Monitoring of Wheat Crop Evapotranspiration and Irrigation in Arid Conditions using Phenology derived from Optical Satellite Data

B. Duchemin, P. Maisongrande, F. Frappart, M. Magnac, G. Chehbouni, G. Dedieu, B. Mougenot,
Centre D'Etudes Spatiales de la Biosphère (CESBIO)
Unité Mixte de Recherche CNES, CNRS, IRD, UPS
18, Av. Edouard Belin31401 Toulouse, France
benoit.duchemin@cesbio.cnes.fr

ABSTRACT - *This paper presents approaches we developed for the spatial and temporal monitoring of evapotranspiration and irrigation of cereals in semi-arid regions surrounding the Mediterranean basin. The test site covers a 3 x 3 km² area located in the plain of Marrakech (Morocco) where wheat crops is dominant. Two methodologies of coupling evapotranspiration models and remote sensing data were compared. They result in estimate of plant maximal transpiration and water requirements corresponding to crop cycles observed by time series of satellite data. The two approaches were tested using eight high spatial resolution images acquired by HRVIR sensor onboard SPOT satellite during one agricultural season. The spatialisation method outlines the spatio-temporal patterns of crop development. The associated maps of seasonal evapotranpiration appear consistent with rainfall and irrigation features. These maps can provide with a suitable overview of plant water consumption as well as deficit in supply of irrigation water. The drawbacks and advantages of each approach are finally discussed, as well as the perspectives on improvement and validation of these first result.*

1 INTRODUCTION

The SUD-MED project aims at monitoring water resources over Mediterranean semi-arid regions by coupling ground truth, process models and satellite measurements. The test area is the water catchment of Tensift river that covers about 30.000 km² around the Marrakech city in Morocco. The climate is arid : a low and irregular pluviometry (≈ 240 mm/year) contrasts with a very high potential evapotranspiration (≈ 2,400 mm/year). Hydrological processes – snow/rain partition, snowmelt, surface and sub-surface runoffs – stresse the water budget on the Atlas mountainous region, while vertical exchanges dominates in the plain. On irrigated areas covered with cereals and orchards (olive and orange trees), the important terms to be known are rainfall, irrigation, drainage and evapotranspiration.

This paper presents two methodologies we developed in order to monitor evapotranspiration of cereals crops in the flat open country surrounding Marrakech. We focus on the possibilities offered by time series of high spatial resolution (20 m) satellite data and coupling with evapotranspiration models. The analysis is performed from eight images acquired by the HRVIR sensor onboard SPOT-4 satellite over a 3 x 3 km² test site where wheat is predominant. Firstly, image classification was used to discriminate irrigated field and cluster them according to crop cycle patterns. This processing also permits to extract major phenological features and track the intra- and inter-class variability in plant development. The impact of this variability is investigated using two models to monitor the surface water budget. One is based on a crop process model (STICS, Brisson et al. 1998) in order to simulate plant maximal evapotranspiration. The other was developed by the FAO (Allen, 1998) to assess crop water requirements. In both case, we present maps of cumulated evapotranspiration for the 2001-2002 agricultural season. These maps were established through remote sensing data by driving phenological stages and calibrating the time course of Leaf Area Index (case of STICS model). They are suitable to estimate the seasonal evapotranspiration averaged over field or countryside. In addition, they could indicate the level of extreme deficit in supply of irrigation water.

2 MATERIAL AND METHODS

2.1 Processing of Satellite Data

A 3 x 3 km² test site where wheat crops is predominant was selected within an area managed by the 'Office Régional de Mise en Valeur Agricole du Haouz' (ORMVAH, which is the regional authority for planning and irrigation of agriculture in the Marrakech plain). During the 2001/2002 agricultural season, a programming request for the HRVIR sensor onboard SPOT-4 satellite resulted in the acquisition of eight high spatial resolution (20 m) optical data. Thanks to the flat topography of the test site, geometric corrections allowed superimposition of images possible with a good accuracy. Surface reflectances in red and near-infrared bands were calculated by performing calibration and atmospheric correction using a code adapted from the SMAC procedure (Rahman and Dedieu 1994). Finally, the Normalized Difference Vegetation Index (NDVI, Rouse et al. 1974) was computed.

