SAMIR a tool for irrigation monitoring using remote sensing for evapotranspiration estimate

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Abstract. SAMIR is software computing spatialized estimates of evapotranspiration (ET) and irrigation water budget on large areas, based on the use of satellite images. Remote sensing offers a synoptic view of the vegetation development, which is a key information for ET reliable computing. ET is obtained using the FAO method, well suited for computation over large areas, where little information is usually available about crops and soils. The computation of the water budget requires climatic data (reference ET — namely "ET0" — and rainfall data), land cover data, and crop development data (for estimating crop coefficients of the FAO method), these last two types of data being obtained from remote sensing. Irrigation may be an input when it is known, but it is most of the time estimated from the computation of the water budget, using hypotheses on the water management modes and especially the average water stress level allowed. The irrigation estimates at the scale of irrigation sectors may be compared with known water inputs from dams and traditional seguias (traditional channels deriving water from rivers) to estimate pumpings in the aquifer. In a context of strong pressure applied on water resources, we emphasize the potential of satellite images for irrigation monitoring and water management at watershed scale.

Keywords. Evapotranspiration – Irrigation – Remote sensing – Water budget – Pumpings.

SAMIR, un outil pour le suivi de l'irrigation estimant l'évapotranspiration par télédétection

Résumé. *SAMIR est un logiciel qui calcule la spatialisation de l'évapotranspiration (ET) et le bilan de l'eau d'irrigation à l'échelle régionale, en utilisant des séries satellitaires. La télédétection permet d'avoir une vue d'ensemble du développement de la végétation, ce qui représente une information fondamentale pour un calcul fiable de l'ET. L'ET est déterminée en utilisant la méthode FAO, qui se prête particulièrement aux calculs sur les grandes surfaces où généralement, les informations sur les cultures et les sols sont insuffisantes. Le calcul du bilan hydrique nécessite des variables climatiques (l'ET de référence — à savoir, l' "ET0" — et les données sur les précipitations), des données sur l'occupation du sol et sur le développement des cultures (en vue d'estimer les coefficients culturaux de la méthode FAO) ; ces deux derniers types de données sont déterminés par télédétection. L'irrigation peut être une autre variable si elle est connue, mais le plus souvent, elle est déterminée sur la base du bilan hydrique, en avançant deux hypothèses sur les modalités de gestion de l'eau et surtout, sur le niveau de stress hydrique admis. Les données estimées pour l'irrigation dans les différents secteurs peuvent être comparées avec les quantités d'eau d'irrigation apportées par les barrages et les seguias (les canaux traditionnels de déviation de l'eau des rivières) afin d'estimer les pompages réalisés dans la nappe. Vu la pression considérable à laquelle sont soumises les ressources en eau, il y a lieu de mettre en évidence le potentiel des images satellites pour le suivi de l'irrigation et la gestion de l'eau à l'échelle du bassin versant.*

Mots-clés. *Evapotranspiration – Irrigation – Télédétection – Bilan hydrique – Pompages*

I – 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 modelling. 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 the 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 to 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 water management of irrigated areas, making extensive use of satellite images. SAMIR is designed to compute the evapotranspiration and water budget of irrigated crops, and thus to estimate irrigation requirements at the irrigation scheme scale. It should be noticed that we don't target the irrigation management at the plot scale. We consider that the farmer may get — by direct observation — more valuable information for water budget assessment than what satellite can offer. This detailed information is not available on the large areas observed by satellite, which conversely allows less accurate water budget but on much larger areas on which local errors are assumed to compensate somehow. We briefly present the main features of this tool.

II – State of the art

Some tools for water budget of crops already exist, which are based on more or less complex soil-vegetation-atmosphere models (Butler 1998, Raes, 2001). 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.

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 provide 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, has for a long time limited their use, but they should soon become more widely available thanks to new or forthcoming missions (Formosat, Venµs / GMES).

