content at field capacity. Therefore $g_{s,sun}$ and $g_{s,shade}$ represent the maximum g_s observed under conditions of 0 MPa of soil water potential and D<0 kPa. Any increase in D will decrease g_s according to the hydraulic model as it is represented in Fig. 1. PPFD is used mainly to filter out the night periods, since in our latitude most of days are sunny or with enough light to saturate g_s early in the morning (PPFD>500 μmolm^{-2} s^{-1}).

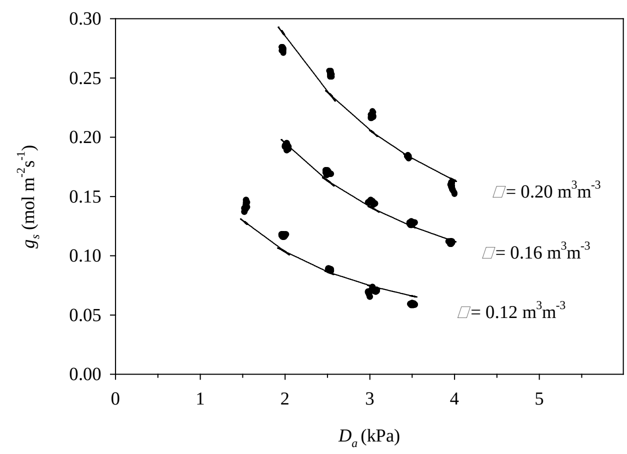

Figure 1. Response of stomatal conductance to air water demand in olive trees under different water regimes (θ being the soil moisture in the root zone). In the practice although the gs,max is related to soil water content, we are estimating gs under full irrigation only, this is field capacity.

Leaf area. This is an important variable to determine total water requirements for the trees. Nowadays, this variable can be measured with different indirect methods, being one of the simplest the app developed for cell phones called VitiCanopy which can be implemented in the approach proposed by Sanz et al., 2018), which has been assessed successfully for olive. One we have the total leaf area the percentage of sunny and shaded leaves were estimated applying a radiation interception model (RATP, Sinoquet et al., 1998).

Irrigation needs. In addition to plant transpiration, soil evaporation (E_s) is estimated according to Orgaz et al. (2006). Finally, IN is estimated as $E_p + E_s$.

Plant-based sensor. A novel aspect is that the g_s values calculated as described above are compared with those simulated through sap flow-related measurements (Hernandez-Santana et al., 2016) as illustrated in Figure 2. This allows us to check if our model is estimating correctly g_s and we are replacing the water used by the plant.

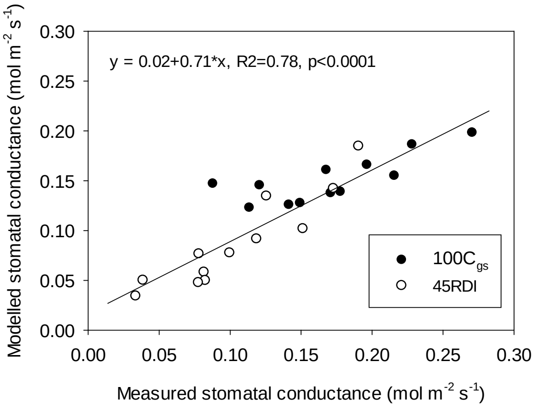

Figure 2. Comparison between measured and modelled stomatal conductance for two irrigation treatments: Control based on modelled stomatal conductance with a water supply corresponding to 100% IN (black circles, 100C$_{gs}$) and a regulated deficit irrigation (white circles, 45RDI)

Accumulated CO_2 assimilation. As we demonstrated recently (Hernandez-Santana et al., 2018) we can estimate how much CO_2 is accumulating a reference leaf according to environmental conditions. This is done applying a biochemical model of photosynthesis to our data of g_s estimated from sap flow. This allow us to estimate the CO_2 assimilated daily and relate it to fruit growth.

Remote sensing. At the farm level remote sensing data acquired with the hyperspectral camera will provide us with information about two things: the heterogeneity in our farm, and the retrieval of two important variables associated to yield: LAI and photosynthetic capacity (V_{cmax} or ETR). LAI is very much related with the NDVI index and V_{cmax} has been related to the indexes SR1, Double Difference, Vogelmann1, mSR705, SRCarter, Maccioni or SR3. All this indexes will be tested and calibrated for our experimental orchard. Calibration of indexes related to V_{cmax} or ETR will be in a first stage done at the leaf level measuring leaf with an IRGA (Licor 6400) and a fluorimeter (mini-PAM, Walz). These single leaf measurements will be related to the leaf spectrum measured in the same leaf with a spectroradiometer (ASD FieldSpec3). Then, we will study if these relationships hold at the tree level by using a hyperspectral camera Cubert S-185 with up to 125 bands from 450 to 950 nanometers on board of the multicopter MD4-1000 from Microdrones. Then, images of Sentinel 2 will be used to compare drones results with those of the satellite.

Innovation : The most standard method to schedule irrigation is the crop coefficient approach (Allen et al., 1998). However, the empirical nature of this method and the no integration of the physiology of the plant make them less attractive as plant-based methods. The described approach has two potential advantages: it is based on absolute values of g_s, which have a solid physiological meaning in relation to plant water stress (Medrano et al., 2002), and allows quantification of the photosynthesis limitation imposed by deficit irrigation, which is an indicator of yield (Hernandez-Santana et al., 2017). Thus, this method overcomes one of the shortcomings of other water stress indicators widely used for scheduling irrigation, which do not consider key intrinsic processes related to fruit development. Although the relationships between gas exchange measurements and fruit growth are not straightforward, g_s and photosynthesis provide more information on fruit growth than other water stress indicators. Stomata regulate the carbohydrate source and, indirectly, the incoming-outgoing fluxes in the fruit, through their effect on leaf, stem and fruit water potentials, driven in turn, by osmotic pressure and hydrodynamics. Finally, the approach can be fully automated and provides values representative of the whole canopy (thereby avoiding errors derived from the natural variability among leaves).

Requirements : The method requirements are the following:

- Meterorological sensors: meteorological sensors to measure solar radiation, temperature and atmospheric humidity. The solar radiation limits g_s, and temperature and atmospheric humidity are used to calculate vapour pressure deficit (*D*), because g_s is estimated based on its known response to *D* (Figure 1).
- Plant-based sensors. Any plant-based sensor which can give us any insight into the level of stress achieved by the plant should be use in parallel to the model. Sap flow sensors are the ideal choice since the derivation of g_s is more direct.
- Forecast service to schedule irrigation in advance (3 days before). In comparison to other methods using the meteorology of the last days, we calculate g_s, and thus, IN, based on the forecast of the following 3 days. In Spain this information is public, although a site-specific service in hourly-basis is been used in this project.
- To implement the method we also need to know the leaf area to calculate Ep (eq. 1). The simplest the app developed for cell phones called VitiCanopy which can be implemented in the approach proposed by Sanz et al., 2018).
- Multispectral and hyperspectral data from drones and satellite (Sentinel-2).

Maturity : The method has been implemented since 2017 to schedule irrigation in an olive orchard. The idea is well-developed, both in theory and in practice but we need to test the method under more conditions and in more species before generalizing its use.

