Evaluation of pan coefficient equations in a semi-arid Mediterranean environment using the ASCE-standardized Penman-Monteith method

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ABSTRACT

Reference crop evapotranspiration (ET_o) is essential for irrigation, water resources management and environmental assessment. The indirect estimation of ET_o is based a) on energy budget approach using meteorological data and b) pan evaporation measurements (E_{pan}) multiplied by pan coefficients (k_p) adapted to the surrounding environmental conditions. Significant interest is shown for the k_p equations, which have to be tested before their use. The purpose of this study is to evaluate six different k_p equations, such as those of Cuenca, Allen and Puitt, Snyder, Pereira *et al.*, Orang, Raghuwanshi and Wallender for the summer growing season (April to October) of Thessaloniki plain in Greece, which is characterized by a semi-arid Mediterranean environment. The evaluation of the k_p equations is performed by two years E_{pan} measurements, using as reference the daily ET_o values estimated by the ASCE-standardized Penman-Monteith equation (ASCE-PM) in hourly time step. The results of this study showed that Cuenca's equation provided more accurate daily estimations. Additional analysis is performed in other methods such as those of FAO-56 and Hargreaves based on the calculation time step (hourly or daily) and their correspondence to the ASCE-PM.

Keywords: Pan Evaporation; Reference Evapotranspiration; ASCE-Standardized Penman-Monteith

1. INTRODUCTION

The reference crop evapotranspiration (ET_o) constitutes the major factor for the accurate estimation of the crop water requirements, which are essential in irrigation planning, scheduling, hydrologic balance studies and watershed hydrology. Many methods have been proposed for the estimation of ET_o, based on the energy budget approach, such as the corrected FAO-24 Blaney-Criddle method [1], the Priestley-Taylor method [2], the corrected FAO-24 Penman method [3], the Shuttleworth and Wallace method [4], the Hargreaves method [5], the FAO-56 Penman-Monteith method [6] and the ASCE-standardized Penman-Monteith method [7]. Numerous of empirical linear and non-linear equations have also been developed but with restricted validity at regional scale. The FAO-56 Penman-Monteith constitutes the most popular methodology in agricultural studies and the ASCE-standardized Penman-Monteith method was recently presented as an improvement of this by the ASCE-EWRI Task Committee [7].

Significant efforts for the correct estimation of ET_o under the Greek environmental-meteorological conditions have been carried out by several researchers, which they focused on comparisons and sensitivity analysis between the aforementioned methods, their parameters and their calculation time step [8-11]. Additional studies have been performed for the development of new methodologies for the estimation of ET_o using empirical equations such as the "Copais model" [12] or equations based on Penman formula with reduced parameters [13].

A different approach for ET_o estimation is the use of pan evaporation measurements (E_{pan}) and pan coefficients (k_p). The k_p is obtained as a constant value adjusted to specific environmental conditions [6] or as equations [14,15]. The use of E_{pan} measurements and k_p coefficients has the advantage of the low cost equipment, while it has the disadvantage of the k_p calibration and the frequent visits for the preservation of water level and clarity versus the agro-meteorological stations.

The objective of this study is to compare and evaluate different equations for the pan coefficient k_p using Class-A pan evaporimeter measurements for the estimation of

ET_o during the summer crop growing season (April to October). Measurements were obtained in Thessaloniki region, which is under a semi-arid Mediterranean environment and constitutes one of the major plains for agricultural production in Greece. Due to the lack of equipment for the direct measurement of the reference crop evapotranspiration (e.g. weighted lysimeters), the method of ASCE-standardized Penman-Monteith method (ASCE-PM) calculated in hourly time step, was selected to be used as reference for the comparisons between the different k_p equations. The comparison between the ASCE-PM and other popular methods such as those of FAO-56 Penman-Monteith and Hargreaves was also performed.