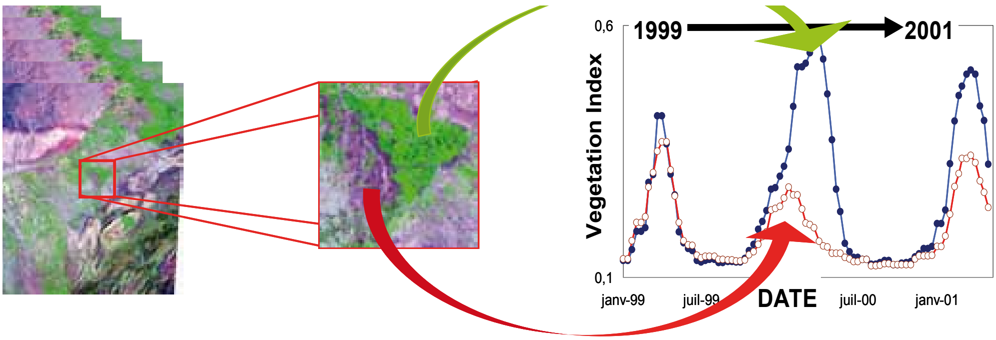

Figure 1. The interest of satellite vegetation indices. On the right part of the image time series extract an area with high vegetation development (in green) and associated high vegetation indices (blue curve). Conversely, the left part of the extract shows an uncultivated area (purple) and a low index (red curve).

III – SAMIR tool features

SAMIR provides for each pixel, at the daily step, ET estimates and a water budget of vegetation. The originality of the approach lies in the extensive use of satellite image time series, which allows an accurate monitoring of the actual vegetation development, and not an assumed one. The images acquired are also used to identify or refine the land cover identification during the acquisition time range. The ET is computed using the FAO dual crop coefficient method, which consider separately the Evaporation and Transpiration processes. The crop coefficients (Kcb) are determined on the basis of vegetation indices like NDVI, obtained from satellite images, and interpolated between two dates of image acquisition. Several land cover classes are considered to define specific NDVI – Kcb relations. The soil water budget is computed using the soil model proposed by Zhang (2006). Although the FAO method is less complex than those based on physical modelling, its simplicity makes it well suited for ET assessment on large areas, for which detailed data needed by more complex models, regarding soil and vegetation, is rarely available. This method has been calibrated and validated on our study area for the main crops encountered (Olive, citrus, wheat) (Er-Raki, 2006). Its implementation was validated on the Haouz area using a Landsat TM image time series (Simonneaux, 2008), and also using low resolution images (BenHadj, 2007). The collaboration with the office in charge of irrigation (Office Régional de Mise en Valeur Agricole 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.

1. Method for water budget computing

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 any vegetated surface using the following equation:

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

where ET0 is the reference evapotranspiration, i.e. the evapotranspiration of a standard well watered grass that would be in the same condition. Kcb is the basal crop coefficient accounting for the transpiration of the vegetation fraction (fc), Ks is the stress coefficient based on the soil water availability obtained from the soil module, 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 the calculation of reference evapotranspiration (ET0), land cover, and periodical information about crop development for adjusting the Kcb and Ke.

The soil module was adapted from Zhang et al. (2006) and includes three compartments: (1) a surface compartment, (2) a root compartment whose thickness is variable and linked to vegetation development, 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.

For each day SAMIR computes the water budget using equation (2). It should be noticed that lateral flows are not taken into account here, as they are considered negligible in irrigated areas.

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

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

2. Input and Output data

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).

The soil module assumes a homogeneous soil over the area, for which field capacity and welting points are input by the user. It is also possible to enter a soil map if available, offering a spatialization of these values.

The land cover module offers to the user standard maps of the area, but it is recommended to use an updated land cover map based on the satellite images of the year, as this input may vary greatly from one year to another. The study area tested, the Haouz plain, 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 Tensift Hydraulic Watershed 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 extent of annuals.

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 only three 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 relations are usually linear, of the following type:

$$Kcb = A * (NDVI - NDVImin) \quad (3)$$

with A and NDVImin constants to fit to each crop.

Various options were developed to take the irrigation into account. The first option is to introduce irrigation data into the model, but this option is rarely used as irrigation data usually lack, especially at the plot scale. The more realistic option is to let SAMIR estimate the irrigations, on the basis of decision rules for irrigation which are linked to soil water content, irrigation amounts observed, etc.

The water budget is computed daily for each pixel, but considering the uncertainties related to the input data, especially regarding soil and irrigations — vegetation being rather well monitored thanks to satellite — the results should be considered at the scale of larger irrigation units. As actual irrigations are the result of complex human decisions, SAMIR will not be able to reproduce them exactly. Thus, the water budget and irrigation amounts shouldn't be considered daily but for longer time intervals.

