Tools for Crop Water Irrigation Assessment: Two Italian Examples

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Abstract. Agriculture is the largest user of water on the planet with a 70% of all freshwater withdrawals. Today the growing scarcity and competition for water among agricultural, industrial, commercial and residential sectors are pushing the water managers to allocate water more efficiently. In this scenario the use of methodologies and tools for better monitor and schedule the irrigation water for the agricultural sector are becoming relevant in the decision making process. In this paper two tools for calculating the crop irrigation requirements are proposed. The tools determinates, based on the complex relationships of the system soil-plant-atmosphere, the quantities and timing of water to be granted to meet the crops needs. The tools, developed by the Italian Institute for Agricultural Economics, are called *Bilancio* and *MARSALa*. *Bilancio* was realized for estimating the irrigation needs at parcel level for the Reclamation and Irrigation Consortia located in Southern Italy. *MARSALa* was developed for the estimation of the irrigation water consumption at farm level for the whole Italian farm universe by using, as a key source of information, the 2010 Italian Agriculture Census.

Keywords irrigation; crop water requirement, water management.

1 Introduction

The use of water for food production is the largest market share among all other uses and its demand is continuously increasing with population growth. Agriculture is the largest consumer of water on the planet with about 70% of all water withdrawals and in the EU as whole, 24% of abstracted water is used in agriculture and in particular in some regions of southern Europe agriculture water consumption rises to more than 80% of the total national abstraction (EEA Report No 2/2009). Over the last two decades agricultural water use has increased driven both by the fact that farmers have seldom had to pay for the real cost of the water and for the Common Agricultural Policy (CAP), having often provided subsides to produce water-intensive crops with low-efficiency techniques. As for the majority of the Mediterranean countries, irrigation represents for Italy one of the most relevant pressures on the environment in terms of use of water due to the occurrence of hot and dry season causing increased water demand to maintain the optimal growing conditions for some valuable crops species. Future scenarios are expected to be worse due to climate change that might intensify problems of water scarcity and irrigation requirements in the Mediterranean region (IPCC 2007, Goubanova and Li 2006, Rodriguez Diaz et al. 2007). Accurately estimating the irrigation demands (as

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well as those of the other water uses) is therefore a key requirement for more precise water management (Maton et al. 2005) and a large scale overview on European water use can contribute to developing suitable policies and management strategies. So far, the main policy objectives in relation to water use and water stress at EU level, set out in the 6th Environment Action Programme (EAP) (1600/2002/EC) and the Water Framework Directive (WFD, 2000/60/EC), aim at ensuring a sustainable use of water resources. In the last decade scientific research has carried out several studies of devising different methodologies and tools for crop water irrigation estimation, based on a better assessment of spatial and temporal variability of water exchanges between crop and atmosphere through the process of evapotranspiration (ET). Some methods are based on direct measurement such as micro-meteorological, used in tree crops or high vegetation (i.e. *Eddy-covariance*, *Surface Renewal* or *Scintillometry* methods). However, the complexity of instrumentation and procedures for data analysis led to the development of simpler methods to be used in operational contexts related to the Water Resources management, such as remote sensing techniques and soil water balance models. Due to the strong physical relationship between the spectral response of cropped surfaces and the corresponding values of evapotranspiration and crop coefficient K_c, during recent years different methodologies have been sought to estimate crop evapotranspiration from EO optical data (Richter & Vuolo, 2009). In this context two different approaches are usually applied. In the first reference evapotranspiration (ET_0), corresponding to the ET of a non-stressed grassed surface, is multiplied by an empirical crop coefficient (K_c) to estimate the potential crop evapotranspiration under standard condition (ETp), i.e. in a disease-free environment with adequate fertilization and sufficient soil water availability (irrigation applied). The value of Kc is retrieved trough a definition of a linear relationship with simple vegetation indices i.e. Normalized Difference Vegetation Index NDVI and soil-adjusted vegetation index SAVI (Cuesta et al., 2005; D'Urso & Calera, 2006). The second procedure is based on the direct application of the Penman-Monteith equation with canopy parameters (such as Leaf Area Index, Albedo, and crop height) estimated from satellite imagery (D'Urso, 2001), in analogy to the direct calculation proposed by F.A.O (Allen et al., 1998). Soil water balance models covering in detail the processes of water transport in the soil-plant-atmosphere, are widely used on the evaluations of the irrigation water volumes.

