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Calibration of Reference Evapotranspiration Equations for Alfalfa under Arid Climatic Conditions

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Abstract. Reference evapotranspiration (ET_r) was measured for two years from alfalfa grown in three drainage type lysimeters and ET_r was estimated from ten well known equations using climatic data obtained from a weather station in the area. Evaporation from class A pan was also measured. The estimated ET_r and A pan evaporation were correlated with the measured data for calibration. The best correlation was obtained with evaporation from A pan. The Penman method gave the best performance of all methods as it had the highest correlation with the observed ET_r during the two years period. Wind function was also developed under local conditions. The values of the developed wind functions could be used to estimate accurately the ET_r under the arid climatic conditions.

Introduction

As the demand for irrigation water increases, it becomes more essential that agriculture uses water more efficiently. Improving water use efficiency requires the development of satisfactory means to estimate crop water requirements or evapotranspiration (ET). Hence the estimation of evapotranspiration is of foremost importance in water response in water resource planning, management, and irrigation development. The ET estimation is particularly important in arid and semi arid areas because of scarcity of water for irrigation purposes. A common procedure for estimating ET from a well watered agricultural crop is to first estimate reference ET from a standard surface or reference evapotranspiration (ET_r) and then apply empirical crop coefficients such as those presented by [1-3]. The ET is usually estimated through direct measurements or indirect methods. The direct methods are precise and accurate, but laborious and time consuming. Lysimeters are generally used to measure the daily or hourly values of ET and used in calibrating the ET micrometeorological equations. Details on lysimetry developments, construction, operation and management with emphasis on ET measurements are presented [4,5]. Horton [6] presented an abstract of literature on the measurement techniques of ET including lysimetery.

The indirect methods involve the estimation of reference evapotranspiration from meteorological data using empirical relationships and assumptions. None of these empirical methods can be applied generally for all purposes as they are developed under different agro-climatic conditions. An excellent review of these empirical methods is presented [7]. One of the problems arising in determining ET is the selection of the most suitable method under the existing micro-climatic conditions. Burman *et al.* [8] focused on the selection of suitable method for estimating crop ET and provided information on the use of the reference ET and crop coefficient approach. Attempts have been made to correlate the measured ET from lysimeters with the reference ET computed by using empirical equations [9-13]. To get high confidence in obtaining practical utility of the empirical equations used for estimating ET, they must be evaluated and calibrated under local or regional conditions, particularly in arid and semiarid regions. This confidence can be obtained by comparing the estimated ET values from these equations with measurements from lysimeters [7].

The grass reference ET_0 can also be obtained from class A pan evaporation and used in water management and irrigation scheduling [14]. Detailed information for using class A pan data to estimate reference ET are given in [1]. Equations for estimating reference ET from U.S. Weather Bureau class A pan evaporation are given [15,16].

Thus the purpose of this work was to calibrate some of the most commonly used ET equations in order to utilize them for estimating accurately the ET_r under extremely arid climatic conditions.

Material and Methods

The experiment was carried out at the Educational farm of the College of Agriculture, King Saud University, Riyadh [Lat. 24 N, Longitude 26 E, elevation 650 m.m.s.l.). Three drainage type lysimeters having dimensions as 2×2×1.5 m, located in the middle of a half hectare field planted with alfalfa were used over a period of two years. Each lysimeter was provided with a drainage system to collect the excess water. The soil was sandy loam (65% sand, 19% silt, 16% clay) with a bulk density of 1.55 gm/cm^3. A gauge tensiometer was provided in each lysimeter at a depth of 300 mm and irrigation was carried out when the suction reached about 30-35 kPa. The alfalfa crop in the lysimeters was irrigated through conventional irrigation method and measured with pre-calibrated flow meters. The surrounding area was irrigated with the same method and at the same time.

