Modelling irrigation management services: the IRMA_SYS case

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Abstract. Since agricultural water use has a substantial share in Greece, irrigation scheduling forecast and management tools constitute significant assets. This study illustrates the concept and implementation of the IRMA_SYS, a regional, user-friendly computer/mobile-based service. IRMA_SYS was implemented as open, fully customizable, modular software capable of estimating field specific crop water requirements and irrigation scheduling at multiple scales, from farm to water basin level. The estimation of irrigation water requirements and irrigation scheduling is based on a modification of the conceptual FAO 56 approach and its tasks are accomplished based on historical and forecast agrometeorological data, along with site specific crop and soil-water data. In this context, IRMA_SYS is addressed to irrigation professionals who have the background and the experience to interpret the information provided and use the system for setting up irrigation schedules, plan and record irrigation events as well as self-training regarding irrigation management.

Keywords: irrigation scheduling, modelling, regional, evapotranspiration forecast, irrigation professionals

1 Introduction

According to the EU Water Framework Directive WFD, 2000/60/EC (EU, 2000 (Greek law (GL) 3199; Govern. Gazette (GG) A’280 9-12-2003) and the Presidential Decree (PD) 51;GG A’54 8-3-2007)), action is needed to protect waters primary in qualitative but also in quantitative terms. Among the various measures which member states are proposed to adopt and develop are added value tools to optimize efficiency in irrigation.

In the framework of the UN Environment Program (UNEP, 2005) it was concluded that a challenge of water-related issues for Mediterranean countries is to
integrate water demand management in agriculture and to develop added value tools to optimize efficiency in irrigation. The EU-report (2012) on identifying water saving potentials for the EU countries mentions that improving irrigation application efficiency would lead up to 60% water (BIO Intelligent Service, 2012). Also CMMC (2013) predicts a reduction up to 60% in water availability for irrigation in extended Mediterranean areas of EU countries. These facts make optimum irrigation water management a top priority goal. Beyond these, the European Landscape Convention (which was adopted by the Greek state in 2010, GL 3827;GG A’30 25-2-2010) promotes protection, management and planning of natural, rural, urban and peri-urban areas including land, inland water and marine areas and must be also taken into account as an integral part of the environmental and agricultural legislative framework.

The purpose of the present study is to illustrate the key features of such a tool, the IRMA_SYS (http://arta.irrigation-management.eu/), which is a regional, user-friendly computer/mobile-based, open and free modular platform for estimating site specific crop water requirements and irrigation scheduling at multiple scales, from farm to water basin level, with high spatial resolution. The system takes into account historical (from the system’s stations) and forecast agrometeorological data, along with crop and soil-water data to accomplish the above mentioned tasks. Also, it is fully customizable, allowing the users to add site specific information in order to customize the output of the system, taking advantage of additional information.


2 Materials and Methods

2.1 Study area

The Region of Epirus (hydrological area GR05; Fig. 1) is located at the North-West part of Greece, it has a total area of 9,203km² (agricultural land corresponds to the 14% of it) and a population of 353,820. The plain of Arta (45,329 ha, the biggest of the region), is located at the south edge of Epirus, it is part of the Arachthos and Louros hydrological basins (GR14 and GR46; WFD, 2013) and intersects with Amvrakikos Wetlands National Park.

2.2 Weather forecast data

The National Observatory of Athens (NOA) provides daily forecast data for 3 days (72 hours) around the study area. All basic meteorological parameters (including rain forecast) are provided at three hour time steps and they are disaggregated in hourly values. The forecasts are provided by Grid 2 of BOLAM model, described by Kotroni and Lagouvardos (2001) and Lagouvardos et al. (2003).
The procedure is fully automated and the file is ingested automatically to the IRMA_SYS interface.

2.3 Estimation of daily and hourly reference evapotranspiration, with the Penman-Monteith equation

The Penman-Monteith (PM) equation was developed to describe reference evapotranspiration (ET) of a grass crop, which is defined as the rate of evapotranspiration from a hypothetical crop with an assumed fixed height (12 cm), surface resistance (70 sm⁻¹) and albedo (0.23), closely resembling the evapotranspiration from an extensive surface of a disease free green grass cover of uniform height, actively growing, completely shading the ground, and with adequate water and nutrient supply (Allen et al., 1998, Eq. 1). To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and without any soil water shortage. Standard methods are proposed by Allen et al. (1998) to compute the parameters of Eq. 1 from the observed climatic variables.