2. METHODOLOGY AND DATA

2.1. Estimation of the Reference Crop Evapotranspiration

2.1.1. The Methods of ASCE and FAO-56 Penman-Monteith

ASCE-EWRI (2005) have proposed two reference crops, a short crop similar to a clipped-grass (0.12 m height) and a tall crop similar to a full cover *alfa-alfa* (0.5 m height) [7]. Considering the two reference crops, the ASCE-EWRI Task Committee revised and improved the FAO-56 Penman-Monteith (FAO56-PM) equation, presenting the new ASCE Penman-Monteith (ASCE-PM) method. The equation of ASCE-PM using daily or hourly time step for the two different cases of reference crop is given by [7]:

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\left(\dfrac{C_n}{\left(T + 273.16\right)}\right)u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + C_d u_2\right)}$$

(1)

where ET_o is the reference crop evapotranspiration for short (ETos) or tall (ETrs) reference crops (mm·d^{-1} for daily time step or mm·h^{-1} for hourly time step), R_n is the net radiation at the crop surface (MJ·m^{-2}·d^{-1} for daily

time step or MJ·m^{-2}·h^{-1} for hourly time step), u_2 is the mean daily or hourly wind speed at 2 m height (m·s^{-1}), T is the mean daily or hourly air temperature at 2 m height (°C), G is the soil heat flux density at the soil surface (MJ·m^{-2}·d^{-1} for daily time step or MJ·m^{-2}·h^{-1} for hourly time step), e_s is the daily or hourly saturation vapor pressure (kPa), e_a is the daily or hourly mean actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa·°C^{-1}), γ is the psychrometric constant (kPa·°C^{-1}), C_n and C_d are constants, which vary according to the time step, the reference crop type (bulk surface resistance, and aerodynamic roughness of the surface) and daytime/nighttime ratio.

According to the time step and the type of the reference crop, the values of C_n, C_d and G are modified and the **Eq.1** is referred to different methods (**Table 1**):
- Two cases for daily time step a) the ASCE-PMos(d) which is the same with the FAO56-PM(d) for short reference crop and b) the ASCE-PMrs(d) for tall reference crop.
- Three cases for hourly time step calculations a) the ASCE-PMos(h) for short reference crop, b) the ASCE-PMrs(h) for tall reference crop and c) the FAO56-PM(h) for short reference crop.

The calculation of saturation vapour pressure e_s, actual vapour pressure e_a, net longwave radiation R_{nl} and soil heat flux G is carried out by different equations accordingly to the time step [6,7]. The selected equations of e_s, e_a and R_{nl}, that concern the daily calculations, were chosen after comparisons with the respective ones that concern the hourly time step calculations (**Table 1** and Appendix).

2.1.2. Hargreaves Method

The Hargreaves equation $HG(d)$ [5] is calculated in a daily step and is given by:

$$ET_o = a_h\left(T_{mean} + b_h\right)\left(T_{max} - T_{min}\right)^{c_h} R_a$$

(2)

where ET_o is the reference crop evapotranspiration (mm·d^{-1}), T_{mean} is the mean daily air temperature (°C),

Table 1. Characteristics of the selected reference crop evapotranspiration methods.

	Method	Calculation step	Coefficients	Heat flux—G	e_s, e_a, R_{nl}
1	ASCE-PMos(h)	hour	$C_n = 37$, $C_d = 0.24$ for $R_n > 0$ $C_n = 37$, $C_d = 0.96$ for $R_n < 0$	$G = 0.1\,R_n$ for $R_n > 0$ $G = 0.5\,R_n$ for $R_n < 0$	(A1, A2, A3)
2	ASCE-PMrs(h)	hour	$C_n = 66$, $C_d = 0.25$ for $R_n > 0$ $C_n = 66$, $C_d = 1.7$ for $R_n < 0$	$G = 0.04\,R_n$ for $R_n > 0$ $G = 0.2\,R_n$ for $R_n < 0$	(A1, A2, A3)
3	FAO56-PM(h)	hour	$C_n = 37$, $C_d = 0.34$ for $R_n > 0$ $C_n = 37$, $C_d = 0.34$ for $R_n < 0$	$G = 0.1\,R_n$ for $R_n > 0$ $G = 0.5\,R_n$ for $R_n < 0$	(A1, A2, A3)
4	FAO56-PM(d) and ASCE-PMos(d)	day	$C_n = 900$, $C_d = 0.34$	$G \approx 0$	(A4, A5, A6)
5	ASCE-PMrs(d)	day	$C_n = 1600$, $C_d = 0.38$	$G \approx 0$	(A4, A5, A6)
6	HG(d)	day	$a_h = 0.0023$, $b_h = 17.8$, $c_h = 0.5$	-	-

T_{min} is the minimum daily air temperature (˚C), T_{max} is the maximum daily air temperature (˚C), R_a is the total extraterrestrial solar radiation (mm·d^{-1}), α_h, b_h and c_h are Hargreaves' equation coefficients (**Table 1**).