IV – SAMIR outputs

1. Evapotranspiration Estimates

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, 2008). 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.2). 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 merging the three plots).

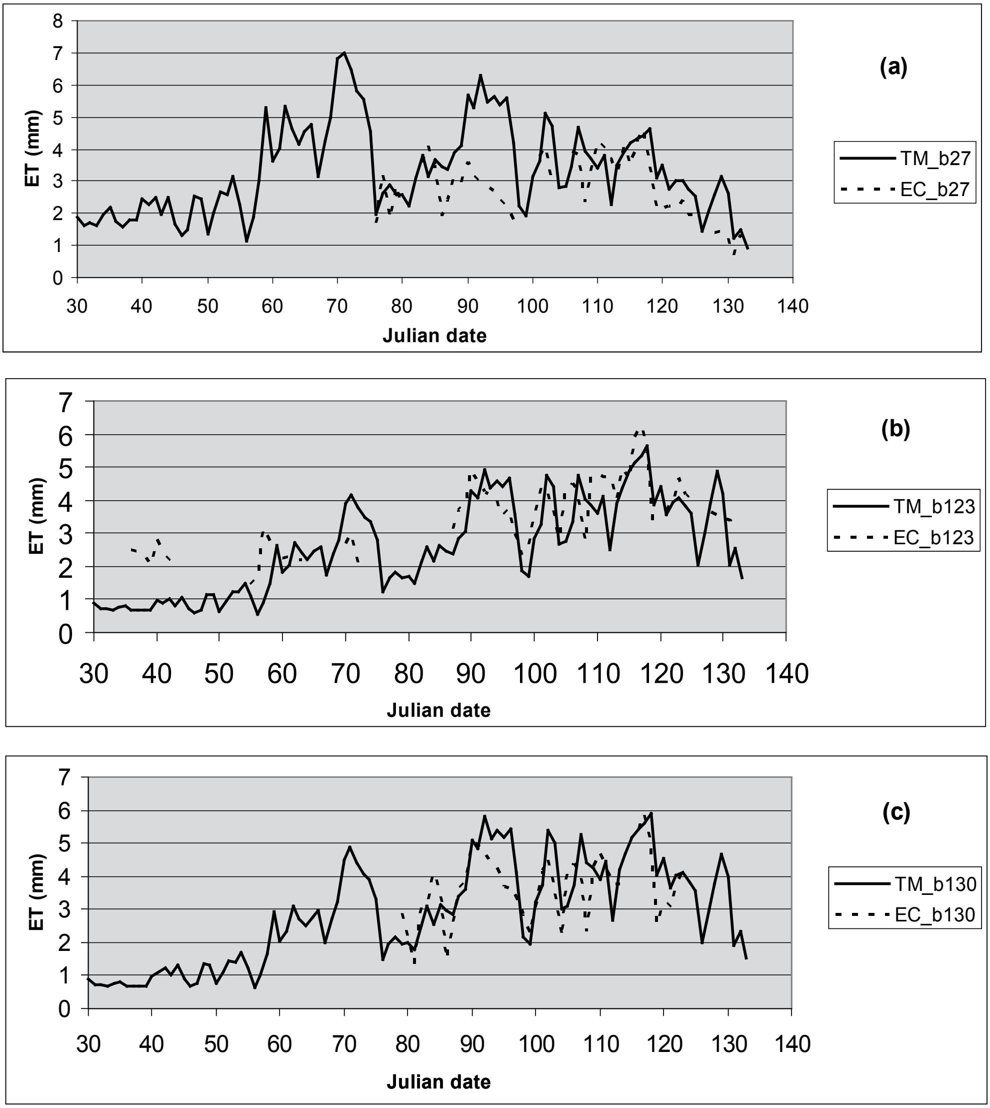

Figure 2. Comparison of actual (EC) vs satellite estimated (TM) evapotranspiration. Example of a plot in the Haouz Plain.

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 the actual vegetation development. The ET obtained using the two methods are very different (Fig. 3).