\[ ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{1 + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \]

(1)

where \( ET_o \) is the grass reference evapotranspiration (mm day⁻¹), \( R_n \) is the net radiation at the crop surface (MJ m⁻² day⁻¹), \( G \) is soil heat flux density (MJ m⁻² day⁻¹), \( T \) is mean daily air temperature at 2m height (°C), \( u_2 \) is wind speed at 2 m height (m s⁻¹), \( e_s \) is saturation vapor pressure (kPa), \( e_a \) is actual vapor pressure (kPa), \( e_s - e_a \) is saturation vapor pressure deficit (kPa), \( \Delta \) is slope of the vapor pressure curve (kPa °C⁻¹), and \( \gamma \) is psychometric constant (kPa °C⁻¹). This equation uses standard meteorological records of solar radiation (net, short wave, or sunshine duration) or sunshine duration, minimum and maximum air temperature, air humidity (preferably minimum and maximum relative humidity) or wet and dry bulb temperature, and wind speed.

In areas where substantial changes in wind speed, dew point or cloudiness occur during the day, calculation of the \( ET_o \) equation using hourly time steps is generally better than using 24-hour calculation time steps. Such weather changes can cause 24-hour means to misrepresent evaporative power of the environment during parts of the day and may introduce error into the calculations. With the use of the IRMA_SYS automated weather stations, weather data are available for hourly periods. Therefore, the PM equation was also applied on an hourly basis for the forecast period (Allen et al., 1998):

\[ ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{1 + 273} u_2 (e_s(T_{hr}) - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \]

\[ e_a = e_s(T_{hr}) \frac{RH_{hr}}{100} \]

(2)
where $ET_o$ is the grass reference evapotranspiration (mm h$^{-1}$), $R_n$ is the net radiation at the grass surface (MJ m$^{-2}$ h$^{-1}$), $G$ is the soil heat flux density (MJ m$^{-2}$ h$^{-1}$), $T_{hr}$ is the average hourly air temperature at 2 m height (°C), $u_2$ is the average hourly wind speed at 2 m height (m s$^{-1}$), $e_o$ is saturation vapour pressure at air temperature $T_{hr}$ (kPa), $e_a$ is the average hourly actual vapour pressure (kPa), $\Delta$ is slope of the vapour pressure curve at air temperature $T_{hr}$ (kPa °C$^{-1}$), $RH$ is the average hourly relative humidity (%) and $\gamma$ is the psychometric constant (kPa °C$^{-1}$).

Figure 2, presents a map of monthly aggregated $ET_o$ (mm/month) for September 2015 according to data collected from IRMA_SYS stations. The upper limit of monthly $ET_o$ was 124.7 mm, located at the north of the study area, while the minimum (96.4 mm) was located at the centre of the study area.

2.4 Estimation of irrigation needs

The irrigation needs are estimated based on an approach that is called root zone soil water depletion, which is a simplified soil water balance based on an initial soil moisture condition and runs for a specified time period (start date, end date).

The basis for the calculation is the following formula (Allen et al., 1998):

$$D_{ri} = D_{ri-1} - (P_i - RO_i) - IR_{ai} + CR_i + ET_{ci} + DP_i$$

(3)

where $i$ is the current time period (i.e. the current day, or hour), $D_{ri}$ is the root zone depletion at the end of the previous time period (mm), $P_i$ is the precipitation (mm), $RO_i$ is the runoff (mm), $IR_{ai}$ is the net irrigation depth (mm), $CR_i$ is the capillary rise (mm), $ET_{ci}$ is the crop evapotranspiration (mm), $DP_i$ is the water loss through deep percolation (mm).

The following limits were imposed on $D_{ri}$:

$$\Theta_s <= D_{ri} / Z_r <= TAW$$

(4)

where $\Theta_s$ (dimensionless or m$^3$ m$^{-3}$) is the soil moisture at saturation, $Z_r$ (mm) is the corresponding rooting depth, assumed to be positive downwards and TAW (dimensionless or m$^3$ m$^{-3}$) is the total available soil water, which is the difference between Field Capacity (FC) and Permanent Wilting Point (PWP) as they are presented in Fig. 3. This approach is slightly different that the one proposed by Allen et al., 1998, since they propose that $D_{ri}$ is always positive.