2.2. Epan and Pan Coefficient Equations

One of the most popular methods for the indirect ET_o estimation is through E_{pan} measurements and k_p coefficients adjusted to the surrounding environment and conditions (e.g. relative humidity, wind speed and windward side distance of green crop or a dry fallow).

The relationship between ET_o and E_{pan} is given by the following equation [6]:

$$ET_o = k_p E_{pan} \tag{3}$$

where E_{pan} is the pan evaporation (mm·d^{-1}) and k_p is the pan coefficient.

Based on literature review, the values of k_p cover a range between 0.3 and 1.1, and are proportional to relative humidity and inverse proportional to wind speed [6,14,15]. Significant efforts have been performed for the indirect estimation of k_p by equations, that use meteorological data and the characteristics of the surrounding environment, such as those of Cuenca [16], Allen and Puitt [3], Snyder [17], Pereira *et al.* [18], Orang [19], Raghuwanshi and Wallender [20] for the case of Class-A pan evaporimeter. The above equations are used for the estimation of ET_o for the short reference crop and are given, respectively, by:

$$
\begin{aligned}
k_p = {} & 0.475 - 2.4 \times 10^{-4} u_2 + 5.16 \times 10^{-3} RH \\
& + 1.18 \times 10^{-3} F - 1.6 \times 10^{-5} RH^2 - 1.01 \times 10^{-6} F^2 \\
& - 8 \times 10^{-9} RH^2 u_2 - 1 \times 10^{-8} H^2 F
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
k_p = {} & 0.108 - 0.000331 u_2 + 0.0422 \ell n(F) \\
& + 0.1434 \ell n(RH) - 0.000631 \left[\ell n(F)\right]^2 \ell n(RH)
\end{aligned} \tag{5}
$$

$$k_p = 0.482 - 0.000376 u_2 + 0.024 \ell n(F) + 0.0045 RH \tag{6}$$

$$k_p = 0.85(\Delta + \gamma) / \left[\Delta + \gamma(1 + 0.33 u_2)\right] \tag{7}$$

$$
\begin{aligned}
k_p = {} & 0.51206 - 0.000321 u_2 \\
& + 0.031886 \ell n(F) + 0.002889 RH
\end{aligned} \tag{8}
$$

$$
\begin{aligned}
k_p = {} & 0.5944 + 0.0242 X_1 - 0.0583 X_2 - 0.1333 X_3 \\
& - 0.2083 X_4 + 0.0812 X_5 + 0.1344 X_6
\end{aligned} \tag{9}
$$

where RH is the mean daily relative humidity (%), u_2 is the mean daily wind speed at 2 m above the soil surface (in km·d^{-1} for the **Eqs.4**, **5**, **6**, **8** and in m·s^{-1} for the **Eq.7**) and F is the windward side distance of green crop or a dry fallow (m). For the **Eq.9**, $X_1 = \ln(F)$, X_2, X_3 and X_4 are wind speed categories of 175 - 425, 425 - 700, and

>700 km·d^{-1}, respectively, and are assigned values of one or zero depending upon their presence. A zero value for these variables represents a wind speed of <175 km·d^{-1}. Similarly, X_5 and X_6 are relative humidity categories of 40% - 70% and ≥70%, respectively. Again the values of one or zero were assigned depending on their presence and a zero value for these variables represents a relative humidity of ≤40%.

2.3. Study Site and Measurements

Hourly meteorological data of temperature, relative humidity, solar radiation, wind speed and precipitation obtained by the meteorological station of the Aristotle University of Thessaloniki farm (40˚32'08"N, 22˚59'18"E), covering the summer growing season (April to October) for three years (2008-2010) were used for the ET_o estimations. The mean monthly values of the meteorological data for the period 2008-2010 are presented in **Table 2**.

Daily E_{pan} measurements were colected using Class-A pan evaporimeter for two years (2008-2009). The data describe adequately the meteorological conditions of the Thessaloniki plain, where the climate is considered as a semi-arid Mediterranean environment.

3. RESULTS AND DISCUSSION

3.1. Estimation and Evaluation of ET_o Methods

The daily ET_o for the summer growing season (April to October) was estimated using the methods presented in **Table 1**. The daily ET_o values of ASCE-PM method, calculated for hourly time-step, were used as reference for the comparisons among the methods presented in **Table 1**. The mean daily values of ET_o (mm·d^{-1}) for each method and the transition coefficients for each one in order to be converted in ASCE-PMos(h) are given in **Table 3**.

