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Comparative analysis of reference evapotranspiration estimation between various methods and the FAO56 Penman - Monteith procedure

N. Efthimiou[1*], S. Alexandris[1], C. Karavitis[1] and N. Mamassis[2]
[1] *Agricultural University of Athens, Department of Natural Resources Development and Agricultural Engineering, Section of Water Resources Management, Athens, Greece*
[2] *National Technical University of Athens, School of Civil Engineering, Section of Water Resources and Environmental Engineering, Athens, Greece*
[*] *e-mail: efthimiounik@yahoo.com*

Abstract: This study aimed to assess the performance of nine empirical methods [FAO-24 Penman (1977), Makkink (1957), Turc (1961), Penman (1963), Priestley-Taylor (1972), Linacre (1977), Kimberly Penman (1982), Hargreaves-Samani (1985), Copais (2006)], for the daily reference evapotranspiration (ET_o) estimation in comparison with the Penman-Monteith method standardized by the Food and Agriculture Organization (FAO56 – PM). The analysis, used data of two meteorological stations at Krania and Kozane, located at Western Macedonia, Greece. Daily values of ET_o were calculated using meteorological data for a time-period of 34 and 48 years of the two stations respectively. Since none of the solar radiation variables was measured on the stations, the net radiation variable (R_{net}) was derived empirically following the procedure outlined in the FAO-56 paper (Allen et al., 1998). Such values were compared using linear regression and statistical indices of quantitative approaches to model performance evaluation. All the statistical indices used were calculated on a daily basis. However, the root mean square error (RMSE) was additionally calculated on a monthly basis in order to evaluate the seasonality differences of the methods to be compared. In regard to the regression equations, the Priestley-Taylor method had the best correlation to the FAO56-PM method at Krania station, while at Kozane station the Turc method gave the best predicted values. By comparing the monthly accumulated values of ET_o it may be concluded that not only on a daily but on a monthly basis as well, all of the methods compared perform good during the winter season (October-February) with smaller deviations in absolute values of ET_o and lower RMSE, but show poor performance during the summer season (March-September) with the opposite characteristics.

Keywords: evapotranspiration, empirical methods, comparative analysis, FAO56-PM

1. INTRODUCTION

Evapotranspiration (ET) is apart from precipitation, the most significant component of the hydrological cycle and a key element for the accurate estimation of the water budget. The reliable and consistent estimation of its spatial and temporal rates is of great importance, in order to determine the water requirement of crops for irrigation scheduling. Appropriate irrigation techniques imply a direct effect on the crop production, as long as other significant issues such as proper sizing and management of the irrigation system, evaluation of the effects of changing land use on crop and water yields etc. Moreover, the growing global concern about environmental sustainability and particularly the use and exploitation of limited water resources, requires more efficient planning, especially in agriculture, and in areas like Greece whereas irrigation is by far the main water consumer.

Evapotranspiration (ET) may be defined as the process of water transfer to the atmosphere, consisted of the combined procedures of evaporation from the soil and water surface and transpiration from a vegetated surface. It depends on the interaction of various climatic elements, such as solar radiation, wind speed, temperature and air humidity and it may be expressed as the equivalent amount of water evaporated per unit of time, generally expressed as water depth per unit of time (e.g. mm $days^{-1}$).

The term reference crop evapotranspiration (ET_o) is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 $s.m^{-1}$, and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, completely shading the ground, and not short of water (Allen et al., 1998).

In the Mediterranean area, the annual long dry summer periods are dehydrating almost completely the soil profile. An accurate estimation of potential evapotranspiration (e.g. Penman method) requires all the pertinent data, plus as stated by definition adequate water status in the soil profile (Allen et al., 1998; Alexandris et al., 2006; Karavitis et al., 2012). In addition to that, most Mediterranean areas and many other regions around the world do not have vegetation reference sites or installed ET_o networks due to high installation or maintenance cost. This leads to systematic use of inappropriate climatic data for ET_o calculations from sites that do not conform to standardizations and consequently, to significant and systematic cumulative errors in irrigation scheduling, as well as confusing conclusions.

Moreover, direct and diffuse solar radiation, a key factor to the estimation of ET_o, is affected by surface characteristics, such as slope, aspect, altitude and shading. It's seasonal allocation and topographic effects are often ignored by the typical hydro-meteorological modeling formulas (Mamassis et al., 2012).

Since direct measurement of ET_o for short grass is difficult, time consuming and costly, the next seemingly most practical approach would be to estimate ET_o from climatic variables, such as solar radiation, air temperature, wind speed, and relative humidity. In connection with, various methods are available for estimating ET_o involving equations ranging from the most complex energy balance method requiring detailed climatic data (Allen et al., 1998) to the simpler method requiring less data (Hargreaves and Samani, 1985).

The Penman−Monteith equation (FAO56 – PM) based on the Penman-Monteith (PM) method as reported by Allen et al. (1998) has been extensively evaluated and compared with measured weighing lysimeter ET under different climatic conditions, ranked as the best method for all climatic conditions (Jensen et al., 1990). Allen et al. (1994) also showed that ET_o computed using the Penman−Monteith equation yielded estimates close to measured ET_o values. Following these studies, the FAO56 Penman−Monteith method (Allen et al., 1998) was adopted as the standard method for definition and computation of ET_o from a grass reference surface (cool season grass) and moreover as a measure of comparison for the evaluation of other estimation methods.

However, this method requires a large number of parameters (air temperature, relative humidity, wind speed, and solar radiation), which are not always available, in many meteorological stations particularly at a given locale where quality of data and difficulties in gathering all of the necessary weather parameters can present serious limitations. Additionally, it also uses complicated unit conversions and lengthy calculations. This leads to the application of other simpler empirical methods, which use a smaller number of parameters and furthermore low-cost data acquisition systems.

The limitations of such methods are easily noticed, but nonetheless they can provide easily and low-cost acquired output values for use in water balance and, in some cases, values almost as accurate as those obtained through direct methods. In the absence of parameters that allow the use of more consistent methods, the simplest empirical formulas are commonly used. To obtain approximate information on water demand through an empirical method, even the simplest one, is better than having no information at all.

Considering the above, the main objective of this study is to compare and evaluate the performance of nine empirical methods (Hargreaves-Samani (Hargreaves and Samani, 1985), Original Penman (Penman, 1963), Kimberly Penman (Wright, 1982), FAO-24 Penman (Doorenbos and Pruitt, 1977), Turc (Turc, 1961), Makkink (Makkink, 1957), Linacre (Linacre, 1977), Copais (Alexandris et al., 2006), Priestley-Taylor (Priestley and Taylor, 1972)) in estimating daily reference evapotranspiration (ET_o) compared to the Penman-Monteith method (FAO56 – PM) for the sites of Krania and Kozane, located at Western Macedonia in Northern Greece, taking under consideration the region climate, land coverage and topographical condition, in order to provide guidance on the selection of the most appropriate ET_o equation under humid conditions. These methods have been adopted for stationary and non-stationary climatic conditions (e.g. Panagoulia, 1991).

2. DATA AND METHODS

2.1 Study area and data measurements

The data used for the calculation of the daily potential evapotranspiration were obtained from the meteorological stations of Krania and Kozane, located at Western Macedonia in Northern Greece. Krania station (Latitude: 39°54'00"N, Longitude: 21°17'00"E, Elevation: 952 m) is located within the catchment of Benetikos River, a tributary of Aliakmonas River and is operated by the National Agricultural Research Foundation (N.AG.RE.F). Kozane station (Latitude: 40°17'00"N, Longitude: 21°41'00"E, Elevation: 625 m) is located within the city of Kozane and is operated by the Hellenic National Meteorological Service (H.N.M.S). Daily values of ET_o were calculated using daily meteorological data [maximum (T_{max}) – minimum (T_{min}) – average (T_{avg}) air temperature, relative humidity (RH_{avg}), wind speed (u_2) at the height of 2 m, cloud cover (C) for a time-period of 34 (01/01/1961 - 30/06/1994) and 48 (01/01/1962 - 31/12/2010) years for the stations of Krania and Kozane, respectively. The station of Krania measures wind speed at the height of 1.5 m whiles the station of Kozane at the height of 8 m. Because none of the solar radiation variables was measured, the net radiation variable (R_{net}) was derived empirically following the procedure outlined in the FAO-56 paper (Allen et al., 1998).

