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ESTIMATION OF ACTUAL EVAPOTRANSPIRATION BY REMOTE SENSING: APPLICATION IN THESSALY PLAIN, GREECE

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ABSTRACT

As evapotranspiration is one of the main components of hydrologic cycle, its estimation is very important. Remote sensing technologies can assist to improve the estimation accuracy also providing means for computing evapotranspiration geographical distribution. In the present study, the daily actual evapotranspiration was calculated for 21 days uniformly distributed during the 2001 summer season over Thessaly plain. Three different methods were accordingly adapted and applied: the remote-sensing methods by Granger (Granger, 2000) and Carlson-Buffum (Carlson & Buffum, 1989) using satellite data together with ground meteorological measurements and an adapted FAO Penman-Monteith method, used as reference method. Satellite data, following the necessary processing, were used in conjunction with surface data from the three closest meteorological stations. All three methods, following their appropriate adaptation, exploit visible channels 1 and 2 of NOAA-AVHRR satellite images to calculate albedo and NDVI and infrared channels 4 and 5 to calculate surface temperature. FAO Penman-Monteith and Granger methods require mean surface temperatures, so NOAA-15 satellite images were used. For Carlson-Buffum method a combination of NOAA-14 and NOAA-15 satellite images was used, since the average rate of surface temperature rise during the morning is required. The results of the application are encouraging. Both Carlson-Buffum and Granger methods follow in general the variations of the FAO Penman-Monteith method. However, they underestimate evapotranspiration during the days with relatively high wind speed.

1 INTRODUCTION

The accurate estimation of actual evapotranspiration is necessary for a sustainable water resources management, mostly in the agriculture, especially nowadays that there is increasing demand and decreasing availability of the water resources. However, this is extremely difficult to achieve, as actual evapotranspiration is a parameter not directly measured, depending on various factors, and varying considerably in time and space.

A large number of more or less empirical conventional methods have been developed over the last 50 years by numerous scientists worldwide to estimate evapotranspiration from different climatic variables. The analysis of the performance of the various calculation methods revealed the need of a standard method for the calculation of the reference crop evapotranspiration. The FAO (Food and Agriculture Organization of the United Nations) Penman-Monteith method has recently been recommended as the standard method (*Allen et al.,* 1998*)*.

Recently, the estimation of actual evapotranspiration at regional scale has been widely studied combining conventional meteorological ground measurements with remotely-sensed data. For this purpose several methods for assessing evapotranspiration have been developed for different time scales. These methods vary in complexity, from statistical / semi-empirical approaches to more analytical approaches with physical background, and finally to numerical models simulating soil, vegetation and atmosphere, heat and water flux.

The first combining methods tried to set empirical relations between actual evapotranspiration and parameters that can be measured from meteorological satellites. Thus, Menenti (1979) estimated actual evapotranspiration as a linear function of temperature and albedo. Reginato et al. (1985) established a linear relation between the ratio of actual to potential evapotranspiration and the variation of the surface temperature. However these first empirical models had very low accuracy, 30 to 40% (Caselles and Delegido, 1987).

For this reason, Jackson et al. (1977) proposed a very simple and useful semi-empirical statistical method for the estimation of the daily actual evapotranspiration, basing on the daily energy balance equation. The daily actual evapotranspiration is expressed as a function of the instant difference between the remotely-sensed surface temperature and the air temperature, both at about noon, and of the daily net radiation.

Several methods were later based on this linear equation and proceeded with various versions concerning either different estimations of the constants (Seguin et al. 1982, Seguin and Itier 1983, Vidal et al. 1986, Seguin et al. 1987, Becker et al. 1987, Sogaard 1988, Riou et al. 1988, Lagouarde and Brunet 1989, Vidal and Perrier 1989, Carlson and Buffum 1989, Sandholt and Andersen 1993) or different forms of the relation between the daily actual evapotranspiration and the temperature (Seguin and Itier 1983, Rambal et al. 1985, Nieuwenhuis et al. 1985, Wetzel et al. 1984, Carlson and Buffum 1989). The advantage of the two latter versions is that they don't require air temperature.