Method Evaluation

The method is implemented in a super-high-density olive orchard (*Olea europaea* L., cv. Arbequina), located 25 km to the south-east of Seville, Spain (37°15'N, -5°48'W). Trees are planted in a configuration of 4 m x 1.5 m (1667 trees ha^{-1}) at the top of 0.4 m high ridges oriented N-NE to S-SW. The average annual precipitation (P) and potential evapotranspiration (ET_o) in the area are 501.2 mm and 1498.1 mm, respectively (period 2002-2016). The olive trees are 11 years old at the time of the implementation in OPERA.

To assess the applicability of the irrigation method based on g_s we have an experimental design including three irrigation treatments: two control treatments, one of them based on the crop coefficient or K_c method ($100C_{Kc}$), and the other one based on the estimation of g_s as a function of vapor pressure deficit and radiation ($100C_{gs}$). Additionally one RDI treatment (45RDI) in which only 45% of the water added to $100C_{gs}$ was applied in the irrigation season. In the periods in which the crop is most sensitive to stress it will be applied 100% or water requirements.

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APSoMoCo – Accurate Predicted Soil Moisture Content (WENR – The Netherlands)

Summary

Accurate prediction of the amount of water in the root zone for the coming several days as a result of weather predictions can provide insight to farmers and water distributors if irrigation is needed the coming days. This is typically of interest to farmers that do not have to irrigate on a regular basis and who have to make decisions on when and where (which field) to use a moving irrigation system. In the current method the soil moisture content is predicted by using a soil water balance simulation model. Major inputs for this model are the weather input variables which determine the input (rainfall) and output (evapotranspiration). Currently weather forecast for several days ahead are available, but these are by definition uncertain. By using ensemble weather forecast (multiple realizations of weather forecasts) will result in multiple estimates of the pattern of simulated soil moisture content for the coming days. Based on the average together with the uncertainty band width of such a predicted soil moisture depletion can help the farmer to plan his decisions on irrigation. The novelty of this approach is: i) by using the ensemble weather forecast provides insight in the uncertainty of predicted soil water depletion, and ii) the soil water depletion is a result of soil water availability and actual evapotranspiration. This approach thus differs from a simple benchmark approach where predicted evapotranspiration based on some reference evapotranspiration times a crop factor; the latter situation refers to some potential evapotranspiration and not to actual evapotranspiration.

Objective of the method

Implementation context:

Farmers and water distributors may need to know when in the (near) future (1-15 days) how much water is required by the cropped area (field in case of a farmer; area in case of water distributor). For this, weather forecasts may help, as these provide information on the needs of water (evapotranspiration demand minus expected rainfall). Since weather forecasts are uncertain, it may be of help to consider ensemble weather forecasts that are available from ECMWF (https://www.ecmwf.int/). In this way decisions to be taken by the farmer or water distributor can be done with insight in the uncertainties of evapotranspiration demand and of expected rainfall.

Irrigation system:

The method described below is independent of irrigation system or crop cultivated. However the following limitations are foreseen :

Drip irrigation: The method described below makes use of a simulation model that is used to determine the water content in the root zone. In this study it is proposed to make use of volumetric water content measurements in the field in order to check whether or not the model fits the field circumstances; if desired, the model could be calibrated based on the sensor information. In this case study we will make use of a one-dimensional model. Therefore, applying the method directly for drip-irrigated circumstances might be a bit more complicated, as it will be difficult how to interpret sensor information and model predictions. IN the model water applied via drip irrigation will be regarded as uniform application to a unit surface area.

Crop not being parametrized in the combined soil crop model: The simulation model is a combined soil-crop model. For major crops standard input parameters for the crop model are available (including: wheat, maize, barley, sugar beet, potato, bean, soy bean, rapeseed, sunflower). However, for less standard crops these are missing.

Climatic conditions: Currently, in OPERA the method will be tested for Dutch climatic conditions. No experience can yet be given for other European climatic conditions. For instance hypothesis made to initialize the soil water content or the bottom boundaries conditions may lead to reconsider the proposed parameterization strategies.

Users:

The primary beneficiaries for such a system are thought to be farmers (field scale); water distributors could use the method when used on a regional scale (multiple field scale) to determine if certain areas require supply of water more or less than the average.

Method description

Rationale of the method:

The overall aim of the method is to provide to the farmer a 15 days forecast of the soil water balance: water content in the root zone, rainfall and evapotranspiration. A decrease in soil water content in the root zone as a result of a decrease in rainfall shortage (rainfall minus evapotranspiration) provides the farmer insight in the need to prepare for irrigation in the coming days.

Roots of crops are responsible for uptake of water (and nutrients) from the top part of the soil. Water in the root zone is there as a result of water supply (rainfall, irrigation; and in some cases due to capillary rise), and losses due to evaporation at the soil surface and water uptake by the roots. Keeping track of the water balance in the root zone is thus a key measure to determine whether or not enough water is accessible for crop uptake. A decrease in total water content in the root zone (e.g. below a certain threshold) determines the need for additional water by irrigation. Taking into account weather forecasts can be of help to determine if actual irrigation is needed in the coming days (e.g. not required if rainfall is expected) or how much irrigation volume is required (e.g. based on expected evapotranspiration demand).

The total water content in the root zone can be modelled by a one dimensional model (SWAP-WOFOST; Kroes et al., 2017, Boogaard et al., 2011; http://swap.wur.nl/). Each day i) the climate inputs (rainfall, air temperature, air humidity, radiation, wind speed) as used in the model will be updated by using the climatic data for the previous day of a nearby weather station (for instance in the network of the Royal Dutch Meteorological Institute (KNMI; http://www.knmi.nl/home)), and ii) ensemble weather forecasts (for instance the 51 ensemble weather forecasts from ECMWF[1]) are obtained for the grid cell in which the site is located. The model simulations result in a predicted time course of the total water content in the root zone for the coming 15 days, which will be visualized as the median of the 51

[1] The ECMWF weather forecasts are obtained via KNMI based on a paid-for license for the duration of the OPERA project (Sept 2017-Sept 2019). The data can only be used for research purposes without commercial intention.

predictions surrounded by a grey area representing the e.g. 80% uncertainty range (Figure 1). This approach can be easily automated (Figure 2).