2.2 Methods of Reference Evapotranspiration

The nine empirical reference evapotranspiration estimation methods, selected to be compared to the Penman-Monteith (FAO56 – PM) standard method, along with their representative equations are presented in Table 1.

The computation of all the parameters required for the calculation of the reference evapotranspiration with the different methods and procedures given in Table 1, is presented and thoroughly explained within the literature references.

The Original Penman method (Penman, 1963) (Eq.1), is a combination method, consisting of an energy and an aerodynamic term. The energy term, describing the energy balance, is given by the mathematical expression $\Delta/(\Delta+\gamma)\cdot(R_n-G)$, where Δ is the slope vapour pressure curve, γ is the psychrometric constant, R_n is the net radiation and G is the heat flux density. The aerodynamic term, describing the drying ability of the atmosphere, is given by the mathematical expression $K_W\cdot\gamma/\Delta+\gamma\cdot w_f\cdot(e_s-e)$, where K_w is a unit conversion constant, w_f is the wind speed function and the $(e_s – e)$ difference is the vapour pressure deficit.

The Kimberly Penman 1982 method (Wright, 1982 – Eq.2) has the same form as Eq.1, but with some variations concerning the calculation of the wind function, w_f (different values of the coefficients a_w and b_w), as referred in Table 1.

The FAO-24 Penman method (Doorenbos and Pruitt, 1977 – Eq.3) also has the same form as Eq.1. The model introduces respective alterations in the calculation of the w_f factor (different values of the coefficients a_w and b_w), attributing additional "sensitivity" to the equation. Moreover, the "c" factor is added, which is the adjustment factor developed by Frevert et al. (1983), to compensate for the effect of day and night weather conditions, as referred in Table 1.

The standard FAO56 Penman-Monteith method (Allen et al., 1998 – Eq.4), additionally to the aforementioned factors and parameters, also depends on the u_2 factor, which is the wind speed at a 2 meter height, as well as the coefficient for the reference crop (for grass 0.34 s m^{-1}).

Table 1. Methods selected for comparison and the representative equations

Method/Literature Reference	*Representative Equation*	*Eq. No*
1963 Penman (Original Penman, 1963)	$ETo = \left[\frac{\Delta}{\Delta+\gamma}\cdot(R_n - G) + K_W \cdot \frac{\gamma}{\Delta+\gamma}\cdot w_f \cdot (e_s - e)\right]\cdot\frac{1}{\lambda}$	*(1)*
1982 Penman (Wright, 1982)	Same form as Eq.1 but with some variations in the calculation of w_f (different values of the coefficients a_w and b_w)	*(2)*
FAO-24 Penman (Doorenbos and Pruitt, 1977)	Same form as Eq.1 but with some variations in the calculation of w_f (different values of the coefficients a_w and b_w) as long as the addition of the "c" factor, which is the adjustment factor to compensate for the effect of day and night weather conditions	*(3)*
FAO-56 Penman-Monteith (Allen et al., 1998)	$ETo = \frac{0.408\cdot\Delta\cdot(R_n - G) + \gamma\cdot\frac{900}{T+273}\cdot u_2\cdot(e_s - e)}{\Delta + \gamma\cdot(1+0.34\cdot u_2)}$	*(4)*
1985 Hargreaves-Samani (Hargreaves and Samani, 1985)	$ETo = 0.0023\cdot(T_{\max} - T_{\min})^{0.5}\cdot(T_m + 17.8)\cdot R_a$	*(5)*
1957 Makkink (Makkink, 1957)	$ETo = 0.61\cdot\frac{\Delta}{\Delta+\gamma}\cdot\frac{R_s}{\lambda} - 0.12$	*(6)*
1961 Turc (Turc, 1961)	$ETo = 0.0133\cdot\frac{T_m}{T_m+15}\cdot(R_s+50)$ (RH>50%) $ETo = 0.0133\cdot\frac{T_m}{T_m+15}\cdot(R_s+50)\cdot\left(1+\frac{50-RH}{70}\right)$ (RH<50%)	*(7)*
1977 Linacre (Linacre, 1977)	$ETo = \frac{500\frac{T_m + 0.006\cdot z}{100-\phi} + 15\cdot(T - T_{dew})}{80-\phi}$	*(8)*
2006 Copais (Alexandris et al., 2006)	$ETo = m_1 + m_2\cdot C_2 + m_3\cdot C_3 + m_4\cdot C_1\cdot C_2$	*(9)*
1972 Priestley-Taylor (Priestley and Taylor, 1972)	$ETo = \alpha\cdot\frac{\Delta}{\Delta+\gamma}\cdot(R_n - G)\cdot\frac{1}{\lambda}$	*(10)*

The FAO-24 Penman method (Doorenbos and Pruitt, 1977 – Eq.3) also has the same form as Eq.1. The model introduces respective alterations in the calculation of the w_f factor (different values of the coefficients a_w and b_w), attributing additional "sensitivity" to the equation. Moreover, the "c" factor is added, which is the adjustment factor developed by Frevert et al (1983), to compensate for the effect of day and night weather conditions, as referred in Table 1.

The standard FAO56 Penman-Monteith method (Allen et al., 1998 – Eq.4), additionally to the aforementioned factors and parameters, also depends on the u_2 factor, which is the wind speed at a 2 meter height, as well as the coefficient for the reference crop (for grass 0.34 s m^{-1}).

The Hargreaves-Samani method (Hargreaves and Samani, 1985 – Eq.5), depending on the difference between daily maximum and minimum air temperature ($T_{max} - T_{min}$), mean daily air temperature (T) and extraterrestrial radiation (R_a), is preferable when solar radiation data, relative humidity data and/ or wind speed data are missing.

The Makkink method (Makkink, 1957 – Eq.6), gives well results in cold and humid climates but doesn't perform equally well in dry climate regions.

The Turc method (Turc, 1961 – Eq.7) consists of two individual similar equations, depending on the amount of relative humidity (RH), mean daily air temperature (T_m) and the incoming solar radiation (R_s). The method was introduced for the estimation of reference evapotranspiration under various climate conditions of Western Europe (France).

Linacre (Linacre, 1977) introduced an equation (Eq.8), depending on the mean daily air temperature (T_m), the dew point temperature (T_{dew}) and the station's latitude (φ) and elevation (z).

The Copais method (Alexandris et al., 2006 – Eq.9) requires data of three meteorological parameters, solar radiation (R_s), mean daily air temperature (T) and relative humidity (RH). The coefficients (C_i) introduced were calculated by the application of surface polynomial analysis in three consecutive stages. The equation was calibrated by using data sets collected from the Copais experimental field, in central Greece. Verification of the validity of the model was obtained by using independent data from Copais as well as data from CIMIS (Davis, Sacramento, CA).

The Priestley-Taylor method (Priestley and Taylor, 1972 – Eq.10) is an empirical approach of the more theoretical 1963 Penman method (Eq. 1), where only the energy term is included, multiplied by a numeric factor (a). The use of Eq.10 provides reference evapotranspiration estimates where low or no advection conditions occur.

Using some of these methods, it is possible to obtain negative values for ET_o on some winter days where the flux density of the long wave radiation (R_{nl}) from the surface is large and the vapour pressure deficit (VPD) is small. It is under these conditions that net condensation of water from the atmosphere is possible. This would be similar to negative evaporation. Negative fluxes of R_n are not unrealistic during high-latitude winter, but negative ET_o is, so negative values of ET_o are set to zero. Negative values of ET_o resulted by calculating ET_o with the Turc and Linacre (1977) methods. Depending on how the Turc equation has been set up, ET_o calculations result in negative values if the average daily temperature (T_{avg}) is negative. As far as the Linacre (1977) equation is concerned, ET_o calculations result in negative values if $T_{avg} < \frac{15 \cdot T_{dew} \cdot (100-\phi) - 3 \cdot z}{500 + 15 \cdot (100-\phi)}$, where T_{dew} is the dew point temperature (^oC), φ is the station latitude (^{o}) and z is the station elevation (m).

During the process of choosing a different method of estimating evapotranspiration than the FAO56-PM reference method, one of the most important considerations is the availability and reliability of meteorological data. The accuracy of such data, moreover the ones of advanced input variables like humidity and radiation, especially at the remote areas of the Greek region, is quite often mediocre. Table 2 shows the data requirements for the various compared equations.