Repeated measurements of evapotranspiration from the alfalfa crop 20-30 cm in height (i.e. ET_{20}) were taken and used as a standard for evaluating and calibration of the methods for ET estimation. Climatic data from the Ministry of Agriculture and Water at Riyadh were used in estimating the evapotranspiration through different equations. The data consisted of daily temperature (maximum, minimum and average), relative humidity (maximum, minimum and average), short wave radiation, net radiation, 2 m wind speed, precipitation and evaporation from U.S. Weather Bureau class A pan. The methods used for ET estimation from climatic data were Penman (1963), Kimberly Penman (1972) and (1982), FAO Penman (Doorenbos & Pruitt, 1977), FAO Radiation, Jensen-Haise, Turc, Priestly-Taylor, Thornthwaite and U.S. Weather Bureau class A Pan. These methods are presented briefly here; detailed definitions and discussions of the equations used for ET estimation are given [1-3,7,17-20].

1. **Penman equation:** The general form of the Penman equation is:

$$ET_r = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} W_f (e_s - e_d) \tag{1}$$

where ET_r is the reference evapotranspiration in mm day^{-1}, Δ is the slope of the sasturation vapor pressure and temperature curve in mb/°C, γ is the psychrometric constant in mb/°C, R_n is net radiation in mm day^{-1}, G is soil heat flux in mm day^{-1} (G was neglected since its value is insignificant as compared to other values), W_f is wind function dependent on daily wind travel and $(e_s - e_d)$ is the mean daily saturation vapor-pressure deficit in mb. The following equations were used to determine the

$$\Delta = 2(0.00738T + 0.8072)^7 - 0.001158; \text{ mb/°C} \tag{2}$$

$$\gamma = 0.386\, P_a/L; \qquad \text{in mb/°C} \tag{3}$$

$$P_a = 1013 - 0.1093\, E; \qquad \text{in mb} \tag{4}$$

$$L = (595 - 0.51\, T); \qquad \text{cal/g} \tag{5}$$

$$W_f = a_w + b_w U_2 \quad (6)$$

where T is the average temperature during the period in °C, P_a is the barometric pressure in mb; L is the latent heat of vaporization cal/g, E is site elevation in meters, and U_2 is wind speed at an elevation of 2 meters above the ground in m/s or km/day as the case may be.

The three versions of the modified Penman considered were:

a. Penman (1963): The same equation with wind function constants a_w as 1 and b_w as 0.00621 with reference crop as clipped grass and wind speed measured in km day^{-1}.

b. Kimberly Penman (1972): The same equation with wind function constants a_w = 0.75; b_w = 0.9 as given by Wright and Jensen (1972) for reference crop alfalfa and wind speed in m s^{-1}.

c. Kimberly Penman (1982): The same equation with wind function constants calculated from the simplified equations for reference crop alfalfa and wind speed in m s^{-1}:

$$a_w = 0.4 + 1.4 \exp \{ - [D - 173)/58]^2 \} \quad (7)$$

$$b_w = 0.605 + 0.345 \exp \{ - [(D\text{-}243)/80]^2 \} \quad (8)$$

The resulting coefficients are applicable only for $90 < D < 305$ where D is the calendar day.

Another modified form of the Penman equation used was the FAO Penman as given by [1]. In this form a more sensitive wind function is used with an introduction of a correction factor C based on local climatic conditions.

2. FAO Penman equation: The FAO and Kimberly Penman versions are commonly used in arid and semi-arid regions [1,7]. The FAO Penman equation uses radiation, vapor pressure, temperature and wind speed to calculate the reference evapotranspiration for grass (ET_0) and is of the following form:

$$ET_0 = [w R_n + (1 - w) W_f (e_s - e_a)] C \quad (9)$$

Where ET_0 is in mm/day, w is the temperature related weighing factor, and equal to $\frac{\Delta}{\Delta + \gamma}$, R_n is the net radiation in equivalent evaporation in mm/day, W_f is the wind related function = 0.27 (1 + U_2/100), in this case U_2 is in km/day, and ($e_s - e_e$) is the difference between the saturation vapor pressure at mean air temperature and the mean actual vapor pressure of the air, both in mb; and C is the adjustment factor to compensate for the effect of day and night weather conditions. The following equation was proposed [15] to calculate the adjustment factor C:

$$\begin{aligned} C = {} & 0.6817006 + 0.0027864\, RH_{max} + 0.018768\, R_s - 0.0682501\, U_d \\ & + 0.0126514\, (U_d/U_n) + 0.0097297\, U_d\, (U_d/U_n) + 0.43025 \times 10^{-4} \\ & RH_{max}\, R_s\, U_d - 0.92118 \times 10^{-7}\, RH_{max}\, R_s\, U_d/U_n \end{aligned} \tag{10}$$

