IJST, Transactions of Civil Engineering, Vol. 38, No. C2, pp 421-437
Printed in The Islamic Republic of Iran, 2014
© Shiraz University

EVALUATION OF SEVERAL REFERENCE EVAPOTRANSPIRATION METHODS: A COMPARITIVE STUDY OF GREENHOUSE AND OUTDOOR CONDITIONS*

H. MOAZED[1] , A. A. GHAEMI[2**] AND M. R. RAFIEE[3]
[1, 3]Dept. of Irrigation, College of Water Sciences, Shahid Chamran University, Ahwaz, I. R. of Iran
[2]Dept. Water Eng., College of Agric., Shiraz University, Shiraz, I. R. of Iran
Email: ghaemi@shirazu.ac.ir

Abstract– Precise estimates of reference evapotranspiration (ET_0) are necessary for the application of irrigation design and scheduling. Numerous empirical methods for predicting ET_0 are available, but their accuracy under different environmental conditions is uncertain. Greater uncertainty exists under greenhouse conditions because these methods were designed to apply to field situations, and greenhouses have an effect on the temperature, humidity and wind, etc. In this study, the results of 13 different common daily ET_0 estimation methods, namely FAO56 Penman – Monteith, Hargreaves-Samanı, FAO-24 Blaney-Criddle, FAO-24 Radiation, Priestley-Taylor, Makkink, Turc, Linacre, Jensen-Haise, Copais, Pan Evaporation, Rn-radiation and Rs-radiation are compared with lysimetric measurements in an area of Fars (Badjgah) in a plastic greenhouse to provide helpful information for selecting the appropriate ET_0 equation to use. In addition to daily values, smoothed daily and mean 10-day ET_0s were estimated to study the effect of daily weather data fluctuations on the precision of predictions. Performances of ET_0 methods are evaluated by four statistical criteria along with regression indices. The results indicate that FAO Penman-Monteith and Linacre are the most and the least appropriate methods for estimating daily ET_0 in greenhouse conditions, respectively. For outdoor conditions the best and worst results were obtained from FAO24- Radiation and Copias methods, respectively. Smoothing weather data, gave better regression fits for FAO Penman-Monteith and FAO24-Radiation methods for both greenhouse and field conditions than those for daily weather data. Better predictions were obtained for field than greenhouse conditions. The total ET_0 values in greenhouse were about 0.85 of those measured in outdoor lysimeters.

Keywords– Estimation methods, microlysimeter, performance evaluation, smoothed data

1. INTRODUCTION

The expansion of greenhouse cultivation all over the world has led to the need for accurate crop evapotranspiration (ET_C) estimations to optimize yields and crop qualities, while reducing water consumption and minimizing environmental impacts.

Values of evapotranspiration are measured by lysimeters [1] but are rarely available. Therefore actual crop evapotranspiration (ET_C) is usually calculated from the estimated reference evapotranspiration (ET_0) using the crop factor method, which consists of multiplying ET_0 with crop specific coefficients (K_C) (i.e., $ET_C = ET_0 . K_C$). ET_0 is defined as the rate of evapotranspiration from an extensive surface of green-grass cover of uniform height, actively growing, completely shading the ground and not short of water [2]. As water is abundantly available at the reference evapotranspiring surface, soil factors do not affect ET_0.As mentioned above, lysimetric ET_0 data is not readily attainable everywhere; therefore, different empirical methods are usually applied in different regions. Noshadi and Sepaskhah compared the evaluation of three

*Received by the editors August 29, 2013; Accepted January 13, 2014.
**Corresponding author

geostatistical interpolation methods including ordinary kriging, residual kriging and cokriging for the interpolation of long-term monthly and yearly reference crop evapotranspiration [3].

Studies have shown that reference ET computed using the Penman-Monteith (PM) equation yields estimates close to observed reference ET values ([4-8]). The FAO has recommended the use of the PM method to compute reference ET from a grass surface and has standardized a form of the PM method (FAO56-PM) as a grass reference equation [9]. Agro meteorological stations, however, are not always sufficiently equipped to collect the necessary data to utilize this procedure [10]. Therefore, other methods are normally employed to determine ET_0, the class A pan being one of the most used in irrigation projects [11]. Among the empirical methods, the temperature based method of Hargreaves and Samani [12] has provided good results for various regions [1, 9]. The accuracy of their method was confirmed by lysimeteric ET_0 measurements in the Kooshkak study area by Sepaskhah and Razzaghi [13].

Since the 1940s about 50 equations have been developed by researchers to estimate ET_0 [14-26], resulting in confusion about which equation to use for the most accurate ET_0 estimates [27].

On the other hand, crop evapotranspiration (ET_C) in a greenhouse is still estimated by outdoor calibrated ET_0 equations, while the applicability of each equation in greenhouse conditions is a matter of uncertainty. This is because in a greenhouse environment, protected crop ET is influenced by the energy balance of the whole system in a greenhouse and depends strongly on the greenhouse characteristics and on the climate control equipment. Different types of greenhouses, from high technology such as closed and controlled greenhouses to traditional plastic rain sheltergreenhouses, will require a reliable method to determine ET.

In this study, pairwise comparisons were made between 13 different common daily ET_0 estimation methods and ET_0 values measured by a microlysimeter in a plastic greenhouse and outdoor conditions to provide helpful information for selecting the appropriate ET_0 equation for plastic greenhouses and climates similar to Badjgah (Fars province, Iran).

2. MATERIALS AND METHOD

a) Setup

The study was conducted in an unheated plastic greenhouse (with the dimensions: height 4.0m, length 12.0 m, width 10 m and 120m^2 area) and the adjacent field with an area of 200m^2 located in Badjgah (29°36'N, 52°32'E), College of Agriculture, Shiraz University, Shiraz, Iran. An automatic weather station was installed in the central part of the greenhouse, to measure net radiation (Rn), air temperature (T_a) and relative humidity (RH). Pan evaporation was recorded with a 35cm pot installed 70 cm above the soil surface. The same system in a nearby college weather station was utilized for monitoring the outdoor data. A class A pan was used in order to determine the outdoor evaporation during the growing season.

50m^2 of the greenhouse area and 200m^2 of the experimental field were in grass cultivation. Luliom cultivar of grass was planted as a reference crop to measure ET_0. The plastic pots with 35 cm diameters and 60 cm heights were filled with the same ground soil from the same depth and were placed in the ground in the center of each block as microlysimeters. Some physical and chemical soil properties are presented in Table 1. The height of the grass was kept at 12cm and irrigated frequently up to field capacity throughout the experiment. The amount of irrigated water in each microlysimeter was calculated by the volumetric method. Daily ET_0 in greenhouse and outdoor microlysimeters was determined by weighting the pots every second day to get W_n and W_{n+1} in grams and using the equation,

$$ET_0 = \frac{10 \times \left[\dfrac{(W_n - W_{n+1}) + (I - D_p)}{\rho_w} \right]}{A} \tag{1}$$

where, ET_0 is the daily reference evapotranspiration (mm), I and D_p are the amounts of applied and drainage water (g), W_n and W_{n+1} are pot masses in two consecutive days (g), A is the top area of the cylindrical pots (cm^2) and) and ρ_w is the density of water (g/cm^2). Daily ET_0 values were measured from May 19th to September 5th, 2012.

Table 1. Some physical and chemical of the soil

Field Capacity (%)	Wilting Point (%)	Bulk Density (gr cm^{-3})	pH	ECe (dSm^{-1})	N_{total} (%)	K ($mgkg^{-1}_{soil}$)	P ($mgkg^{-1}_{soil}$)	Organic matter (%)
30.5	11	1.03	7.72	0.55	0.2	600	12.5	1.65

b) Methods for estimating ET_0

Following is the description of 13 different common ET_0 estimation methods, evaluated in this study. Each equation gives daily ET_0 in mm/day. A list of all parameters used in the methods, along with their definition and units are presented Table 2.