Soer (1980), Gurney and Camillo (1984), Van de Griend et al. (1985), and Taconet et al. (1986) developed models which describe with detail the water and heat transfer in the soil-plant-atmosphere system. However, the application of such models for the estimation of the daily actual evapotranspiration requires a lot of input parameters (Thunnissen and Nieuwenhuis, 1990).

A popular energy balance model is SEBAL (Surface Energy Balance Algorithm for Land), an image-processing model comprised of twenty-five computational submodels which calculates evapotranspiration and other energy exchanges at the earth's surface.

SEBAL uses digital image data collected by remote-sensing satellites measuring thermal infrared radiation in addition to visible and near-infrared (Allen at al, 2001).

The remote-sensing methods of estimating evapotranspiration can refer to different time scales: a) Hourly to daily time scale, appropriate for atmospheric, hydrologic and agricultural applications (Kustas and Norman, 1996) and b) Monthly to annual time scale, appropriate for climatological applications (Choudhury, 1991).

By using remotely-sensed data the estimation of regional evapotranspiration is technically and economically feasible, since the remotely-sensed data provide estimations of high spatial and temporal resolution, while the conventional methods based on ground data provide accurate measurements but only for an homogenous region (in terms of relief and land cover) around the station.

2 CASE STUDY

In the present study, the contribution of remote-sensing data to the estimation of evapotranspiration was examined for Greece. More specifically, the daily actual evapotranspiration was calculated for 21 days uniformly distributed during the 2001 summer season (June – July – August) over Thessaly plain. Three different methods were accordingly adapted and were applied: remote-sensing methods Granger (*Granger*, 2000) and Carlson-Buffum (*Carlson & Buffum*, 1989) using satellite data in conjunction with ground meteorological measurements and an adapted with remote-sensing data FAO Penman-Monteith method, which constituted the reference method.

2.1 Area of study

The Thessaly plain, being a region of intensive agricultural activity of great importance for the Greek agriculture and economy, was selected as the case study area since the accurate estimation of actual evapotranspiration is crucial for the irrigation. Furthermore, the ground stations network in this area is relatively reliable; therefore the available meteorological measurements can be used in order to calculate the additional parameters required by the three methods.

The Thessaly plain is situated in central Greece (Figure 1), in the Pinios river basin, the largest river basin in Greece (area 10.700 km^2) with mean annual rainfall 779 mm or 7.965 hm^3 and mean annual runoff 3.500 hm^3.

2.2 Period of study

The summer season (June – July – August) was selected as the case study period in order to estimate the irrigation needs for the Thessaly plain. The study covered the year 2001, which was the only one reliably processed and available in the archive of the National Observatory of Athens at the time of the study (2002).

The daily actual evapotranspiration was calculated for 21 days of this period uniformly distributed in the time frame of the study (7 days per month), which were selected according to a series of criteria related to the satellite and meteorological data availability, methodological considerations and uniformity of temporal distribution.

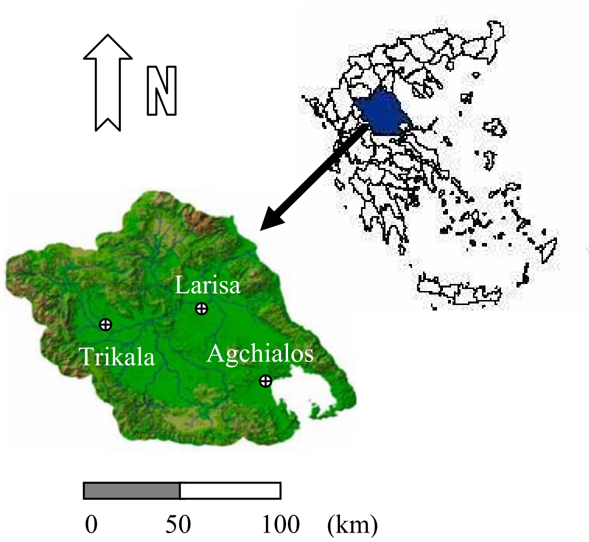

Figure 1. The Pinios River basin in Thessaly plain, located in Central Greece. The three meteorological stations operated by the Hellenic National Meteorological Service in Larisa, Trikala and Agchialos are illustrated.