The comparisons among the methods for the short reference crop are given in **Figures 1(a)-(c)**, while for the tall reference crop in **Figure 1(d)**. The statistical tests of the coefficient of determination (R^2), the root mean square error (RMSE) and the mean bias error (MBE) were used for the comparison analysis [12,21] and are given by:

$$R^2 = \left[\frac{\sum_{i=1}^{N}(C_i - C_m)(O_i - O_m)}{\sqrt{\sum_{i=1}^{N}(C_i - C_m)^2} \cdot \sqrt{\sum_{i=1}^{N}(O_i - O_m)^2}} \right]^2 \tag{10}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_i - O_i)^2} \tag{11}$$

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Table 2. Mean monthly values of the meteorological parameters during the period of April-October for 2008-2010.

Month	Mean monthly temperature T (°C)	Mean monthly relative humidity RH%	Mean monthly incident solar radiation R_s (w·m^{-2})	Mean monthly wind speed u_2 (m·s^{-1})	Mean monthly precipitation (mm)
April	14.5	71.8	202.9	1.6	42.5
May	19.9	63.3	268.0	1.7	31.8
June	24.3	61.3	285.4	1.5	47.3
July	27.1	54.2	304.4	1.6	20.4
August	27.5	55.9	260.6	1.3	26.7
September	21.7	63.4	181.3	1.3	35.3
October	16.4	73.8	127.3	1.2	63.4

Table 3. Mean daily values of ET_o (mm·d^{-1}) for each method and transition coefficients for each method using the daily ET_o values of ASCE-PMos(h) as reference.

Method	Short reference crop								Tall reference crop			
	ASCE-PMos(h)		FAO56-PM(h)		ASCE-PMos(d) FAO56-PM(d)		HG(d)		ASCE-PMrs(h)		ASCE-PMrs(d)	
Month/unit	(mm·d^{-1})		(mm·d^{-1})		(mm·d^{-1})		(mm·d^{-1})		(mm·d^{-1})		(mm·d^{-1})	
April	3.13†	(1.00)‡	3.00	(1.043)	2.87	(1.091)	2.83	(1.106)	3.70	(0.846)	3.44	(0.910)
May	4.78	(1.00)	4.60	(1.039)	4.49	(1.065)	4.36	(1.096)	5.73	(0.834)	5.38	(0.888)
June	5.48	(1.00)	5.31	(1.032)	5.31	(1.032)	5.18	(1.058)	6.52	(0.840)	6.30	(0.870)
July	6.22	(1.00)	6.04	(1.030)	6.10	(1.020)	5.85	(1.063)	7.55	(0.824)	7.42	(0.838)
August	5.35	(1.00)	5.22	(1.025)	5.19	(1.031)	5.07	(1.055)	6.46	(0.828)	6.29	(0.851)
September	3.38	(1.00)	3.29	(1.027)	3.21	(1.053)	3.11	(1.087)	4.13	(0.818)	3.96	(0.854)
October	1.98	(1.00)	1.92	(1.031)	1.78	(1.112)	1.88	(1.053)	2.40	(0.825)	2.23	(0.888)

†Mean daily values ‡Transition coefficients calculated as ASCE-PMos(h)/other method.

$$MBE = \frac{1}{N}\sum_{i=1}^{N}\left(C_i - O_i\right) \qquad (12)$$

where *O* are the observed values (the reference values of ASCE-PM in hourly time step), *C* are the computed values by the other methods and O_m and C_m are the mean observed and computed values, respectively.

The results showed a relative underestimation of the calculated ET_o (relatively small values of RMSE and negative values of MBE) for all the methods compared to the daily ET_o values of ASCE-PM method in hourly time-step, for both cases of the reference crop. Considering the simplicity of the Hargreaves model, it was found a very good correspondence with the ASCE-PMos(h), but it deflects for the days where the wind speed override the values of 1.5 - 2.0 m·s^{-1}. In order to correct the results of each method using the ASCE-PM(h) as reference for the summer growing season, either the transition coefficients for each month or the regression equations from **Figure 1** can be used. The ET_o values of the ASCE-PM(h) for the tall reference crop were found about 10% - 20% higher of those for short reference crop. The transition coefficients also allow the conversion from tall to short ET_o values and the opposite.