Table 2. Parameters used in the studied ET_0 methods

Parameter	Definition	Unit	Methods using the parameter
R_n	net radiation at the crop surface	MJ/(m^2day)	FPM, P/T, R_n-rad.
G	soil heat flux density	MJ/(m^2day)	FPM, P/T
T_{mean}	mean daily air temperature	°C	FPM, B/C, FAO24 Rad., Turc, Linacre, J/H, Copais, R_n-rad., R_s-rad.
RH_{mean}	mean relative humidity	%	FAO24 Rad., Turc, Copais, Pan
u_2	wind speed at a height of 2 m	m/s	FPM, B/C, FAO24 Rad., Pan
e_s	saturation vapor pressure	kPa	FPM
e_a	actual vapour pressure	kPa	FPM
Δ	the slope of the vapour pressure curve	kPa/°C	FPM, FAO24 Rad., P/T, Makkink
γ	the psychrometric constant	kPa/°C	FPM, FAO24 Rad., P/T, Makkink, Turc
R_a	vertical component of the extraterrestrial solar radiation	mm/day	H/S
T_{max}	daily maximum temperature	°C	H/S, J/H
T_{min}	daily minimum temperature	°C	H/S, J/H
p	the mean percentage of annual daytime hours (defined as the percentage of the total annual daylight hours that occur in the timeperiod being examined, such as daily or monthly)	%	B/C
RH_{min}	minimum relative humidity	%	B/C
n/N	the ratio of possibleto actual sunshine hours	-	B/C
R_s	solar radiation	MJ/(m^2day)	FAO24 Rad., Makkink, Turc, J/H, Copais, R_s-rad.
λ	latent heat of vaporization	MJ/kg	P/T,Makkink, Turc
Td	mean dew point temperature	°C	Linacre
L	the latitude of the station	degrees	Linacre
T_m	temperature adjustment with the station elevation	°C	Linacre
h	the station elevation	m	Linacre, J/H
R	the mean daily range of temperature	°C	Linacre
R_{ann}	the difference between the mean temperatures of the warmest and coldest month	°C	Linacre
$e(T_{max})$	saturated vapor pressure in the maximum temperature	kPa	J/H
$e(T_{min})$	saturated vapor pressure in the minimum temperature	kPa	J/H
K_P	pan coefficient	-	Pan
E_{pan}	pan evaporation	mm/day	Pan
FET	the fetch distance of the green crop	m	Pan

***-FAO56 Penman -Monteith method* (FPM)** *[9]*

The FAO56-PM equation for predicting ET_0 on a daily basis has the form:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

The soil heat flux is ignored (G=0) in daily applications.

***-Hargreaves-Samani method* (H/S)** *[12]*

The original Hargreaves equation can be written as:

$$ET_0 = 0.0023(T_{max} - T_{min})^{0.5}(T_{mean} + 17.8)R_a \quad (3)$$

***-FAO24 Blaney-Criddle method* (B/C)** *[2]*

The FAO-24 Blaney-Criddle method is based on the general linear relationship found between measured reference evapotranspiration and the Blaney-Criddle factor from many worldwide sites in various classifications based on ranges of daytime wind speed, minimum RH and sunshine expressed as n/N. The method is presented as follows:

$$ET_0 = a + bf \tag{4}$$

$$f = p(0.46T_{mean} + 8.13) \tag{5}$$

$$a = 0.0043RH_{\min} - \frac{n}{N} - 1.41 \tag{6}$$

$$\begin{aligned} b = {} & 0.908 - 0.00483RH_{\min} + 0.7949\frac{n}{N} + 0.768[\ln(U_2+1)]^2 - 0.0038RH_{\min}\frac{n}{N} \\ & - 0.000443RH_{\min}U_2 + 0.281\left[\ln\left(\frac{n}{N}+1\right)\right] - 0.00975[\ln(U_2+1)][\ln(RH_{\min}+1)]^2\left[\ln\left(\frac{n}{N}+1\right)\right] \end{aligned} \tag{7}$$

***-FAO24 Radiation method* (FAO24-Rad.)** *[1]*

The FAO-24 Radiation equation, as defined by Jensen et al. (1990) is,

$$ET_0 = A + B\left(\frac{\Delta}{\Delta+\gamma}R_S\right) \tag{8}$$

Where A is -0.3 (mm/day); B is an adjustment factor that varies with the mean relative humidity and daytime wind speed calculated by Eq. (9).

$$B = 1.066 - 0.13\times10^{-2}RH_{mean} + 0.045U_2 - 0.2\times10^{-3}RH_{mean}U_2 - 0.315\times10^{-4}RH_{mean} - 0.11\times10^{-2}U_2^{\,2} \tag{9}$$

***-Priestley-Taylor method* (P/T)**

Priestley & Taylor [28] replaced the aerodynamic terms with a constant value of 1.26. The Priestley-Taylor method needs only long-wave radiation and temperature to estimate ET.The Priestley-Taylor equation is given below:

$$ET_0 = 1.26\frac{\Delta}{\Delta+\gamma}(R_n - G)\frac{1}{\lambda} \tag{10}$$

-Makkink method

Makkink [29] proposed a simple method for ET_0 estimation by using only temperature and radiation parameters:

$$ET_0 = 0.61\frac{\Delta}{\Delta+\gamma}\frac{R_S}{\lambda} - 0.12 \tag{11}$$

-Turc method

The Turc [30] method was a simplification of an older Equation [1]. Turc has been used to some extent in the United States [31]. As defined for operational use by Allen [32]:

$$ET_0 = a_T\,0.013\frac{T_{mean}}{T_{mean}+15}\frac{23.8856R_S + 50}{\lambda} \tag{12}$$

The coefficient a_T is a humidity-based value. If the mean daily relative humidity (RH_{mean}) is greater than or equal to 50 percent, then a_T = 1.0. If the mean daily relative humidity is less than 50 percent, then a_T has the value of:

$$a_T = 1 + \frac{50 - RH_{mean}}{70} \tag{13}$$

-Linacre method

The initial equation derived by Linacre [33] for grass-reference evapotranspiration is:

$$ET_0 = \frac{\left(\frac{500 T_m}{100 - L}\right) + 15(T_{mean} - T_d)}{(80 - T_{mean})} \tag{14}$$

$$T_m = T_{mean} + 0.006h \tag{15}$$

$$(T_{mean} - T_d) = 0.0023h + 0.37T_{mean} + 0.53R + 0.35R_{ann} - 10.9 \tag{16}$$

***-Jensen-Haise method* (J/H)**

Under situations of limited data, Jensen-Haise method is used in computing reference evapotranspiration as reported by James, [34] and is given as:

$$ET_0 = C_T (T_{mean} - T_X) R_S \tag{17}$$

$$C_T = \frac{1}{\left[\left(45 - \frac{h}{137}\right) + \left(\frac{365}{e(T_{\max}) - e(T_{\min})}\right)\right]} \tag{18}$$

$$T_X = -2.5 - 0.14\left(e(T_{\max}) - e(T_{\min})\right) - \frac{h}{500} \tag{19}$$

-Copais method

The Copais equation was derived by surface bilinear polynomial regression for Central Greek, using three meteorological attributes (R_s, RH_{mean}, T_{mean}) as shown below [35]:

$$ET_0 = m_1 + m_2C_2 + m_3C_1 + m_4C_1C_2 \tag{20}$$

$$C_1 = 0.6416 - 0.0078RH_{mean} + 0.372R_s - 0.00264R_sRH_{mean} \tag{21}$$

$$C_2 = -0.0033 + 0.00812.T_{mean} + 0.101.R_s + 0.00584.R_s.T_{mean} \tag{22}$$

Where, m_1, m_2, m_3 and m_4 are 0.057, 0.277, 0.643 and 0.0124 respectively.

***-Pan Evaporation method* (Pan)**

The basic form of the 24PAN method, as described by Allen et al. [9] is:

$$ET_0 = K_P E_{Pan} \tag{23}$$

$$K_P = 0.108 - 0.0286U_2 + 0.0422\ln(FET) + 0.1434\ln(RH_{mean}) - 0.00063\left[\ln(FET)\right]^2 \ln(RH_{mean}) \tag{24}$$

-Irmak method

Rs-based method and Rn-based method presented by Irmak et al. [36] is:

R_n-radiation (R_n-rad.): $$ET_0 = 0.489 + 0.289R_n + 0.023T_{mean} \tag{25}$$

R_s-radiation (R_s-rad.): $$ET_0 = -0.611 + 0.149 R_S + 0.79 T_{mean} \quad (26)$$

c) Smoothing data and Statistical Analysis

Daily weather data fluctuate sharply on consecutive days and show noise [37] which should be smoothed for proper application. Such data are smoothed by Hargreaves and Allen [38] weighted average method using five consecutive data with specific weights (i.e. 1, 2, 3, 2, and 1) as shown below:

$$S_j = \frac{x_{j-2} + 2x_{j-1} + 3x_j + 2x_{j+1} + x_{j+2}}{9} \quad (27)$$

j = 3 to n-2

where n is the total number of data, S_j is the value of smoothed data on j^{th} day, x's are the values of original data, and j is the day number.

ET_0 values were estimated by daily and smoothed data for the different methods and the results were compared with the original and smoothed data from the lysimeterics. The mean 10-day weather data were also used to calculate ET_0 and were then compared with the mean 10-day measured ET_0 by the lysimeter. Performances of ET_0 methods were evaluated by various parameters including: Mean absolute error (MAE), Index of Agreement (d) [39], variance of the distribution of differences (s_d^2), normalized root mean square error (NRMSE) [40].Computational forms of all the indices are given below:

$$MAE = \frac{\sum_{i=1}^{n} |O_i - P_i|}{n} \quad (28)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left[\left(P_i - O_{avg}\right) + \left(O_i - O_{avg}\right) \right]^2} \right] \quad (29)$$

$$s_d^{\ 2} = \frac{\sum_{i=1}^{n} \left(P_i - O_i - \frac{\sum_{i=1}^{n} (P_i - O_i)}{n}\right)^2}{n-1} \quad (30)$$

$$NRSME = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^{n} (P_i - O_i)^2}}{O_{avg}} \quad (31)$$

In which, P_i, O_i and O_{avg} are ET_0 predicted, observed and average of observed values respectively.