2.3 Crop characteristics

The main crops of the Thessaly plain are maize and cotton, whose characteristics in Greece are presented in Table 1. The crop coefficient K_c values for this study were estimated in daily basis for the entire study period, according to the single crop coefficient method (*Allen et al.*, 1998) and the following assumptions:

- The crops in the Thessaly plain are 50% maize and 50% cotton.
- The sowing date is the 1st of May for both crops.
- The durations of the development stages for both crops are: 30 days for the 1st stage, 50 days for the 2nd stage, 50 days for the 3rd stage and 25 days for the 4th stage.
- For both crops: for the 1st stage constant K_c=K_{c1}=0.325, for the 2nd stage linearly increasing K_c from K_{c1}=0.325 to K_{c3}=0.875, for the 3rd stage constant K_c=K_{c3}=0.875 and for the 4th / final stage constant K_c=K_{cf}=0.

Table 1. Crop characteristics for maize and cotton in Greece.

Crop	**Sowing period**	**Durations of crop development stages (days)**				**Crop coefficient Kc (-)**		
		1st	**2nd**	**3rd**	**4th**	**K_{c1}**	**K_{c3}**	**K_{cf}**
Maize	15/4-5/5	25	40	60	25	0.35	0.85	0
Cotton	20/4-15/5	30	60	45	25	0.30	0.90	0

(Source: Ministry of Agriculture, 1992 - Adaptation: Koutsoyiannis & Xanthopoulos, 1999, p232)

2.4 Ground meteorological data

In the wider case study area three meteorological stations of the Greek National Meteorological Service are available: Larisa, Trikala and Agchialos stations (Figure 1).

The meteorological climatological Larisa station is by far the most representative and reliable one over the Thessaly plain, since it is situated in the centre of the plain, in an open-space area outside the town of Larisa (inside a military camp), with elevation approaching the mean elevation of the plain. The Trikala station is located to the west and in hilly area, while Agchialos station is located to the south and by the sea. Therefore it is justifiable to expect that the meteorological measurements in the latter two sites vary sensibly in relation to the actual measurements in the interior of the plain.

For the above-mentioned reasons, the meteorological data of the Trikala and Agchialos stations were taken into account with lower weight compared to the data of the Larisa station.

2.5 Satellite data

The satellite images that were used in this study were captured by the ISARS/NOA (Institute for Space Applications and Remote Sensing, National Observatory of Athens) receiving stations. NOAA-AVHRR (National Oceanic and Atmospheric Administration, Advanced Very High Resolution Radiometer) satellite images were selected given their availability and their appropriate spatial resolution (1 km x 1 km) proportionally to the size of the case study area. The value of NOAA satellite data for agricultural and hydrological applications has always been widely recognised (*Vidal & Perrier*, 1989).

The FAO Penman-Monteith and Granger methods require mean daily surface temperatures, so NOAA-15 satellite images were used (local receiving time from 9:39 to 10:36) and the instant morning values were converted to daily ones. For the Carlson-Buffum method a combination of satellite images NOAA-15 and NOAA-14 (local receiving time from 7:15 to 8:30) were used, since the average rate of surface temperature rise during the morning is required.

Therefore, in total, the number of the satellite images processed was 42 (21x2). The necessary processing of the satellite data includes radiometric calibration, geometrical correction (using control points and a second order polynomial) and georeference (mercator projection), image to image geometrical correction (afine transformation), correction of sun illumination conditions (normalization of the reflectances of bands 1and 2 for the sun zenith angle) and area of interest masking (exclusion of cloud, sea, bare soil, etc. areas).