In this paper two examples of tool developed in Italy for crop water irrigation assessment are presented. The first one, called *Bilancio*, was conceived as a tool to be provided to Land Reclamation and Irrigation Consortia to assess the temporal and spatial variability of irrigation requirements at district scale by filling in the hydrological balance in the soil-plant-atmosphere. The second, called *MARSALa*, is a multi-model tool developed to compute an estimation of the irrigation water consumption of the whole Italian farm universe by using as key source of information the Sixth General Agricultural Census 2010. Since both Models are based on the soil water balance computation, in the next chapter will given a brief description on the state of the art in this sector.

2 Materials and methods

The water balance of a volume of soil affected by plants' roots is usually derived from the law of continuity whereas changes in the amount of water present in the volume are dependent on water flows at the boundary of the domain.

It usually refers to the following equations:

$$\Delta W = \left(P_e + I + U\right) - \left(D + E_s + T_c\right) \quad \textbf{(1)}$$

which allows to calculate the change in the volume of water stored in soil in a fixed time interval, as the difference between the amount of water entering the system and that going out at the same time interval. The increase of water in the system is related to the effective rainfall (Pe), the irrigation water volume (I), which seeps through the soil surface and the contribution due to the rising water from underground water (U), the negative terms of the budget instead are represented by percolation to the underground movement (D), evaporation (Es) from the soil surface and transpiration (Tc) from the crop, which usually added up to define real evapotranspiration (ET) of the cultivated area (ET = Es + Tc). There are many models in literature that can be used to the water management (FAO, 1994.b) and which can be classified into two types: models that use a static schematization of the system (Smith, 1992), models based on numerical solution of the equations of motion of the water in the soil-plant-atmosphere (Belmans et al., 1983; Santini, 1992). In models of the first type, called *static*, the soil is generally seen as a reservoir, whose capacity depends on the depth of the root system and parameters related to characteristics of the soil profile and water volumes are set to filling up the reservoir-soil field capacity. The static models, for their simplicity, are widely used in irrigation practices, but to obtain quantitative estimates require empirical correction parameters to be determined from time in time with reference to specific local conditions. The second type of model, called *dynamic*, describe the continuous system in which water, under its energetic state, moves into the soil, in part goes to the roots, through the tissues and the vascular system of plants, reaches the leaves, evaporates and diffuses through the stomata into the atmosphere. These models refer to global parameters that take on the radical drawing and widespread throughout the area explored by the roots and water flow extracted from the roots, which varies continuously from point to point, is related not only to the characteristics of plants but also the local values of water content in the soil and transpiration demand.

2.1 *Bilancio*: a GIS-based tool for crop water irrigation estimation at parcel level

Bilancio has been developed within the Multiregional Objective 1 Programmes, founded by the EU, "Technical Assistance to Southern Italy Land Reclamation and Irrigation Consortia" in collaboration with the University of Naples Federico II. The structure of the model is schematically represented by three components: (I) the core of the system is represented by the agrohydrological model Soil Water Atmosphere Plant (SWAP), (Dam et al., 1997), developed at the Wageningen Agricultural University (Netherlands). The source code of the model is free available, and has been adapted to the soil and agrohydrological condition of the Southern Italy irrigated areas; (II) the Geographic Information System (GIS), which allows to provide georeferenced information to run the SWAP calculation and to display information output, trough the graphical interface; (III) the database containing the parameters of the soil, crop and climate. In this model, the irrigation district is divided into elementary parcel, homogeneous in terms of climate, crop and soil (minimum set of required data to the user, throughout access the archives of internal software procedure for the generation of input parameters of the model), and defined as tertiary unit (located at the end of the distribution network, Fig. 1) where the water balance is calculated.

Each parcel contains an unique ID with the link to the soil, crop, and meteorological database.

Crop database - It contains the parameter related with the crop growth (K_c, Leaf Area Index, root depth and tolerance to water stress).

Soil database - The minimum data set required regards the physical and chemical properties of each horizons (texture, density bulk and organic matter) and hydrologic properties (hydraulic conductivity and water retention capacity). If the latter aren't available they can be estimated using a procedure implemented in the model which use the HYPRES pedotransfer functions (Wosten, 1998), these were developed from a database of thousands of soils on a European scale, including the flood plain soils typical of southern Italy.

Agro-meteorological database - The data required are: reference evapotranspiration (ET_0) and rainfall (P), they can be provided directly from local Agro-meteorological Services or computed inside the model by the Hargreaves-Samani formula, if only temperature data are available, or by the Penman-Monteith equation if the database contains all the required parameters.