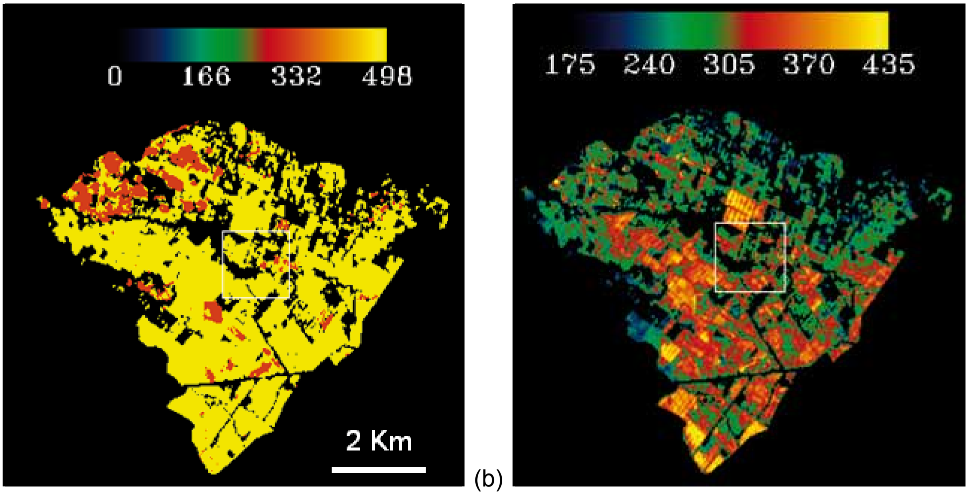

Figure 3. Maps illustrating the benefit of using satellite monitoring of the vegetation compared to standard development. (a) Cumulated ET estimated from standard FAO values : 13.1 Mm3, (b) Cumulated ET estimated from remote sensing : 8.2 Mm3.

2. Pumping 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. Irrigation amounts were estimated using SAMIR for the 2002/2003 season using the above mentioned Landsat TM time series. The ORMVAH provided us with the volumes of surface water irrigation distributed on each irrigation sector, including modern irrigation and traditional irrigation through the seguia network (traditional channels diverting water from rivers). The following equation was used to model the water budget :

$$\begin{gathered}\text{ET + Percolation} + \Delta\ \text{Soil Water} \\ = \\ \text{Rainfall + Surface Irrigation + Pumpings}\end{gathered} \tag{3}$$

To validate SAMIR pumping estimates, we used investigations made by the ABHT regarding the water pumping points all over the Haouz plain. For each point, three estimations of pumped water volumes had been made: energetic, hydraulic and agronomic. The confrontation between the investigation data and results obtained through the SAMIR tool show a significant correlation with the agronomic assessment (fig.4).

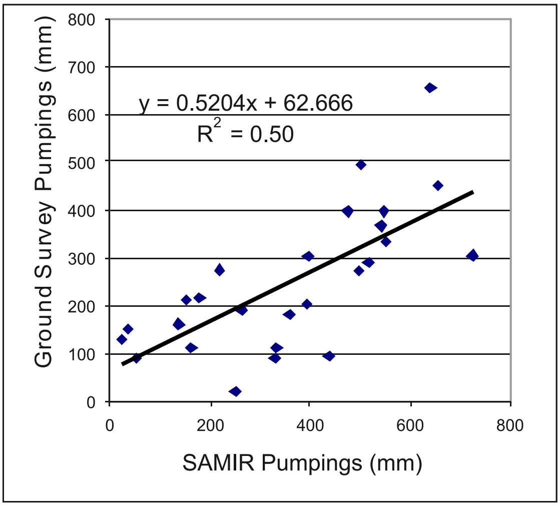

Figure 4. Comparison between pumpings estimated using SAMIR for the 2002/2003 campaign and values obtained from the watershed agency (agronomic method) for the irrigated sectors of the Haouz plain.

However, a bias can be observed in the relation, which can be due to an overestimation of the irrigation volumes with the SAMIR tool. This bias may also be due to the possible non-exhaustivity of the agronomic assessment method or of the ground investigations conducted. The hydraulic and energetic methods show very bad correlations, 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 these estimates on large scales. It requires huge amount of reliable data, which is hardly found.