3. RESULTS AND DISCUSSION

a) Climatic data

The meteorological data of the outdoor and greenhouse stations covering the period from May 19 to September 5, 2012 were analyzed for purposes of calculating evapotranspiration using the different methods. Figure 1 shows daily temperature (on left ordinate of top graph), relative humidity (on right ordinate of top graph) and net radiation data for greenhouse and outdoor conditions (on left ordinate of bottom graph) and evapotranspiration (on right ordinate of bottom graph), respectively.

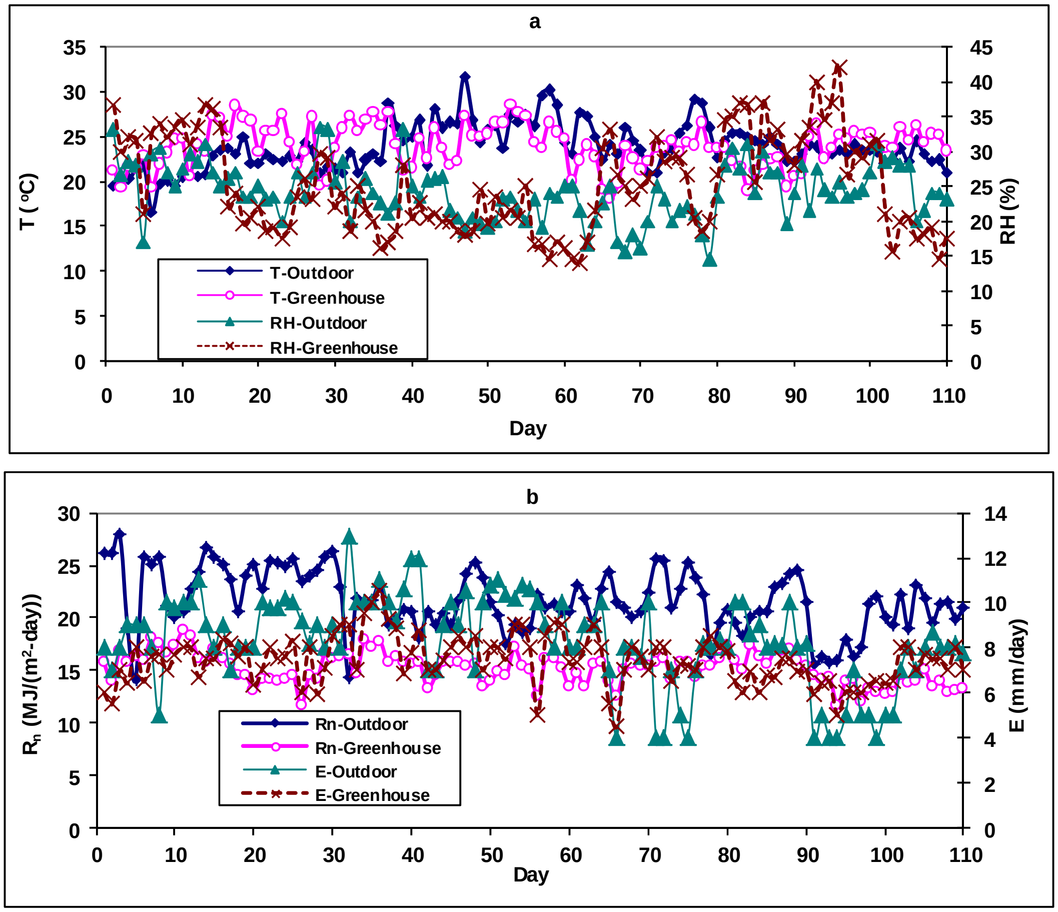


Fig. 1. Daily variations of a) temperature (T) and relative humidity (RH) and b) net radiation (Rn) and pan evaporation (E)

b) Comparison of the performance of different methods

Linear regressions were used for all comparisons in order to determine the correlation of estimated daily, smoothed daily and 10-day average ET_0 values with the measured lysimeteric values, as follows:

$$ET_{0\text{-PR}} = A + B(ET_{0\text{-Act.}}) \tag{32}$$

Where $ET_{0\text{-PR}}$and $ET_{0\text{-Act}}$ represent the estimated and measured values of ET_0, respectively. A and B are the regression coefficients. The best prediction method according to linear regression is the one with the highest coefficient of determination (R^2), B value closest to zero and A value closest to unity.Despite being widely used to assess the "goodnessoffit" of evapotranspiration equations, R^2 is oversensitive to extreme values (outliers) and is insensitive to additive and proportional differences between estimated and measured values. Considering these limitations, R^2 values might misjudge the best method, when used alone. Therefore, method performance was evaluated by using both regression and difference indicesMAE, s_d^2, NRMSE and d for estimated and measured values.

***-Daily** ET_0*

The daily ET_0 values estimated by different methods were compared with those of measured ET_0 for greenhouse and outdoor conditions. The trends of the calculated ET_0 were in were in agreement with the applied methods; however, none of the methods gave identical results. Tables 3 and 4 indicate a summary of comparisons between measured and estimated values of ET_0 in greenhouse and outdoor conditions, respectively. In these tables, different methods are ranked according to their appropriateness. The results indicate that in greenhouse conditions, FAO Penman-Monteith and Linacre methods are the most and the least appropriate methods, respectively (Table 3). The slope of the linear regression equation in the FAO Penman-Monteith method is 0.94 which is very close to 1.0. The R^2 is 0.91, which is high and near 1. The value of the index of agreement (d) for the FAO Penman-Monteith method was average (0.576) while MAE, s_d^2 andNRMSE are low (0.8, 0.02 and 0.007, respectively). However, the method showed a 12 percent underestimation in ET_0. Next to that equation, Priestley-Taylor showed the closest results to the lysimeteric ET_0 with low MAE, s_d^2 and NRMSE values of 0.548, 0.065 and 0.005, respectively and with near one values of d = 0.75, A =1.13 and R^2 = 0.84.

Table 3. Ranking and statistical analysis of different daily ET_0 method estimations vs. measured lysimeter values in greenhouse

No.	ET_0 Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FPM	0.807	0.022	0.007	0.576	0.94	-0.42	0.911	110
2	P/T	0.548	0.065	0.005	0.751	1.13	-1.38	0.836	110
3	FAO24-Rad.	1.423	0.059	0.013	0.357	1.19	0.17	0.874	110
4	B/C	0.753	0.134	0.007	0.601	1.05	0.43	0.668	110
5	H/S	0.580	0.147	0.006	0.664	0.89	0.39	0.561	110
6	Copias	0.841	0.080	0.008	0.572	1.08	0.29	0.785	110
7	Rn-rad.	0.932	0.055	0.009	0.445	0.76	0.65	0.778	110
8	Pan	1.923	0.042	0.018	0.199	0.76	0.39	0.814	110
9	Turc	1.338	0.049	0.012	0.273	0.71	0.58	0.811	110
10	Makkink	2.001	0.047	0.018	0.138	0.67	0.21	0.850	110
11	J/H	0.778	0.719	0.009	0.685	2.18	-7.33	0.757	110
12	Rs-rad.	1.581	0.058	0.015	0.185	0.60	1.09	0.829	110
13	Linacre	2.032	0.275	0.019	0.231	1.36	-0.36	0.651	110

Table 4. Ranking and statistical analysis of different daily ET_0 method estimations vs. measured lysimeter values in outdoor conditions

No.	ET_0 Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FAO24-Rad.	0.593	0.011	0.005	0.806	1.05	0.22	0.976	110
2	FPM	0.235	0.070	0.003	0.943	1.21	-1.46	0.908	110
3	H/S	0.542	0.031	0.005	0.767	0.74	1.45	0.966	110
4	B/C	0.578	0.144	0.006	0.763	1.01	-0.61	0.719	110
5	Rn-rad.	0.555	0.088	0.006	0.824	1.27	-1.55	0.905	110
6	J/H	0.729	0.049	0.007	0.733	1.11	1.56	0.908	110
7	Turc	1.927	0.028	0.018	0.259	0.91	-1.23	0.923	110
8	Pan	0.951	0.106	0.009	0.614	1.12	-1.85	0.817	110
9	Linacre	0.583	0.138	0.006	0.808	1.21	-1.14	0.815	110
10	Makkink	2.514	0.039	0.023	0.166	0.88	-1.59	0.894	110
11	P/T	1.939	0.309	0.018	0.374	1.69	-3.43	0.884	110
12	Rs-rad.	2.213	0.053	0.020	0.202	0.87	-1.21	0.854	110
13	Copias	0.362	0.245	0.005	0.794	0.66	2.71	0.437	110

For outdoor conditions (Table 4), FAO24- Radiation method provided the best performance with NRMSE value of 0.005, and MAE and s_d^2 values of 0.593 and 0.011, respectively. The index of agreement of the method was 0.806 which is close to 1. Furthermore, linear regression parameters A, B and R^2 were 1.05, 0.22 and 0.976, respectively, which show the goodness of fit of the evapotranspiration equation.The FAO Penman-Monteith and Hargreaves-Samani methods were placed as the second and third best methods, respectively. According to the error indices, the FAO Penman-Monteith showed an even better performance than the FAO24-Radiation method. MAE, s_d^2, NRMSE and d were 0.235, 0.07, 0.008 and 0.943, respectively which were more satisfactory than those of FAO24-Radiation. But the regression parameters A, B and R^2 were not satisfying. The slope of the straight regression line and the intercept in the FAO Penman-Monteith method were 1.21 and -1.46, respectively, which do not properly coincide with the first quarter half angle. The Copias method was ranked lowest according to its large values of s_d^2 and B (0.245 and 2.71, respectively), and very low values of A and R^2 (0.66 and 0.437, respectively).