Table 2. Comparison of each method in terms of the number of parameters required

Method	***Variables*** [a], [b]				
	Temperature	*Relative Humidity*	*Wind Speed*	R_s	R_n
1963 Penman	•	•	•		•
1982 Penman	•	•	•		•
FAO-24 Penman	•	•	•		•
FAO-56 Penman-Monteith	•	•	•		•
1985 Hargreaves-Samani [c]	•				
1957 Makkink	•			•	
1961 Turc	•	•		•	
1977 Linacre [c]	•				
2006 Copais	•	•		•	
1972 Priestley-Taylor	•				•

[a] *Mean daily values of the variables used*
[b] *Data used are not distinguished in measured or estimated but refer to the natural character of the variable*
[c] *Mean, maximum, minimum daily values of temperature required*

2.3 Statistical Methods

A statistical analysis was executed in order to evaluate the model performance using different statistical indices for the estimated values.

Commonly used correlation measures, such as (R) and (R^2) and tests of statistical significance in general, are often inappropriate or misleading when used to compare model predicted (P) and observed (O) variables (Fox, 1981; Willmott, 1982).

The "Index of Agreement" (d) is alternatively proposed as a descriptive measure which can be applied in order to make a cross-comparison between the models, is both a relative and bounded measure (Willmott and Wicks, 1980; Willmott, 1981, 1982). Fox (1981) recommends that four types of different measures should be calculated and reported. The mean bias error (MBE) which describes the bias, the variance of the distribution of differences (s_d^2) which expresses the variability of the difference between predicted (P_i) and observed (O_i) values around the MBE, the root mean square error (RMSE) or the mean absolute error (MAE) which express the average difference.

RMSE and MAE are among the best overall measures of model performance because they summarize the mean difference between observed and predicted values. Despite the fact that RMSE and MAE are similar measures, in many cases is appropriate to report both indices. MAE is less sensitive to large forecast errors and is preferred for small or limited data sets. RMSE is practical as it shows the errors in the same unit and scale as the parameter it shelf. Both MAE and RMSE can range from zero to infinity with the lower values being the better.

Furthermore $RMSE_s$ and $RMSE_u$ are the systematic and unsystematic component respectively and are calculated and presented in addition to RMSE (Willmott, 1981). Systematic RMSE is determined by the distance between the linear regressions best-fit line and the 1:1 line, while unsystematic RMSE is determined by the distance between the data points and the linear regression best-fit line. The unsystematic component is representative of the “noise” level in the model being tested and is a measure of the scatter about the regression line; it can be interpreted as a measure of the potential accuracy (Berengena and Gavilan, 2005). The systematic component is a measure of the space available for local adjustment. A good model is considered to have a very low unsystematic RMSE and the systematic RMSE close to the RMSE (Alexandris et al., 2008).

Intercepts (b) and slopes (a) for the least squared regression analysis were also calculated and reported. Computational forms of all the indices are given bellow:

$$MBE = N^{-1} \cdot \sum_{i=1}^{N} \left(P_i - O_i \right) \tag{11}$$

$$MAE = N^{-1} \cdot \sum_{i=1}^{N} \left| P_i - O_i \right| \tag{12}$$

$$s_d{}^2 = \left(N - 1 \right)^{-1} \cdot \sum_{i=1}^{N} \left(P_i - O_i - MBE \right)^2 \tag{13}$$

$$RMSE = \left[N^{-1} \cdot \sum_{i=1}^{N} \left(P_i - O_i \right)^2 \right]^{0,5} \tag{14}$$

$$RMSE_u = \left[N^{-1} \cdot \sum_{i=1}^{N} \left(P_i - \hat{P}_i \right)^2 \right]^{0,5} \tag{15}$$

$$RMSE_s = \left[N^{-1} \cdot \sum_{i=1}^{N} \left(\hat{P}_i - O_i \right)^2 \right]^{0,5} \tag{16}$$

$$d = 1 - \frac{\sum_{i=1}^{N} \left(P_i - O_i \right)^2}{\sum_{i=1}^{N} \left(\left| P_i' \right| + \left| O_i' \right| \right)^2}, \; 0 \leq d \leq 1 \tag{17}$$

where O_i stands for observed values (estimated by FAO56-PM) and P_i stands for values predicted by the compared methods $\hat{P} = aO_i + b$, $P_i' = P_i - O$ and $O_i' = O_i - O$.

3. RESULTS AND DISCUSSION

3.1 Comparative Analysis

Comparisons for each empirical equation were made between daily reference evapotranspiration values and daily values calculated using the FAO56-PM method. FAO56-PM was selected as a benchmark method for comparison, taking into account that is a globally accepted model, used under a variety of climatic regimes and reference conditions. In order to have a quantitative evaluation, the correlations among the nine empirical methods against the FAO56-PM estimates were analyzed using the linear regression equation Y=b·X+a depicted (Figure 1) by the red colored line (Y=X line (45^o or slope=1) is depicted with black color), where X axis represents daily ET_o computed by the FAO56-PM Equation and Y axis is the daily ET_o estimated from the above-mentioned nine methods, and b and a are constants representing the intercept and slope of the regression equation, respectively. The resulted regression equations together with the cross-correlation coefficient (R^2) are presented in Figures 1 and 2 for the sites of Krania and Kozane, respectively. In order for R to be statistically significant, it must have a value greater than $2/\sqrt{n}$ (Koutsoyiannis and Xanthopoulos, 1999) where n is the number of the ET_o daily value pairs resulted (12.234 at Krania Station and 17.897 at Kozane station), a case that is verified for all the R coefficients computed on both stations.

Although the coefficient of determination (R^2) has been widely used to evaluate the "goodness−of−fit" of evapotranspiration equations, it is oversensitive to extreme values (outliers) and insensitive to additive and proportional differences between estimated and measured values (Legates and McCabe, 1999). Because of these limitations, R^2 values when used alone can indicate that an equation is the best estimator of ET_o when it is not. For that, additional statistical measures were included in the present effort.

It must be noticed that the Priestley-Taylor method performed sufficiently for both Krania and Kozane stations (Figures 1, 2; Tables 3, 4), meaning that the original dimensionless empirical multiplier (a=1.26), which is replaced by the Penman-Monteith aerodynamic term in the Priestley-Taylor equation, provides good estimations for the specific climatic conditions. In other words, the advection component of the energy balance is not considered significant for the local conditions on a daily basis.

All statistical measures are in agreement with the illustrated results obtained by the regression analysis method. All relevant statistics of daily methods are listed in Tables 3 and 4.

For Krania station, in regard to regression equations, the Priestley-Taylor method correlated very well with the FAO56-PM method. It resulted in a value of R^2=0.950 (d=0.983) and a slope close to unity (1.094) having also a low value of intercept (0.126). In addition it had MAE, RMSE and RMSEu close to zero and also a small deviation between the $RMSE_s$ and RMSE (Table 3). In general, in regard to the a constant (slope), all but two methods overestimated ET_o from a 4.2% (Hargreaves-Samani) to a 23% (Penman FAO24) percentage variance apart from Makkink and Linacre (1977) which underestimated ET_o (15% and 22% respectively).

For Kozane station, Turc method gave the best predicted values, resulting in a value of R^2=0.886 (d=0.995) and a slope close to unity (1.019) having also a low value of intercept (0.006). In addition, it had MAE, RMSE and RMSEu close to zero and also a small deviation between the $RMSE_s$ and RMSE (Table 4). In general, in regard to the a constant (slope), most of the methods (Penman 1963, Kimberly Penman 1982, Penman FAO24, Hargreaves-Samani, Copais) overestimated ET_o (13.5%, 22.4%, 24.5%, 0.8%, and 8.3% respectively) while fewer (Makkink, Linacre (1977), Priestley-Taylor) underestimated ET_o (23%, 6.5% and 1.5% respectively).

Another way to evaluate the performance of the methods, in order to check whether one overestimates or underestimates ET_o in comparison to FAO56-PM method, is to compare the monthly accumulated values of ET_o, derived from the summed average daily values of each station per day (mm month^{-1}) by estimating the difference and the % deviation of their values against the FAO56-PM method (Tables 5 to 10).