$RO_i$ equals the amount of water that exceeds soil moisture at saturation after heavy rain, i.e.:

$$RO_i = P_i + (\Theta_{ri-1} - \Theta_s) Z_r$$

(5)

where $\Theta_{ri-1}$ is the soil moisture at the previous time step. $CR_i$ and $DP_i$ are considered equal, in terms of equilibrium between them, since in the case of the Arta plain there is a shallow water table.

Equation 3 therefore becomes:

$$D_{ci} = D_{ci-1} - P_i - IR_{ai} + ET_{ci} + RO_i$$

(6)

$ET_{ci}$ is calculated using crop coefficient approach by multiplying reference evapotranspiration by crop coefficient $K_c$ (Allen et al., 1998).
Each time the user irrigates, the initial depletion derives from the provided irrigation water volume. Different sets of initial conditions are implemented when the user:

- does not provide any information considering irrigation
- provides only the last irrigation date
- provides both the last irrigation date and the applied irrigation water

If the user does not provide the irrigation water volume, the system assumes that enough water was applied in order for the soil moisture to reach FC (i.e. zero depletion). Therefore, in this case we have \( i=1 \) and \( D_{r,1}=0 \).

The point \( i=1 \) is specified by \( \text{start\_date} \), which is a datetime object. The \( \text{initial\_soil\_moisture} \) will usually equal FC (this, according to the essential simplifying assumption, means that the crop was irrigated on \( \text{start\_date} \)). However, if the crop has not been irrigated recently, \( \text{initial\_soil\_moisture} \) will be set to another value (such as a soil moisture measurement made at \( \text{start\_date} \)).

Soil moisture \( (\Theta) \) and depletion \( (D_r) \) at time step \( i \), are related with this formula:

\[
\Theta_i = FC - \frac{D_r}{Z_r} \tag{7}
\]

where soil moisture and field capacity (FC) are dimensionless or expressed in \( \text{m}^3\text{\cdot m}^{-3} \), while depletion and rooting depth \( (Z_r) \) are expressed in mm.

So, since the \( \text{initial\_soil\_moisture} \) is given, \( D_{r,1} \) is also known. \( D_{r,1} \) given, irrigation is triggered when the following condition is met:

\[
D_{r,1} \geq \text{RAW} \times Z_r \tag{8}
\]

where \( \text{RAW} \) is the readily available soil water (dimensionless or \( \text{m}^3\text{\cdot m}^{-3} \)) calculated from \( \text{TAW} \):

\[
\text{RAW} = \text{MAD} \times \text{TAW} \tag{9}
\]

depending on the management allowed depletion (MAD).

In this case, the net irrigation depth \( (\text{IR}_{n,i}) \) is set equal to the corresponding root zone depletion from the previous time step, therefore:

\[
\text{IR}_{n,i} = D_{r,i-1} \tag{10}
\]

The method returns the root zone depletion for \( \text{end\_date} \) in mm. Precipitation and \( \text{ET}_c \) must have non-null records for all days from the day following \( \text{start\_date} \) to \( \text{end\_date} \).

The system takes into account historical (from the system’s stations) and the necessary agrometeorological forecasts along with soil water information, in order to estimate the above mentioned soil water balance variables throughout the study area.

### 2.5 Spatial interpolation

All the data that are collected by the meteorological stations pass through a spatial interpolation process in order to develop the necessary data for any point of the area. A web application was developed, that retrieves and processes the available data from the system’s database in order to produce the necessary raster maps, of the
involved parameters. In this way, raster maps for each parameter involved in the soil water balance are produced.

Spatial variation of reference evapotranspiration ($ET_o$) will be estimated from calculations between raster maps of the involved parameters, instead of applying a methodology to spatially interpolate calculated $ET_o$ values at stations locations. This is essential for the system calibration, since live lysimeter data are unavailable, thus $ET_o$ cannot be measured and obviously cannot be calibrated. On the other hand, each of the parameters involved in the estimation procedure of $ET_o$ is measured at stations locations and thus capable for calibration.

Since IRMA_SYS utilizes variables in hourly time step for the current day, twenty four raster maps of all parameters are stored and used for the detailed calculation of the soil water balance components. At the end of the day (i.e. at 24:00) the next daily raster maps are produced by aggregation based on the three hour weather forecasts provided by NOA.