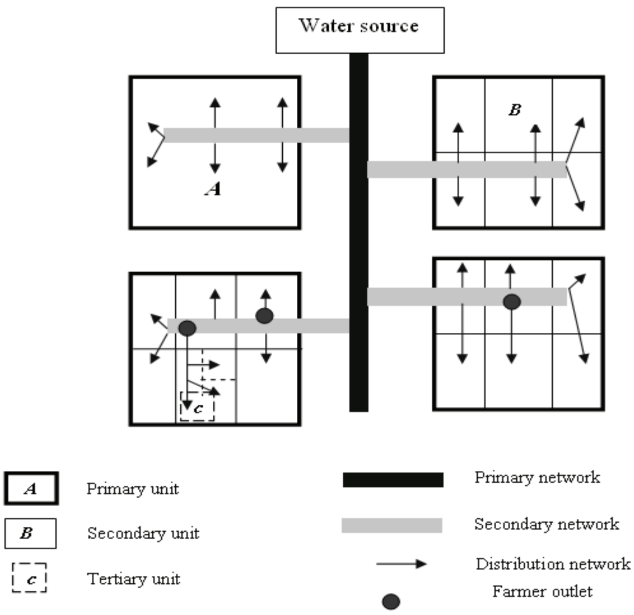

Figura 1 - Schematic representation of the water transport system in a irrigation network.

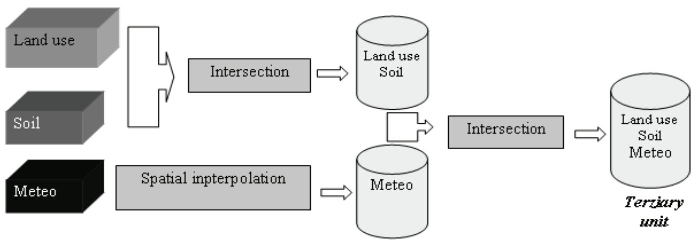

Figure 2 - General schema of geospatial operations to build the tertiary unit.

Tertiary units have been built through geospatial operation, as shown in Fig. 2. The temporal variation of soil water content $\theta(z,t)$ [cm^3(water) cm^{-3}(soil)], in a given time interval *t*, of each tertiary unit, at given depth (*z*) is described by means of the following differential equation (Hillel, 1998: Feddes et al., 1988, Santini, 1992) , which are the basic relationship of the SWAP model:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]-S \quad \textbf{(2)}$$

Where θ is the soil water content, *K(h)* (cm day^{-1}) is the unsaturated hydraulic conductivity, *h* is the soil water pressure head (cm), z the vertical coordinate (positive upward) and *S* is the water uptake by roots per unit of soil per time [cm^3(water) cm^{-3}(soil) day^{-1}].

Root water uptake S, according to the model proposed by Feddes et al. (1998), can be described as function of h:

$$S = S(h) = \alpha(h)\frac{T_p}{z_r} \tag{3}$$

with z_r (cm) being the thickness of the root zone, T_p (mm) the potential transpiration, and $\alpha(h)$ a semi empirical function of pressure head h. As shown in Fig. 3 the shape of the function $\alpha(h)$ depends on four critical value of h, related to the crop type and to the potential transpiration rates.

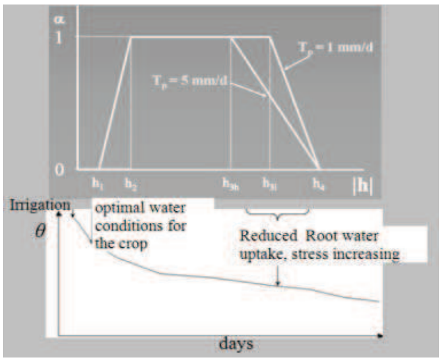

Figure 3. – Root water uptake function $\alpha(h)$: h_3 has two different value respectively for high (h_{3h}) and low (h_{3l}) potential transpiration rate.