From the Tables 5, 6, 7 and the Figures 3, 4 it may be derived that, at Krania station the Penman 1963, Penman FAO24, Hargreaves-Samani, Copais and Priestley-Taylor methods overestimate ET_o throughout the whole year while the other methods don't show a particular pattern. Additionally, all of the methods compared perform better during the winter season (October-February) but show larger deviations of ET_o during the summer season (March-September).

Considering the yearly accumulated values of ET_o deriving from the summed average monthly values of ET_o, on a yearly basis all other methods apart from the Makkink and the Linacre (1977) method overestimate ET_o. Additionally, the Turc, Makkink and Linacre (1977) methods have the smallest deviations in comparison to the FAO56-PM estimated ET_o values, while the Penman FAO24, Copais and Penman 1963 methods have the largest deviations as it is depicted in Tables 5, 6, 7.

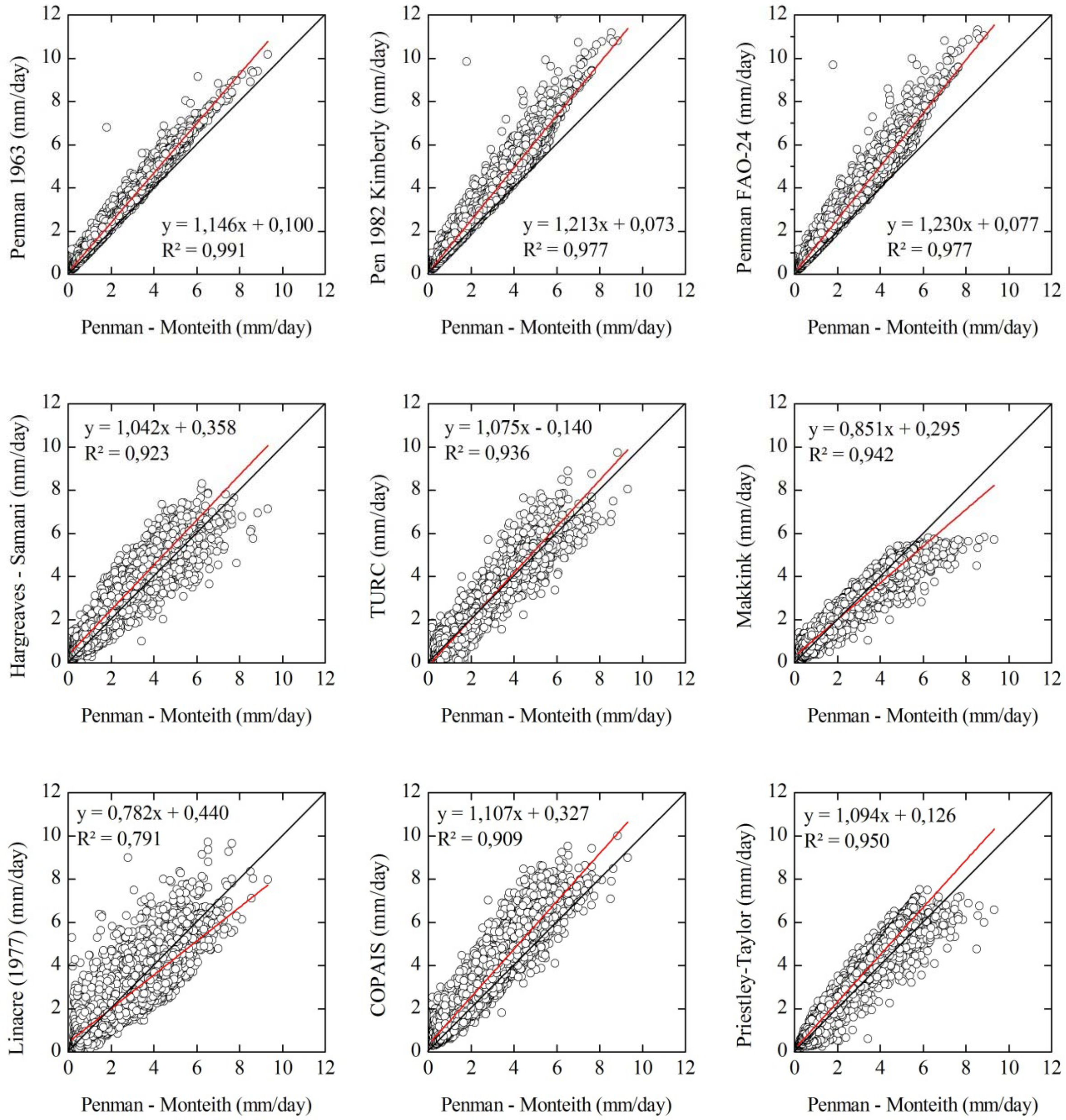

Figure 1. Comparison of daily FAO56-PM ET_o versus 9 empirical methods daily estimated ET_o for Krania station

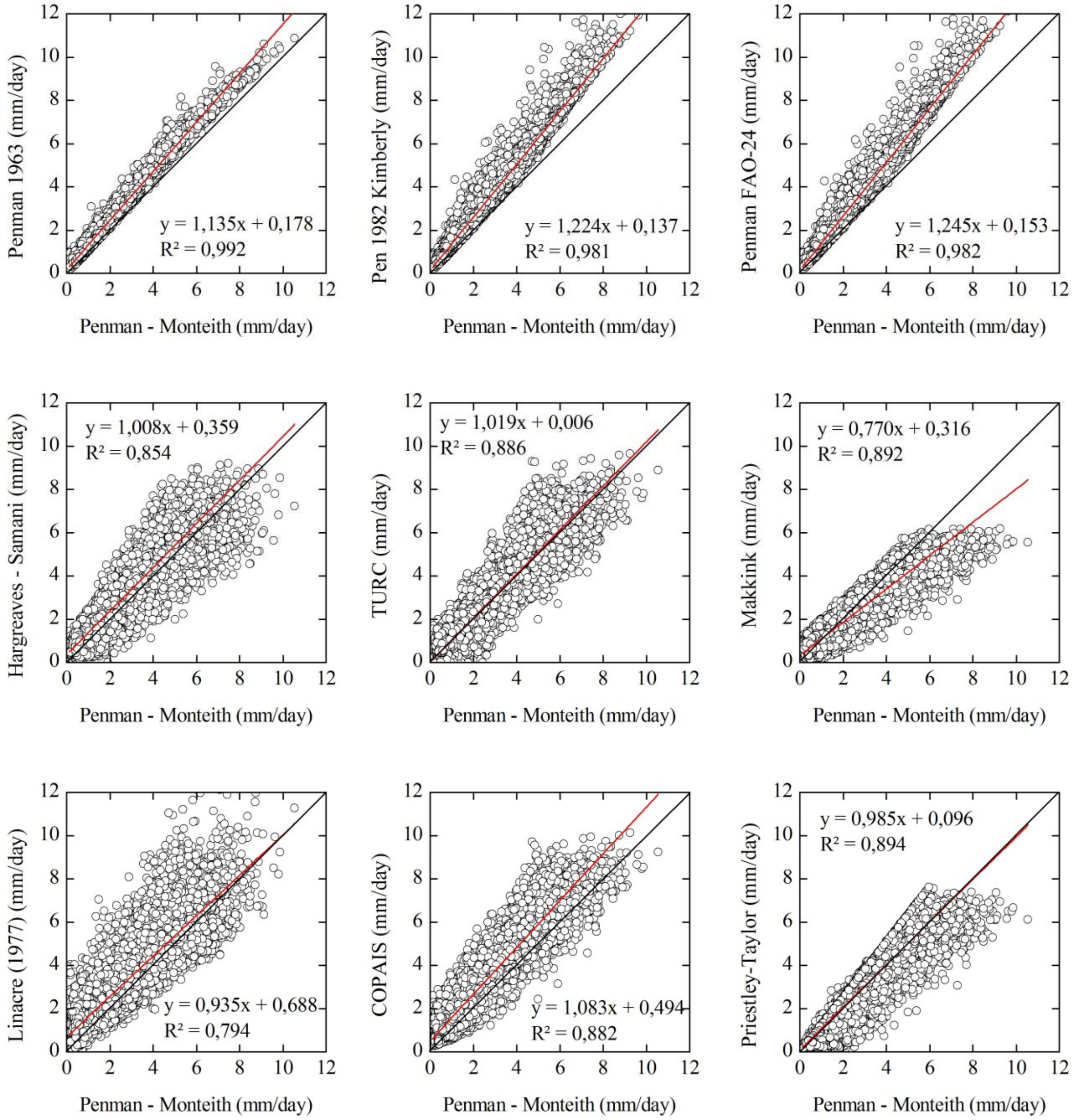

Figure 2. Comparison of daily FAO56-PM ET_o versus 9 empirical methods daily estimated ET_o for Kozane station