An unsupervised classification of the eight NDVI images allowed to define 15 classes (Fig.1). One among them is predominant and covers up to 85% of the total surface. This class featured systematically low NDVI values (around 0.13). It includes crops that farmers could not irrigate this year and was removed of our analysis. A visual analysis of NDVI time series led to exclude two other minor classes (covering less than 2% of the total surface). These two classes exhibited very high and nearly constant values, which were found incompatible when compared to wheat typical seasonal signatures. Over the remaining 13%, the time courses of NDVI satisfy expected trajectories for irrigated cereals, although a wide range of patterns were observed. To track this variability, 12 classes were considered and, for each class, three scenario of crop development were built. Our idea is twofold : 1) consider a mean scenario in order to provide field and area averaged estimates of crop development and evapotranspiration, 2) analyse the difference between maximum and minimum scenario in term of extreme case of water deficit. Mean growth conditions were obtained by averaging the NDVI over the class, while minimal and maximal conditions correspond to the pixel of the class where the temporal sums of NDVI are respectively the lowest and the highest. This processing allows to define 36 cases that encompass all agricultural practices over the test site. Figure 2 illustrates the result of this processing for class 12 where the NDVI seasonal signature is characteristic of well-watered plants.

Figure 1. Classification of the test site based on the NDVI time series derived from SPOT/HRVIR

2.2 Approaches for Estimating Evapotranspiration

The first approach is based on the STICS model (Brisson et al., 1998-a and 2002), which was conceived as a simulation tool able to work under actual agricultural conditions. Although the model was chosen for its abilities to estimate yields and environmental budgets (water, fertilisers), we were interested here in the resistive scheme that estimates latent heat fluxes (Brisson et al. 1998-b Shuttleworth and Wallace 1985). A sensitivity analysis has pointed out the major parameters that act upon evapotranspiration : humidity at field capacity and at wilting point, apparent soil density, sowing date, date of maximum Leaf Area Index (LAI) and maximum rate of LAI setting up. The three latter can be derived from remote sensing data, since NDVI and LAI are highly correlated. Soils properties were determined through the analysis of soil maps provided by ORMVAH and pedo-transfert rules (Jensen 1990) : a high clay content was found, joined with a 15% value for the soil water content available for roots uptake. To run the model at a daily step, a climatology was built from three years (1999-2001) of data acquired at the ORMVAH weather station located 30 km North of the test site. Only rainfall data actually correspond to the period of simulation (October 2001 – June 2002).

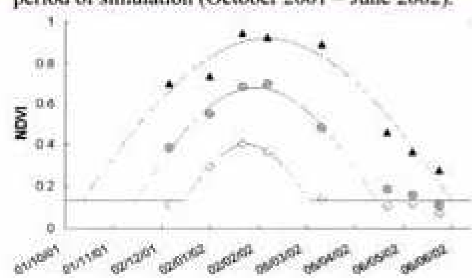

Figure 2. NDVI time series derived from SPOT/HRVIR images associated to minimum (diamonds), mean (circles) and maximum (triangles) scenario of crop development. The lines highlight sinus curves are together with sinusoidal curves that were fitted on NDVI time series (see the 2.3 section).

The second method, developed by FAO (Allen 1998), is based on the concept of reference evapotranspiration (ET0) that allows to study the evaporative power of the atmosphere independently of crop type, crop development and agricultural practices. The reference surface is an 'hypothetical' extensive green grass actively growing (with adequate water) and completely shading the ground. This description is linked with assumptions on physical variables that lead to unambiguous definition and derivation of ET0 through the so-called FAO Penman-Monteith equation (after Penman 1948 and Montheith 1985). Only climatic parameters affect the reference evapotranspiration, which have been calculated from the above-mentioned weather data set. For other crops, the evapotranspiration under standard conditions (ETC) corresponds to disease-free and well-fertilised plants that 'hypothetically' grow under optimum soil water conditions for achieving full production. ETC is obtained by multiplying ET0 with a cultural coefficient that varies according to phenological stages with the distinction of initial (from sowing to 10% growth cover), mid (from effective full cover to the start of maturity) and late season (until harvest or full senescence). Note that the effective full cover is also defined as the date when LAI reaches 3. Thus, it seems relevant that remotely-sensed optical data can contribute to infer crop coefficients and run the FAO model.