Graphs of the regressions of the daily ET_0 methods with the best and worst performance in greenhouse and outdoor conditions are shown in Figs. 2 and 3 respectively. The intercept and the slope of each regression line are also shown for comparing the measured and the estimated values.

According to Tables 3 and 4, no great difference (more than one or two steps) was observed in the ranking of various methods in greenhouse and outdoor conditions. Hargreaves-Samani, FAO Penman-Monteith and FAO24-Radiation were ranked in the best five methods under both conditions. However, the Priestly-Taylor and Copias methods were exceptions. The Priestly-Taylor method which was ranked as the second best method in the greenhouse condition, degraded to the 11th step in open conditions. This can be related to good estimations of the Priestly-Taylor method under low or no advective conditions [41], which prevailed in the greenhouse. In other words, the advection component of the energy balance is not considered significant for greenhouse conditions on a daily basis. The Copias method superiority in greenhouse conditions is related to its being calibrated in warm and humid circumstances, which are compatible with greenhouse conditions.

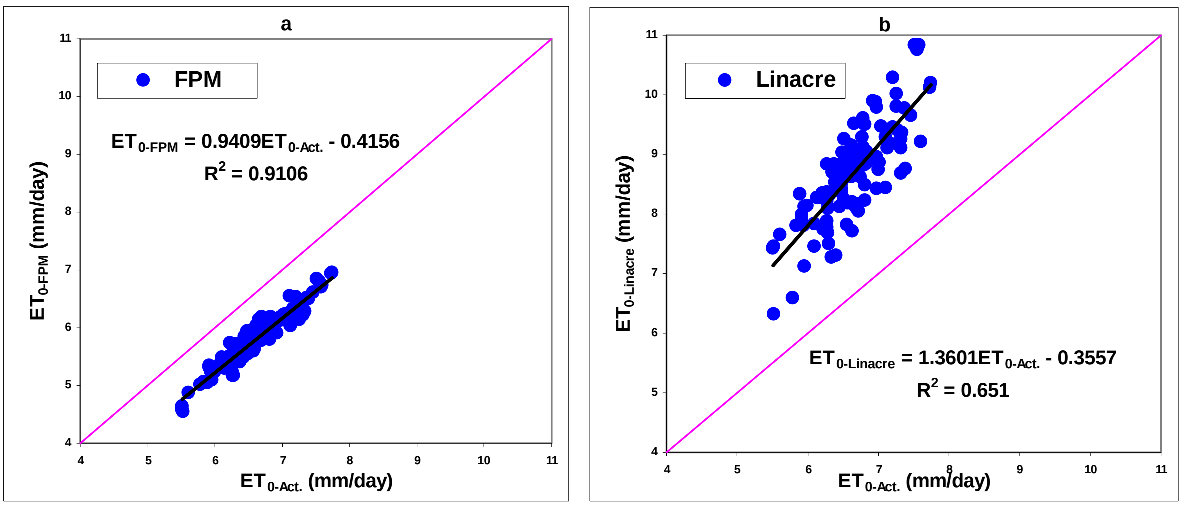


Fig. 2. Comparison between measured ET_0 ($ET_{0\text{-Act}}$) values and those calculated with a)FAO Penman-Monteith (FPM) and b)Linacre methods as the best and worst estimating methods in greenhouse conditions

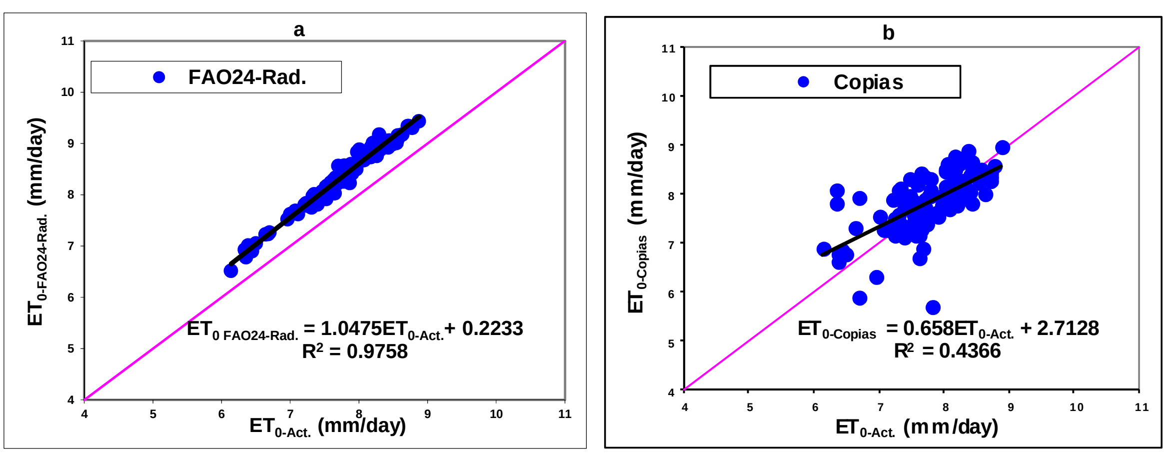


Fig. 3. Comparison between measured ET_0 ($ET_{0\text{-Act}}$) values and those calculated with a)FAO24-Radiation (FAO24-Rad.) and b)Copias methods as the best and worst estimating methods in outdoor conditions

-Smoothed Daily ET$_0$

Tables 5 and 6, show the ranks and accuracy of the methods in greenhouse and outdoor conditions, respectively. The methods performance was evaluated by a comparison between the predicted ET$_0$ using the smoothed data and smoothed lisymeteric measurement values from regression and difference indices. As indicated in Table 5, again FAO Penman-Monteith and Linacre are the best and the least accurate methods, respectively. The regression coefficients between the FAO Penman-Monteith method versus smoothed measured values are 0.98 and -0.60, respectively; although the results still show an underestimation of daily ET$_0$ in this method. Smoothing the climatic data has led to a decrease in MAE, s_d^2 and NRMSE, along with an increase in d and R^2 in the majority of the methods. However no significant transposition was observed in the methods' performance rankings, in comparison with the normal daily ET$_0$ modeling, except the 3 step raise in the Rn-Radiation method ranking, which indicates the method sensitivity to weather data fluctuation.

Table 5. Ranking and statistical analysis of different smoothed daily ET$_0$ method estimations vs. measured lysimeter values in greenhouse

No.	ET$_0$ Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FPM	0.709	0.006	0.020	0.510	0.98	-0.60	0.955	36
2	P/T	0.448	0.032	0.013	0.739	1.22	-1.90	0.891	36
3	FAO24-Rad.	1.325	0.021	0.037	0.262	1.17	0.19	0.917	36
4	Rn-rad.	1.082	0.020	0.030	0.269	0.81	0.16	0.859	36
5	H/S	0.544	0.065	0.017	0.542	0.81	0.72	0.601	36
6	Copias	0.742	0.038	0.021	0.500	1.09	0.13	0.818	36
7	B/C	0.644	0.071	0.019	0.502	0.90	1.31	0.614	36
8	Pan	1.821	0.009	0.051	0.133	0.95	-1.50	0.938	36
9	Turc	1.240	0.024	0.035	0.194	0.70	0.75	0.852	36
10	J/H	0.691	0.374	0.024	0.604	2.11	-6.77	0.753	36
11	Makkink	1.903	0.024	0.053	0.088	0.66	0.38	0.890	36
12	Rs-rad.	1.483	0.031	0.041	0.125	0.59	1.24	0.857	36
13	Linacre	1.937	0.163	0.055	0.155	1.33	-0.26	0.625	36

Table 6. Ranking and statistical analysis of different smoothed daily ET$_0$ method estimations vs. measured lysimeter values in outdoor conditions