Table 3. Summary statistics of daily ET_o estimated methods tested against the FAO56-PM model – Krania Station

Indices	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves - Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
MBE (mm d^{-1})	0.428	0.552	0.595	0.454	0.030	-0.040	-0.047	0.568	0.336
MAE (mm d^{-1})	0.428	0.552	0.595	0.454	0.234	0.190	0.419	0.568	0.340
s_d^2	0.052	0.092	0.106	0.033	0.075	0.050	0.236	0.020	0.064
RMSE (mm d^{-1})	0.235	0.397	0.459	0.239	0.075	0.051	0.238	0.342	0.177
$RMSE_{(s)}$ (mm d^{-1})	0.233	0.394	0.456	0.229	0.019	0.045	0.161	0.332	0.168
$RMSE_{(u)}$ (mm d^{-1})	0.002	0.003	0.003	0.011	0.056	0.006	0.077	0.010	0.009
d	0.978	0.965	0.960	0.977	0.992	0.994	0.966	0.966	0.983
R^2	0.991	0.977	0.977	0.923	0.936	0.942	0.791	0.909	0.950
a (slope)	1.146	1.213	1.230	1.042	1.075	0.851	0.782	1.107	1.094
b (intercept)	0.100	0.073	0.077	0.358	-0.140	0.295	0.440	0.327	0.126

MAE, RMSE, $RMSE_{(u)}$ values preferably close to 0
$RMSE_{(s)}$ values preferably close to RMSE values
Index of agreement (d) is a "correction" measure for the R^2 coefficient

Table 4. Summary statistics of daily ET_o estimated methods tested against the FAO56-PM model – Kozane Station

Indices	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
MBE (mm d^{-1})	0.529	0.720	0.791	0.374	0.049	-0.289	0.519	0.702	0.057
MAE (mm d^{-1})	0.529	0.720	0.791	0.374	0.208	0.319	0.560	0.702	0.176
s_d^2	0.060	0.112	0.136	0.062	0.059	0.111	0.174	0.037	0.045
RMSE (mm d^{-1})	0.340	0.630	0.762	0.202	0.061	0.194	0.442	0.530	0.048
$RMSE_{(s)}$ (mm d^{-1})	0.338	0.627	0.758	0.176	0.015	0.185	0.283	0.514	0.024
$RMSE_{(u)}$ (mm d^{-1})	0.001	0.003	0.004	0.026	0.046	0.009	0.159	0.015	0.024
d	0.975	0.956	0.948	0.984	0.995	0.980	0.960	0.959	0.996
R^2	0.992	0.981	0.982	0.854	0.886	0.892	0.794	0.082	0.894
a (slope)	1.135	1.224	1.245	1.008	1.019	0.770	0.935	1.083	0.985
b (intercept)	0.178	0.137	0.153	0.359	0.006	0.316	0.688	0.494	0.096

MAE, RMSE, RMSE $_{(u)}$ values preferably close to 0
$RMSE_{(s)}$ values preferably close to RMSE values
Index of agreement (d) is a "correction" measure for the R^2 coefficient

Table 5. Krania Station – Cumulative Monthly ET_o (mm/month)

ET_o	FAO56-PM	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	15.7	20.4	22.1	22.3	23.4	8.8	20.7	24.6	29.2	16.9
Feb	23.7	30.0	31.8	32.1	30.7	12.9	27.1	26.4	36.9	28.2
Mar	45.6	56.6	59.7	60.2	54.7	33.9	47.1	42.5	63.8	54.7
Apr	71.4	86.8	91.2	92.1	83.9	66.1	68.9	61.9	92.0	84.7
May	102.7	121.3	126.5	127.8	122.6	103.9	96.2	82.5	120.0	122.6
Jun	128.7	150.4	157.5	159.4	146.1	131.9	117.5	104.5	148.7	148.9
Jul	143.9	167.8	176.0	178.5	163.6	150.5	131.2	123.8	166.7	163.6
Aug	126.0	146.8	152.8	155.5	147.2	135.6	117.9	119.0	147.3	142.9
Sep	83.1	98.2	101.7	103.8	101.7	95.5	83.6	88.6	101.2	94.8
Oct	45.6	55.2	57.0	58.5	59.9	56.2	50.5	62.5	61.5	51.3
Nov	22.6	28.3	29.7	30.7	32.7	26.7	28.1	41.0	36.2	23.3
Dec	13.8	17.9	18.9	19.7	22.4	11.7	19.6	28.4	27.2	13.7
Year	822.8	979.6	1025.0	1040.5	988.9	833.7	808.3	805.7	1030.7	945.6

Table 6. Krania Station – Differences of Mean Monthly ET_o values against the FAO-56 Method (mm/month)

ET_o[a]	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	4.7	6.4	6.5	7.7	-6.9	5.0	8.9	13.4	1.2
Feb	6.3	8.2	8.4	7.0	-10.8	3.5	2.7	13.2	4.5
Mar	11.0	14.1	14.6	9.0	-11.7	1.5	-3.1	18.1	9.1
Apr	15.4	19.8	20.7	12.5	-5.3	-2.5	-9.6	20.6	13.3
May	18.6	23.8	25.1	19.9	1.2	-6.5	-20.2	17.3	19.9
Jun	21.7	28.8	30.7	17.3	3.2	-11.2	-24.2	20.0	20.2
Jul	23.9	32.1	34.6	19.7	6.6	-12.7	-20.1	22.8	19.7
Aug	20.8	26.9	29.5	21.2	9.7	-8.0	-7.0	21.3	16.9
Sep	15.1	18.7	20.7	18.6	12.4	0.5	5.5	18.1	11.7
Oct	9.5	11.4	12.8	14.3	10.6	4.9	16.9	15.9	5.7
Nov	5.6	7.0	8.1	10.1	4.1	5.4	18.4	13.6	0.7
Dec	4.2	5.1	5.9	8.7	-2.1	5.8	14.6	13.4	-0.1
Year	156.8	202.2	217.6	166.1	10.9	-14.5	-17.1	207.9	122.8

[a] The negative sign shows the underestimation of the mean monthly ET_o

Table 7. Krania Station – Deviations of Mean Monthly ET_o values against the FAO-56 Method (%)

ET_o	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	29.7	40.7	41.6	49.2	-43.9	31.5	56.8	85.5	7.4
Feb	26.7	34.4	35.4	29.4	-45.6	14.6	11.4	55.9	19.2
Mar	24.1	30.9	32.0	19.8	-25.7	3.2	-6.8	39.7	19.9
Apr	21.5	27.8	29.0	17.5	-7.4	-3.5	-13.4	28.8	18.6
May	18.1	23.2	24.4	19.4	1.2	-6.4	-19.6	16.9	19.4
Jun	16.8	22.4	23.9	13.5	2.5	-8.7	-18.8	15.6	15.7
Jul	16.6	22.3	24.0	13.7	4.6	-8.8	-14.0	15.9	13.7
Aug	16.5	21.3	23.4	16.8	7.7	-6.4	-5.6	16.9	13.4
Sep	18.2	22.5	25.0	22.4	14.9	0.6	6.6	21.8	14.1
Oct	20.9	25.0	28.2	31.4	23.2	10.7	37.1	34.9	12.5
Nov	24.9	31.1	35.6	44.7	18.0	24.1	81.3	59.9	3.1
Dec	30.3	37.2	43.0	63.0	-15.2	42.1	106.1	97.5	-0.7
Year	19.1	24.6	26.5	20.2	1.3	-1.8	-2.1	25.3	14.9