3.2. Evaluation of Pan Coefficients Equations

The evaluation of k_p selected equations (**Eqs.4** to **9**) was performed using as reference the ASCE-PMos(h) and the daily E_{pan} measurements of a Class-A pan evaporimeter, which was established at $F = 0.25$ m from active growing crop (**Figures 2(a)-(f)**). The mean monthly observed values of k_p derived by the ratio ASCE-PMos(h)/E_{pan}, for the total period of April to October, were 0.7 and 0.71 for 2008 and 2009, respectively. The mean monthly k_p values for the 2-years study period using the **Eqs.3** up to **9** are given in **Table 4**. Using the ASCE-PMos(h) for the estimation of the daily ET_o and the statistical criteria of R^2, RMSE and MBE (**Figure 2**) from the comparison analysis between the different k_p equations, resulted the following order in prediction ac-
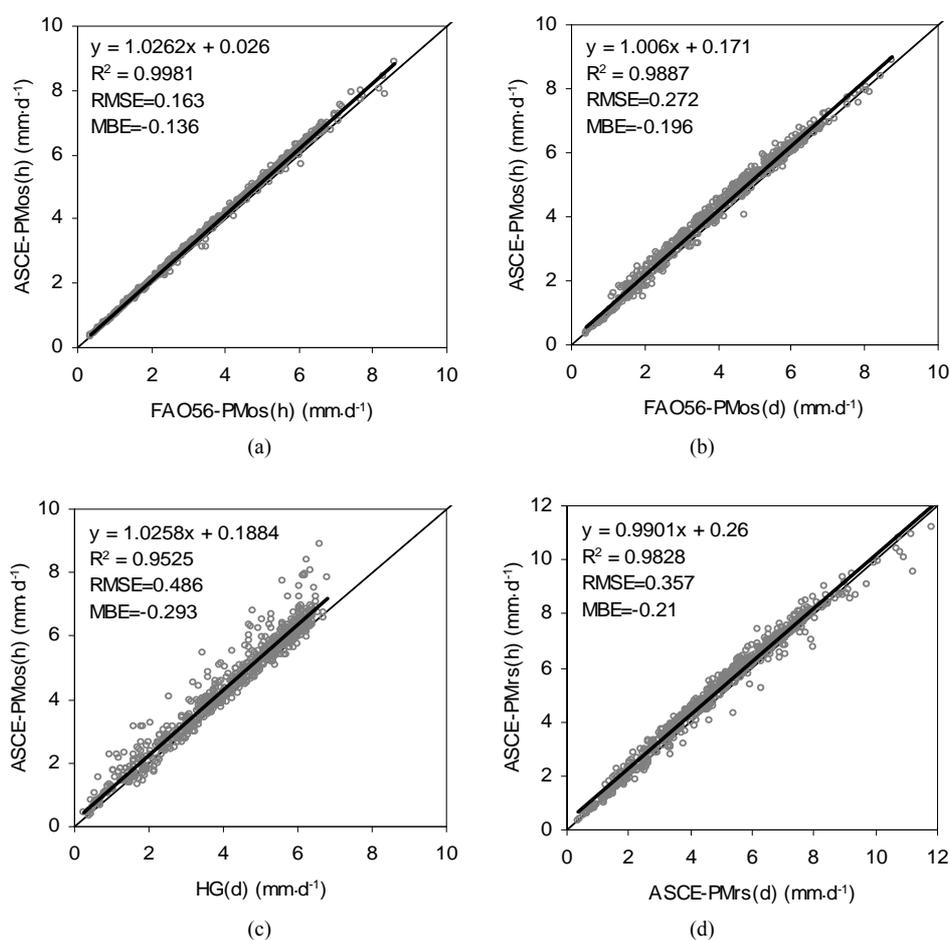
Figure 1. Comparison of the daily ET_o estimated by the methods of ASCE-PMos(h) against (a) FAO56-PMos(h); (b) FAO56-PMos(d); (c) HG(d) for short reference crop and (d) by ASCE-PMrs(d) for tall reference crop.

Table 4. Mean monthly values of the observed k_p (ET_o/E_{pan}) and mean monthly values using the different k_p equations.