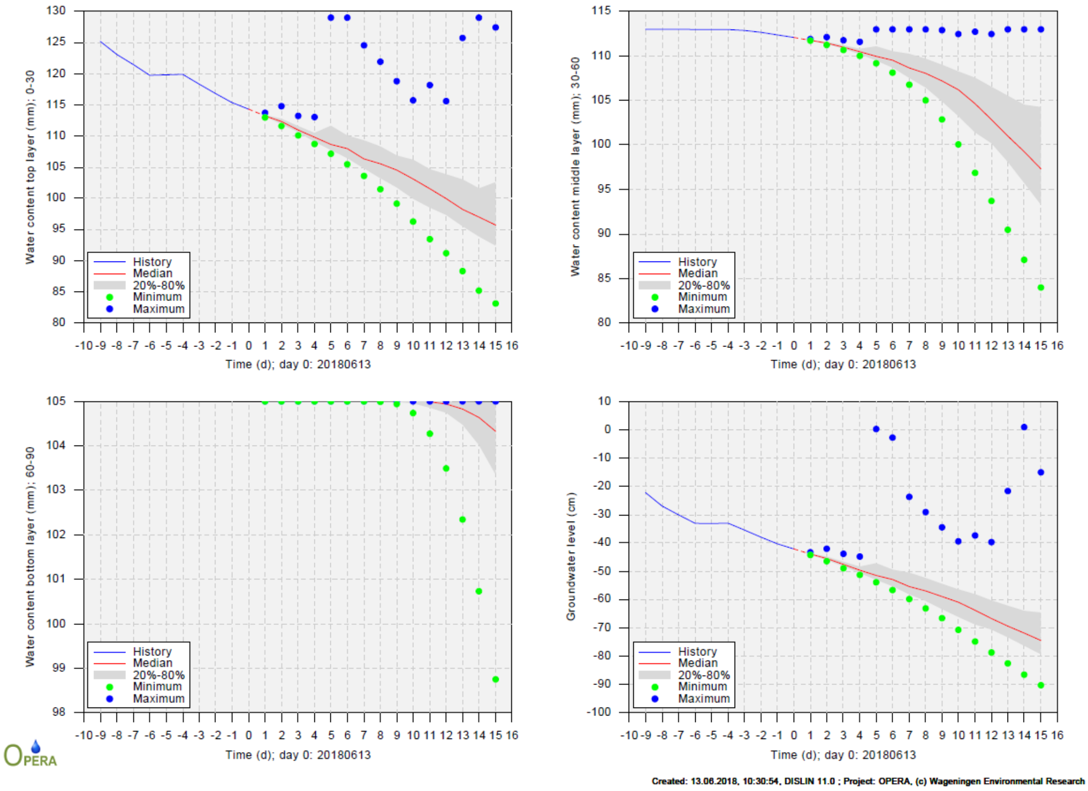

Figure 1. *Example of the visualization of the predicted time course of water content in the root zone obtained for date June 13, 2018: (upper left) layer 0-30 cm, (upper right) layer 30-60 cm, (lower left) layer 60-90 cm, and (lower right) position of groundwater level. The blue line represents the actual, historic condition for the last 10 days, the red line represents the median of 51 predictions for the coming 15 days, the grey area represents the 20%-80% confidence interval of the 51 predictions, and the green and blue symbols refer to the minimum (green) and maximum(blue) of the 51 predictions.*

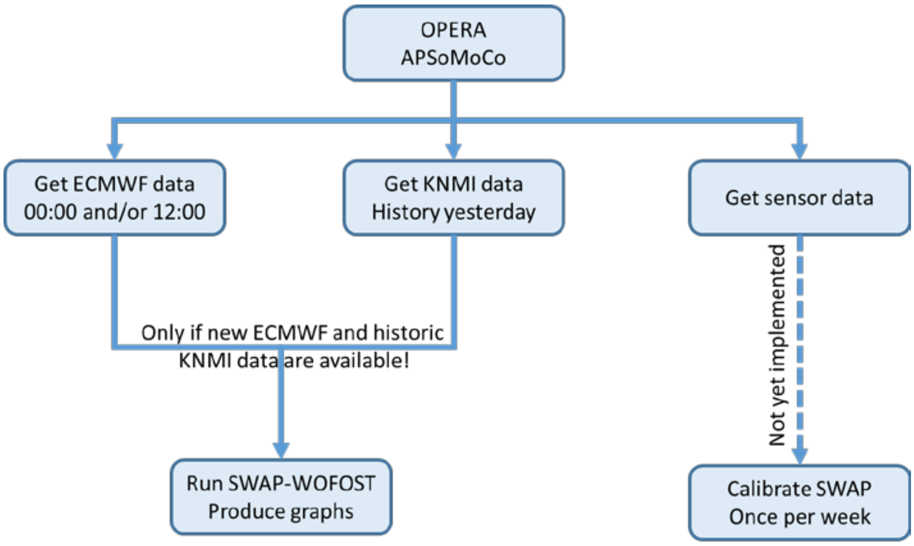

Figure 2. *First draft of the basic scheme of the method.*

As models are approximations of reality, the model prediction may differ from the actual situation. To improve the robustness of the system, some model parameters could be updated based on observations in the field. This could be any information, as long as it has a direct link to the processes considered in the simulation model. Examples could be: soil moisture content measured by soil sensors or estimated from remote sensing data, or some plant status information. Such information could be used to calibrate part of the model, such as soil physical parameters (only for those layers where sensor information is available) or crop parameters. In OPERA we will not implement this in the automatic procedure, but we will present a comparison between model predicted changes in volumetric water content versus measured water contents.

Innovation:

In the Netherlands a commercial tool is available for farmers to determine the amount of irrigation to apply (http://beregeningssignaal.zlto.nl/). It is currently only available for grass and maize, and makes use of weather predictions for the coming 5 days. In this tool detailed information on the soil water balance is lacking.

The innovation of the current method is that i) it takes into account 15 days weather forecasts, ii) it also gives insight in the uncertainty of the dryness of the root zone, and iii) it aims to makes use of feed-back information from the field so as to make the method more robust. For systems with permanent installed irrigation systems, looking ahead in time for long periods may not be necessary. For movable irrigation systems (e.g. overhead sprinkling systems) future predictions for several soil-crop fields can help the farmer in his management decisions where to plan irrigation. Looking ahead for 15 days may not always be required or realistic; however, since such predictions are available, they are currently all used.

The method is not focussed on supplying an exact advice to the farmers on the amount of irrigation water to apply. At first, the data can be used by the farmer to make his/hers own decisions. Of course, if information is available on threshold water contents, we could provide calculations of the required amount of irrigation water. This is yet to be determined in the project.

Requirements:

The method is still under development, and requires knowledge of the simulation model and its underlying theory. The currently used SWAP-WOFOST model also needs to be parameterized with input data describing the soil and crop system. For details on the required input, the reader is referred to the SWAP-WOFOST manual (http://swap.wur.nl). For major crops there are standard crop input files available (https://www.wur.nl/en/Research-Results/Research-Institutes/Environmental-Research/Facilities-Products/Software-and-models/WOFOST.htm). For proper soil input parameter, use can be made of local soil maps, soil physics maps, groundwater models (for defining proper bottom boundary conditions). For example, in the Netherlands a national schematisation for thre SWAP model is available from which the input files for a certain location can be chosen. Improvements of the input can be obtained from a field visit to check or improve the soil layer descriptions. Even better improvement can be obtained when soil physical properties are measured from soil samples. It goes beyond the scope of the current OPERA project to investigate the sensitivity of such different parameterization options.

Currently, historical climatic data and ECMWF weather forecast are automatically downloaded from the KNMI server; the historic data a freely available, whereas the ECWMF data have to be paid for. Currently, since the method is a research activity the weather forecast data are provided at reduced costs. It is unknown what the costs for commercial application would be, and whether these costs are dependent on the number of potential users or licensees.