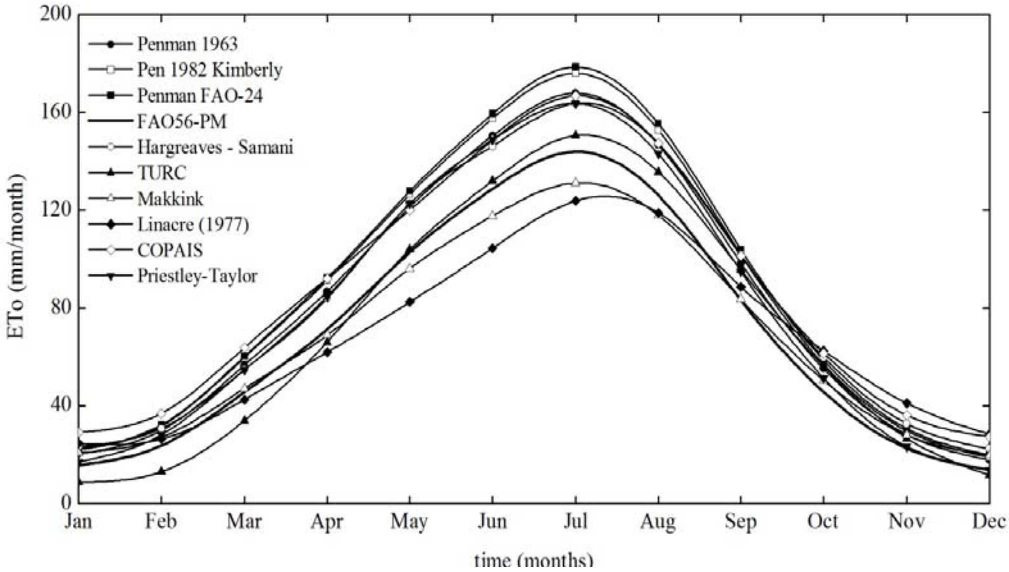

Figure 3. Krania Station – Cumulative Monthly ET_o (mm/month)

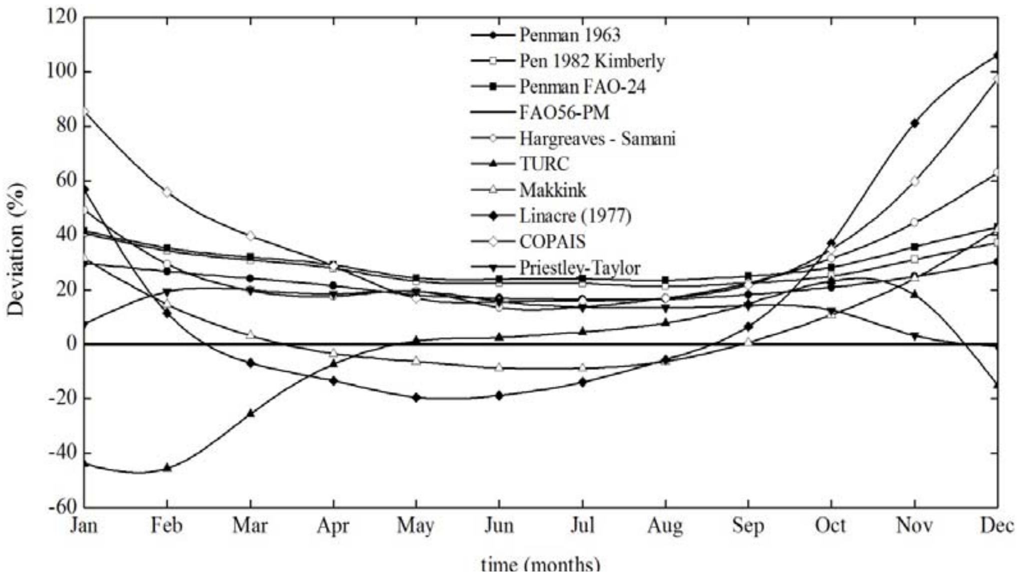

Figure 4. Krania Station – Deviations of Mean Monthly ET_o values against the FAO-56 Method (%)

Table 8. Kozane Station – Cumulative Monthly ET_o (mm/month)

ET_o	FAO56-PM	Penman (1963)	Penman K(imberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	20.5	27.6	31.7	32.0	23.0	13.3	21.0	37.7	36.4	15.6
Feb	31.2	40.3	44.9	45.3	33.5	21.3	29.2	44.1	48.7	28.4
Mar	54.7	68.3	73.5	74.4	61.5	47.8	50.1	64.6	77.5	56.4
Apr	80.9	98.0	103.8	105.2	94.5	79.6	72.1	83.1	104.0	87.9
May	115.3	136.1	142.1	144.1	138.7	118.4	101.7	110.8	137.3	128.9
Jun	146.6	171.4	180.6	183.5	168.5	149.7	124.6	146.3	171.4	157.1
Jul	166.8	194.7	206.7	210.8	181.9	171.6	138.5	180.0	195.5	170.7
Aug	144.2	170.1	179.1	183.4	160.0	153.3	123.8	172.2	173.6	147.2
Sep	94.1	113.8	119.6	123.2	108.0	104.3	85.2	125.8	117.9	94.4
Oct	54.0	67.2	70.9	73.5	64.6	64.0	52.6	86.0	72.9	51.5
Nov	25.7	33.7	35.9	37.7	33.4	31.4	28.5	52.5	41.9	22.1
Dec	18.1	24.2	26.7	28.3	21.4	15.2	19.1	38.6	31.8	12.4
Year	952.0	1145.6	1215.5	1241.4	1088.9	969.9	846.4	1141.8	1209.0	972.7

Table 9. Kozane Station – Differences of Mean Monthly ET_o values against the FAO-56 Method (mm/month)

ET_o	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	7.1	11.2	11.5	2.5	-7.2	0.5	17.2	15.9	-4.9
Feb	9.1	13.7	14.2	2.3	-9.9	-1.9	13.0	17.5	-2.8
Mar	13.6	18.9	19.8	6.8	-6.8	-4.6	10.0	22.9	1.7
Apr	17.1	22.9	24.3	13.6	-1.3	-8.8	2.2	23.1	7.0
May	20.8	26.8	28.8	23.4	3.1	-13.6	-4.5	22.0	13.6
Jun	24.8	33.9	36.9	21.9	3.0	-22.1	-0.4	24.8	10.5
Jul	27.9	40.0	44.0	15.1	4.8	-28.3	13.2	28.8	3.9
Aug	25.9	34.9	39.2	15.8	9.1	-20.3	28.0	29.4	3.0
Sep	19.8	25.6	29.1	14.0	10.2	-8.9	31.8	23.8	0.3
Oct	13.1	16.8	19.4	10.5	10.0	-1.4	32.0	18.8	-2.5
Nov	8.1	10.3	12.0	7.7	5.7	2.8	26.8	16.2	-3.5
Dec	6.1	8.7	10.2	3.3	-2.8	1.0	20.6	13.7	-5.7
Year	193.6	263.6	289.5	136.9	17.9	105.6	189.8	257.0	20.7

[a] The negative sign shows the underestimation of the mean monthly ET_o

Table 10. Kozane Station – Deviations of Mean Monthly ET_o values against the FAO-56 Method (%)

ET_o	Penman 1963	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	34.7	54.7	56.0	12.1	-35.1	2.3	83.9	77.5	-23.7
Feb	29.2	44.1	45.6	74.0	-31.8	-6.1	41.6	56.2	-9.0
Mar	24.9	34.5	36.2	12.5	-12.5	-8.3	18.3	41.9	3.2
Apr	21.2	28.3	30.0	16.8	-1.6	-10.9	2.7	28.6	8.7
May	18.1	23.2	25.0	20.3	2.7	-11.8	-3.9	19.1	11.8
Jun	16.9	23.1	25.2	14.9	2.1	-15.1	-0.3	16.9	7.2
Jul	16.7	24.0	26.4	9.1	2.9	-17.0	7.9	17.2	2.4
Aug	18.0	24.2	27.2	11.0	6.3	-14.1	19.4	20.4	2.1
Sep	21.0	27.2	31.0	14.8	10.8	-9.5	33.8	25.3	0.3
Oct	24.3	31.2	36.0	19.5	18.5	-2.6	59.2	34.9	-4.7
Nov	31.4	40.0	46.7	30.0	22.2	11.0	104.5	63.1	-13.8
Dec	34.0	48.0	56.3	18.2	-15.7	5.7	113.8	75.9	-31.4
Year	20.3	27.7	30.4	14.4	1.9	-11.1	19.9	27.0	2.2