Month	[†]ET_o/E_{pan}	Snyder	Pereira *et al.*	Orang	Allen & Pruitt	Cuenca	Raghuwanshi & Wallender
April	0.76	0.43	0.71	0.65	0.66	0.73	0.67
May	0.74	0.38	0.73	0.62	0.64	0.70	0.65
June	0.69	0.37	0.75	0.61	0.63	0.69	0.65
July	0.67	0.32	0.75	0.58	0.61	0.66	0.63
August	0.70	0.36	0.77	0.60	0.62	0.68	0.64
September	0.75	0.40	0.76	0.63	0.64	0.71	0.65
October	0.76	0.42	0.75	0.65	0.65	0.73	0.66
Average	0.71	0.38	0.75	0.61	0.63	0.69	0.65

[†]ET_o is calculated using ASCE-PMos(h) method.

curacy: Cuenca (**Eq.4**) > Raghuwanshi & Wallender (**Eq. 9**) > Allen & Pruit (**Eq.5**) > Pereira *et al.* (**Eq.7**) > Orang (**Eq.8**) > Snyder (**Eq.6**). The equation of Cuenca indicated the best adaptation to the ASCE-PMos(h) method compared to the other equations and adequate performance for the estimation of ET_o under the climatological-environmental conditions of the study area.

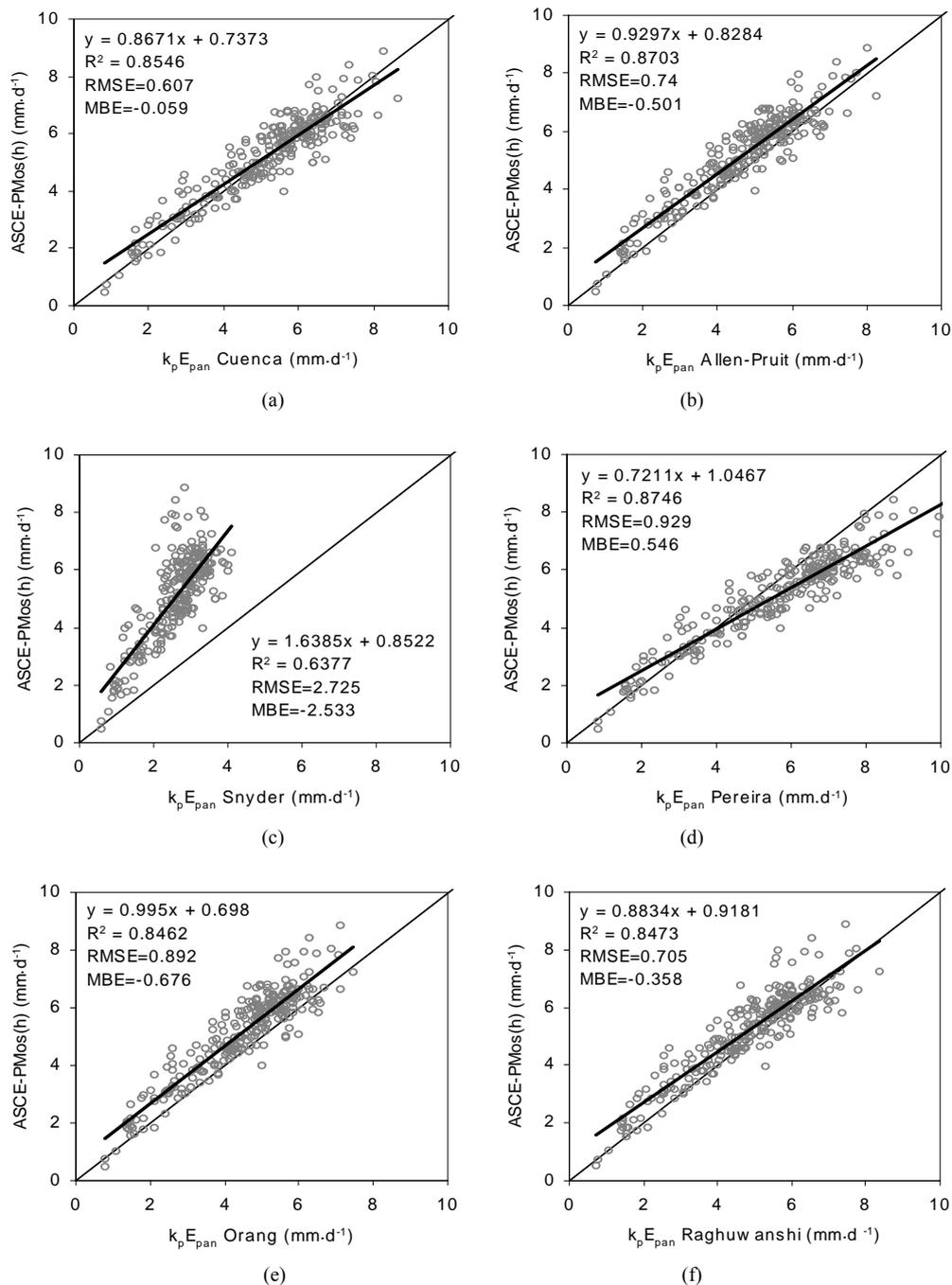Taking into account the results of other similar studies