Maturity:

The idea of making use of ensemble weather forecast data was previously studied in project NaVoBoVo (https://www.tkideltatechnologie.nl/project/nauwkeurigheid-voorspeld-bodemvochtgehalte-navobovo/). At that time we only had historic weather forecasts available, and we investigated (hind-casting) how the uncertainty increases when looking ahead in time for multiple days, and if this uncertainty varies over the seasons (**Figure 3**). It is obvious that the further we look ahead in time the wider the plume of predicted water content becomes. This can also be illustrated as decreasing correlation coefficients with increasing looking-ahead time (data not shown). The cause of increasing uncertainty in time is dominated by the uncertainty in precipitation. At the end of the OPERA project we could repeat such an analysis as well.

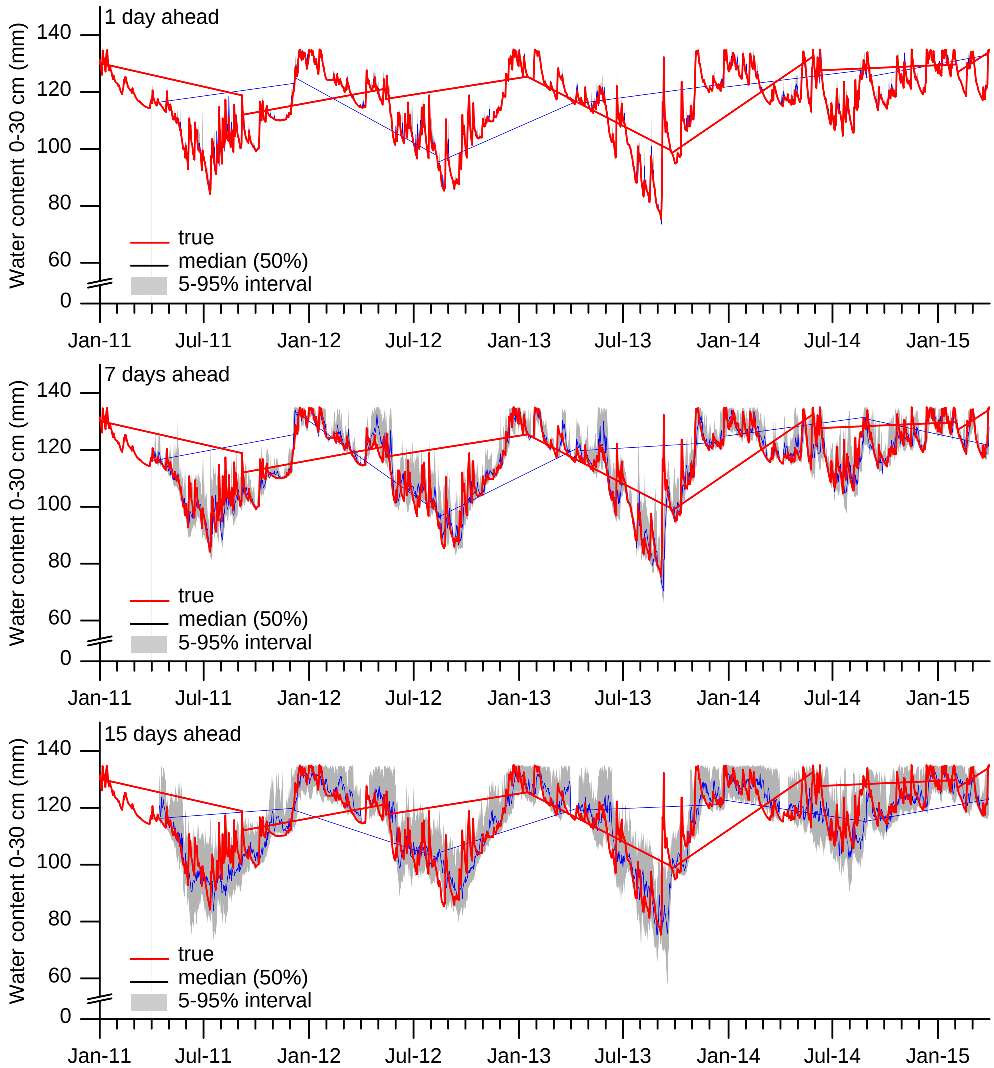

Figure 3. *Result from the previous project NaVoBoVo: time course of the soil water content in the layer 0-30 cm for situations of the coming 1, 7 and 15 days for 4 hydrological years. The red line represents the actual situation based on actual weather, the blue line represents the median of 51 scenarios, and the grey band encompasses the range 5%-95% of the 51 scenarios*.

In OPERA we now concentrate on the possibility to fully automate the process of real-time predictions of the water content in the root zone. Thus, it mainly will be a demonstration or proof-of-principle aspect. Currently, there is no intention to start a commercial service within the duration of OERA (NB: currently we are not allowed to set-up a commercial service based on the license agreement with ECMWF; data can only be used for research purposes).

Method Evaluation

The method will be employed on a test field (likely at a potato farmer in the south of the Netherlands). Focus will be on i) the technical aspects of the method, ii) the obtained resulting predictions of the water content in the soil root zone, and iii) the reaction of the farmer (relevancy of the delivered information, trust in the delivered information).

It is stated here that due to the limited project budget, it will not be possible to fully test the new method e.g. in an experimental trial with three treatments (a reference treatment according to a farmer's practice, a benchmark treatment, and a treatment according to the new method).

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Real time predicting crop water demand and irrigation scheduling – model CROPIRR (ITP - Poland)

Summary

The method is intended to aid the operation of irrigation systems using real time information on meteorological conditions and forecast. The CROPIRR model, coupled with the data collection, transmission and processing techniques is used to predict on real time crop water demand and schedule irrigation. Evapotranspiration and soil water content changes in the preceding period are calculated using measured values of meteorological parameters as well as soil and plant parameters. For a 5-day planning horizon crop water demand, soil water content changes and required water application are predicted.
Innovation relies on modelling of the crop-soil-atmosphere continuum coupled with measured actual weather conditions, short-term weather forecast to make predictions of soil water content up to 5 days ahead. It will enable the best fitting of irrigation water supply to the actual crop water demand in a more flexible way. It could prevent water shortage as well as water excess and ensure more effective water use. It will lead to rationalizing of decision making in irrigation. Innovation also relies on the application of the method in Kujawy region in Poland. The method will be used in the scale of a field as well as for the region (county scale) by modelling irrigation water demand and scheduling irrigation for different types of soils and crops on the basis of soil maps. Benchmarks of the method are: (1) criteria of assessment of forecasts and modelling (from literature) - acceptable errors of forecast and soil moisture modeling; (2) irrigation water demand assessed with the method in comparison with irrigation water use by farmers using current irrigation control practice.

Objective of the method

Implementation context:

Limited water supplies in the demonstration region (the subcatchments in the Zglowiaczka and upper Notec catchments, Poland) put constraints on agriculture. Surface and groundwater availability is becoming increasingly limited and environmental conditions are forcing the implementation of water management strategies for the sustainability of agriculture and food security. Irrigation systems are the significant water-users in agriculture. Under conditions of increasing competition for water and observed and predicted climate change, there is a need for optimum use of limited water resource at field and regional scale. Irrigation scheduling is one of the important strategies to conserve water and achieve high and good quality crop yield. This need can be met by precision irrigation which aims at delivering water at the right time, at the right amount, at the right place to the crop, adapted to local soil conditions and taking into account actual and forecast meteorological conditions and crop growth. According to the results of the performed surveys, farmers expectations in the region are to get the reliable information on actual meteorological and soil moisture conditions as well as when, how much and which crop should be irrigated in the near future up to 5 days.
The objective is an innovative irrigation control method being a nexus of monitoring, modelling and weather forecasting for supporting decisions in irrigation. The method aims at providing a useful and accurate forecast of the soil water balance components at short term for operational planning irrigation.