No.	ET$_0$ Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FAO24-Rad.	0.524	0.004	0.015	0.767	1.01	0.45	0.982	36
2	H/S	0.478	0.017	0.014	0.745	0.78	1.24	0.962	36
3	B/C	0.476	0.045	0.014	0.775	1.00	-0.45	0.837	36
4	FPM	0.164	0.052	0.007	0.951	1.26	-1.89	0.914	36
5	J/H	0.644	0.026	0.018	0.695	1.10	-1.45	0.923	36
6	Turc	1.890	0.015	0.053	0.185	0.89	-1.06	0.940	36
7	Linacre	0.593	0.122	0.018	0.681	1.00	0.52	0.661	36
8	Copias	0.224	0.083	0.008	0.880	0.67	2.59	0.647	36
9	Makkink	2.436	0.023	0.068	0.126	0.94	-1.97	0.902	36
10	Rn-rad.	0.570	0.237	0.019	0.726	1.33	-2.10	0.662	36
11	Rs-rad.	2.160	0.099	0.061	0.147	0.90	-1.40	0.663	36
12	Pan	0.870	0.081	0.025	0.560	1.69	-2.19	0.811	36
13	P/T	1.897	0.175	0.054	0.286	1.66	-3.23	0.899	36

In outdoor conditions, FAO24-Radiation was the most appropriate method using smoothed daily data, followed by the Hargreaves-Samani, FAO-Blaney-Criddle and FAO Penman-Monteith, respectively (Table 6). Statistical indicators viz. MAE, s_d^2, NRMSE and d in combination with linear regression parameters in methods show better performance in outdoor conditions than in greenhouse,especially in FAO24-Radiation with the values of A, d and R^2 closest to 1 and MAE, s_d^2, NRMSE and B closest to 0. With smoothed daily data the Priestly-Taylor method declined to the table bottom with the slope of the straight regression line and the intercept of 1.66 and -3.23, respectively. Figures 4 and 5 show the regression graphs of the smoothed daily ET_0 methods with the best and worst performance in greenhouse and outdoor conditions, respectively.

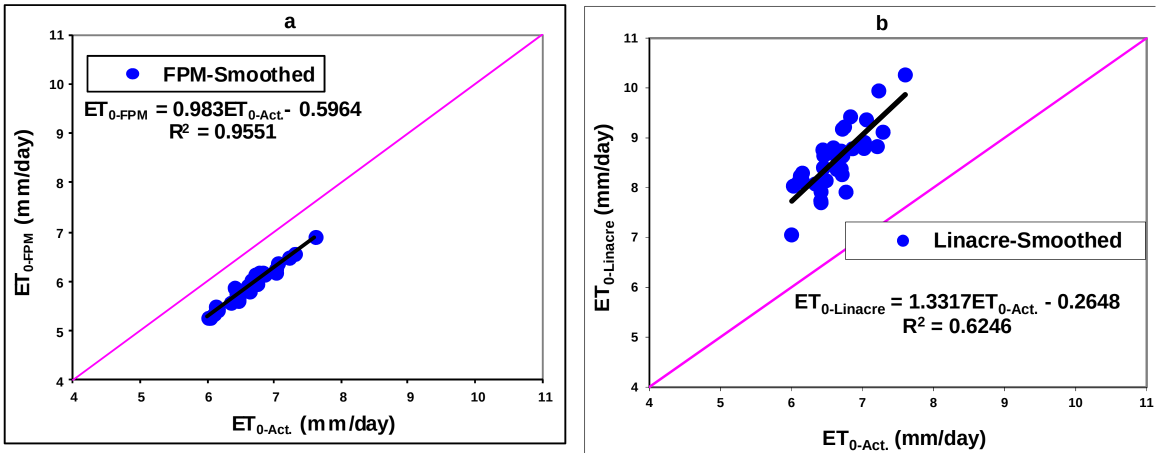


Fig. 4. Comparison between smoothed measured ET_0 ($ET_{0\text{-Act}}$) values and those calculated with a)FAO Penman-Monteith (FPM) and b)Linacre methods as the best and worst estimating methods in greenhouse conditions

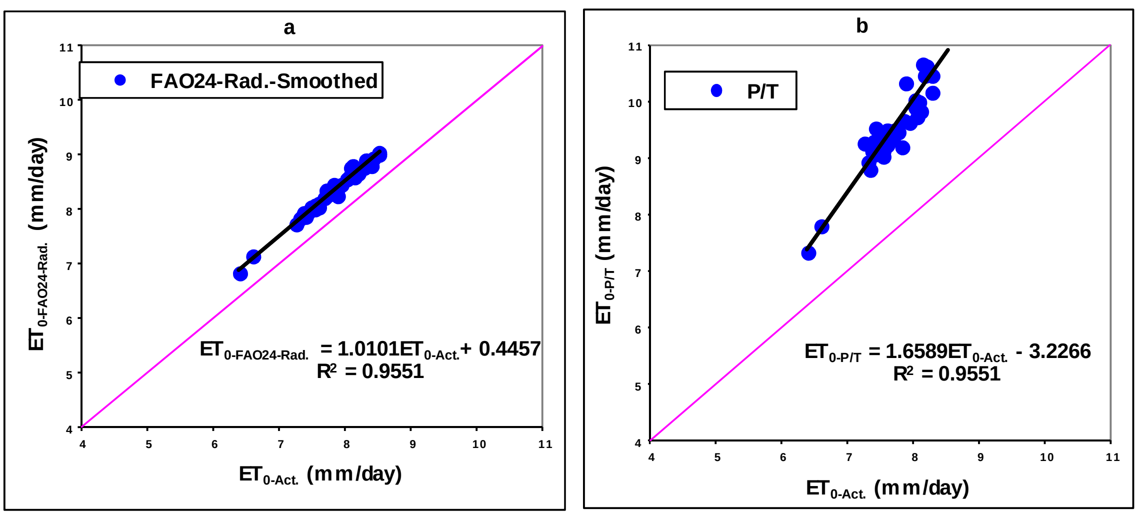


Fig. 5. Comparison between smoothed measured ET_0 ($ET_{0\text{-Act}}$) values and those calculated with a)FAO24-Radiation (FAO24-Rad.) and b)Priestly-Taylor (P/T) methods as the best and worst estimating methods in outdoor conditions

-Mean 10-day ET_0

Analysis of results of Table 7 reveals that, the FAO Penman-Monteith method is the one that demonstrated the best performance in estimating mean 10-day ET_0 in greenhouse conditions, according to the parameters used, with NRMSE of 0.07 and small values of MAE and s_d^2, together with the largest d index of 0.37. The Lincre and Rs-radiation methods were again ranked as the worst methods for greenhouse mean 10-day ET_0 estimations. Altogether, for the mean 10-day ET_0 method no significant difference was observed in the method's ranking in comparison with smoothed daily and daily methods in the greenhouse. The relationships between the mean 10-day ET_0 estimates for each method versus 10-day average values of measured ET_0 are shown in Fig. 6.

Table 7. Ranking and statistical analysis of different mean 10-day ET_0 method estimations vs. mean 10-day measured lysimeter values in greenhouse conditions

No.	ET_0 Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FPM	0.807	0.004	0.074	0.365	0.99	-0.77	0.963	11
2	H/S	0.528	0.039	0.051	0.523	0.91	0.07	0.692	11
3	Copias	0.840	0.025	0.078	0.378	1.17	-0.30	0.865	11
4	FAO24-Rad.	1.423	0.013	0.130	0.179	1.17	0.28	0.934	11
5	P/T	0.547	0.025	0.052	0.590	1.22	-2.03	0.886	11
6	Rn-rad.	0.932	0.022	0.086	0.261	0.83	0.21	0.793	11
7	Pan	1.923	0.005	0.175	0.092	0.99	-1.87	0.955	11
8	Turc	1.338	0.016	0.122	0.129	0.70	0.62	0.884	11
9	B/C	0.737	0.046	0.070	0.346	0.82	1.95	0.623	11
10	J/H	0.573	0.270	0.065	0.611	2.11	-6.83	0.764	11
11	Makkink	2.001	0.017	0.182	0.058	0.65	0.33	0.909	11
12	Rs-rad.	1.581	0.021	0.144	0.083	0.60	1.07	0.888	11
13	Linacre	2.032	0.130	0.187	0.110	1.38	-0.52	0.636	11

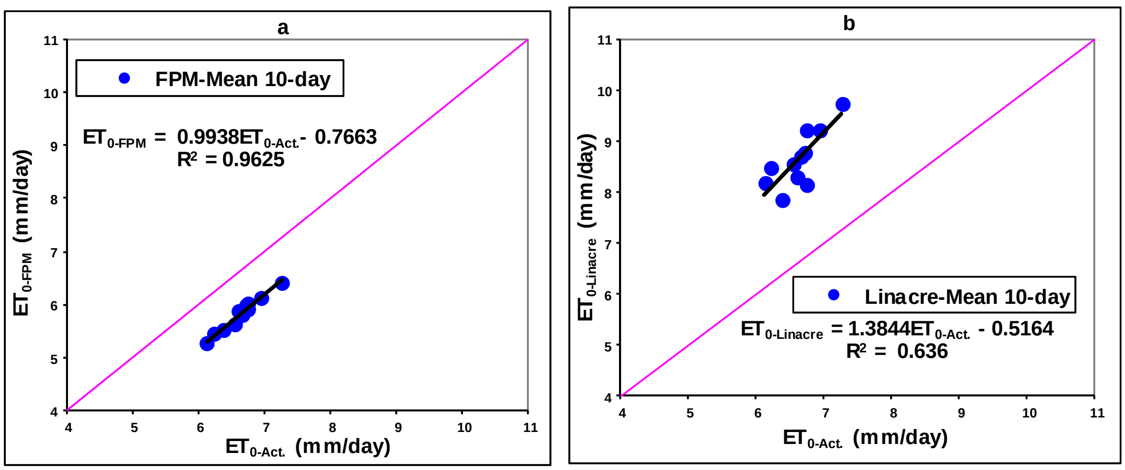


Fig. 6. Comparison between mean 10-day measured ET_0 ($ET_{0\text{-Act}}$) values and those calculated with a)FAO Penman-Monteithand (FPM) b)Linacre methods as the best and worst estimating methods in greenhouse conditions

