« SAMIR », *A tool for irrigation monitoring using remote sensing for landcover mapping and evapotranspiration estimates.*

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ABSTRACT - *The sudmed project, carried out by CESBIO (Toulouse, France) and University Cadi Ayyad (Marrakech, Morocco), is studying the hydrological functioning of the Tensift semi-arid Watershed (Marrakech, Morocco), to help monitoring its hydrological resources. The evapotranspiration (ET) of the irrigated crops of the plain is one of the major fluxes of this watershed, which consumes 85% of the water used. To assess the evapotranspiration at the plain level (10000 km2), we built the SAMIR software based on the «FAO» model (Allen et Al. 1998). FAO method was chosen because of the good trade off it achieves between data requirements and results accuracy. ET estimation requires 3 types of data : (1) climate to compute reference ET0, (2) land cover and (3) vegetation development (= Kc). SAMIR includes also a simple soil module allowing to compute the water budget of the crop and thus the irrigation requirements. An example of pumpings estimates at the Haouz plain scale is given.*

1 INTRODUCTION

The SudMed project is aimed at developing methods for the sustainable monitoring of water resources in the Tensift basin (Marrakech, Morocco), based on ground data, remote sensing and physical modeling. The climate of this area is semi arid, characterized by low rainfall amount (240mm on average) affected by a strong spatiotemporal irregularity. Several drought periods occurred during last years. Irrigated cultivation covers about 450000 ha and uses about 85% of the whole available water, which means that optimal use of the resources is one key of the development of the area. Irrigation optimization requires the control of all the terms of the water budget, and especially the crops water consumption, i.e. their evapotranspiration (ET). This means that at any time, estimates of their past consumption are needed for computing the water budget of the crops. Moreover, forecasting of their water requirements is necessary for a better irrigation planning. This knowledge is useful for the irrigation manager, but it is also useful for the water resources manager, i.e. the watershed agency, as this flux is one major component of the water cycle in this watershed. To fulfil these objectives, we designed the SAMIR tool (Satellite Monitoring of Irrigation) dedicated to the spatialization of the irrigation water budget, making extensive use of satellite images.

2 STATE OF THE ART

Some tools for none spatialized water budget of crops already exists. Some of them like GAPS (Butler 1998) and BUDGET (Raes 2001), are based on more or less complex soil-vegetation-atmosphere models (SVAT). Due to their complexity and the detailed parameters needed, they are usually valid at the plot level. Other models like CROPWAT (Clarke 1998), are based on the well known FAO method (Allen et al. 1998) and may provide budgets for agricultural areas only on the basis of the area covered by each crop. Applications providing an actual spatialization of the water budget, including the spatialization of climate and phenology of the vegetation, are much rarer. The irrigation management system AWARDS (hartzell 1998) offers a spatialization of ET based on daily climatic data, including radar estimates of precipitations. However, this system uses a fixed land cover map, and doesn't account for the actual development of the vegetation.

Remote sensing provides a spatialized and regularly updated information about vegetation, which is primarily and widely used for land cover mapping. Temporal image series also offer the opportunity of mapping land cover (Simonneaux 2003), but above all they give information about the vegetation development, which is a major driving factor of ET. The low availability of such time series, for financial as well as technical reasons, as long been a restraint to their use, but they should soon become more widely available thanks to new or coming missions (Formosat, Venµs / GMES). Image time series are thus particularly suited for crop monitoring.

The thermal information acquired by some sensors (Thematic Mapper, ASTER, AVHRR, MODIS…) gives access to an instantaneous energy balance of the vegetation cover. The SEBAL method (Bastiaanssen 2000) uses this information to compute an instantaneous evaporation. This kind of information may be useful for crop water budget, but the fact that the variations in the temperature of a vegetation cover are quicker than the reflectance in the visible range makes this method inadequate with the low repetitivity of this type of images, at least at high resolutions. Thus, thermal bands alone are not sufficient for a full ET monitoring, but they can be used as a periodic additional information to check the water stress level of vegetation. In this way, they may be used for calibration or assimilated in ET models. However, considering the potential of thermal information to monitor plant water stress, future research should focus on the use of thermal data, and especially the disaggregation of low resolution and high repetitivity thermal data (MODIS, AVHRR).

Among the more recent tools for irrigation monitoring, the DEMETER project developed an application dedicated to the computation of spatialized ET based on the FAO method (Calera et al. 2003, Jochum 2006). The strength of this system is that it is designed to work in operational conditions, making extensive use of different types of high resolution visible satellite images (ASTER, SPOT, TM…) for the computation of the cultural coefficients, and providing ET estimates in the best cases only one day after image acquisition. This tool focuses on the instantaneous ET of plants in optimal conditions, as this is the information directly accessible from satellite data, and it doesn't take into account neither the full water budget including the soil compartment, nor the long term forecasting of water needs.