Irrigation system :

Irrigation in the case-study area is used in short periods during the season. It has to supplement water supply if there is a precipitation deficit and thus maintain crop yielding at the planned high level.
Systems with pressure irrigation (pumped systems) are used: sprinkler irrigation to which water is supplied by the use of pressure pipelines. Mechanized "traveling guns" are most suitable in small and medium-size farms, i.e. where they are best adaptable to the existing systems of agricultural machines;

where traction and driving forces are constituted by agricultural tractors. In the majority of cases, the reel hose-traveling guns are used.

Irrigated field crops: cereals, root crops, industrial crops, field vegetables (wheat, barley, potato, sugar beet, rape, maize, onion, parsley, carrot, lettuce and cruciferous vegetables and others).

The limits of the method:

1) Suitable for crops for which crop coefficients to calculate crop water demands with the Penman-Monteith method are available.
2) Fields with deep groundwater table with no capillary rise to the root zone.

Users :

- farmers;
- regional agricultural advisory service in the scope of dissemination and promotion of the tool among farmers, training farmers.

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Method description

Rationale of the method :

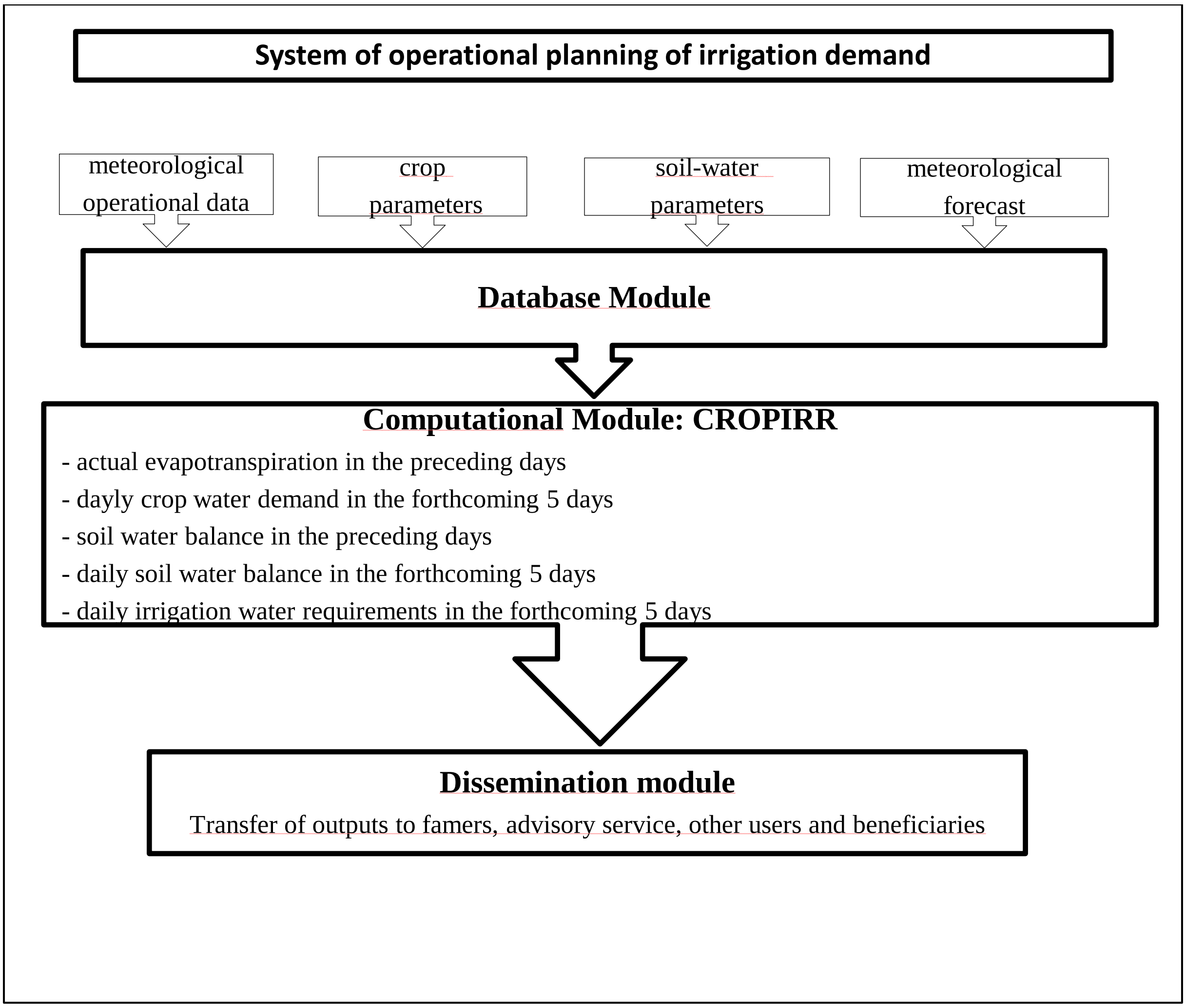
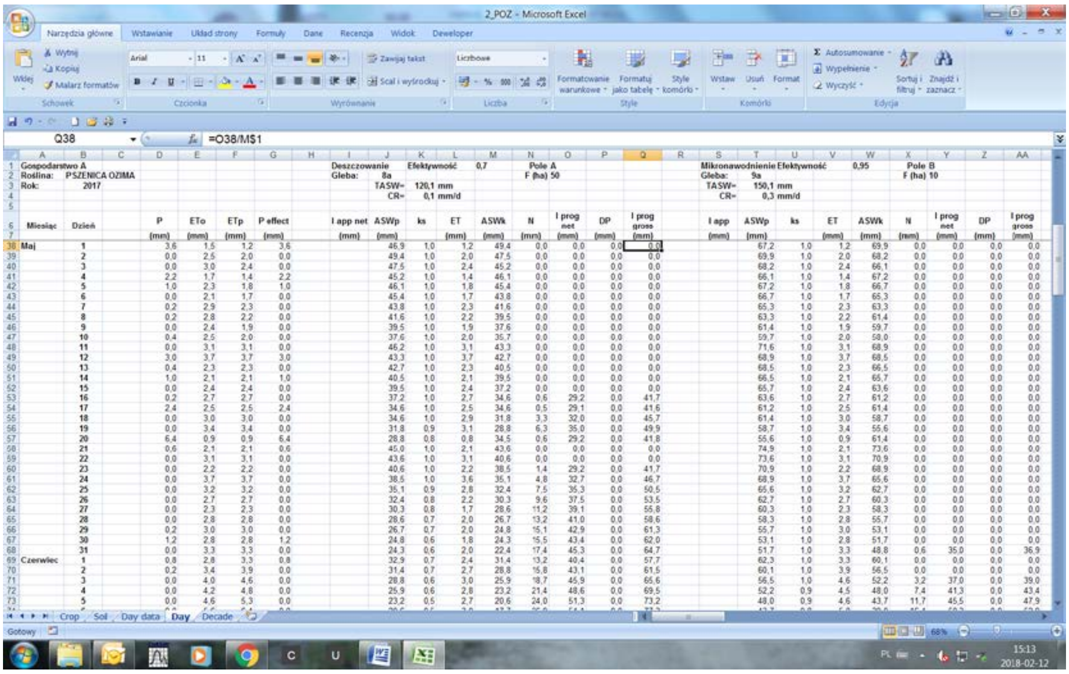