V – Conclusion

Thanks to the information regularly provided regarding vegetation, remote sensing is a particularly valuable data source for the water budget monitoring of irrigated areas. SAMIR is a first version of a tool dedicated to irrigation budget management on large scale, especially useful in arid and semi-arid areas where this information is scarce although critical for the regional water budget.

One weakness of the tool lies in the difficulty to control the soil water content and actual water inputs. Thermal satellite data may help getting direct information about plant stress to improve the soil water management and thus ET assessment. In this manner, Er-Raki (2007) has successfully assimilated ASTER thermal data in an FAO model to improve the water budget assessment. One other difficulty of this approach is the lack of accurate validation data needed to validate the results on large scales, but this problem should be solved by using many local validation datasets on various crops.

Managers of irrigation and water resources need forecasting of water requirements over large areas, at various runs going from the next day to the end of the season. Forecasting for the whole season is already made by ORMVAH to plan the water distribution, on the basis of previous year data. These forecasts are adjusted two times during the season, on the basis of visual observation of actual crop areas. In order to better account for the actual vegetation development, we are developing in SAMIR forecasting capabilities based on the image set acquired from the beginning of the season. Finally, SAMIR should help testing land cover and climate change scenarios on large scales.

VI – Acknowledgments

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References

Allen R.G., Pereira L.S., Raes D., and Smith M., 1998. *Crop evapotranspiration. Guidelines for computing crop water requirements.* FAO Irrig. and Drainage Paper 56.

Bastiaanssen W.G.M., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. *Journal of Hydrology* 229 (2000) 87–100.

Benhadj I, Duchemin B, Simonneaux V, Maisongrande P, Khabba S, Chehbouni A G., 2008. Automatic unmixing of MODIS multi-temporal data for inter-annual monitoring of land use at regional scale (Tensift, Morocco). *International Journal of Remote Sensing* ; in printing.

Buttler I.W. and Riha S.J., 1989. GAPS: a general purpose simulation model of the soil-plant-atmosphere system, Version 1.1 User's Manual. Ithaca, NY: Cornell University Department of Agronomy.

Clarke D., Smith M. and El-Askari K., 1998. "New software for Crop Water requirements and Irrigation Scheduling." J*ournal of the International Commission on Irrigation and Drainage,* 47(2), 45-58

Duchemin B., Hadria R., Er-Raki S., Boulet G., Maisongrande P., Chehbouni A., Escadafal R., Ezzahar J., Hoedjes J., Kharrou M.H., Khabba S., Mougenot B., Olioso A., Rodriguez J-C. and Simonneaux V., 2006. Monitoring wheat phenology and irrigation in Center of Morocco: on the use of relationship between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. *Agricultural Water Management*, 79:1-27.

Er-Raki S., Chehbouni A., Guemouria N., Duchemin B., Ezzahar J. and Hadria R., 2006. Combining FAO-56 model and ground-based remote sensing to estimate water consumptions of wheat crops in a semi-arid region. *Agricultural Water Management,* 87: 41-54.

Er-Raki S., Chehbouni A., Hoedjes J., Ezzahar J., Duchemin B. and Jacob F., 2008. Improvement of FAO-56 method for olive orchards through sequential assimilation of thermal infrared-based estimates of ET, *Agricultural Water Management*, in press.

Raes D., Van Goidsenhoven B., Goris K., Samain B., De Pauw E., El Baba M., Tubail K., Ismael J. and De Nys E., 2001. BUDGET, a management tool for assessing salt accumulation in the root zone under irrigation. ICID 4th Inter-regional Conf. on Envir.-Water, 27-30 Aug., Fortaleza, Brazil: 244-252.

Ray S.S. and Dadhwal V.K., 2001, Estimation of crop evapotranspiration of irrigation command area using remote sensing and GIS. *Agricultural Water Management,* vol. 49, p.239-249.

Simonneaux V., Duchemin B., Helson D., Er-Raki S., Olioso A. and Chehbouni A.G., 2008. « The use of high-resolution image time series for crop classification and evapotranspiration estimate over an irrigated area in central Morocco ». *International Journal of remote Sensing,* 29:1, 95 – 116.

Zhang Y. and Wegehenkel M., 2006, Integration of MODIS data into a simple model for the spatial distributed simulation of soil water content and evapotranspiration, *Remote Sensing of Environment*, 104 : 393-408.