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Brief communication
"The integration of remote sensing and meteorological data for monitoring irrigation demand in Cyprus"

G. C. Papadavid[1,2], A. Agapiou[1], S. Michaelides[3], and D. G. Hadjimitsis[1]

[1]Department of Civil Engineering and Geomatics, Faculty of Engineering and Technology, Cyprus University of Technology, 3603, Lemesos, Cyprus
[2]Agricultural Research Institute of Cyprus, 1516, Athalassa, Nicosia, Cyprus
[3]Meteorological Service of Cyprus, Nicosia, Cyprus

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Abstract. This paper examines and evaluates the integrated use of satellite remote sensing and meteorological data for estimating crop water requirements over agricultural areas of Cyprus. Intended purpose of this project is to estimate evapotranspiration using modeling techniques, satellite and meteorological data for monitoring irrigation demand. *ETc* was calculated with the FAO Penman-Monteith method by using satellite images acquired from July to December 2008. *ETc* estimates obtained in this project were compared to previous empirical data found by using in-situ techniques. *ETc* values have been correlated with the meteorological data to cross-check the significance of the meteorological inputs.

1 Introduction

In Cyprus, 70% of the total water consumption is spent for irrigation purposes (Hadjimitsis et al., 2008). Currently, the island faces a prolonged period of severe drought which has inevitably revealed a series of irrigation related problems having a detrimental effect on Cyprus' agriculture. Monitoring of irrigated agricultural areas in Cyprus provides important data for efficient water supply plans and for avoiding unnecessary water losses due to inefficient irrigation systems. From this perspective, satellite remote sensing techniques, in conjunction with meteorological data, are useful as efficient tools for monitoring irrigation demand in agricultural areas. In most of the irrigation projects, irrigation is managed and supplied on the basis of historic precedence and existing conventional data; however, irrigation demand is not adequately met since weather conditions are changing dramatically and water availability deteriorates. Remotely sensed satellite data can be used to accurately identify cropped areas and estimate the needed water quantity for irrigation. If this information is combined with local climatic data, it is possible to identify the seasonal crop water demand in fields through evapotranspiration (*ETc*) and schedule irrigation, accordingly (Hadjimitsis et al., 2008).

A single Landsat-7 ETM+ image of Cyprus covers almost the entire island, and there is generally little or no cloud cover over the island, especially during summer and autumn period. Therefore, it is possible that the use of satellite remote sensing technologies can increase the efficiency and effectiveness of existing irrigation procedures. The FAO Penman-Monteith method (FAO, 1998) adapted to satellite remote sensed data, is widely used as an accurate method to estimate reference evapotranspiration (*ETo*). The climatic data required for the method are readily available from meteorological stations and from satellite images. The purpose of this study is to employ the FAO Penman-Monteith method in estimating crop evapotranspiration under standard conditions (*ETc*) for monitoring irrigation demand. The project's results provide a useful tool for a decision-making policy, since it is possible to determine the irrigation demand and therefore help to avoid any water losses for agricultural purposes.

2 Review and basics

Evapotranspiration is the combination of two separate processes whereby water is lost, on the one hand, from the soil surface by evaporation and, on the other hand, from the crop by transpiration (FAO, 1998; Allen et al., 2000). It is often used to describe the total water escaping from crop to air. Both evaporation and transpiration processes are driven by energy from solar radiation, air temperature, relative humidity and wind speed (Boegh et al., 2004).

Correspondence to: G. C. Papadavid
(gc.papadavid@cut.ac.cy)

Evapotranspiration constitutes one of the main components of the hydrological cycle and its estimation demands auxiliary meteorological data (Telis and Koutsogiannis, 2007). Many formulas have been developed by scientists to calculate *ETc* taking into account all the energy sources which are available to plants (French et al., 2008). In recent decades, the estimation of *ETc* by combining conventional meteorological ground measurements with remotely-sensed data has been widely studied, while several methods have been developed for this purpose (Tsouni and Koutsogiannis, 2003). An accurate estimation of actual *ETc* is necessary for hydro-resources management. *ETo* values, can be calculated by measuring weather parameters and typical reference crops using specialized instruments, namely, lysimeters.

Today, several researchers recommend a breadth of mathematical equations and modelling (Bastiaanssen and Ali, 2003; D'Urso and Menenti, 1995; Menenti et al., 1989). The methods of estimating *ETc* are generally classified as: a) energy balance methods, b) aerodynamic or mass transfer methods, c) empirical or semi-empirical methods, d) water depletion methods, and e) numerical or modeling methods (Metochis, 1997; Eliades et al., 1995).