Figure : principle sheme

The CROPIRR model, coupled with the data collection, transmission and processing techniques is used to predict on real time crop water demand and schedule irrigation. The developed system consists of:

- a telemetric system including automatic meteorological measurements of precipitation, air temperature and humidity, wind velocity and solar radiation (for model simulation) with data collection and transmission by GPRS,
- a system of short-term (for each day of the 5-day period ahead) meteorological forecast including daily precipitation, air temperature and humidity, wind velocity and solar radiation for evapotranspiration estimation, predicting crop water deficit and required water application in irrigation,
- a model representing water transfer in a soil-plant-atmosphere system crop evapotranspiration, crop water demand, soil water balance and irrigation water requirement calculation,
- information tools to disseminate recommendations to farmers supporting their decision on irrigation performance: the method is foreseen to be used directly by farmers after training or by regional agricultural advisory service (Regional Advisory Centre, water users associations, producers groups), disseminating recommendations by local media, internet, sms.

In the model CROPIRR, using measured values of meteorological parameters as well as soil and plant parameters, evapotranspiration and soil water content changes in the preceding period are calculated; for a 5-day planning horizon in each day crop water demand, soil water content changes and required water application are predicted; for every day of this planning period the information is generated how much water (irrigation dose), for which crop, on which soil should be used. Soil water deficit and irrigation need are estimated when readily available soil water RASW, maintained by the suction force expressed by the potential of soil water in range of –10 kPa and –100 kPa, is depleted. Irrigation scheduling is generated every day (recommended not less frequently than every 5 days) for the forthcoming 5 days. The FAO approach based on a simple soil water balance model CROPWAT is used (Smith 1992a, 1992b; Allen et al. 1998). The standard modelling approach is based on the FAO guidelines to estimate crop water requirement. The model simulates soil water content changes using water balance equation. The methods and equations used are presented by Łabędzki and Kanecka-Geszke (2009), Ostrowski, Łabędzki and Kanecka-Geszke (2015) and Łabędzki and Ostrowski (2018). Actual crop evapotranspiration and crop water demand are assessed using the Penman-Monteith reference evapotranspiration and crop coefficients K_c. K_c coefficients for highly yielding crops are determined in lysimeter investigations carried out in Poland as well as from literature (Allen et al. 1998). They are tabulated for crop development stages and for 10-day periods of a growing season for a given plant. When soil water reserves are below readily available soil water, soil-water stress coefficient is used to reduce evapotranspiration, according to the method shown by Allen et al. (1998). The model also predicts potential crop yield reduction due to the lack of irrigation or insufficient irrigation using yield response factor K_y (Doorenbos and Pruitt 1997; Allen et al. 1998).
The calculations are performed in Excel Worksheets.
Example of the model output:



Innovation :

The method is intended to aid the operation of irrigation systems using real time information on meteorological conditions and forecast. Irrigation water requirements vary considerably on a time scale of a few days because of spatio-temporal variability of meteorological conditions (mainly rainfall) and soils. There is no possibility to generate reasonable fixed instructions in the irrigation control system. Currently, most farmers in the region make decisions in irrigation based on experience, current status of the crop, empirical assessment of soil moisture and a farmer's interpretation of the not very reliable weather forecast presented in the media.

Innovation relies on modelling of the crop-soil-atmosphere continuum coupled with measured actual weather conditions, short-term weather forecast to make predictions of the root zone water content up to 5 days ahead. It will enable the best fitting of irrigation water supply to the actual crop water demand in a more flexible way. It could prevent water shortage as well as water excess and ensure more effective water use. It will lead to rationalizing of decision making in irrigation. Innovation also relies on the application of the method in Kujawy region in Poland. The method will be used in the scale of a field as well as for the region (county scale) by modelling irrigation water demand and scheduling irrigation for different types of soils and crops on the bases of soil maps.

Requirements :

For every field we need to determine the following data to implement the method:

1) Meteorological data: measured and forecasted daily values of solar radiation, air temperature and humidity, wind speed and rainfall.
2) Soil profile description :
    a. number and depths of horizons,
    b. soil water content at WP and FC or available soil water content (measured in the field, derived from texture using PTF, derived from soil map, derived from pF curve).
3) Crop data:
    a. area of irrigated units (fields),
    b. standard rooting depth on the base of observations and literature,
    c. crop coefficient K_c, for highly yielding crops, determined in lysimeter investigations carried out in Poland or literature (e.g. Allen et al. 1998).
    d. yield response factor K_y as a function of the development stage, determined form literature (e.g. Doorenbos and Pruitt 1997; Allen et al. 1998).

automatic weather station

Method Evaluation

description of the use case implemented in OPERA (link with WP3 – evaluation in pilots):
The method is used to assess crop water demand and irrigation need in the demonstration farms in Poland (in the Zglowiaczka and upper Noteć river catchments). Based on the actual measured meteorological parameters the simulation of crop water demand and irrigation need was performed for two crops: sugar beet and parsley.

Reference

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IRRICROP: Irrigation advisory services based on integrated use of earth observation data, information technologies and crop modeling (UNIFI - Italy)

Summary

IRRICROP provides a calculation of evapotranspiration from Sentinel. It comprises optimal approaches for dynamic forecasting of crop water demand based on sequential assimilation of RS (Sentinel-2A) observations and numerical weather predictions (ensemble weather forecasts) in a crop growth model. The aim is to develop rules for optimum water management under climate variability and uncertainties in the Mediterranean, especially in Italy. Use is made of ransdisciplinary involvement of end users in development process. IRRICROP allows farmer's associations, regional government, land and water reclamation authorities to schedule irrigation in a more rational way, thus achieving the following advantages: decrease of water and energy consumption, optimization of production and work, crop growth monitoring in real time and updated according to weather forecast.

Objective of the method

Implementation context: Water use optimization in Mediterranean areas implies a decision-making process under significant hydroclimatic uncertainty. The purpose of the method is to drive crop irrigation through a dynamic forecasting of crop water requirements based on sequential assimilation of RS (remote sensing) observations and numerical weather predictions in a crop growth model (AquaCrop).

Irrigation system:

Selected irrigated crops are silage maize and tomato for industry. The main irrigation systems adopted are sprinkler and drip irrigation already characterized by different levels of efficiency. The optimization is foreseen not at irrigation method level (i.e. drip irrigation is already efficient) but at water management level, through the availability of dynamic information about the crop evapotranspiration and it (near) future trend based on pedo-climatic conditions, (forecast of the water status of the soil - plant system based on the crop model).