All three methods, following their appropriate adaptation, exploit the remotely-sensed albedo, NDVI (Normalised Difference Vegetation Index) and surface temperature, for the estimation of evapotranspiration.

The albedo is calculated as the mean value of the normalized reflectances in visible channels 1 and 2 of NOAA-AVHRR satellite images. NDVI is calculated by the normalized reflectances in visible channels 1 and 2 of NOAA-AVHRR satellite images (Equation (1)).

$$ALBEDO = \frac{R_1 + R_2}{2} \qquad NDVI = \frac{R_2 - R_1}{R_2 + R_1} \tag{1}$$

The surface temperature (T_s) during the day is calculated by the reflectances in infrared channels 4 and 5 of NOAA-AVHRR satellite images according to the following algorithm (*NOA*, 1997):

$$T_S = cT_{SV} + (1-c)T_{SS} \tag{2}$$

where c is a coefficient representing the vegetation percentage in the pixel, T_{sv} is the temperature of a surface fully covered by vegetation and T_{ss} is the temperature of a bare soil surface. These variables are calculated by the following equations:

$$c = \frac{NDVI - NDVI_{\min}}{NDVI_{\max} - NDVI_{\min}} \tag{3}$$

where $NDVI_{min}$ corresponds to the NDVI of the bare soil and $NDVI_{max}$ corresponds to the NDVI of the full vegetation.

$$T_{SV} = T_4 + 2.6(T_4 - T_5) - 2.4 \qquad T_{SS} = T_4 + 2.1(T_4 - T_5) - 3.1 \tag{4}$$

3 METHODOLOGY

3.1 FAO Penman-Monteith method

The FAO Penman-Monteith method is derived from the original Penman-Monteith equation in combination with the equations of the aerodynamic and surface resistance. It is a method with strong likelihood of correctly predicting the reference crop evapotranspiration ET_o in a wide range of locations and climates and has provision for application in data-short situations (*Allen et al.*, 1998).

According to the FAO Penman-Monteith method, the crop evapotranspiration under standard conditions (ET_c) is calculated by multiplying reference crop evapotranspiration (ET_o) by crop coefficient (K_c):

$$ETc = K_c ETo \tag{5}$$

In this method, the reference crop evapotranspiration (ET_o) is calculated by the following equation:

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{\mathrm{T} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{6}$$

where ET_o is the reference crop evapotranspiration (mm d^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), Δ is the slope vapour pressure curve (kPa $^oC^{-1}$), γ is the psychrometric coefficient (kPa $^oC^{-1}$), T is the mean daily air temperature at 2 m height (^oC), u_2 is the wind speed at 2 m height (m s^{-1}), e_s-e_α is the saturation vapour pressure deficit (kPa), e_s is the saturation vapour pressure (kPa) and e_α is the actual vapour pressure (kPa).

In order to derive the mean daily surface temperature from the morning surface temperature of NOAA-AVHRR 15, the mean surface temperature T_{15} was calculated in each image in a small area around the Larisa station. This value was subtracted from the respective mean daily surface temperature T calculated by the conventional data of the Larisa station and the amount dT occurring for each day of the study period was added to each pixel of the corresponding surface temperature satellite image:

$$dT = T - T_{15} \tag{7}$$

The crop coefficient K_c was estimated on daily basis, for the entire study period according to the single crop coefficient method and a series of assumptions for the crops of the study area.

The net radiation at the crop surface R_n (MJ m^{-2} d^{-1}) is given by the equation:

$$R_n = (1-a)\ R_s - R_{nl} \tag{8}$$

where α is the albedo (-), R_s is the incoming solar radiation (MJ m^{-2} d^{-1}) and R_{nl} is the net outgoing longwave radiation (MJ m^{-2} d^{-1}).

The parameters u_2, e_s-e_α, R_s and R_{nl} are calculated by the conventional data of the three meteorological stations for the 21 selected days of the case study and subsequently they are interpolated in the surface of the entire study area using a second order polynomial.