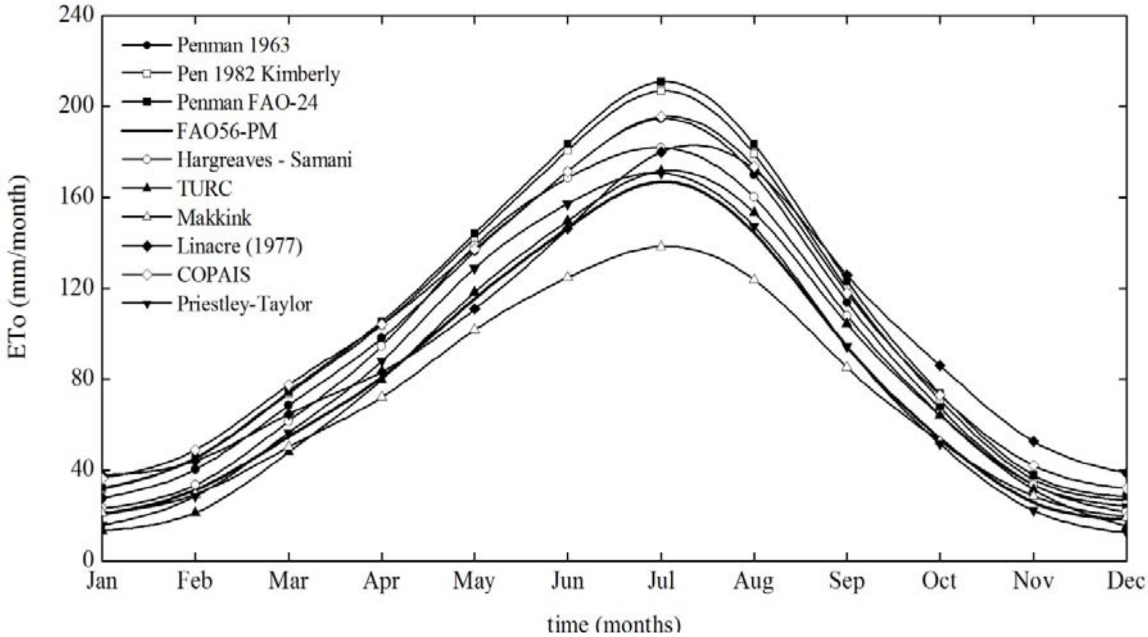

Figure 5. Kozane Station – Cumulative Monthly ET_o (mm/month)

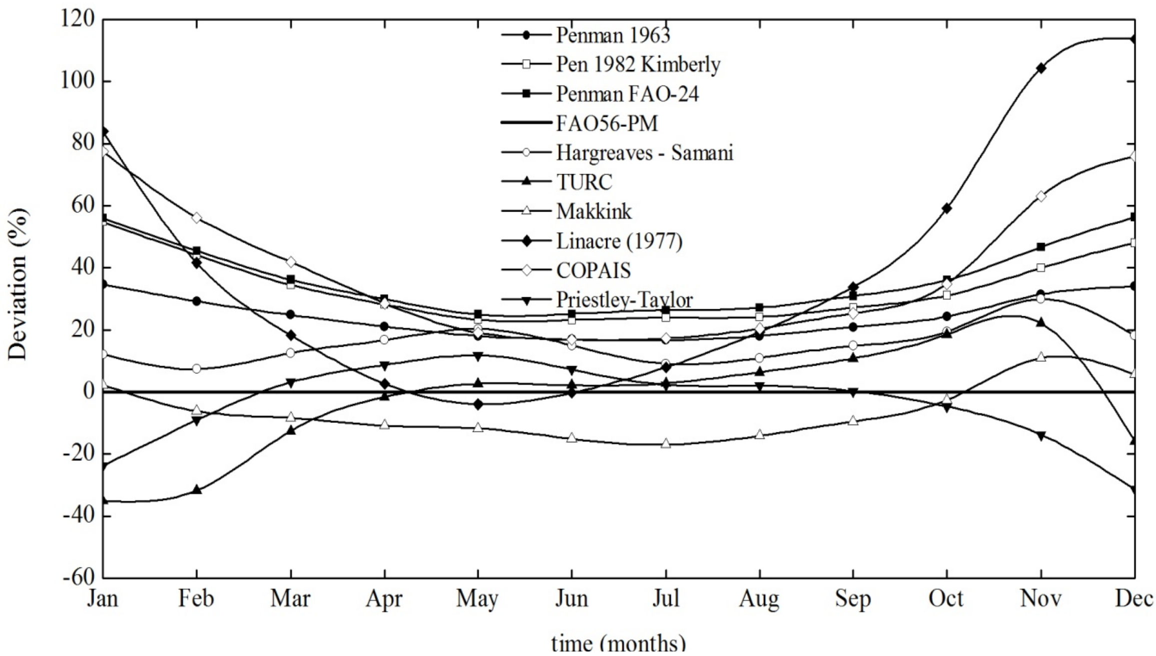

Figure 6. Kozane Station – Deviations of Mean Monthly ET_o values against the FAO-56 Method (%)

Based on Tables 8, 9, 10 and the Figures 5, 6, at Kozane station the Penman 1963, Penman 1982 Kimberly, Penman FAO24, Hargreaves-Samani and Copais methods overestimate ET_o throughout the whole year while the other methods don't show a particular pattern. Additionaly, all of the methods compared perform better during the winter season (October-February) but show larger deviations in absolute values of ET_o during the summer season (March-September).

Considering the yearly accumulated values of ET_o deriving from the summed average monthly values of ET_o, on a yearly basis all other methods apart from the Makkink method overestimate ET_o. Additionally, the Turc and Priestley-Taylor methods have the smallest deviations in comparison to the FAO56-PM estimated ET_o values, while the Penman FAO24, Copais and Penman 1963 methods have the largest deviations as it is depicted in Tables 8, 9, 10.

In order to cross-check seasonality deviations of the ET_o between the nine empirical methods and the FAO56-PM method estimates, mean monthly RMSE (monthly average of per day RMSE) was divided by the mean daily ET_o of the FAO56-PM method, per month for both stations (Tables 11, 12). All methods in both stations perform equally (Table 11, 12; Figure 7, 8), with the lower RMSE/ET_o appearing during the winter period and the higher during the summer period.

Table 11. Krania Station – Mean Monthly RMSE/mean daily ETo (FAO56-PM) per month

ET_o	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	0.34	0.49	0.50	0.64	0.70	0.60	0.89	1.08	0.33
Feb	0.28	0.39	0.39	0.38	0.57	0.32	0.42	0.67	0.27
Mar	0.28	0.38	0.39	0.29	0.37	0.19	0.27	0.51	0.26
Apr	0.23	0.32	0.33	0.26	0.17	0.13	0.24	0.37	0.22
May	0.19	0.26	0.27	0.26	0.10	0.11	0.27	0.24	0.22
Jun	0.17	0.24	0.25	0.21	0.09	0.12	0.23	0.20	0.19
Jul	0.17	0.24	0.26	0.20	0.12	0.13	0.22	0.21	0.18
Aug	0.17	0.23	0.25	0.22	0.13	0.12	0.18	0.22	0.18
Sep	0.19	0.25	0.27	0.27	0.19	0.13	0.22	0.27	0.19
Oct	0.23	0.29	0.32	0.40	0.33	0.25	0.48	0.47	0.23
Nov	0.27	0.36	0.41	0.59	0.51	0.48	0.93	0.79	0.29
Dec	0.34	0.44	0.51	0.80	0.69	0.73	1.37	1.24	0.35

Table 12. Kozane Station – Mean Monthly RMSE/mean daily ETo (FAO56-PM) per month

ET_o	Penman (1963)	Penman Kimberly (1982)	Penman FAO24	Hargreaves-Samani	Turc	Makkink	Linacre (1977)	Copais	Priestley-Taylor
Jan	0.39	0.68	0.69	0.64	0.80	0.57	1.13	1.06	0.56
Feb	0.30	0.50	0.50	0.40	0.53	0.33	0.56	0.69	0.32
Mar	0.27	0.40	0.42	0.33	0.35	0.24	0.35	0.56	0.22
Apr	0.22	0.32	0.33	0.29	0.18	0.18	0.21	0.37	0.18
May	0.19	0.26	0.27	0.28	0.13	0.16	0.18	0.26	0.19
Jun	0.17	0.24	0.26	0.24	0.13	0.19	0.18	0.23	0.17
Jul	0.17	0.25	0.28	0.23	0.16	0.22	0.23	0.24	0.17
Aug	0.19	0.26	0.29	0.24	0.19	0.21	0.29	0.28	0.18
Sep	0.22	0.29	0.33	0.31	0.25	0.22	0.42	0.35	0.22
Oct	0.26	0.35	0.40	0.42	0.39	0.31	0.69	0.51	0.30
Nov	0.34	0.47	0.54	0.63	0.65	0.51	1.18	0.86	0.45
Dec	0.39	0.59	0.68	0.72	0.78	0.64	1.42	1.08	0.67

3.2 Discussion

In regard to regression equations, the Priestley-Taylor method had the best correlation to the FAO56-PM method at Krania station, while at Kozane station the Turc method gave the best predicted values.