For outdoor conditions, as indicated in Table 8, the FAO24-Radiation method estimations show the best acceptance with mean 10-day measured ET_0 values, with MAE, s_d^2, NRMSE and d values of 0.593, 0.005, 0.054 and 0.649, respectively. For linear regression parameters, values of 1.06 and 0.14 were obtained for A and B values, respectively with a satisfying R^2 of 0.977. The Priestly-Taylor method again gave the least accurate estimates with significant overestimation of the mean 10-day ET_0 values (Fig.7).

Table 8. Ranking and statistical analysis of different mean 10-day ET_0 method estimations vs. mean 10-day measured lysimeter values in outdoor conditions

No.	ET_0 Model	MAE	S_d^2	NRMSE	d	A	B	R^2	n
1	FAO24-Rad.	0.593	0.005	0.054	0.649	1.06	0.14	0.977	11
2	FPM	0.218	0.035	0.024	0.921	1.26	-1.82	0.919	11
3	Linacre	0.529	0.029	0.050	0.685	1.07	0.00	0.873	11
4	H/S	0.542	0.015	0.050	0.596	0.73	1.56	0.976	11
5	J/H	0.729	0.019	0.067	0.537	1.02	-0.90	0.906	11
6	Turc	1.927	0.007	0.175	0.133	0.92	-1.30	0.961	11
7	Copias	0.200	0.064	0.022	0.885	0.75	2.02	0.644	11
8	B/C	0.553	0.049	0.054	0.611	0.89	0.33	0.742	11
9	Rn-rad.	0.549	0.048	0.053	0.699	1.29	-1.71	0.894	11
10	Makkink	2.514	0.014	0.229	0.087	0.97	-2.31	0.920	11
11	Rs-rad.	2.213	0.020	0.202	0.097	0.85	-1.01	0.883	11
12	Pan	0.951	0.073	0.090	0.438	1.21	-2.62	0.796	11
13	P/T	1.939	0.145	0.179	0.212	1.68	-3.39	0.944	11

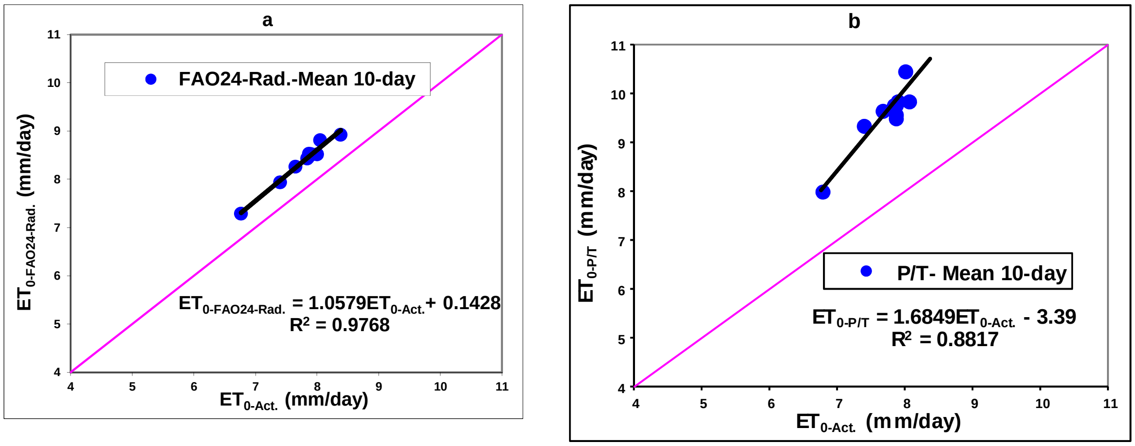


Fig. 7. Comparison between mean 10-day measured ET_0 ($ET_{0\text{-}Act}$) values and those calculated with a)FAO24-Radiation (FAO24-Rad.) and b)Priestly-Taylor (P/T) methods as the best and worst estimating methods in outdoor conditions

***-Accumulated** ET_0*

A comparison was made between corresponding cumulative values of reference evapotranspiration (CET_0), estimated by different methods with measured accumulated values, for further evaluations of the method s' performances. The progressing daily accumulated values of ET_0 of various methods in greenhouse and outdoor conditions are shown in Fig. 8. Figure 9 also shows the cumulative difference (cumulative over/underestimation) of all the applied methods in the aforesaid conditions. As shown in Fig. 8a, Linacre and Makkink methods obtained the largest and smallest values of total ET_0 as 952.8 and 509.2 mm, respectively; while the Hargreaves-Samani method gives the closest CET_0s to actual values. In Fig. 8b, Priestly-Taylor and Makkink methods give extreme CET_0 values of 1069.2 and 579.3 mm, respectively. The FAO56 Penman–Monteith method obtained the closest CET_0 values to the measure ones, while the FAO24-Radiation and the Hargreaves-Samani methods demonstrated a slight over and underestimation in CET_0 by ±50 mm approximately. As shown in Figs. 9a and 9b a greater under/over estimation by different methods was observed in greenhouse conditions relative to outdoor conditions. The total ET_0 value measured in greenhouse and outdoor lysimeters were 729.3 and 855.9 mm, respectively. Due to sharp changes in outdoor daily ET_0 variations, developing a significant relationship between outdoor and greenhouse daily ET_0 values was impracticable. As shown in Fig. 10 the differences between inside and outside daily ET_0 values varied between 0 and 2.7 mm/day during the experiment; however it can be deduced that the average ratio of daily greenhouse ET_0 values to the outdoor ones was about 0.85.

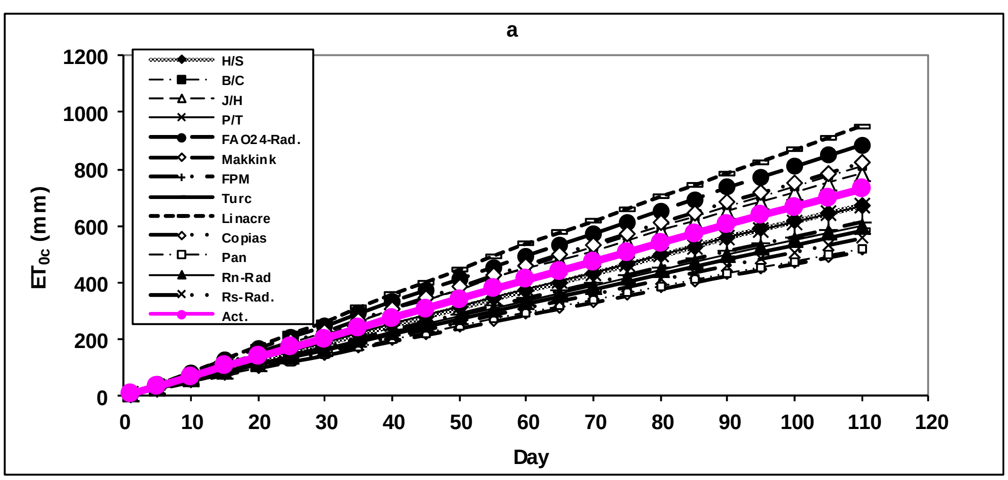


Fig. 8. Accumulated values of daily ET_0 (ET_{0c}) using various methods in a) greenhouse and b)outdoor conditions

Figure 8 continued.