The parameters h_1 and h_2 depend mainly on the soil type, while the values of h_3 and h_4 are the tolerance to water stress of crops of interest. For values of soil water pressure head greater than h_{3h} or h_{3l} there aren't limitation in the root water uptake, since water availability is optimal, and the plant can then transpire according to the demands of the atmosphere. The two values are variable as a function of potential evapotranspiration, the first refers to the potential evapotranspiration flow of 5 mm / day, while the second is valid when the daily potential evapotranspiration takes values around 1 mm. When the water pressure head in the area of soil explored by the roots exceeds these values and stands in an intermediate zone between h_{3x} and $_{h4}$, the root uptake is reduced linearly beginning zero for values greater than or equal to h_4. In this range of water pressure head crop is under water stress, which is manifested by a decrease in transpiration flows and a consequent reduction in yields. For values of water potential which goes beyond h_4 roots are not able to extract water from the soil, conditions related to the concept of the "wilting point".

From the simulation of the daily water balance in each parcel the vertical profiles of water content $\theta(z)$ and soil water pressure head h (z) are estimated, and parcels where irrigation is needed are identified, and the corresponding volume as a function of soil water deficit is calculated. Furthermore is possible, using the GIS tools, to map the water evaporation from the soil, the crop transpiration, and actual spatial distribution of water demand for irrigation in the whole district.

The simulation can then be extended to assess the demand for water during the irrigation season or during periods of particular interest.

Bilancio has been developed in the form of COM libraries for Windows 32-bit as an extension of the GIS application Terranova SHARC. The database management engine used is jet-MS (DAO3.6) version 2.0 that ensure the compatibility with older versions of Windows. The tool has been delivered as standalone application to a group of Irrigation and land reclamation consortia located in Southern Italy who participated to performance evaluation of the system for a whole irrigation season.

2.2 *MARSALa: a multi-model tool based on agricultural census data for irrigation water consumption estimation at farm level.*

MARSALa is made up of three integrated models (Fig. 4): Crop Irrigation Requirements Model (Model A), Irrigation Efficiency Model (Model B) and Irrigation Strategy Model (Model C). The Models use readily available information (agricultural census data, administrative statistics, spatial data, etc.) as well as information collectable through regular surveys and expert expertise.

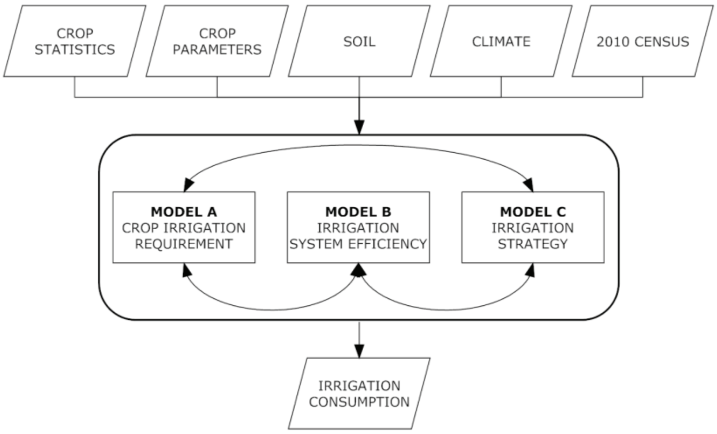

Figure 4 - Framework of the methodology: typology of required data and models relationships.

Model A simulates the amount of water required by each crop of the farm and the relative irrigation dates by computing a daily root zone water balance:

$$RZWD_i = RZWD_{i-1} - \mathrm{Re}_i - I_i + ET_i + (RO_i + D_i) \qquad \textbf{(4)}$$

where *RZWDi* and *RZWDi-1* (mm) are the root zone soil water deficit on days *i* and *i-1*, respectively, and Re_i (mm), I_i, ET_i, RO_i and *Di* (all in mm) are the effective rainfall, irrigation, crop evapotranspiration, irrigation runoff and drainage, respectively, on day *i*.

Generally the root zone is full of water (*RZWD=0*) when the water content is at field capacity, and it is empty when the water content is at the wilting point. Runoff of rain water is not directly considered but through the concept of effective rainfall, while runoff of irrigation water is set as negligible. Drainage of rain water is computed as the excess of the root zone soil water content over field capacity, on the given day of the water balance. Drainage of irrigation water depends on the applied water depth in relation to the required depth and the irrigation uniformity, this part is treated by Model B. The root zone water holding capacity (*RZWHC*) is the depth of water (within the root zone) between field capacity and wilting point.

Effective rainfall as well as reference evapotranspiration (*ETo*, mm), estimated by Penman-Monteith equation, are derived from the agro-meteorological database.