Users: key users are farmers and farmer's associations, regional government, land and water reclamation authorities. IRRICROP allows key users (farmer's associations, regional government, land and water reclamation authorities) to schedule irrigation in a more rational way, thus achieving the following advantages: decrease of water and energy consumption, optimization of production and work, crop growth monitoring in real time and updated according to weather forecast..

Method description

Rationale of the method:

Crop evapotranspiration under standard conditions (ETcrop) is calculated using a Penman and Monteith approach based on albedo, LAI and meteorological data. Albedo and LAI are retrieved from

Satellite (Sentinel-2A) using ANN algorithms. Existing algorithms will be adapted to determine leaf chlorophyll content and leaf water content from satellite image processing and then adapted in the AquaCrop model. ETcrop, LAI and meteorological data will be used to monitor plant growth and health, for effective yield prediction and implement the crop growth model (AquaCrop). Numerical weather predictions of ensemble global circulation models are used for forecasting evapotranspiration. A Bayesian sequential procedure will be then applied in order to retrieve future crop water requirements by assimilating the crop states observed from the satellite images and the ensemble weather forecasts into AquaCrop model.

Innovation: currently, in the pilot area irrigation decisions are taken only based on farmer's experience and the role of the land reclamation consortium is strategic for the distribution of water to the farmers. Some but not all of them are equipped with counters for irrigation water accounting.

In this sense, the innovation will be the availability of information to farmers about the real water requirements of their crops and the availability of the same information together with real data about water use to land reclamation consortia. The results will include a more efficient water crop water use in the field, a more efficient water management at catchment level and a more correct distribution of water among different users (and consequently the pricing policy).

Requirements:

The following data are necessary :

- Meteorological data (rainfall, temperatures, solar radiation, wind speed, relative humidity are measured by existing weather stations);
- ensemble numerical predictions of weather variables (NOAA and ECMWF platforms are used);
- crop data (plant density, canopy cover, plant phenology, produced biomass and final yield are measured during field campaign);
- soil data (soil moisture and soil physical properties as texture, soil surface area, soil structure) requiring field sampling and lab analysis (better to have but not mandatory)
- satellite imagery (Sentinel 2A imagery are used);
- simulation model (AquaCrop is applied).

Maturity:

The method for estimating crop water requirement through satellite imagery is already developed and applied (IRRISAT), while the dynamic forecasting based on sequential assimilation of RS observations and numerical weather predictions in a crop growth model is at experimental stage. Field testing and validation of data assimilation procedure will be carried on in the pilot area.

Method Evaluation

The pilot area is located in Campania, a region in the south west of Italy characterized by a typical Mediterranean climate. In selected farms, and in agreement with local farmers and land reclamation authority, field campaigns are carried on. In particular, silage maize and tomato for industry are monitored. The activity is organized as follow

1 – Data collection and processing

- Crops: sowing/transplant date, plant density, plant phenology, biomass production, yield,irrigation supplied.
- Soil: soil characteristic (texture, bulk density, organic matter, composition, moisture with tensiometers).
- Climate: weather variables for model run (rainfall, air temperature, relative humidity, solar radiation, wind speed); ensemble numerical predictions of weather variables relevant for assessing crop evapotranspiration.
- Satellite: Sentinel 2A imagery for crop state assessment (Sentinel 2A) of study areas.

2 - Implementation and validation of the sequential RS and weather prediction data assimilation procedure into crop growth model (AquaCrop).

3 – Evaluation of the performance of the assimilation procedures (comparing all crop model states and fluxes with the data collected in the pilot area). The data collected by own field campaign, by farmers experiences, and provide by the IRRISAT system, already implemented in the area. IRRISAT is similar to the proposed approach without the part related to weather forecast and the assimilation into the simulation model AquaCrop.

Irrigation requirements at the territory level (INRA - France)

Summary

The developed method aims at providing irrigation requirement maps at the field resolution to provide an objective assessment of the actual water needs. Such information is crucial to better manage the water sharing under water shortage period. The method is based on a two steps process. 1) Irrigated crops are mapped using satellite imagery and in particular the Sentinel imagery which enable frequent observations at high spatial resolution. 2) The evaluation of the irrigation needs is made by a modelling framework that combines crop simulators and a spatial simulation case generator. According to the crop type, the crop simulator is either the comprehensive STICS crop model, AquaCrop or a simple Kc – ET0 model. The spatial simulation case generator prepares over the territory of interest the required information to implement the crop models and thus take into account the spatial variability of soil, climate and cropping systems. Satellite imagery will be used to better characterize the agricultural practices and crop water needs. The method will be implemented in the French pilots that are the CRAU Area and the Ouveze river basin. The evaluation will be done on water consumption recorded at different levels (field, farm, irrigation sectors).

Objective of the method

Implementation context: In many situations surface water distribution is regulated by administration authorities or farmers associations. The surface water taken in river and/or channels is distributed through a hydraulic infrastructure (channels, pipes, reservoirs …) and regulations authorities have to maintain the distribution and manage the sharing rules. During the last decades, the occurrence of water shortage is increasing due to both climate change and change in river regulation rules that led to leave more water in the river to preserve their ecological quality and thus reduce uptake, particularly in critical periods. To handle water shortage events, there is a need to reduce water allocation and before reducing water allocation at the field level, there is a need to determine the actual need (which are not yet well established at the irrigated territory level). The goal of the methods is to provide irrigation need maps at the field levels and different temporal terms (meteorological forecast for the coming weeks, over the irrigation period using climatology (past and future), seasonal forecast).

The recent progress allowed by the Sentinel missions opens very promising avenue thanks to the progress in terms of spatial resolution, acquisition frequency and spectral content. Moreover, the satellite image processing has reached a good level of maturity with operational processing frameworks that take in charge the atmospheric corrections, the cloud identification and the spatial registration. The availability of advanced product makes the direct use of surface information derived from satellite observation easy for end user and makes their integration in operational decision tools possible

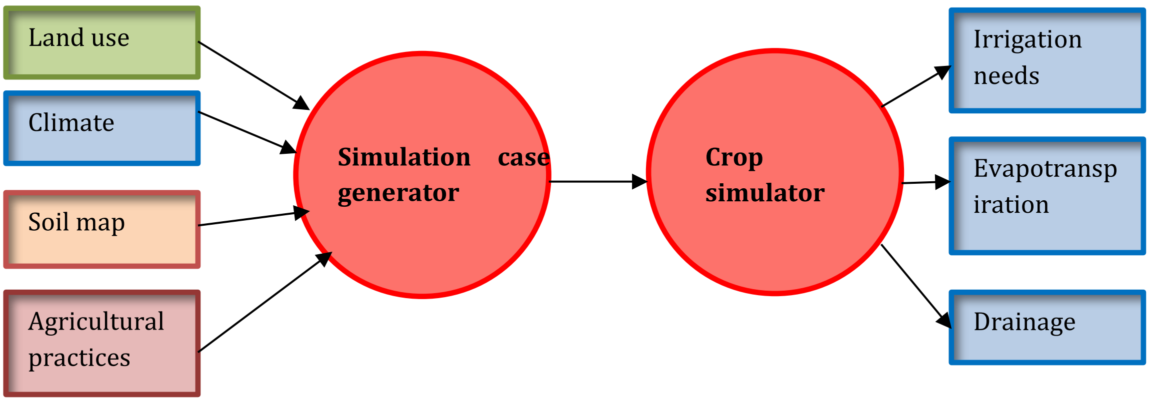
Irrigation system : The irrigation systems are diverse (drip, sprinkler, flooding irrigation) and the irrigation strategies depends on the considered crops. One of the issues is to take this variability into account. For the irrigation system there is a water cost due to irrigation method that needs to be considered (loss by evaporation with sprinkler and flooding system, loss by drainage with flooding technique, which depends on the length of the irrigated area, the surface roughness, the soil infiltration characteristics or the irrigation inflow. Considering the crop needs we have to combine ecophysiological needs and agricultural practice aiming at optimizing the quality of the product. In the French area irrigation of vine for wine is recent and limited in time to mitigate water stresses at some critical period. This recent evolution led to additional water needs that may be critical in shortage period.