3 SAMIR TOOL FEATURES

SAMIR, SAtellite Monitoring of Irrigation, is a tool for irrigation management focusing on the use of remote sensing, and running at a daily time step. The collaboration with the office in charge of irrigation (Office Régional de Mise en Valeur du Haouz (ORMVAH)) led us to adapt the tool to the needs of the end-users. Conversely, the end-users needs, which were not accurately expressed at the beginning of the process, became refined along with their takeover of the tool.

3.1 Method for water budget computing

The computing of ET is based on the FAO dual crop approach linked to a soil model that allows to better take account of water stress and soil evaporation. The evapotranspiration of a field is the sum of the transpiration of the vegetative parts and of the soil water evaporation. The FAO dual crop coefficient method calculates the total ET of a vegetated surface using the following equation:

$$ET = ET0 * (Kcb + Ke) \qquad (1)$$

where ET0 is the reference evapotranspiration, Kcb is the basal crop coefficient accounting for the transpiration of the vegetation fraction (fc), and Ke the evaporation coefficient accounting for evaporation of the soil fraction (1 – fc).

Computing equation (1) requires basically three types of data: climatic variables for calculation of reference evapotranspiration (ET0), land cover for computing crop coefficients (Kcb), and periodical phenological information for adjusting the Kcb. This first stage of computation gives a maximal ET in that it doesn't take account of the water availability of soil. This preliminary ET value is thus input the soil compartment.

The soil module was adapted from Zhang et al. (2006) and includes three compartments (1) a surface compartment, (2) a root compartment, and (3) a deep compartment. Water goes down the compartments by gravity, and is also able to rise by diffusion. These fluxes are linked to the relative humidity of the compartments. This soil model enables the separated calculation of transpiration (from the root compartment) and evaporation (from the surface compartment), taking into account the water availability in each compartment and thus a stress coefficient Ks. Besides, the user can input rain and irrigation information if available. It should be noticed that lateral flows at not taken into account here, as they are considered negligible in irrigated areas. The crop budget is thus:

$$ET + DP + \Delta SW = R + I \qquad (2)$$

with :

DP	deep drainage
Δ SW	soil water content variations
R	rainfall
I	irrigation

Although less complex than physical SVAT based methods, the simplicity of the FAO method makes it well adapted for spatialization over large areas, where physical modelling would lack from the physical variables needed as input. The good trade-off it realizes between ease of use and performance makes it the current reference method for agricultural monitoring of ET over large areas.

3.2 Input and Output data

Typically the inputs of the model are rainfall, ET0, Kc coefficient issued from satellite imagery and soil properties if available. The outputs are the evapotranspiration of the crop and the updated water content of soil. Various options were developed to take the irrigation into account: on the one hand irrigation data are available and introduced into the model by the final user; on the other hand, the model calculates irrigation volumes according to irrigation rules. If only one part of the irrigation is input (e.g. dam irrigation), the remaining part is estimated (e.g. pumpings).

The computation is achieved at the pixel scale, which is the elementary calculation of SAMIR, may suffer from uncertainties due to the input variables and parameters. The outputs may thus be affected by errors and should be considered carefully. The relevance of SAMIR ET estimates rely more on the scale of the irrigation unit, and on long enough durations.

The climate module needs daily values of ET0. These values may be taken from climate statistics (e.g. LocClim CD published by the FAO), and interpolated at the daily time step. It is also possible to introduce ground data from climate recording stations. One station only may be used, if homogeneous climate is assumed over the studied area. If several stations are available, they will be interpolated over the area using robust algorithms (Inverse distance or kriging) that prevent from drifts occurring when interpolating far from the input points. However, one interesting data source is the daily fields of climatic variables produced according to a regular 16 km grid by the ALADIN model of the Moroccan Meteorological Agency (DMN). This data has already been tested and validated by comparing it to ground recorded data, and in the scope of a fully operational tool, it would be of course the best solution for climate input.

The land cover module offers to the user a standard map of the plain, that was achieved through the compilation of several images available for different years to improve its reliability. The irrigated area is covered by 25% trees plantation, from which 80% are olive trees, and 75% annuals, from which 75% are wheat. Tree areas are rather stable over years, whereas the variability of annuals area is very high according to the water availability for the season. This availability is driven mainly by the quotas of dam water granted to ORMVAH by the water agency (ABHT), and also by the rainfall amount at the beginning of the season, these two factors conditioning the decision of the farmers about whether or not to sow. Thus, satellite images may be very useful for controlling the annuals extent.