IRMA_SYS uses the Inverse Distance Weighting (IDW) method as a quick interpolator capable to address the characteristics of the study area. IDW is a straightforward and non-computationally intensive method. It has been regarded as one of the standard spatial interpolation procedures in geographic information science (Burrough and McDonnell, 1998) and has been implemented in many GIS software packages as a default method to generate a surface when attribute values are available only at sampled locations. Formally, the IDW method is used to estimate the unknown value $\hat{y}(S_0)$ in location, $S_0$ given the observed $y$ values at sampled locations $S_i$ in the following manner:

$$\hat{y}(S_0) = \sum_{i=1}^{n} \lambda_i y(S_i)$$

(11)

Essentially, the estimated value in $S_0$ is a linear combination of the weights ($\lambda_i$) and observed $y$ values in $S_i$ where $\lambda_i$ is defined as:

$$\lambda_i = d^{-\alpha}_{0i} / \sum_{i=1}^{n} d^{-\alpha}_{0i}$$

(12)

with:

$$\sum_{i=1}^{n} \lambda_i = 1$$

(13)

In Equation (12), the numerator is the inverse of distance ($d_{0i}$) between $S_0$ and $S_i$ with a power $\alpha$, and the denominator is the sum of all inverse-distance weights for all locations $i$ so that the sum of all $\lambda_i$'s for an unsampled point will be unity (Equation 13). The $\alpha$ parameter is specified as a geometric form for the weight while other specifications are possible. This specification implies that if $\alpha$ is larger than 1, the so-called distance-decay effect will be more than proportional to an increase in distance, and vice versa. For the case of IRMA_SYS the parameter $\alpha$ was set to $\alpha = 2$, as proposed from literature.

2.6 System implementation

The system is a product of cooperation between experts in the fields of meteorological data acquisition, agricultural cultivation and landscapes water needs, irrigation management, irrigation controllers manufacturing and software developers.
The general organisation of the system is presented in Fig. 4, while the flowchart of the system modules is presented in Fig. 5.

The IRMA_SYS is a user-friendly computer/mobile-based, open and free modular software, with its source available at: https://github.com/openmeteo/aira, under the terms of the GNU General Public License as published by the Free Software Foundation, written in Python and Django, along with NumPy (http://www.numpy.org/) and GDAL - Geospatial Data Abstraction Library (http://www.gdal.org/) modules.

The Enhydris database (http://system.igription-management.eu, https://enhydris.readthedocs.org) web interface, with the available meteorological stations is presented in Fig. 6. It includes a map that provides information about the location of each station, together with the identification numbers, water basin, water division, owner and type of the meteorological stations.

Agrometeorological data time-series and crop water requirements estimations are provided to users and visitors, while irrigation advices and a series of other utilities are available only to registered users.

Agriculturalists, green infrastructure managers, farmers and gardeners are able to use the system for setting up irrigation schedules, plan and record irrigation events as well as self-training regarding irrigation management.

Figure 7 presents the home page of the system. The main feature is the map presentation of the different variables, in daily time scale, that are involved in the irrigation requirements methodology presented above, such as: Rainfall, Reference Evapotranspiration, Humidity, Temperature, Wind speed and Solar Radiation, with high spatial resolution of 70×70 m grid. The maps are produced by implementing the Inverse Distance Weighting (Burrough and McDonnell, 1998) method for spatial interpolation, found in the GDAL library.

The system provides this information of the study area, through the WMS service provided by the Mapserver that was set for the purposes of the present project (http://mapserver.org/). The historical data are kept from 1/1/2015 onwards, while several maps produced by satellite images are also available.

Registered users can add their fields into the system (Fig. 8) using a map, in order to pinpoint the geographic location of each field, with the help of the Hellenic Cadastre orthophoto imagery basemap (http://gis.ktimanet.gr/wms/ktbasemap) that allows zoom in scales up to 1 m. The user should provide information regarding the field’s area, crop, irrigation type and strategy. Also, a list of the user’s already register fields is available at the bottom of the page.

If appropriate information is available to the registered users, they are able to modify the properties of each field, based on this information, as shown in Fig. 8. This information consists of parameters grouped in three major categories, which regard:

- irrigation system and management,
- crop and
- soil

Irrigation Management includes information regarding irrigation efficiency and strategy. Crop includes information regarding the crop coefficient (Kc), the management allowed depletion factor (MAD), the estimated maximum and minimum root depth. Soil includes information regarding the FC, PWP and Θ. Appropriate
ranges and the system’s default values, according to literature, are available to the user in order to provide guidance.