3.2 Carlson-Buffum method

The Carlson-Buffum method calculates daily actual evapotranspiration ET_d from the daily surface energy budget using remotely-sensed surface temperature from the infrared satellite channels and several meteorological variables estimated by ground stations. In order to optimise the results we used remotely-sensed albedo values from the visible satellite channels.

This method is based on the assumption that the soil moisture (and therefore the evapotranspiration) is sensitive to the rate of temperature rise during the morning (e.g. between 8 and 10 local time) (*Carlson & Buffum*, 1989).

The corresponding equation can be written as:

$$ET_d = R_{nd} - B'\left(\frac{\Delta T_s}{\Delta t}\right)^{n'} \tag{9}$$

where ET_d is the daily actual evapotranspiration (cm d^{-1}), R_{nd} is the daily net radiation (cm d^{-1}), $\Delta T_s/\Delta t$ is the average rate of temperature rise during the morning (^oC h^{-1}) and B', n' are constants (-) depending on wind speed, surface roughness, vegetation, and reference height, estimated either by representative values or by charts.

The average rate of temperature rise during the morning $\Delta T_s/\Delta t$ is calculated dividing the difference of the surface temperature images of NOAA-AVHRR 15 and NOAA-AVHRR 14 T_{15}-T_{14} by the difference of their corresponding receiving times Δt.

In order to achieve higher accuracy, the estimation of the constants B and n for vegetation (B_v, n_v) and bare soil (B_s, n_s) is done according to the method's charts (not according to the representative indicative values), as a function of the surface roughness and the wind speed at 6.4 m height.

Basing on the NDVI images, the maximum NDVI value is corresponded to the vegetation (namely to the constants B_v, n_v) and the minimum NDVI value is corresponded to the bare soil (namely to the constants B_s, n_s) (it was estimated that $NDVI_v = NDVI_{max} = 0.570$ and $NDVI_s = NDVI_{min} = 0.010$). So, using the values $NDVI_v$, $NDVI_s$, B_v, n_v, B_s, n_s of the Carlson-Buffum method, the respective B and n images are calculated from the NDVI images using linear interpolation for each day of the study period.

3.3 Granger method

The Granger method estimates daily actual evapotranspiration ET applying a conventional evapotranspiration model in which some ground data are imported as well as remotely-sensed estimations of net radiation (with albedo calculated by the visible satellite channels data) and vapour pressure deficit (using a feedback relationship with surface temperature calculated by the infrared satellite channels data).

This method is based on two assumptions: i) the feedback links between the surface and the overlying air are such that the observed surface temperature T_s may be a sufficiently reliable indicator of the humidity of the air and ii) the net long-wave radiation R_{nl} is driven by the energy supplied to the surface, and thus, its daily values can be estimated from the incoming short-wave radiation R_s (Equation (10)) (*Granger*, 2000).

$$e_s - e_a = -0.278 - 0.015 T_{ltm} + 0.668 e^o(T_s) \qquad R_{nl} = -4.25 - 0.24\, R_s \tag{10}$$

where e_s-$e_α$ is the saturation vapour pressure deficit (kPa), e_s is the average saturation vapour pressure (kPa), $e_α$ is the actual vapour pressure (kPa), $e^o(T_s)$ is the saturation vapour pressure (kPa), T_s is the mean daily surface temperature (°C), T_{ltm} is the climatic air temperature in the region (°C), R_{nl} is the net long-wave radiation (MJ m^{-2} d^{-1}), and R_s is the incoming short-wave radiation (MJ m^{-2} d^{-1}).

Granger's equation can be written as:

$$ET = \frac{\Delta \frac{R_n - G}{\lambda} + \gamma\, \mathrm{E}_\alpha}{\Delta + \frac{\gamma}{g}} \tag{11}$$

where $E_a = f(u)(e_s - e_a) \quad g = \dfrac{1}{1 + 0.028\, e^{8.045 * D}} \quad D = \dfrac{E_a}{E_a + \frac{R_n - G}{\lambda}}$ (12)

In the above equations ET is the daily actual evapotranspiration (mm d^{-1}), Δ is the slope vapour pressure curve (kPa °C^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), λ is the latent heat of vaporization (MJ kg^{-1}), γ is the psychrometric coefficient (kPa °C^{-1}), $E_α$ is the drying power of the air (mm d^{-1}), g is the relative evaporation (-), $f(u)$ is the wind speed function (mm d^{-1} kPa^{-1}), e_s-$e_α$ is the saturation vapour pressure deficit (kPa) and D is the relative drying power (-).