2.3 First analysis of satellite data

From the previous discussion, we reached the conclusion that two kinds of parameters – LAI and phenological stages – both appear crucial for modelling evapotranspiration and derivable from optical satellite data. In order to facilitate their retrieval and to drive the FAO approach at a daily step, sinus curves were fitted on each NDVI time series. The curves obtained for each growth scenario within class 12 are given in Fig.2. They are determined by three parameters : the date when NDVI begins to increase, which roughly corresponds to plant emergence ; the amplitude, which provides an index of maximum crop vigour ; the date when NDVI stops to decrease, which indicates harvest or full senescence. By comparing the latter with the day of emergence, the length of crop cycle can easily be estimated. Figure 3 (next page) displays maps where these three parameters were obtained class by class considering mean growth conditions (the sinus curves were fitted on time courses of NDVI after spatial averaging over each class). These maps provide a quick and synthetic overview of crop development on the test site for the 2001/2002 agricultural season. A simple analysis of this figures suggests that growth was weak and irregular. Amplitudes are always lower than 0.55, while the seasonal dynamics of NDVI may be generally higher for well-watered cereals (see the case of maximum growth condition for class 12 in Fig.2). Crop cycles are generally short, with a median value of 92 days to be compared with the values collected in Allen (1998) that ranges between 105 to 140 days. The probable cause is the severe droughts from years 2000 to 2002 that have limited dams filling and therefore the supply of irrigation water. Furthermore, two different phenological patterns come up from the map of emergence dates, acknowledging the fact that NDVI starts to increase either in January-February or in March-April (blue/green or yellow/red colors in Fig.3). The first pattern corresponds to that encountered in the Marrakech plain when rainfall and irrigation-flooding events are normally distributed. The second one indicates a delay in emergence date due to unavailability of water for irrigation and late-season rainfall.2.4 Spatialisation of evapotranspiration models

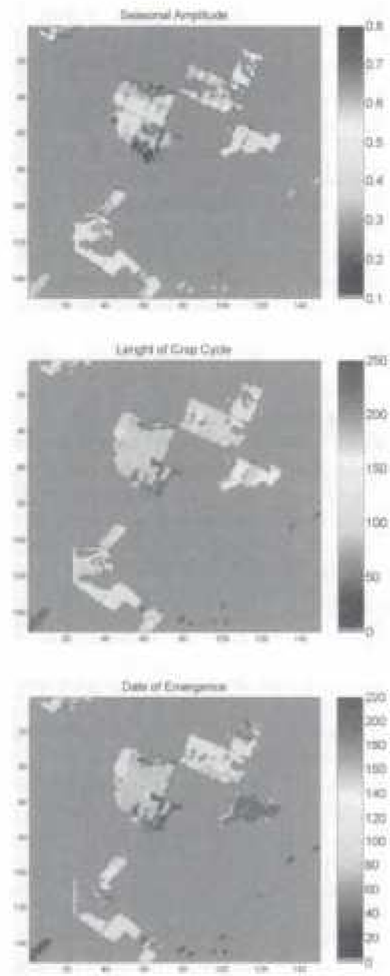

Figure 3. Features of crop development pattern extracted from the sinusoidal curves fitted on NDVI time series : seasonal amplitude (up, in NDVI units), length of crop cycle (middle, in days), date of plant emergence (bottom, in days).

The maps previously built from NDVI times series (see Fig.3) provide two useful phenological features in order to run the STICS model : 1) the day of maximum LAI, which can be taken as the middle between emergence and full senescence ; 2) the date of sowing, which can be assumed to occur 15 days before emergence according to Allen (1998). The most complex parameter to fit is the maximum rate of LAI setting up because the knowledge of LAI is required. However, sound relationships between NDVI and LAI have been established on wheat crops. We here calibrate the one given in Eq.1 (after Asrar et al. 1984), assuming that the pixel which displays minimal and maximal NDVI values (both spatially an temporally) corresponds respectively to bare soil ($NDVI_S$ = 0.13 in Eq.1) and 'infinitely' dense vegetation ($NDVI_\infty$ = 0.94 in Eq.1). Eq.1 allows us to derive LAI at SPOT-HRV acquisition dates. Retrieved LAI values are then used to optimise the maximum rate of LAI setting up by comparing satellite observation and STICS simulation through a Simplex Algorithm (Nelder and Mead 1965). After optimisation, the model was run at a daily step. Since the automatic irrigation mode was activated, plants are watered as soon as they are stressed. We also assume there is no deficit in soil nitrogen content in order to have plant maximal transpiration.