Since the initial soil moisture is included in the initial conditions of the soil water balance module of the IRMA_SYS, register users should add the irrigations that they have applied for each field, in order to get the appropriate irrigation advices. If the user does not provide information about the applied irrigation water volume, the system assumes that the applied water was enough in order for the soil to reach field capacity.

Since the registered users provide the above information, the system produces detailed irrigation advice estimates, in hourly basis, based on both historical and forecast data as presented in Figures 9, 10.

The “Irrigation Performance” graph provides users means to visualize and access information about the estimated water amount, the applied irrigation water and the effective precipitation during the irrigation period that for Greece spans from 1st of April to 30th of September. Also, the data will be available for downloading as “comma separated values - csv” file for further processing.

Also, the quantities of Total Effective Precipitation (mm) together with the Total Estimated Irrigation Water Amount (mm) and the Total Applied Water Amount (mm) along with their Percentage difference (%) will be available to the users, based on the registered irrigation events and the IRMA_SYS estimates, for the above specified period as presented in Figure 11.

2.7 Irrigation supervisors, notifications and tools

2.7.1 Irrigation supervisors

In the context of IRMA_SYS the irrigation supervision was conceived and implemented. A supervisor is assigned to another system user, by the user himself, in order to utilize the IRMA_SYS in his account. Every registered user is able to declare himself as a supervisor, in his/hers “Account” menu, or choose his supervisor from the list of available supervisors and provide access to his fields to him.

A supervisor is considered to be either:

1. An irrigation expert, which is a scientist in the field of Irrigation and Drainage.
2. A certified professional that can supervise a number of irrigators as generic consultant or in the framework of an applied quality cultivation system (i.e. organic farming, integrated management etc.).

or

3. A user with great experience regarding irrigation and drainage issues.

A supervisor has no access to any other information apart from the registered fields in the IRMA_SYS. The user, at his will, removes or changes the supervisor from his “Account” menu also.
2.7.2 Notifications

At the beginning of each day, the system runs a soil water budget routine and sends an email at 5:00 a.m. to the users that have agreed for this, which contains an estimation regarding the need of irrigation for the current and the three upcoming days. For the latest, the available weather forecast is used.

2.7.3 Tools

The “Tools” page contains a set of useful tools for unit conversions, as:

- From mm to m³ of irrigation water and vice versa, since the corresponding field area is provided.
- Irrigation duration in hours (h) according to mm of irrigation water and station flow rate (m³/h).
- Station flow rate (m³/h) according to mm of irrigation water and desired irrigation duration in hours (h).

2.8 Evaluation and feedback

A feedback procedure will be available for users that want to contribute to the improvement and evolution of the system by evaluating it. A series of training seminars for agriculturalists, which are expected to be the main type of users (in order to analyze the provided information before make relevant suggestions to farmers and green spaces managers) will follow the development. Also special seminars for end users, in order to have a basic understanding of the system operation will be made. Relevant training and help material will be available at the tool’s web site.

IRMA_SYS field evaluation is currently held for both agriculture and landscaping case studies, against soil moisture readings from installed sensors at the agrometeorological stations and irrigation water amount recordings.

3 Conclusions

The IRMA_SYS is an added value regional management and planning tool designed to contribute along with the other tools of IRMA project (http://www.irrigation-management.eu/) to the improvement of efficiency in irrigation techniques and irrigation scheduling forecast from farm to water basin level, with high spatial resolution.

It is a user-friendly computer/mobile-based, open and free modular software that provides crop water requirements estimations and irrigation advices to users and visitors, based on agrometeorological data timeseries and a modified FAO 56 approach.
The system is fully customizable, allowing the users to add site and crop specific information in order to customize the output of the system, taking advantage of additional information. It is easily expandable, since the individual modules are independent of the number of stations and accepts all kinds of forecast data.

Also, the system provides notifications through e-mail to registered users regarding the need of irrigation for the current and the three upcoming days and through the concept of irrigation supervisors incorporates expertise regarding irrigation and drainage issues.

The feedback and experimental evaluation procedures will contribute to the further improvement and versatility of the system, aiming at increased experience gain at regional level with different type of farms, crops and soil water information.

IRMA_SYS is addressed to irrigation professionals who have the background and the experience to interpret the information provided and use the system for setting up irrigation schedules, plan and record irrigation events as well as self-training regarding irrigation management.

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Fig. 1. Hydrological basins of Greece, along with the hydrological basins of Epirus. (WFD, 2013)
Fig. 2 Monthly $ET_o$ (mm/month) map of the study area, for September 2015
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