The following equation was updated by Allen and Pruitt and is reported by Jensen *et al.* [7]:

$$\begin{aligned} C = {} & 0.892 - 0.07\, U_d + 0.00219\, U_d\, R_s + 0.000402\, RH_{max}\, R_s \\ & + 0.000196\, U_d/U_n\, U_d\, RH_{max} + 0.0000198\, U_d/U_n\, U_d/RH_{max}\, R_s \\ & + 0.00000236\, U_d^2\, RH_{max}\, R_s - 0.0000086\, (U_d/U_n)^2\, U_d\, RH_{max} \\ & - 0.0000000292\, U_d/U_n\, U_d^2\, (RH_{max})^2\, R_s \\ & - 0.0000161\, RH_{max}\, R_s^2 \end{aligned} \tag{11}$$

The coefficient given by [15] was rounded by Cuenca as given by [7] as follows:

$$\begin{aligned} C = {} & 0.68 + 0.0028\, RH_{max} + 0.018\, R_s - 0.068\, U_d + 0.013\, (U_d/U_n) \\ & + 0.0097\, U_d\, (U_d/U_n) + 0.430 \times 10^{-4}\, RH_{max}\, R_s\, U_d \end{aligned} \tag{12}$$

Where RH_{max} is the maximum relative humidity in percentage, U_d is the daytime wind speed in m/s, U_n in the nighttime wind speed in m/s R_s is the short wave radiation in mm/day.

3. Jensen-Haise method (J&H): This method is referred to as a solar radiation method and produces an estimate of an alfalfa ET_r as defined by [7]. The following equation known as the "Modified Jensen-Haise equation" was used:

$$ET_r = C_T\, (T - T_x)\, R_s \tag{13}$$

where ET_r is the alfalfa based reference ET, having the same units as the solar radiation (R_s), C_T is a temperature coefficient (slope of the regression line) and T_x is the intercept of the temperature axis.

$$C_r = \frac{1}{C_1 + 7.3\, C_H} \tag{14}$$

$$C_H = \frac{50}{(e_2 - e_1)} \tag{15}$$

$$C_1 = 38 - \frac{2E}{305} \tag{16}$$

$$T_x = -2.5 - 0.14\,(e_2 - e_1) - E/550 \tag{17}$$

Where e_2 is the saturation vapor pressure of water in mb at the mean monthly maximum air temperature of the warmest month in the year (long term climatic data), e_1 is the saturation vapor pressure of water in mb at the mean monthly minimum air temperature of the warmest month in the year and E is the site elevation in meters.

4. Priestley-Taylor: In this method the aerodynamic term is deleted and instead the energy term is multiplied by a coefficient fixed as $\alpha = 1.26$, hence

$$ET_r = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \tag{18}$$

where all the terms and their units are as defined earlier.

5. Turc method: The Turc method gives

$$ET_r = 0.013 \frac{T}{T + 15} (R_s + 50)\, C/L \tag{19}$$

where ET_r is the reference evapotranspiration in mm day^{-1}, T is the temperature °C and R_s is the solar radiation in cal cm^{-2}/day, L is the latent heat in cal/g as defined earlier and C is a correction factor depending upon average relative humidity (RH) and given as:

$$C = 1 \quad \text{for RH} > 50\%; \tag{20}$$

and for RH < 50%,

$$C = 1 + \frac{50 - RH}{70} \tag{21}$$

6 Thornthwaite method: This formula is expressed by the following general equation to predict potential evapotranspiration or reference evapotranspiration as:

$$ET_o = 1.6 \left(\frac{10T}{I}\right)^a \tag{22}$$

Where ET_o is the monthly potential evapotranspiration in cm; T is monthly mean air temperature in °C and a is a coefficient which depends on the location and given as:

$$a = 0.00000675 \; I^3 - 0.0000771 \; I^2 + 0.017921 \; I + 0.49239 \tag{23}$$

Where I is the annual or seasonal heat index and is the sum of the monthly heat indices which can be calculated from the equation:

$$i = (T/5)^{1.514} \tag{24}$$

Where i is the monthly heat index and T is the monthly mean temperature in °C.