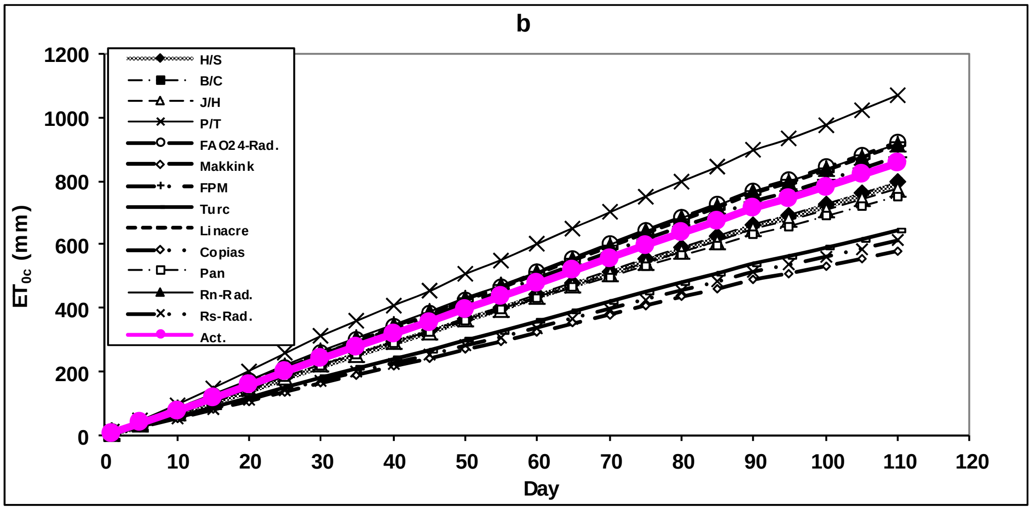
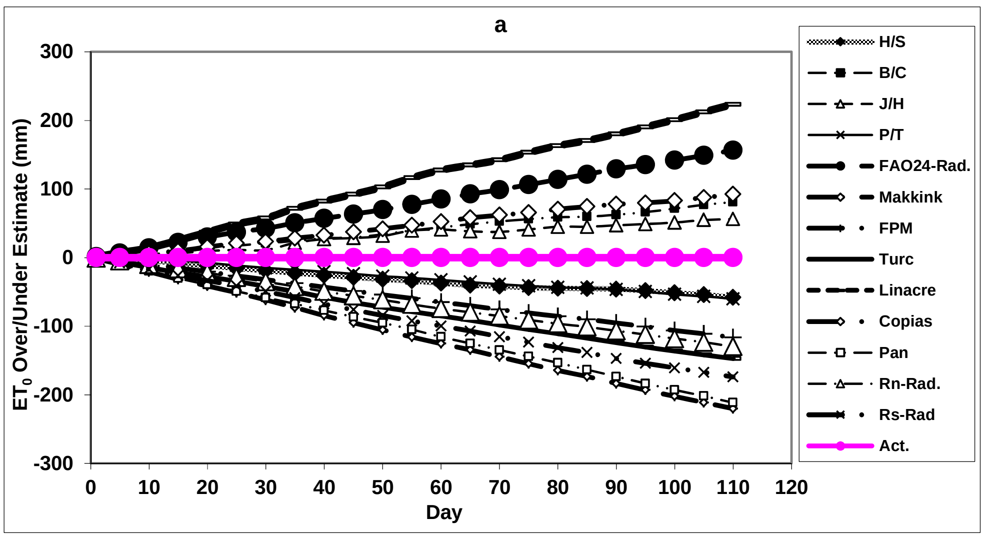


Fig. 8.



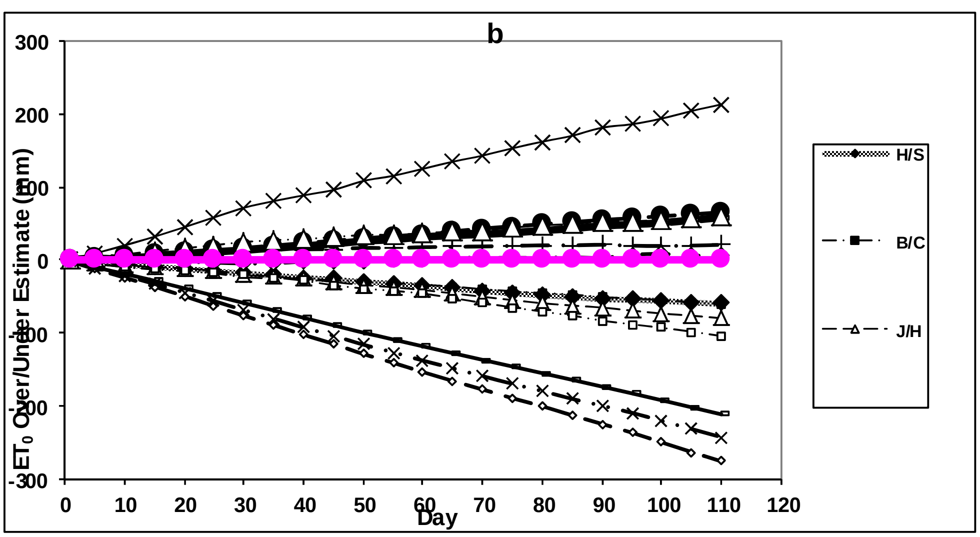


Fig. 9. ET_0 Over/Under estimate values by different methods in a) greenhouse and b) outdoor conditions

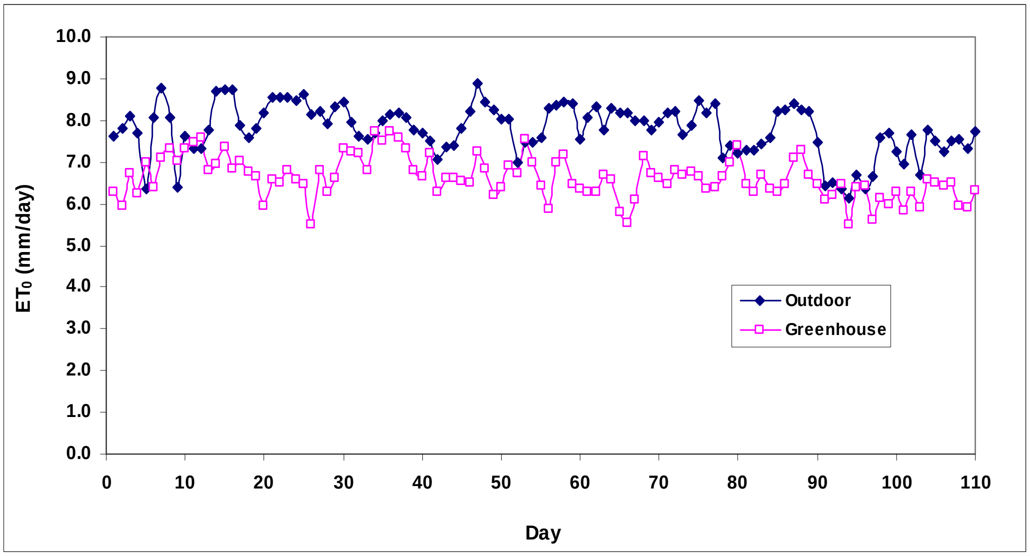


Fig. 10. Daily variations of ET_0 values under greenhouse and outdoor conditions

4. CONCLUSION

This study presents a comparison of the results using thirteen different daily ET_0 estimation methods with lysimeteric measured values in greenhouse and outdoor conditions. Four statistical difference criteria along with regression indices were applied to establish the optimal methods in each environment. The results indicate that the FAO Penman –Monteith, Priestley-Taylor and FAO24-Radiation methods were the most accurate methods for estimating daily ET_0 in greenhouse conditions, respectively. In outdoor conditions, FAO24-Radiation, FAO Penman –Monteith and Hargreaves-Samani get the three top ranking. The basic obstacle to widely applying FAO methods is the numerous weather parameters required, which are lacking in many areas. In such areas simpler empirical methods are needed. Priestley-Taylor and Hargreaves-Samani ranked first among the empirical methods estimating daily ET_0 in greenhouse and outdoor conditions, respectively. The accuracy of the Priestley-Taylor method in greenhouse estimations can be related to low or no advective conditions, prevailed in greenhouse environments; while the preference of the Hargreaves-Samani method in outdoor conditions can be expounded by the fact that it was introduced and calibrated for semi-arid regions, which conforms to the study area climate.

Smoothing weather data, in general, gave better regression parameter values for FAO Penman-Monteith and FAO24-Radiation methods in greenhouse and outdoor conditions, than those for daily weather data. Comparing the results of smoothing weather data in the greenhouse with outdoor ET_0 predictions, it can be stated that such a method was more effective in outdoor predictions than in the greenhouse, which can be explained according to the apparent fluctuation in outdoor daily weather data in comparison with that of the smoother greenhouse.

Altogether the methods analyzed seem to show greater accuracy in outdoor conditions than in greenhouse conditions, which reveals the necessity to calibrate these methods for greenhouse conditions.

REFERENCES

1. Jensen, M. E., Burman, R. D. & Allen, R. G. (1990). Evapotranspiration and irrigation water requirements. *Committee on Irrigation Water Requirements, Irrigation and Drainage Division of ASCE*, Manual No. 70. Am. Soc. Civil. Eng., New York, 332p.