For the FAO approach, the issue to be addressed is the translation of NDVI curves into time dependent crop coefficients (Kc). Given Eq.1 and the hypothesis of linearity between LAI and Kc in the FAO method, we can suppose that the relationship between NDVI and crop coefficient is exponential. The problem is thus to determine two points where both NDVI and Kc are known in order to fit the $Kc = A \cdot e^{B \cdot NDVI}$ equation. Looking at the tables reported in Allen (1998), we chose the extreme ranges expected in Kc values for wheat in semi-arid conditions : the minimal value (Kc=0.3) corresponds to the initial stage from sowing to 10% growth cover, while the maximal one (Kc=1.15) is observed at mid-season when full cover is effective (ie. LAI ≈ 3). The joined NDVI values (0.13 and 0.9) were determined by applying Eq.1 with LAI successively equal to 0 and 3. Once the relationship was established, NDVI sinusoidal curves were used to track the variability of phenology and determine the time course of crop coefficient as follow. From sowing to emergence (i.e. initial stage), Kc is assumed minimal. When the NDVI is larger than 0.9 (mid-season stage), Kc is assumed maximal. Otherwise (growing period and late-season stage), the exponential relationship between NDVI and Kc is applied.

3 RESULTS AND DISCUSSION

Fig. 4 (last page) displays seasonal evapotranspiration obtained with the FAO- and STICS-based approaches over the test site for the 2001/2002 agricultural season. The two approaches were successively applied for the three scenario of crop development within each class. For the FAO method, daily values have been cumulated between sowing and full senescence stages, and figure 4 furnishes seasonal crop water requirements. For the STICS-based approach, evapotranspiration is constrained by climate (rainfall) as well as irrigation practices as observed by remotely sensed-data through crop development. Thus daily values can be (and have been) cumulated during the whole simulation period. In this case, simulations end up with seasonal plant maximal transpiration for the observed LAI time course. Thus the difference with cumulated rainfall, which is close to 200 mm, estimates the minimum supply of irrigation water required to satisfy plant needs.

The hierarchy between the three scenario of crop development is clearly visible in Figure 4. The mean scenario, based on averaged NDVI per crop class, is the most suitable to estimate the average values on field and countryside. For the two approaches, it leads to values lower than those expected on arid regions.

$$NDVI = NDVI_\infty + (NDVI_S - NDVI_\infty)\, e^{-K \cdot LAI} \quad (1)$$

(with K = 1 after Baret et al. 1989)

This result is plausible since supply of irrigation water was limited. For the maximal scenario that corresponds to the plants that are the most watered, the highest values on the test area (600 mm for FAO, 450 mm for STICS) appears regular for wheat in arid condition. The minimum value provided by the STICS model corresponds to the value of cumulated rainfall. In this case, the crop development is low enough to be sustained by rainfall, and STICS simulates no irrigation.

When considering the FAO method, seasonal evapotranspiration can even in some case be under the amount of precipitation. The large differences between maximum and minimum scenario indicate the cases of extreme deficit in water consumption. Since we crossed two approaches and three scenario of crop development, we believe that the range of seasonal evapotranspiration displayed in Figure 4 is correct.