7. Pan evaporation: Pan evaporation data can be used to estimate reference ET using simple proportional relationship such as:

$$ET_r = K_p \, . \, E_p \tag{25}$$

Where E_p is pan evaporation in mm/day and K_p is pan coefficient dependent on the type of pan used and other factors such as the pan environment, obstructions and the climate itself. U.S. Weather Bureau class A pan was used in this study.

For comparison, the ET estimates obtained for grass were converted to alfalfa based reference by multiplying the values by 1.15 [7].

Wind function: The wind function was obtained by rearranging the terms of equation (9) as follows:

$$f_u = \frac{\frac{ET_o}{C} \, W.R._n}{(1 - W)\,(e_s - e_d)} \tag{26}$$

where ET_o is the ET from grass. Since the evapotranspiration was measured from alfalfa, $ET_o = ET_r / 1.15$.

Results and Discussion

The measured ET from the lysimeters were compared with the reference evapotranspiration (ET_r) using the different versions of the Penman equations (Penman 1963, Kimberly Penman 1972 and 1982, FAO Penman) and seven other empirical equations. The measured and estimated values of ET_r are presented in Figs. 1-3. To avoid repetition, data are plotted for the year 1992 only. It is observed from Fig. 1 that the three versions of Penman equation follow the same pattern as the measured ET_r. It is also observed from this figure that the classic Penman 1963 underestimates the ET_r during the summer months, while the closest is the Kimberly 1982 followed by Kimberly Penman 1972.

It is observed from Fig. 2 that the Penman (with Allen & Pruitt correction factor) underestimates ET_r mostly but gives close values duirng the period (100-180 Julian days). The FAO Penman overestimates the ET except during the month of September. The Jensen-Haise method tends to under the ET although it gives close values in some cases.

The ET estimates from the Turc, Priestly-Taylor, FAO radiation and Pan A evaporation are shown in comparison to the measured ET_r in Fig. 3. The Priestly-Taylor, Turc and FAO radiation method underestimate the ET_r during the entire period. Since the Priestly-Taylor method does not include the aerodynamic component, and was developed for humid areas where the advective effects are usually negligible, the ET_r estimates are the lowest and do not follow the general trend of measured ET. The FAO radiation is the closest to the measured evapotranspiration. The evaporation from class A pan is higher than the measured evapotranspiration except in a few cases in winter.

The regression analysis for all the methods for the two year data are presented in Table 1. The coefficient of determination (R^2) varies with the methods, ranging from the lowest of 0.25 in Thornthwaite method to the highest of 0.93 in class A pan. The Penman equations give higher correlation than the other empirical methods and varies from 0.72 with the correction factor taken from Allen to 0.84 in Kimberly Penman 1982.

The FAO radiation, J-H and Turc methods give a correlation somewhat similar to the FAO Penman with the correction factor C from Allen as given by Jensen