Users : The main expected users are the water managers that have to implement decisions in the water allocation to the farmers (amount of water, distribution calendar). But a fair evaluation of the water needs will be also appreciated by the individual farmer by providing an objective basis to decide restriction that usually arise tensions.

Method description

Rationale of the method: The proposed method is a suite of models that lead to estimate on every field of the area the required irrigation water amount. This led to the following steps:

- Step 1 : detect irrigated crop using the temporal series of satellite images. We will start with existing land use product as a benchmark and then identify patterns in temporal evolution of satellite vegetation practices that improves the identification of irrigated crop and if possible the cropping system variants that lead to different requirements (irrigated vine vs non-irrigated, grassy inter-rows. This step will take profit of the characteristics of the Sentinel satellites offering frequent observations to get time series able to capture dynamic patterns of the vegetation development, at high spatial resolution able to address small fields, which are frequent in irrigated area, and rich spectral content useful to characterize plant traits (LAI, fapar, vegetation water content …).



- Step2 : set up the water estimation modelling framework. The simulator is based on two components: a simulation case generator to address the spatial variability and a crop simulator to represent the crop behaviour and in particular quantity linked to the water cycle.
  - **The crop simulators** differed from one crop to another. The STICS crop model[2] (Brisson et al., 1998, Brisson et al., 2008) will be privileged when possible (irrigated grass in the case of our pilot site, and maybe vine). For the other crops (orchard, garden market, olive tree, vine) we intend to use either AquaCrop or simpler the K_c ET_0 approach. ET_0

[2] https://www6.paca.inra.fr/stics/

is the potential evapotranspiration as determined by the FAO method (Allen et al., 1998) based on the Penman Monteith approach. The main innovation we expect intend to is the determination using foliar cover as observed by the Satellite observations

- **The simulation case generator :** it is a preprocessing module that will prepare the different crop simulations cases. For every simulation unit (here a field) it is necessary to gather :
  - The crop type (to orient the choice of the model) according to the land use map.
  - The crop characteristics:
    - Crop parameters and simulation options when using STICS.
    - Parameters allowing the determination of the K_c Parameter (Aquacrop, K_c model).
  - The soil characteristics (soil depth, stone content, water content at field capacity and wilting point).
  - Agricultural practices:
    - Irrigation dose and date, harvest date, fertilisation dose and date.
    - Parameter to represent management in Kc determination.
  - Climate spatial reference.

In crop models irrigation need are evaluated differently according to the crop type.

- For irrigated grassland using flooding techniques, the irrigation calendar is determined by a fixed water access calendar, the soil moisture at the beginning and the end of the season to determine the start and the end of the irrigation period, the occurrence of heavy rains. The dose takes into account the distance to be covered by the water from the source of the water to the outlet of the field. The longer this distance, the larger is the dose, due to the fact that it needs more time to flood the whole field. An additional term can be added, which is the constraint on the flooding itself. As a matter of fact, sometimes a minimum flow in the channel is required to allow the flooding from the channel.
- For orchards and garden market production, the principle is to fulfil the water demand by maintaining the soil moisture above a threshold as a way to consider the interactions between irrigation and precipitation. If the evapotranspiration lead to a moisture lower than the threshold, the irrigation is estimated as the amount of water we have to introduce in the soil to keep the soil moisture at the defined thresholds. During a dry period, this lead to a daily irrigation at the level of K_cET_0
- For vine, an agronomic survey will be done to depict irrigation strategy (when, how much, and what criteria) and propose a conceptual framework to represent the farmer decision rules.

Innovation : The main innovations of the proposed tool is the implementation framework of the different models and the use of satellite images to detect irrigated fields and to determine K_c.

Requirements : To implement the method the main information to run the models are given in the following table

Input Type	Variable identification and metric	Temporal and spatial scale	source of data in past	Source of data for future scenarios and forecast
Climate	Precipitation (mm), air temperature min and max (°C), wind speed (m/s), vapor pressures (mbar), Solar radiation (MJ/m^2) PET (mm) Not mandatory CO_2 (ppm)	Daily – spatial unit	ERA-Interim (Europe -40 km)–, National reanalysis product (France : SAFRAN 8km), meteorological networks, –	Ensemble regionalized scenarios, meteorological forecast, seasonal forecast
Soil	Nb of layer (max 5) Layer thickness Wilting point (g/g) Field capacity (g/g) Stone content (g/g) Dry Bulk density Organic Nitrogen (g/g) Texture Initial water content (g/g) Initial NO_3 content (Kg N/ha)	Spatial unit	European texture map combined with pedotransfer functions, local pedological maps and associated description of reference profiles	
Agricultural practices	Crop type and variety Crop residue management (amount and composition) Sowing (date, depth, density) Irrigation (rules or calendar) Fertilization (amount, calendar, type)	Crop cycle, representative fields	Eurostat, MARS Local expertise	

Frequent remote sensing images in the optical domain (as delivered by Sentinel 2 and Landsat 8) are mandatory. The benefit of other images acquired in other spectral domain (microwave, thermal infrared will be explored during the OPERA project.

Maturity : The modelling framework was already implemented in previous studies and the crop simulator benefit from a strong background. The implementation of the crop model is mature for field crop and grassland, but remains challenging for orchards, olive trees, vine and garden market where the variety of production options make a generalization at the territory level difficult. If some K_c references have established for the major crops (given in agricultural reference document established at national or regional scale, or in worldwide synthesis as that of the FAO 66 report (Allen et al, 1998), these information should be considered as a backup. The goal in OPERA is to refine K_c determination by considering the foliar development given by satellite images and knowledge on irrigation practices collected at the local level.

Concerning the irrigated crop identification, existing methodology are already implemented for land use inventory. Methods are established at national or even European levels and can just be considered as a first guess. To get a better precision in determining such fields and ideally the cropping practices (pruning, inter-row management, row-spacing), method to take advantages of times series characterizing the whole vegetation cycle has to be developed in the frame of OPERA.

Method Evaluation

The method will be implemented and evaluated in two use cases in the CRAU area (the main issue is the irrigation of the grass land) and the Ouvèze area where there is various irrigated crop and frequent restriction due to the variability of the Ouvèze river flow. Some component of the modeling frameworks might be testes in the other pilot sites

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