Figure 2. Comparison of the daily ET_o estimated by ASCE-PMos(h) method and by **Eq.3** using the different k_p equations (a) Cuenca; (b) Allen & Pruitt; (c) Snyder; (d) Pereira *et al.*; (e) Orang and (f) Raghuwanshi & Wallender.

[14,15], different predictive accuracy is observed among the aforementioned k_p equations, which can be ascribed a) mainly to the different reference evapotranspiration method, which is used for the comparisons and b) secondly to the different climatic-environmental conditions. This indicates the necessity to validate these equations before their use.

4. CONCLUSIONS

Reference crop evapotranspiration was calculated for the irrigation period and three succeeding years using the proposed by ASCE, FAO and Hargreaves methods. Meteorological data from Thessaloniki in Northern Greece were used. ASCE-standardized Penman-Monteith method considered the reference method to evaluate the per-

formance of the other methods.

Evaluation of the FAO-56 and Hargreaves methods was based on the calculation time step (hourly or daily) and their correspondence to the ASCE-PM. From the comparison between the different ET_o methods a relative underestimation of the calculated ET_o was found for all the methods compared to the daily values of ASCE-PM(h), calculated in hourly time step, for both cases of the reference crop. Considering the simplicity of the Hargreaves model, it was found a very good correspondence with the ASCE-PMos(h), but it deflects for the days where the wind speed override the values of 1.5 - 2.0 m·s^{-1}.

ET_o was also calculated using measurements of pan evaporation and six equations for pan coefficient (k_p) estimation. These values evaluated in relation of ASCE-PM method. The comparison analysis between the different k_p equations resulted the following order in prediction accuracy: Cuenca > Raghuwanshi & Wallender> Allen & Pruit > Pereira *et al.* > Orang > Snyder. The Cuenca's equation indicated the best adaptation to the ASCE-PM method compared to the other equations and adequate performance for the estimation of ET_o under the climatological-environmental conditions of the study area.

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APPENDIX. EQUATIONS FOR INTER-CALCULATIONS (ASCE-EWRI, 2005)

For hourly time step calculations:

$$e_s = e^o(T) = 0.6108 \exp\left(\frac{17.27\, T_{h\,mean}}{T_{h\,mean} + 237.3}\right) \qquad (A1)$$

$$e_a = e^o(T_{h\,mean})\frac{RH_{h\,mean}}{100} \qquad (A2)$$

$$R_{nl} = \sigma f_{cd}\left(0.34 - 0.14\sqrt{e_a}\right)T^4_{K\,h\,mean} \qquad (A3)$$

For daily time step calculations:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \qquad (A4)$$

$$e_a = \frac{e^o(T_{max})\dfrac{RH_{mean}}{100} + e^o(T_{min})\dfrac{RH_{mean}}{100}}{2} \qquad (A5)$$

$$R_{nl} = \sigma f_{cd}\left(0.34 - 0.14\sqrt{e_a}\right)\frac{T^4_{K\,max} + T^4_{K\,min}}{2} \qquad (A6)$$

where RH_{hmean}: mean hourly relative humidity (%), T_{hmean} and T_{Khmean}: mean hourly air temperature in (°C) and in (K), respectively, R_{nl}: mean hourly or daily net long-wave radiation (MJ·m^{-2}·h^{-1} or MJ·m^{-2}·d^{-1}), σ: Stefan-Boltzman constant, e_s: daily or hourly saturation vapor pressure (kPa), e_a: daily or hourly mean actual vapor pressure (kPa), f_{cd}: factor of relative cloudiness $0.05 \le f_{cd} \le 1.0$, T_{mean}, T_{max}, T_{min}: mean, maximum and minimum daily temperature, respectively in (°C), T_{Kmean}, T_{Kmax}, T_{Kmin}: mean, maximum and minimum daily temperature, respectively in (K), and RH_{mean}, RH_{max}, RH_{min}: mean, maximum and minimum daily relative humidity (%).