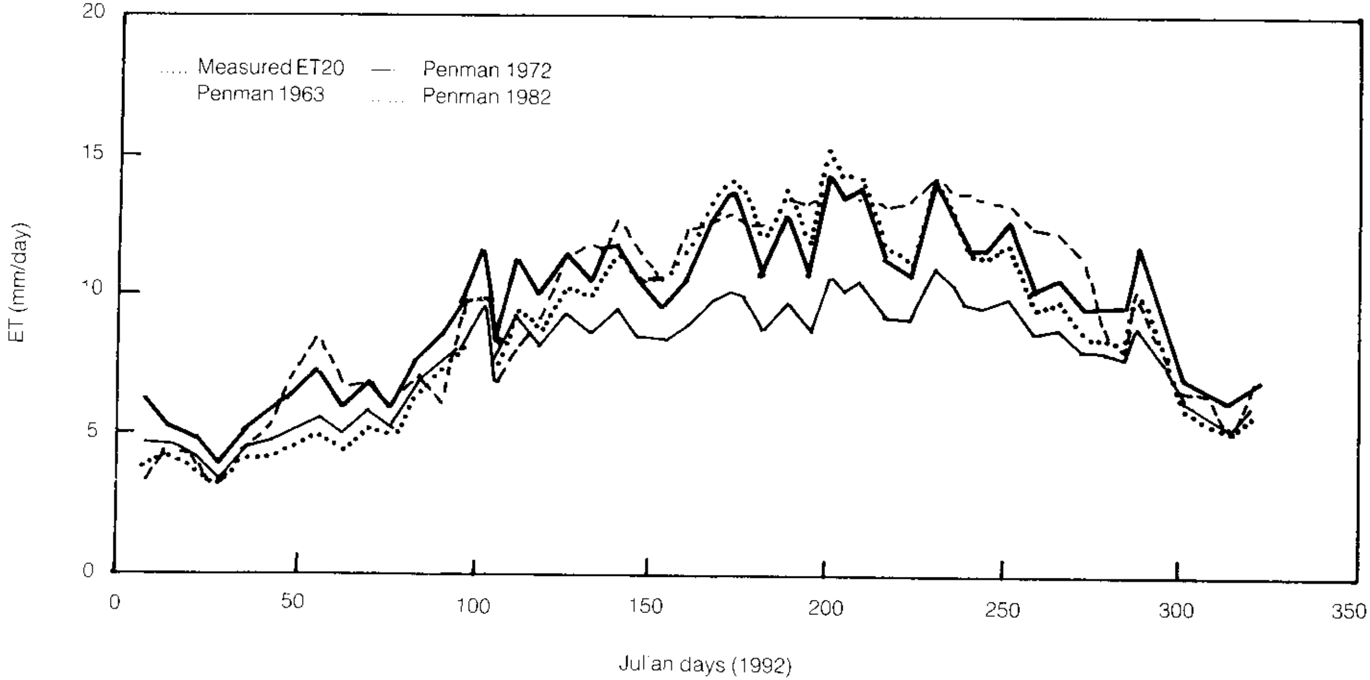

Fig. 1. Measured ET20 vs ET (Penman) with different wind functions.

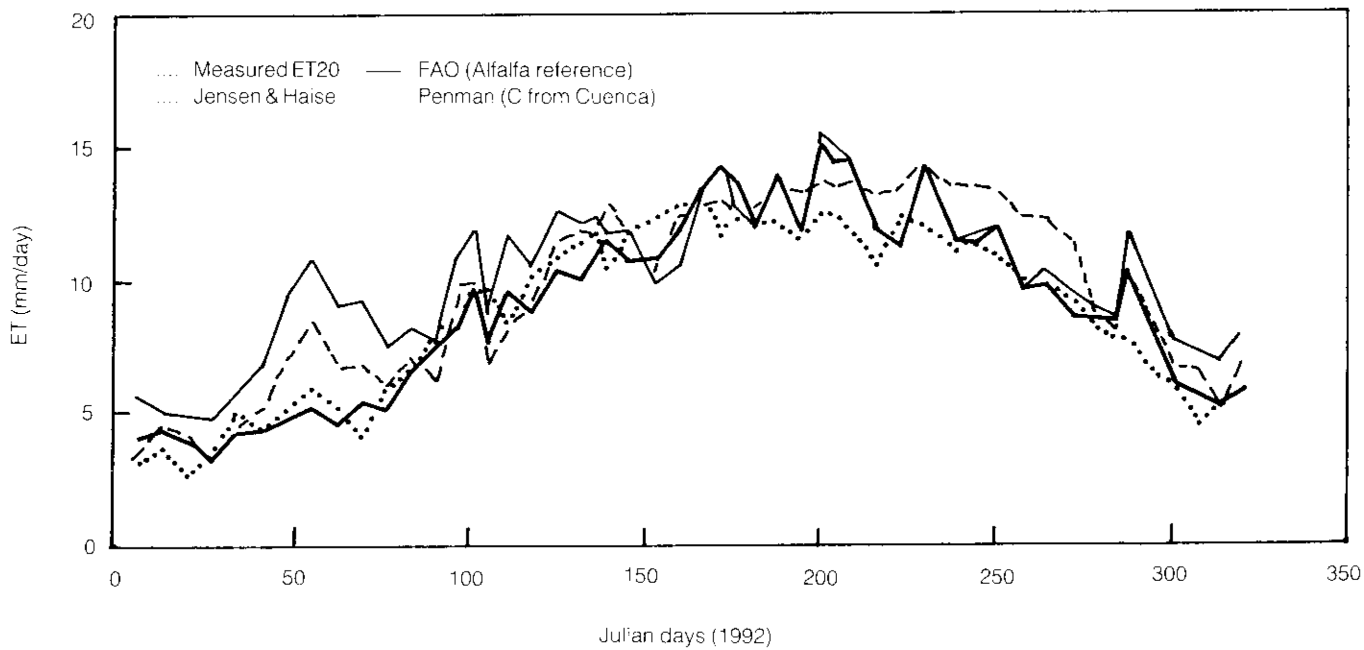

Fig. 2. Measured ET20 as compared to ET (Penman), FAO and J&H methods.