The wind speed function $f(u)$ is calculated by the Dalton formula:

$$f(u) = \frac{0.622 \dfrac{D_{wv}}{D_m} k^2 \dfrac{\rho_\alpha}{\rho_w} u}{P \left[\ln\left(\dfrac{z_a - z_d}{z_o} \right) \right]^2} \tag{13}$$

where D_{wv} and D_m are the water vapour and momentum diffusion coefficients respectively (-), k is von Karman's coefficient (k = 0.4), ρ_α is the air density (=1.229 kg m^{-3}), ρ_w is the water density (=1000 kg m^{-3}), u is the wind speed (mm d^{-1}), P is the atmospheric pressure (kPa), z_α is the wind measurement height (m), z_d is the displacement height (m) and z_o is the roughness length (m), defined as:

$$z_d = 0.7\, z_v \qquad\qquad z_o = 0.1\, z_v \tag{14}$$

where z_v is the vegetation height (m).

Granger's method assumes that D_{wv}/D_m=1. However, this assumption is not valid as the vegetation height increases and the atmospheric stability deviates from neutrality (*University of Arizona*, 2003). For this reason, in the present application Equation (13) is transformed as:

$$f(u) = \frac{0.622}{P} \frac{\rho_\alpha}{\rho_w} C_{at} \tag{15}$$

where C_{at} is the atmospheric conductance (mm d^{-1}).

Based on the values of the wind speed u and the vegetation height z_v, the atmospheric conductance C_{at} is estimated by Dingman's chart for each day of the study period. Subsequently the wind speed function can be calculated.

4 RESULTS

The daily actual evapotranspiration ET was calculated according to the three methods for all the 21 days of the study period. In this paper the three corresponding calculated satellite images are presented indicatively for a selected date (Figure 2).

In order to evaluate the results with higher accuracy, the daily actual evapotranspiration calculations for each day of the study period are presented additionally in Table 2 and in Figure 3 for all three methods for the centre of Thessaly plain.

The wind speed values of Larisa station (centre of Thessaly plain) are also shown in Table 2 to indicate the influence of the wind in the results of the methods.

Table 2. Daily actual evapotranspiration in the centre of Thessaly plain according to the three methods: Carlson-Buffum (ETc), FAO Penman-Monteith (ETp) and Granger (ETg) and wind speed from Larisa station.

No	**Date**	**Daily actual evapotranspiration ET for area in the centre of Thessaly plain**			**Wind speed from Larisa station u_2 (m s^{-1})**
		Carlson-Buffum method ETc (mm)	**FAO Penman-Monteith method ETp (mm)**	**Granger method ETg (mm)**	
1	07/06/2001	0,9	2,6	5,7	1,54
2	12/06/2001	3,0	3,5	7,3	0,58
3	20/06/2001	2,5	3,3	5,9	0,96
4	23/06/2001	4,2	4,8	7,4	1,15
5	25/06/2001	5,7	5,6	7,3	2,21
6	28/06/2001	3,4	5,6	7,3	1,73
7	29/06/2001	1,6	5,1	6,3	1,88
8	04/07/2001	7,6	5,3	7,2	1,64
9	07/07/2001	7,7	5,9	7,2	1,78
10	15/07/2001	5,7	6,5	7,3	0,96
11	17/07/2001	6,3	6,6	6,7	1,44
12	21/07/2001	3,9	8,1	6,6	*2,65*
13	24/07/2001	5,6	7,1	7,2	1,68
14	26/07/2001	4,1	6,4	6,5	1,30
15	02/08/2001	6,4	7,3	6,9	1,78
16	04/08/2001	5,6	6,4	6,9	1,06
17	06/08/2001	5,7	6,4	6,6	1,06
18	12/08/2001	5,3	6,9	5,5	*3,08*
19	19/08/2001	3,4	5,7	5,8	1,25
20	20/08/2001	4,6	5,6	5,7	0,87
21	28/08/2001	3,3	5,3	5,3	1,35