Finally, the phenology module offers the possibility to use standard Kcb profiles issued from the FAO tables, but the interest of SAMIR is rather to use satellite time series (about 10-12 images each year). Such a time series was previously used by Ray (2001) on a reduced number of images. Kcb-NDVI relations are available for all crops of the area, some of them were tested on some fields of olive trees and wheat (Duchemin et al. 2006 ; Er Raki et al., 2006). These relation are usually linear, of the following type:

$$Kcb = 1.64 * (NDVI - NDVImin) \qquad (2)$$

NDVImin is the value of a bare soil, and may be adjusted depending on the soil properties, and also the radiometric quality of the satellite data. These linear relations are usually of good quality (determination coefficients usually around 0.90), which makes the roundabout by the LAI concept useless, unless it is needed as input for other modelling.

4 SAMIR OUTPUTS

4.1 Spatialized ET

Evapotranspiration was estimated for the whole Haouz plain during the 2002/2003 season, on the basis of nine Landsat TM images acquired from November to May (Simonneaux et al., 2006). The processing of the series began with its radiometric correction to get reflectance data, which is never a trivial task because of uncertainties regarding the atmospheric parameters. Additional relative inter-calibration of the images, based on invariant features, is often useful to improve the initial correction. In a next step, three land cover classes were identified on the basis of shape analysis of the NDVI times series: annuals, trees on bare soil, trees on annuals understorey, bare soil

(Simonneaux et al., 2003). Because of the very heterogeneous signatures of the land cover classes, due to highly variable farmer practices, this type of classification revealed itself to be more efficient than traditional classifications based on distances between spectral signatures.

Accuracy assessment was possible for the wheat class, on the basis of ground measurements of the actual ET using eddy correlation systems installed on three plots (fig.1). The average error between remote sensing estimates and ground measurements was 27% at the daily scale, 18% when aggregating results at the weekly scale, and only 5% when considering the full data set (160 days of measurements available when grouping the three plots).

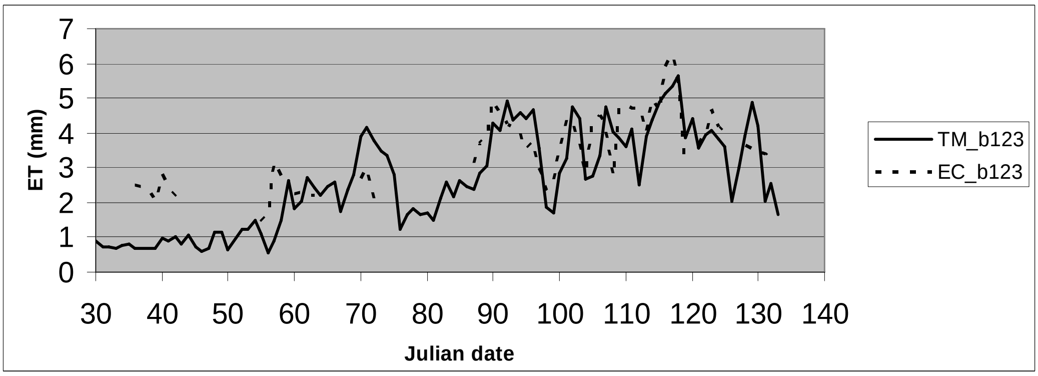

Fig. 1 – Comparison of actual (EC) vs satellite estimated (TM) evapotranspiration. Example of the "b123" plot in the Haouz Plain.

The ET computed only on the basis of kcb obtained from NDVI is a better estimate of the actual ET than the one based on standard Kcb profiles assuming ideal growing conditions throughout the cycle, because it considers actual vegetation development. Anyway this ET is still not the actual ET as it does not take into account the actual soil evaporation (Ke) and the possible water stress periods due to the non optimal irrigation practices (Ks), quite frequent in this area. The succession of these periods of stress have a long term effect on the whole subsequent part of the vegetation cycle, which is taken into account through NDVI. But the short term effect, which can reduce drastically the ET by stomatic control, is not accounted for. However, thanks to its soil compartment, SAMIR is able to model the Ke and Ks factors, and produce ET estimates closer to the actual values.