The analysis of the performance of these models revealed the need for formulating a standard method for the computation of *ETo* (Tsouni and Koutsogiannis, 2003; Hoedjes et al., 2008). The FAO Penman-Monteith method, which was derived from the Penman-Monteith equation, has recently been recommended as the sole standard method. It is a method with strong likelihood of correctly predicting *ETo* in a wide range of locations and climates (Aaron et al., 1996; D' Urso and Menenti, 1995).

3 Resources and methodology

3.1 Resources

For estimating *ETc*, multispectral (visible and infrared bands) Landsat-7 ETM+ satellite images have been used, along with meteorological data. Air temperature, atmospheric pressure, wind speed and other data were collected from an automatic meteorological station (placed at 1.2 m height above ground surface), located at Paphos International Airport, in the vicinity of our study area. These data were interpolated to 2.0 m height as required by FAO Penman-Monteith method. Indeed, these interpolated values were in good agreement with those values found from a customized mobile meteorological station that we employed for calibrating and validating reasons. ERDAS IMAGINE (v.9.3 professional) has been used in the pre-processing and post-processing of the available multi-series imagery. The GER 1500 field spectro-radiometer has been used to assist the application of the atmospheric correction of the satellite images.

Fig. 1. Landsat-7 ETM image of Cyprus. The study area is marked.

3.2 Study area

The study area is located near Paphos International Airport in the Paphos District area in Cyprus (Fig. 1). The area of interest is a traditionally agricultural area where annually crops are cultivated through the whole year. The mild microclimate of the area contributes to the healthy production and full time agriculture activity during the year but especially from July to December in which production is off-season and is very valuable.

3.3 Methodology

The overall methodology consists of the following steps:

- Pre-processing of satellite data (images).
  - Processing the satellite images in order to retrieve surface albedo of crops.
  - Apply the FAO Penman-Monteith method along with crop factors (Kc) to determine *ETc*.
  - Compare the results found using the proposed method and the semi-empirical "Epan method" that was widely used in Cyprus, by the Agricultural Research Institute (Metochis, 1997).
  - Apply statistical analysis for retrieving possible correlation between the meteorological data and the estimated *ETc*. This will assist the users in order to assess the significance of each meteorological parameter.

3.3.1 Pre-processing of satellite images

Geometric correction has been applied, using standard techniques with ground control points and a first order polynomial fit. All satellite images were geo-referenced at the World Geodetic System '84 (WGS 84/UTM).

For the radiometric correction, the images were converted from digital numbers (DN) to units of radiance using standard calibration values (Chander and Markham, 2003). The next step was to convert the at-satellite radiance values into at-satellite reflectance using the solar irradiance at the top of the atmosphere, sun-earth distance correction and solar zenith angle. The removal of atmospheric effects, also a part of radiometric correction, has been applied: the darkest pixel (DP) atmospheric correction method, also termed as histogram minimum method, was applied to the multi-series satellite images, since it has been found to be the most effective atmospheric correction algorithm (Hadjimitsis et al., 2004). Finally, the albedo was derived from the satellite images. Albedo was derived using a standard method as described by Liang (2000). Albedo is subsequently used to estimate net radiation at the crop surface, as an input to the FAO model.

3.3.2 The FAO Penman-Monteith method

The FAO Penman-Monteith method has been shown to be a suitable method for this study area (Courault et al., 2005). Indeed, the homogeneity of the area renders the method as the most appropriate for estimating ET, for the various crops cultivated in the area. The estimation of ET focuses only on annual crops cultivated in the area.

After preprocessing, the satellite data are ready for extracting the necessary inputs for the irrigation demand model for the area of interest. According to FAO Penman-Monteith method (FAO, 1998), *ETo* can be calculated from the following equation:

$$Eto = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\mu_2)} \quad (1)$$

where,

ETo:	reference evapotranspiration	[mm day^{-1}],
R_n:	net radiation at the crop surface	[MJ m^{-2} day^{-1}],
G:	soil heat flux density	[MJ m^{-2} day^{-1}],
T:	is the mean daily temperature	[°C],
u_2:	wind speed at 2 m height	[m s^{-1}],
e_s:	saturation vapour pressure	[kPa],
e_a:	actual vapour pressure	[kPa],
$e_s - e_a$:	saturation vapour pressure deficit	[kPa],
Δ:	slope vapour pressure curve	[kPa °C^{-1}],
γ:	psychrometric constant	[kPa °C^{-1}].