Crop evapotranspiration (ET, mm) is computed using FAO methodology, based on the concepts of crop coefficient and reference evapotranspiration (Doorembos and Pruitt, 1977). The crop coefficients are derived using the dual approach (Wright, 1982) in the form popularized by FAO (Allen et al., 1998). The approach separates crop transpiration from soil surface evaporation as follows:

$$ET = (K_{cb}K_s + K_e)ET_o \tag{5}$$

where K_{cb} is the basal crop coefficient, K_e is the soil evaporation coefficient and K_s quantifies the reduction in crop transpiration due to soil water deficit.

The variation of K_{cb} is typically represented based on the values of K_{cb} at the initial, middle and final stages of the crop growth cycle and the duration of the initial, rapid growth, mid season, and late season phases. K_e is obtained by calculating the amount of energy available at the soil surface as follows:

$$K_e = K_r\left(K_{c\,max} - K_{cb}\right) \tag{6}$$

where K_r is a dimensionless evaporation reduction coefficient dependent on topsoil water depletion (Allen et al., 1998) and $K_{c\ max}$ is the maximum value of K_c following rainfall or irrigation. The stress coefficient, K_s, is computed based on the relative root zone water deficit as:

$$K_s = \frac{RZWHC - RZWD_i}{(1-p)RZWHC} \quad \text{if RZWDi} < \text{(1-p)RZWHC} \tag{7}$$

$$K_s = 1 \quad \text{if RZWDi} \geq \text{(1-p)RZWHC} \tag{8}$$

where p is the fraction of the *RZWHC* below which transpiration is reduced.

Irrigation is triggered in the model when the soil water deficit in the root zone reaches the management allowed depletion, which is then computed by Model B and C.

Model B takes into account the irrigation application efficiency and the irrigation drainage losses that are related to the irrigation system and the management factors. The irrigation system is characterized by its application uniformity, while the management factors are considered by a management deficit coefficient. If the deficit coefficient is high, a large fraction of the field will not receive the water required to maintain full evapotranspiration; contrary, if it is low and the application uniformity is low as well, then a significant part of the applied irrigation will be lost as drainage, i.e., the application efficiency will be low. By assuming the frequency distribution of the applied depth relative to the required depth across the field as a uniform statistical distribution, for a given required depth may be identified three areas that represents: the water available for crop consumption, the water lost by percolation and the part of the root zone receiving any irrigation water.

Therefore, three irrigation performance indicators may be defined: Irrigation Application Efficiency (Ea), Percolation Coefficient (CP) and Deficit Coefficient (CD), (Wu, 1988).

$$E_a = \frac{X}{(1-CD)} \quad \textbf{(9)}$$

$$CP = 1 - E_a \quad \textbf{(10)}$$

$$CD = \frac{(X-a)^2}{2bX} \quad \textbf{(11)}$$

where a and b are determined by the application uniformity and X is the ratio between required and applied depth. The parameters a and b can be derived by using the distribution uniformity *DU* (Warrick, 1983), defined as one minus the ratio between the average applied depth in the quarter of the field receiving less water and the average applied depth in the whole field. DU, which is characteristic for each irrigation system, has been tabulated by analysing experimental researches carried out in Spain and Italy and by expert judgment (eg. Irrigation system like Furrow or Basin have on average a *DU* of 70% while Drip/Micro-irrigation have a *DU* of 90%). *Ea* can be computed by the first equation after deriving X by using the management deficit coefficient (*CD*) provided by Model C. The irrigation drainage losses can be expressed as $Ii \times Ea$ where *Ii* is the irrigation computed knowing the required water depth estimated by Model A.

Model C concerns the strategy adopted by the farmer in relation to the degree of stress to which the crop will be subjected and it depends on crop type as well as other factors such as water availability, distribution system, economic dependence on irrigated crops, farmer's educational level, irrigation equipment, size of the farm, etc. Model C consist of a set of rules organized into a decision tree for defining a value of the management deficit coefficient (*CD*) to be used in Model B. The rules are defined through the analysis of the farm data collected during the calibration campaign and from experts advise. The decision tree allows to assign a value for *CD* per each crop based on a set of information related to farmer irrigation strategy. *CD* can be greater, less or equal to p (the fraction of the total available soil water a crop can extract from the root zone, under no water stress conditions).

Since the tool is expected to be applied for irrigation farm water consumption estimation for the all possible Italian farms data identification, quality assessment and collection have been the main issue of the methodology development process. In fact, the data collection process for the whole country revealed a context where data are scattered among several institutions (national, regional and local) and with different standards in terms of data quality, data collection, data storage, scale and resolution.