4.2 Pumpings estimates

Farmers do not only use surface water distributed from the dams to irrigate their crops but also water pumped directly from the aquifer. Owing to the overexploitation of the Haouz aquifer, it is of a great matter for water managers to assess the volumes of irrigation water and particularly the volumes of pumpings. Pumpings were thus assessed through SAMIR outputs for the 2002/2003 season using the same nine Landsat TM images as for the spatialized ET and knowing the volumes of surface water irrigation distributed on each irrigation sector, that is to say modern irrigation water and traditional irrigation water distributed through the seguia network. The following equation was used to model the water budget :

$$\text{ET} + \text{Percolation} + \Delta\ \text{Soil Water} = \text{Rainfall} + \text{Surface Irrigation} + \text{Pumpings} \qquad (3)$$

To validate SAMIR pumping estimates, we used investigations made by the hydraulic agency of the Tensift watershed (ABHT) concerning the water pumping points all over the Haouz plain. For each extraction point, three estimations of pumped water volumes had been made: energetic, hydraulic and agronomic. The confrontation between the investigation data from the hydraulic agency and results obtained through the SAMIR tool show a good correlation with the agronomic assessment, which is promising (fig.2). However, a bias can be observed in the relation, which can be due on the one hand to an overestimation of the irrigation volumes with the SAMIR tool. On the other hand, this bias may be due to the possible non-exhaustivity of the agronomic assessment method or of the ground investigations conducted. The hydraulic and energetic methods shows very bad correlation, emphasizing the fact that farmers usually underestimate these values as they fear the questions of investigators associated with fees collection. It is less possible to lie with farm areas which are easier to control. Pumping estimates appears to be a very touchy task, as it is very difficult to validate this estimates on large scales. It requires huge amount of data, and reliable ground survey methods.

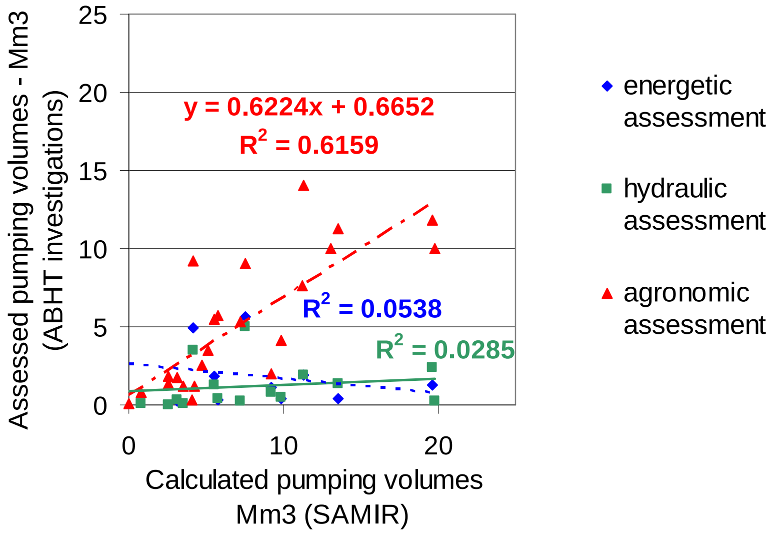

Fig.2 – Assessment of pumpings in the irrigated sectors of the Haouz plain. Comparison between SAMIR and ground survey estimates.

5 PROSPECTS

The accurate monitoring and validation of the soil water budget is not an easy task because irrigations are difficult to know as their knowledge rely on ground truth or farmers declaration, none of these two ways being easy to conduct accurately. In fact, in addition to the regular water supply by ORMVAH coming from big dams, many farmers use also ground water pumping. These problems in knowing and assessing water input explain why advances in the use of remote sensing for soil moisture monitoring is a big challenge. The two ways currently under investigation by the scientific community are thermal and microwave satellite data. As mentioned previously, thermal data may help getting direct information about plant stress, thus soil water content, but the problem is that current satellite offer is either insufficient regarding frequency (high resolution sensors) or regarding resolution (daily frequency sensors). Nevertheless, Er-Raki (2007) has successfully assimilated ASTER thermal data in an FAO model to improve the water budget assessment. On the other hand, active or passive microwaves are sensitive to soil water content, but the same problem of frequency-resolution trade off hampers its use for soil water monitoring at the plot scale.

To answer managers of water resources and irrigation, and also possibly farmers, it is planed to develop in SAMIR forecasting capabilities at terms going from the next day to the end of the season. Forecasting for the whole season is currently made by ORMVAH to plan the water distribution, on the basis of previous year data. These forecasting are adjusted two times during the season, on the basis of visual observation of estimated areas and development of crops. In order to better account for the actual vegetation development, we are developing a forecasting tool based on the image set acquired from the beginning of the season, along with any relevant information available (ground observations). This extrapolation of the phenology will be achieved using algorithm of different levels of complexity, going from simple graphic extrapolations of standard FAO profiles when poor data is available, to the use of crop models constrained by previously acquired images. A simple model of crop development compatible with large area modeling has already been proposed by Duchemin (2005).

The functionalities of the SAMIR tool will make possible the testing of land cover and climate change scenarios on large scale. This agricultural surface modelling should on the long term be included in larger watershed models, including especially rainfall, runoff and ground water modeling. The watershed scale is actually the most relevant for sustainable management of water resources.

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