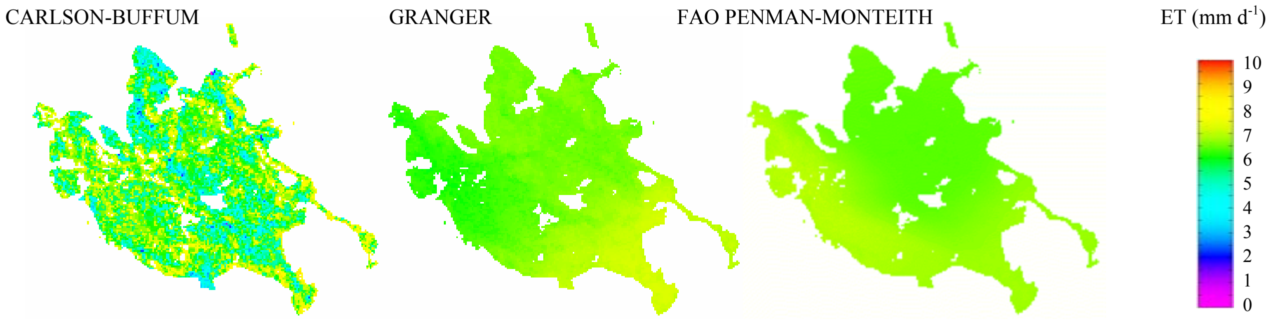

Figure 2. Daily actual evapotranspiration ET for 17/07/2001 according to methods Carlson-Buffum (left), Granger (middle) and FAO Penman-Monteith (right).

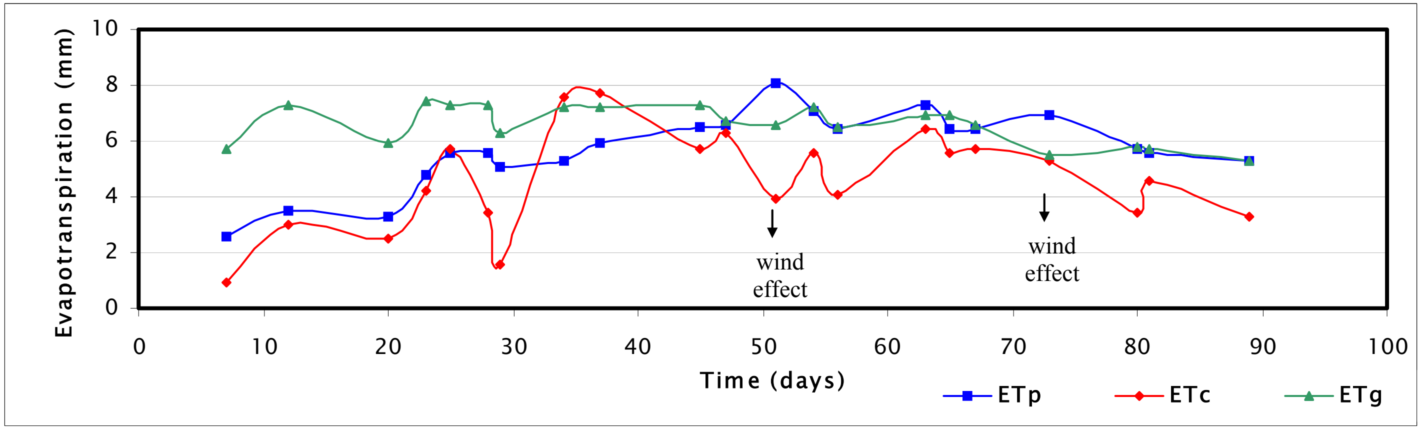

Figure 3. Daily actual evapotranspiration in the centre of Thessaly plain according to the three methods: FAO Penman-Monteith (ETp), Carlson-Buffum (ETc) and Granger (ETg) and illustration of the wind effect.