Given the context, data were collected with priority to the standardization at national level and the available resolution, in addition both geographical and statistical data were reported to the municipal level: the minimum computational unit. Only the data acquired by the Census have higher resolution being clearly gathered at farm level. Hereafter all the database, the relative information contained and the collection procedure are described.

Agro-meteorological database - The national scenario is characterised by a strong anisotropy of the quality and standard of the available dataset, thus we settled for a less accurate agro-meteorological database that ensure a complete standardisation and full coverage at national level. The chosen database, widely exploited by several research projects, contains a complete series of daily values of precipitation and evapotranspiration (ET_0, calculated with the Penman-Monteith formula) estimated for 544 grid nodes covering the whole Italian territory. The daily values have been estimated by kriging techniques over a grid geometry with a regular structure where each node is the centroid of a "meteo cell" with a side length of 30 km. The values are attributed to each municipality by means of a GIS spatial join function.

Soil database - Soil data availability in Italy shows the same pattern of the agro-meteorological data in terms of dispersion among local (regional) and national authorities. In order to realize an homogeneous database, to be used at national level for the model simulation, we have set off a huge soil data collection activity to make an inventory of all the available soil maps and data produced by the various Italian regions. The database contains, for all prevalent soil of each municipality, the parameters required by Model A: field capacity, wilting point and soil depth that are evaluated by a weighted average along the soil profile till a maximum depth of 120 cm.

Crop database - The database of crop characteristics is fundamental for crop irrigation calculation and it has been built by collecting information all the irrigated crops cultivated in Italy. The main parameters requested for each irrigated crop are: planting and harvesting date, duration of the growing phases, crop coefficients (Kcb) for the initial, development, mature and final stage, crop height, root depth and depletion fraction. Data have been collected from experimental projects, literature review and FAO-56 book. Since climate in Italy is very different for geographical reasons, data are acquired for three macro-areas: North, Central and South Italy.

Census database 2010 - Agricultural Census data provides the key source to be used to feed the three models, official data will be released in 2012 by the Italian National Institute of Statistics. The data required by the models are: crops acreages and relative irrigation system, crops location (at municipality level), farmer educational level, farm technological level and irrigation water supply (e.g. self-supply by wells/ponds/canals, supply by a public management authority on-demand/rotation).

Models A, B and C were tested preliminarily for a single crop through a Ms Excel spreadsheet and then integrated and implemented through a software application along with a set of routines necessary to extract all the required input data coming from the census questionnaire as well as all the other databases. Software implementation was realized through a client-server architecture where the client is a Ms Windows application written in C# language and devoted to the import, pre-process and storage the data into a database structure. The server is responsible for the databases management by an open-source RDBMS (MySQL version 5.1). The connection and communication between the client and server applications is ensured by a MySQL connector. The client application is made up of two modules:

- Module 1- the component acting as data disaggregator by generating the complete irrigated farm land use by using the data coming from a database containg the census questionnaire data;
- Module 2 – the component dealing with the irrigation water consumption estimation.

3 Conclusion

We described two tools developed in Italy to estimate the crop irrigation requirement by using the so-called soil water balance models.

Bilancio can be considered an useful tool to support the operational activity of the Reclamation and Irrigation Consortia especially in Southern Italy where water must be allocated carefully among farmers due to the frequent water shortage phenomena. In addition the comparison between the water allocated to farmers and the irrigation estimated can be a useful indicator on irrigation efficiency.

MARSALa can perform estimation at farm level by using the Sixth Italian Agricultural Census data that will be released in 2012 and it will provide a detailed picture of the irrigation consumption of the whole Italian farm universe. The figures that will be produced will be useful to water managers and to support the decision making process in the coming years.

Both tools can provide simulation of the irrigation needs with a level of accuracy that depends on the quality and spatial resolution of the input data (crop, soil, and agro-meteorological data). Further improvements for both tools can be achieved by a better calibration and validation process by considering a wider set of soil, crop and climate characteristics as well as different economical and structural farm features.

It is difficult to establish the “cost-benefit” effectiveness of such techniques within the contex of actual irrigation systems. The implementation of this tools as a real-time irrigation system could be considered feasible in areas with high value crops and a high price of irrigation water. Presently, however, irrigation water is not yet fully considered as an economic good subject to the rules of economic market, even in areas with serious water scarcity. Nevertheless, in the future we may expect a turn round of this tendency which will increase the attractiveness of tools in the management of water resources in irrigated areas (D’Urso, 2001).

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