2. Doorenbos, J. & Pruitt, W. O. (1977). Guidelines for predicting crop water requirements. *Irrigation and Drainage Paper 24 (revised) Food and Agricultural Organization of the United Nations*, Rome.
3. Noshadi, M. & Sepaskhah, A. R. (2005). Application of geostatistics for potential evapotranspiration estimation. *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 29, No. B3, pp. 343-355.
4. Allen, R. G. (2001). REF-ET reference evapotranspiration software, version 2.0. For FAO and ASCE standardized equations. Kimberly, Idaho: University of Idaho Research and Extension Center.
5. Allen, R. G., Walter, I. A., Eliot, R., Mecham, B., Jensen, M. E., Itensifu, D., Howell, T. A., Snyder, R., Brown, P., Echings, S., Spofford, T., Hattendrof, M., Cuenca, R. H., Wright, J. L. & Martin, D. L. (2000). Issues, requirements, and challenges in selecting and specifying a standardized ET equation. *4th National Irrigation Symposium*, 201-208. St. Joseph, Mich., ASAE.
6. Ventura, F., Spano, D., Duce, P. & Snyder, R. L. (1999). An evaluation of common evapotranspiration equations. *Irrig Sci*., Vol. 18, pp. 163-170.
7. Howell, T. A., Evett, S. R., Schneider, A. D., Duseck, D. A. & Copeland, K. S. (2000). Irrigation fescue grass ET compared with calculated reference grass ET. *4th National Irrigation Symposium*. American Society of Agricultural Engineers, St. Joseph, Mich., pp. 228-242.
8. Wright, J. L., Allen, R. G. & Howell, T. A. (2000). Conversion between evapotranspiration refernce and methods. *4th National Irrigation Symposium*. American Society of Agricultural Engineers, St. Joseph, Mich., pp. 253-259.
9. Allen, R. G., Periera, L. S., Raes, D. & Smith, M. (1998). Crop evapotranspiration: guidelines for computing crop requirements. *Irrig. and Drain*. Paper No. 56, FAO, Rome, Italy, 300 p.
10. Chiew, F. H. S., Kamaladasa, N. N., Malano, H. M. & McMahon, T. A. (1995). Penman-Monteith, FAO-24 reference crop evapotranspiration and class-A pan data in Australia. *Agric. Water Manage*, Vol. 28, pp. 9-21.
11. Pereira, A. R., Villanova, N. A. & Sediyama, G. C. (1997). Evapo(transpi)raç?o. Piracicaba: FEALQ, 183 p.
12. Hargreaves, G. H. & Samani, Z. A. (1985). Reference crop evapotranspiration from temperature. *Applied Engrg. In Agric*., Vol. 1, No. 2, pp. 96-99.
13. Sepaskhah, A. R. & Razzaghi, F. (2009). Evaluation of the adjusted Thornwaite and Hargreaves-Samani methods for estimation of daily ET0 in a semi-arid region of Iran. *Arch Agron Soil Sci*., Vol. 55, No. 1, pp. 51-66.
14. Alexandris, S. & Kerkides, P. (2003). New empirical formula for hourly estimates of reference evapotranspiration. *Agric. Water Manage*, Vol. 60, pp. 181-198.
15. Karam, F., Breidy, J., Stephan, C. & Rouphael, J. (2003). Evapotranspiration, yield and water use efficiency of drip irrigated corn in the Bekka Valley, Lebanon. *Agric. Water Manage*, Vol. 63, pp. 125-137.
16. Garcia, M., Raes, D., Allen, R. & Herbas, C. (2004). Dynamics of evapotranspiration in Bolivian highlands (Altipano). *Agric. Forest Meteorol*., Vol. 25, Nos. 1-2, pp. 67-82.
17. Utset, A., Farre, I., Martinez-Cob, A. & Cavero, J. (2004). Comparing Penman-Monteith and Priestley-Taylor approaches as referenceevapotranspiration inputs for modeling maize water-use under Mediterranean conditions. *Agric. Water Manage*, Vol. 66, p. 202.
18. Karam, F., Masaad, R., Steir, T., Mounzer, O. & Rouphael, Y. (2005). Evapotranspiration and seed yield of field grown soyabean under deficit irrigation conditions. *Agric. Water Manage*. Vol. 75, pp. 226-244.
19. Medaires, G. A., Arruda, F. B. & Sakai, E. (2005). Crop coefficients for irrigated beans derived using three reference evapotranspiratin methods. *Agric. Forest Meteorol*., Vol. 135, Nos. 1-4, pp. 135-143.
20. Pauwels, V. R. N. & Samson, R. (2006). Comparison of different methods to measure and model actual evapotranspiration rates for a wet sloping grasslands. *Agric. Water Manage*, Vol. 82, pp. 1-24.
21. Brunel, J., Ihab, J., Droubi, A. M. & Samaan, S. (2006). Energy budget and actual evapotranspiration of an arid oasis ecosystem: Palmyra (Syria). *Agric. Water Manage*, Vol. 84, pp. 213-220.

22. Xinmin, Z., Lin, H., Xiuju, B., Bingxiang, Z., Fahe, C. & Xinzhang, S. (2007). The most economical irrigation amount and evapotranspiration of the turfgrasses in Beijing City, China. *Agric. Water Manage*, Vol. 89, pp. 98-104.
23. Suleiman, A. A., Soler, C. M. T. & Hoogenboom, G. (2007). Evaluation of FAO-56 crop coefficient procedures for deficit irrigationmanagement of cotton in a humid climate. *Agric. Water Manage*. Vol. 91, pp. 33-42.
24. Gavilan, P., Berengena, J. & Allen, R. G. (2007). Measuring versus estimating net radiation and soil heat flux: Impact on Penman-Monteithreference ET estimates in semiarid regions. *Agric. Water Manage*, Vol. 89, pp. 275-286.
25. Pereira, A. R., Green, S. R. & Nova, N. A. V. (2007). Sap flow, leaf area, net radiation and Priestlay-Taylor formula for irrigated orchard and isolated trees. *Agric. Water Manage*, Vol. 92, pp. 48-52.
26. Sauer, T. J., Singer, J. W., Prueger, J. H., DeSutter, T. M. & Hatfield, J. L. (2007). Radiation balance and evaporation partitioning in a narrow-row soyabean canopy. Agric. *Forest Meteorol*, Vol. 145 Nos. 3-4, pp. 206-214.
27. Itenfisu, D., Elliot, R. L., Allen, R. G. & Walter, I. A. (2000). Comparison of reference evapotranspiration calculations across a range of climates. *Proc., 4th National Irrigation Symp*., American Society of Agricultural Engineers, St. Joseph, Mich.
28. Priestley, C. H. B. & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using largescale parameters. *Monthly Weather Review*, Vol. 100, pp. 81– 90.
29. Makkink, G. F. (1957). Testing the Penman formula by means of lysimeters. *Journal of the Institution of Water Engineers*, Vol. 11, pp. 277–288.
30. Turc, L. (1961). Evaluation des besoins en eau d'irrigation, evapotranspiration potentielle, formuleclimatiquesimplifeeetmise a jour. (In French). *Annales* Agronomiques, Vol. 12, No. 1, pp. 13-49.
31. Amatya, D. M, Skaggs, R. W. & Gregory, J. D. (1995). Comparison of methods for estimating REF-ET. *J. Irrig. Drain. Eng*., Vol. 121, No. 6, pp. 427-435.
32. Allen, R. G. (1999). Reference evapotranspiration calculation software for FAO and ASCE standardized equations. University of Idaho Research and Extension Center. p.76.
33. Linacre, E. T. (1977). A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agric. Meteo*., Vol. 18, No. 6, pp. 409-424.
34. James, L. G. (1988). *Principles of farm irrigation system design*. New York: John Willey and Sons Inc.
35. Alexandris S., Kerkides, P. & Liakatas, A. (2006). Daily reference evapotranspiration estimates by the "Copais" approach. *Agricultural Water Management*, Vol. 82, Issue 3, 24, pp. 371-386.
36. Irmak, S., Irmak, A., Allen, R. G. & Jones J. W. (2003). Solar and net radiation-based equations to estimate reference evapotranspiration in humid climates. *J. Irrig. Drain. Eng*., Vol. 129, No. 5, pp. 336-347.
37. Razzaghi, F. & Sepaskhah, A. R. (2010). Assessment of nine different equations for ET0 estimation using lysimeter data in a semi-arid environment. *Arch Agron Soil Sci*., Vol. 56, No. 1, pp. 1-12.
38. Hargreaves, G. H. & Allen, R. G. (2003). History and evaluation of Hargreaves evapotranspiration equation. *J. Irrig. Drain. Eng*., Vol. 129, No. 1, No. 53-63.
39. Willmott, C. J. & Wicks, D. E. (1980). An empirical method for the spatial interpolation of monthly precipitation within California. *Physical Geography*, Vol. 1, pp. 59-73.
40. Fox, D. G. (1981). Judging air quality model performance: A summary of the AMS workshop on dispersion model performance. *Bull. Am. Meteorol. Soc*., Vol. 62, pp. 599-609.
41. Alexandris, S., Stricevic, R. & Petkovic, S. (2008). Comparative analysis of reference evapotranspiration from the surface of rainfed grass in central Serbia, calculated by six empirical methods against the Penman-Monteith formula. *Europ. Water*, 21/22:17-28.