5 CONCLUSIONS

5.1 Contribution of remote-sensing to the estimation of evapotranspiration

The combination of ground and remotely sensed data is important in areas with insufficient or inexistent ground stations network. The satellite images can provide estimations of albedo, normalised difference vegetation index and surface temperature. Over the last decades several methods have been developed in order to estimate the actual evapotranspiration combining conventional and remotely-sensed measurements. The parameters estimated by the satellite images can be used as input data not only for the remote-sensing methods, but also for the surface extrapolation of the FAO Penman-Monteith method. The accuracy of the methods estimating the regional evapotranspiration is expected to increase even more if data from different types of satellites with increased spatial and spectral pixel resolution are combined (e.g. NOAA-AVHRR, LANDSAT (Land Satellite), SPOT (Satellite Pour l' Observation de la Terre), SEVIRI (Spinning Enhanced Visible and Infra Red Imager)) and also if detailed land cover maps from high resolution satellite data are used.

5.2 Results of the application in Thessaly plain, Greece

The results of the application are encouraging.

The adapted FAO Penman-Monteith reference method requires the following conventional input data: R_s, R_{nl}, u_2, e_s-e_a, P, K_c. The surface extrapolation of surface temperature and albedo increases the reliability of the results and also makes possible the estimation of the geographical distribution of evapotranspiration.

Granger method requires the following conventional input data: R_s, R_{nl}, u_2, T_{ltm}, P, z_v. It generally reproduces the tendency and the variations of the FAO Penman-Monteith method, apart from the days with relatively high wind speed values, where it underestimates evapotranspiration. It overestimates evapotranspiration during the development of the crop in systematic way with ongoing decreasing trend. In the first half of the crop development stage the overestimation is more than 50% with absolute error of more than 2 mm. From the middle of the crop development stage to the beginning of its last fifth the error varies between 1 and 2 mm with overestimation ranging from 20 to 35%. In the last fifth of the crop development stage and in the entire stable crop stage the error is maintained less than 1.5 mm, with a deviation between -20% and +10%. If the two overestimated values due to the wind effect are ignored, the error in the end of the crop development stage and in the entire stable crop stage is limited between 0 and 0.5 mm, with negligible deviation from -5% to +10%.

Carlson-Buffum method requires the following conventional input data: R_s, R_{nl}, u_2, z_o. It generally reproduces the tendency and the variations of the FAO Penman-Monteith method, but it has definitely larger deviations compared to the Granger method, which are not due only to the high wind speed values, where overestimation is observed. Its estimates seem to be very satisfactory at the end of the first half of the crop development stage, where underestimation error has decreased from 1.7 (65% underestimation) to 0 mm. On the contrary, in the second half of the crop development stage it presents significant unreliability, with error ranging from -4.2 to +2.3 mm, and deviation from -70% to +40%. If the value with error -4.2 mm (due to the wind effect) is ignored, the error in the second half of the crop development stage is reduced at levels between -3.5 and +2.3 mm, which however still remains unsatisfactory. During the stable crop stage it underestimates continuously the daily actual evapotranspiration, with error ranging between 0.7 to 2.3 mm (deviation from -10% to -40%).

In some cases large deviations of the actual daily evapotranspiration are observed on the boundaries of the study area. The Granger method is more stable and accurate in comparison with the Carlson-Buffum method. Besides it is also more reliable regarding its theoretical background. The Carlson-Buffum method is simpler and requires fewer conventional input data; however it requires two satellite images of accurate temperature estimates for each day. The Carlson-Buffum method provides better estimates of the daily actual evapotranspiration during the first half of the crop development stage, while the Granger method provides better estimates during the remaining period.

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