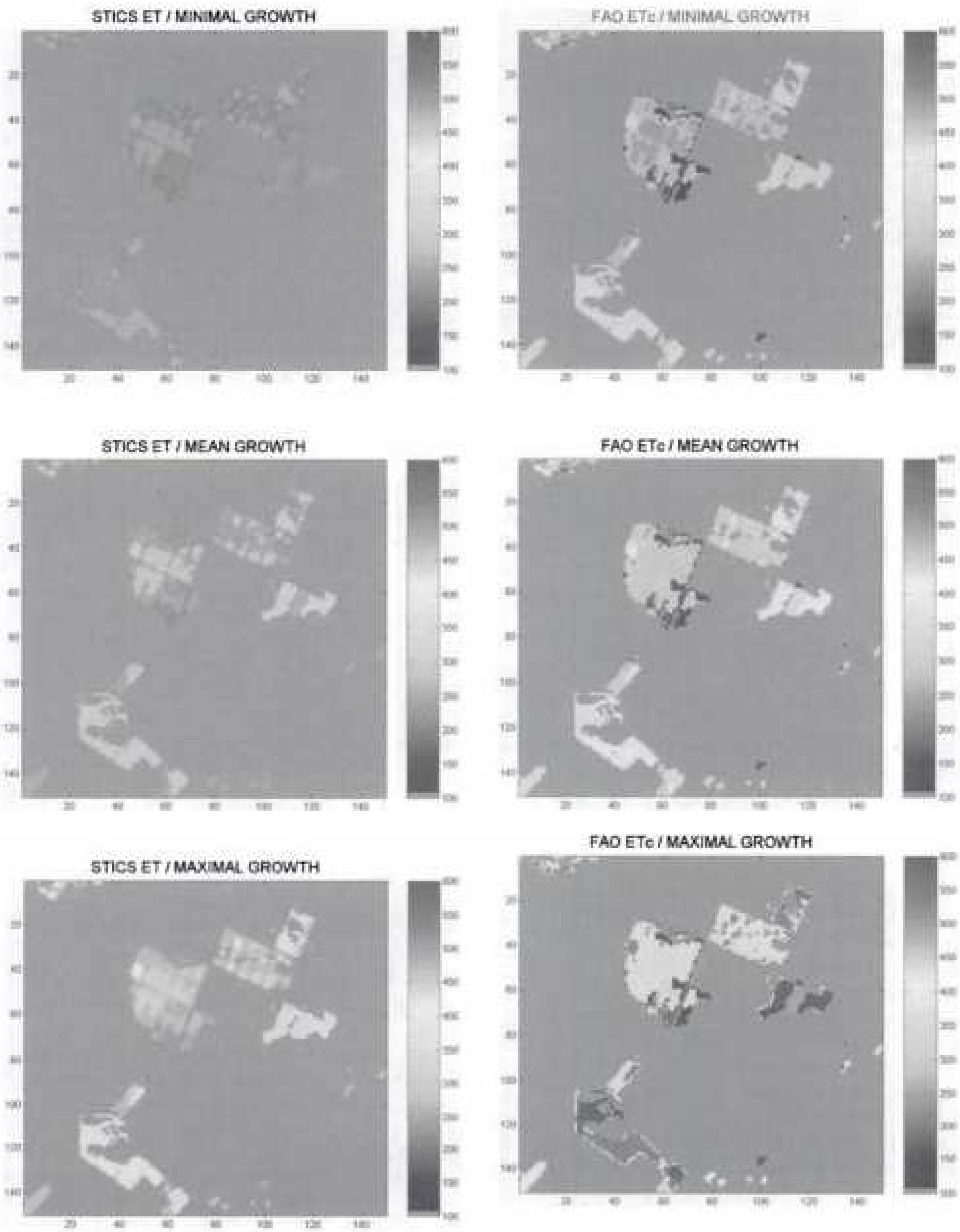

Figure 4. Estimate of crop water requirement (mm) during the agricultural season for the minimum (up), the mean (middle) and the maximum (bottom) scenario of crop growth. These results are obtained by cumulating the daily values obtained with STICS-based (left) and FAO-based (right) approaches.

There is nevertheless a strong need for ground data to analyse these first results. Therefore, our team plans to held important experimental efforts during the 2002/2003 agricultural season. Local validation should permit quantitative analysis of the accuracy of both FAO- and STICS-based approaches.

A quite good correlation is observed between the results of the two methods (Fig.5). The explanation mostly lies in the fact that no stress was implemented in the STICS model. Consequently, the simulation ends up with maximal plant transpiration. However, the soil evaporation is reduced because the soil surface is rapidly drying after wetting events, while it is always assumed wet in the FAO approach. This partially explains the bias observed between FAO- and STICS-estimates. The second difference is due to the fact that the crop coefficient at full senescence was approximately taken equal to that of the initial stage.

The previous statements first point out the need for an improvement in coupling the FAO model and remote sensing data to better discriminate soil and vegetation latent heat fluxes and account for the decrease in water requirements during late-season. Improvements will be first proposed to separate growing and senescence periods as well as to revisit the fit of NDVI time series using physically-based models (with for instance phenology inferred by degree day approach with photoperiodic slowing, see Weir et al. 1984). Further effort will be paid to test the dual (soil and vegetation) crop coefficients developed by the FAO. Finally, the most important issue to be addressed concerns the driving of approaches designed with the assumption of well-watered plants with remotely-sensed data that observe fields in actual agricultural conditions. Developments should be done to cope with the monitoring of soil moisture in order to better account for the impact of water stress on crop development.