The FAO Penman-Monteith method determines *ETc* from a hypothetical grass reference surface and provides a standard to which *ETc* in different periods of the year or in other regions can be compared and to which *ETo* from other crops can be related. According to Allen (1996), for estimating *ETc* one should multiply the reference ETo which was found through the FAO Penman-Monteith method with the crop coefficient:

$$ETc = Kc \times ETo \quad (2)$$

where,

ETc:	crop evapotranspiration	[mm d^{-1}],
Kc:	crop coefficient	[dimensionless],
ETo:	reference crop evapotranspiration	[mm d^{-1}].

The crop coefficient, *Kc*, is basically the ratio of *ETc* to the reference *ETo*, and it represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass. These characteristics are the crop height, the albedo, the canopy resistance and the evaporation from exposed soil. In this research, the *Kc* was estimated on a 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 crop coefficient *Kc*, was estimated consecutively, for each image, using remote sensing techniques as described by D'Urso and Menenti (1995). After estimating *ETc* using satellite and meteorological data, a statistical processing was applied. More specific correlations among the different meteorological inputs – ceteris paribus – where made to justify the relationship between *ETc* and each input. Finally, a regression analysis was performed to create an empirical equation among evapotranspiration and the meteorological data.

4 Results

The processing of meteorological data along with the satellite data and the FAO Penman-Monteith method have given an estimation of *ETc* for the area of interest. The results are shown in Table 1 and are contrasted to those of previous research that made use of the empirical Epan method (Metochis, 1997). It is obvious that both methods give comparable results, their difference being less than one mm/day, for all cases. The results represent the crop water requirement for healthy vegetation for the specific place and crop. These data can be used for irrigation scheduling in order to avoid excessive water use in irrigation. The data is useful also in the hands of policy makers, not only for irrigation planning purposes, but also for macroeconomic scheduling in agriculture by excluding crops which have high water requirements.

Having examined the relationship between the meteorological parameters (namely, pressure, wind speed, relative humidity and temperature) and *ETc* within the framework of a regression analysis model, it became apparent that there is a strong relationship between *ETc*, on the other hand, and relative humidity and wind speed, on the other hand, at the confidence level of 95% and 99%, respectively. The correlation results and the fitted equations are given in Table 2. The statistical F test was employed to verify the significance of each fitted model. The correlations found are acceptable since the corresponding value of F is greater than the given

Table 1. Meteorological data from Paphos International Airport station and calculated values of *ETc*. The results found by applying the FAO 56 method are contrasted to those found by using the Epan method.

Date	Sunshine duration	Mean wind speed	Mean relative humidity	Mean station pressure	Mamixum temperature	Minimum temperature	*ETo*	*ETc*	*ETc* found using Epan method
	h	m/s	%	hPa	°C	°C	mm/day	mm/day	mm/day
19 Dec 2008	9.1	5.15	53.0	1016.4	23.0	9.1	4.40	2.89	2.10
17 Nov 2008	9.2	2.06	62.0	1016.5	23.5	15.5	2.30	1.50	1.41
1 Nov 2008	9.6	2.06	64.0	1019.6	25.8	17.0	2.20	1.43	1.33
16 Oct 2008	8.9	2.57	83.0	1018.5	26.6	20.4	1.80	1.18	1.98
30 Sep 2008	6.6	7.21	55.0	1016.0	26.2	21.1	4.90	3.19	3.30
14 Sep 2008	11.7	6.18	66.0	1012.8	29.9	23.0	4.20	2.73	3.00
29 Aug 2008	11.6	4.12	76.0	1019.0	31.4	23.5	2.70	1.75	2.10
28 Jul 2008	13.3	4.12	71.0	1017.0	30.3	21.7	2.90	1.89	2.20

Table 2. Regression analyses between *ETc* and relative humidity and between *ETc* and wind speed (R is the correlation coefficient and R^2 is the coefficient of variation).