At Krania station, all but two methods overestimated ET_o from a 4.2% (Hargreaves-Samani) to a 23% (Penman FAO24) percentage variance apart from Makkink and Linacre (1977) which underestimated ET_o (15% and 22% respectively). At Kozane station, most of the methods (Penman 1963, Kimberly Penman 1982, Penman FAO24, Hargreaves-Samani, Copais) overestimated ET_o (13.5%, 22.4%, 24.5%, 0.8%, and 8.3% respectively) while fewer (Makkink, Linacre (1977), Priestley-Taylor) underestimated ET_o (23%, 6.5% and 1.5% respectively).

By comparing the monthly accumulated values of ET_o, it may be concluded that as far as seasonality is concerned, not only on a daily but on a monthly basis as well, all of the methods compared perform better during the winter season (October-February) with smaller deviations in absolute values of ET_o and lower RMSE, but show poorer performance during the summer season (March-September) with the opposite characteristics. In addition, all the methods compared, during the summer season perform equally while during the winter season are showing deviations, in both stations.

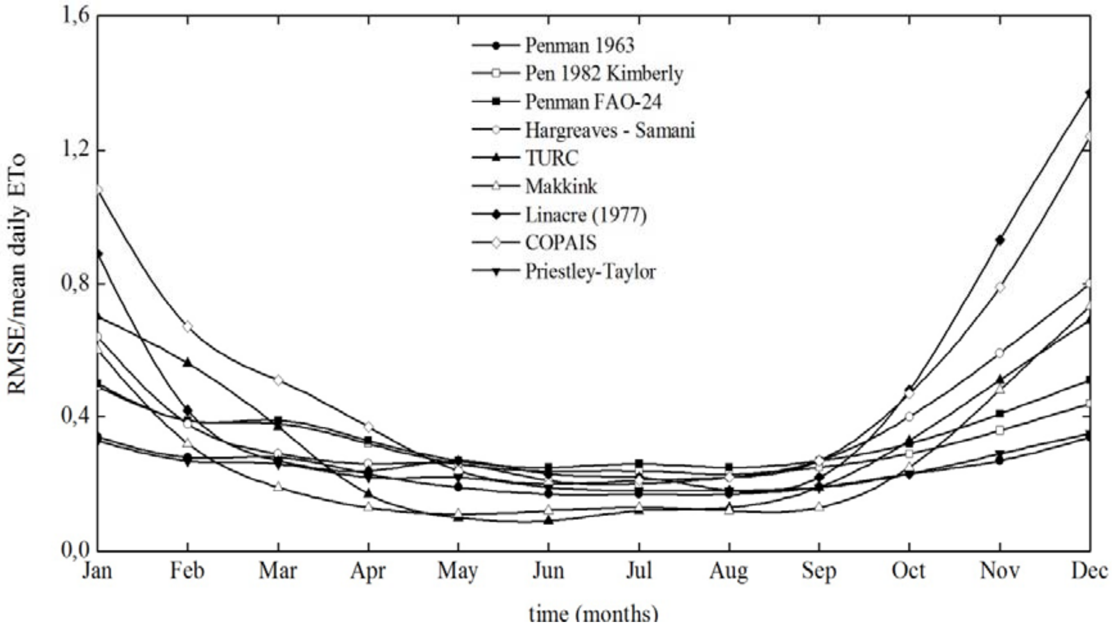

Figure 7. Kranja Station – Mean Monthly RMSE/mean daily ET_o (FAO56-PM) per month

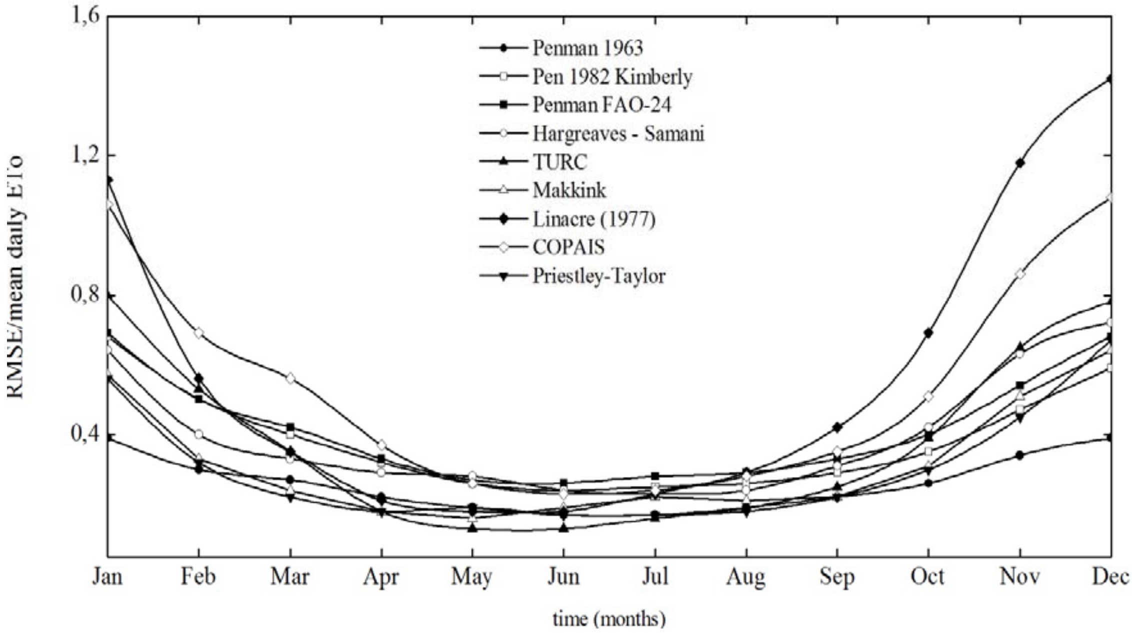

Figure 8. Kozane Station – Mean Monthly RMSE/mean daily ET_o (FAO56-PM) per month

4. CONCLUSIONS

The main objective of this study was an effort to provide guidance on the selection of the most appropriate ET_o equation under humid conditions, prevalent in the study area, using daily meteorological data from the stations of Krania and Kozane at Western Macedonia in Northern Greece for a time-period of 34 and 48 years respectively. Nine ET_o methods were evaluated with the Food and Agriculture Organization Penman-Monteith FAO56-PM equation to be used as a basis for the comparison with the other methods. These values were compared using linear regression and statistical indices of quantitative approaches to model performance evaluation.

All in all, it can be emphasized that the use of the FAO56-PM as a standard method remains the most appropriate method for estimating if the accuracy of the data collected is the main consideration. Yet, that factor alone should not be the sole selection criterion, since some of the data can be estimated with acceptable accuracy from other meteorological variables (e.g. solar radiation during bright sunshine hours). But in many cases, especially in areas where accurate data collection is difficult to be collected, the application of empirical equations could be utilized for accurate and consistent estimates of daily ET_o relative to the FAO56-PM method especially in humid conditions. However, the difference in the ET_o estimates using these methods has provided a significant range of uncertainty. It is therefore important to compare and validate these methods considering the region climate, land coverage and topographical condition.

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