Despite the above-discussed limitations, our study points out the potential of remote sensing data to calibrate and spatialise evapotranspiration models. The spatial results we obtained using the STICS model in arid conditions and for a wide range of irrigation practices are consistent. This first analysis was necessary to take advantage of all the possibilities offered by the model, such as yield estimation. The range of evapotranspiration derived from our adaptation of the FAO-based approach is also satisfactory. This second approach appears promising since we conceived it as an operational tool, paying attention to simplicity in order to provide helpful information for decision makers and end-users

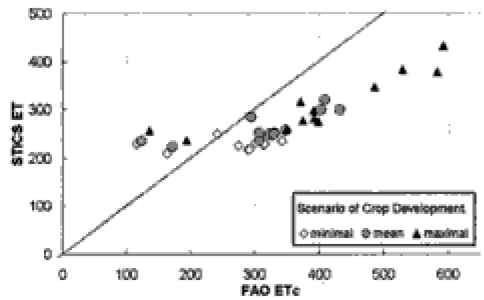

Figure 5. Comparison of seasonal crop water requirement estimated by the STICS model and the FAO method.

ACKNOWLEDGEMENTS

This study was conducted with support from the WATERMED project (WATer use Efficiency in natural vegetation and agricultural areas by Remote sensing in the MEDiterranean basin, see http://www.uv.es/ucg/watermed), which have been funded by the European Union 5th Framework INCO-MED Programme. We thank the ISIS ('Incitation à l'utilisation Scientifique des Images SPOT' by 'Centre National D'Etudes Spatiales', see http://medias.obs-mip.fr/isis) for providing us with satellite data. The authors are very grateful to ORMVAH and University Cadi Ayyad of Marrakech (Morocco), for their helpful scientific and technical help.

REFERENCES

Asrar G., Fuchs M., Kanemasu E.T., Hatfield J.L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron. J. 76 : 300-306.

Baret F., Guyot G., Major D.J., 1989 – a. Crop biomass evaluation using radiometric measurements. Photogrammetria 43 : 241-256.

Brisson N., Mary B., Ripoche D., Jeuffroy M.H., Ruget F., Nicoullaud B., Gate P., Devienne-Baret F., Antonioletti R., Durr C., Richard G., Beaudoin N., Recous S., Tayot X., Plenet D., Cellier P., Machet J.M., Meynard J.M., Delécolle R., 1998 – a. STICS : a generic model for the simulation of crops and theirwater and nitrogen balances. I. Theory and parametrization applied to wheat and corn. Agronomie 18 :311-346.

Brisson N., Ruget F., Gate P., Lorgeou F., Nicoullaud B., Tayot X., Plenet D., Jeuffroy M.H., Bouthier A., Ripoche D., Mary B., Justes E., 2002. STICS: a generic model for the simulation of crops and theirwater and nitrogen balances. II Model validation for wheat and maize. Agronomie 22:69-92.

Brisson N., Itier B., L'Hôtel J.C., Lorendeau J.Y., 1998 – b. Parametrization of the Shuttlewort-Wallace model to estimate daily maximum transpiration for use in crop models. Ecological Modelling 107 : 159-169.

Jensen M.E., Burman R.D., Allen R.G. (editors), 1990. ASCE manual and reports on engineering practice, No 70. Rahman H. and G. Dedieu, 1994. SMAC: a simplified method for the atmospheric correction of satellite measurements in the solar spectrum. International Journal of Remote Sensing 15:123-143.

Monteith J.L., 1985. Evaporation from lansurfaces: progress in analysis and prediction since 1948. Proceedings of the ASAE Conference on Evapotranspiraiton, Chicago, Ill, ASAE, St. Joseph, Michigan.

NelderJ.A. and Mead R., 1965. A simple methode for function minimization. Computer Journal 8:308-318.

Penman H.L., 1948. Natural evaporation fromopen water, bare soil and grass. Proc. Roy. Soc. London, A193, 120-146.

Rouse J.W., Haas R.H., Schell J.A.,, Deering D.W., Harlan J.C., 1974. Monitoring the vernal advancement and retrogradation of natural vegetation. NASA/GSFC, Type III, Final report, Greenbelt MD : 1-371.

Shuttleworth W.J., Wallace J.S. 1985. Evaporation from sparse canopy: an energy combination theory. Quart. J. Royal Meteorol. Soc. 111:839-855.

Weir A.H., Bragg P.L, Porter J.R, Rayner J.H., 1984. A winter wheat crop simulation odel without water or nutriteiens limitations. Journal of Agric. Science 102:371382.