ETc correlated to:	Equation	R	R^2	$F_{observed}$	$F_{statistical}$	Confidence level
Relative humidity	Y=5.6–0.53X	0.716	0.513	6.324	5.99	0.95
Wind speed	Y=2.37X–0.72	0.938	0.879	43.677	13.75	0.99

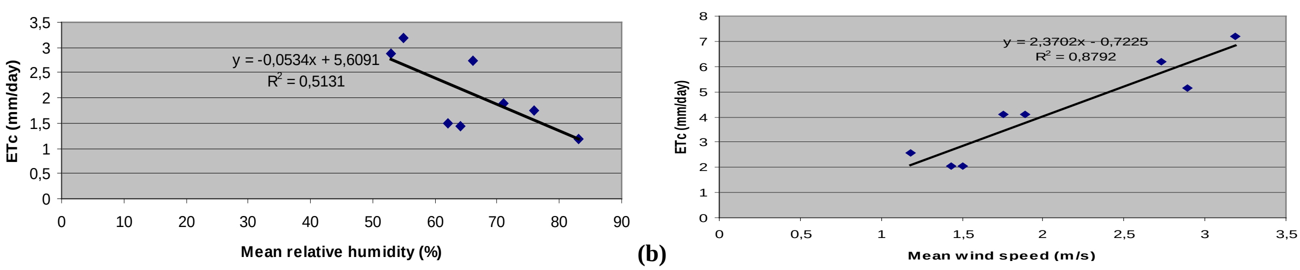

Fig. 2. Relation between **(a)** *ETc* and relative humidity, and **(b)** *ETc* and wind speed. The solid line is the fitted regression line.

statistical value of F ($F_{observed} > F_{statistical}$, where $F_{observed}$ is the value of F which is derived from the results of the statistical analysis and $F_{statistical}$ is the value for F from statistical tables). The strongest correlation was found between *ETc* and wind speed with the coefficient of variation, R^2, reaching almost 88%. Figure 2 shows separately the relation of each of the two variables and *ETc*.

The results of the separate correlations of *ETc* to Relative Humidity have shown that they are related by an apparent inverse proportionality: *ETc* decreases with increasing relative humidity. As expected, relative humidity has a negative effect on evapotranspiration, since it decreases the stomatal flux of water vapour to air through the leaves, due to high level of water vapour concentration in the atmosphere. Contrary to relative humidity, wind speed has the opposite effect on the water vapour flux to the air, and thus a positive effect on *ETc*.

It was expected that *ETc* would be higher during the summer, when the temperature is higher and sunshine duration is longer. Surprisingly, the higher *ETc* was calculated in September when the wind speed obtains a higher value (the corresponding calculations are not shown here for brevity). During summer, relative humidity takes higher values and contributes to lower *ETc*. The least values of *ETc* were calculated in November when the wind speed was low and relative humidity was moderate.

5 Conclusions and future work

This paper presents a methodology adopted to estimate *ETc* by using an integration of the following tools: the FAO Penman-Monteith method, remotely sensed and meteorological data. For the first time, all of these data are used in order to estimate *ETc* in Cyprus since, until now, semi-empirical and field-applied methods have been used. The results are close to the results by previous researchers who made use of the Epan method. This fact validates the methodology employed here. *ETc* estimations can be used by policy-makers on a technocratic level to apply the most efficient irrigation policy. The results show the minimum and maximum water that the crops require so as to maintain a healthy vegetation. Based on these results, irrigation scheduling can be planned for the specific crops, in order to avoid excess irrigation water usage from the dams. These results can also be the basis for an optimum plan for Cyprus agriculture, which has as a standard constraint the water efficiency of crops (optimization procedures).

The paper demonstrates the future potential of the remote sensing methods and water balance models for estimating *ETc* in agricultural areas of Cyprus, in order to determine the spatial variation of actual evapotranspiration for agricultural areas. Finally, it was found that wind speed and humidity are of great importance in the procedure of estimating ETc, and their values have to be very accurate when collecting the specific data.

Future work will comprise further validation of the results, not only by using the FAO Penman-Monteith method for other cultivations but other acceptable methods and models for estimating *ETc*. An intensive field campaign is planned for collecting more ground data in the next agricultural season, by considering the whole cycle of each crop. Further investigations using parametric analysis of the field and meteorological factors that are interrelated to *ETc* with irrigation demand, will also be conducted. Finally, lysimeters will be employed in the agricultural fields in order to compare directly the values of *ETc* obtained both from ground measurements and the proposed methodology.

Parametric and sensitivity analysis of the factors affecting *ETc* are also in the future plans in order to obtain a more detailed idea how these parameters have an effect on *ETc*.

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