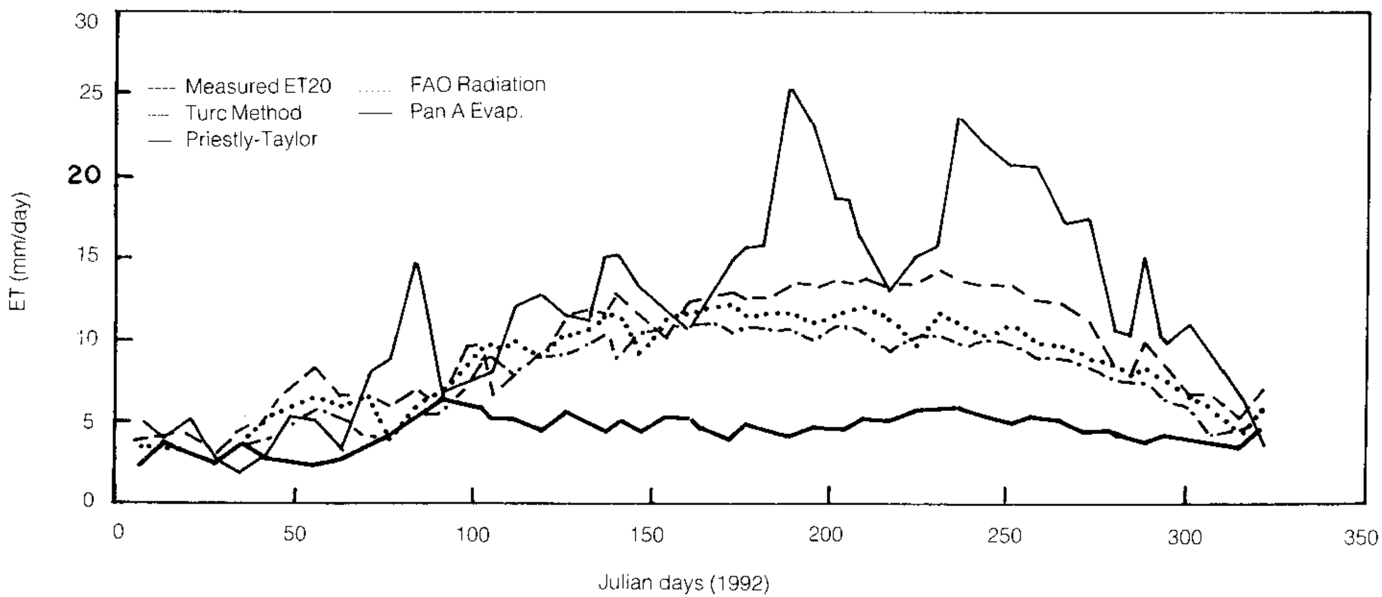

Fig. 3. Measured ET20 as compared to ET (estimated) and Pan evaporation.

Table 1. Results of the linear regression analysis of measured ET versus the estimated ET for two years data from different methods (with and without intercept)

Method	Equation	Standard error	R^2	Standard error of coefficient
1. Original Penman 1963	1 $ET = -2.473 + 1.53\ ET_{est}$	1.410	0.820	0.079
	2. $ET = 1.219\ ET_{est}$	1.537	0.785	0.0220
2. Kimberly Penman 1972	1 $ET = -0.827 + 1.076\ ET_{est}$	1.540	0.787	0.0619
	2. $ET = 0.992\ ET_{est}$	1.549	0.781	0.0179
3. Kimberly Penman 1982	1 $ET = 1.266 + 0.924\ ET_{est}$	1.266	0.836	0.0558
	2. $ET = 1.042\ ET_{est}$	1.240	0.821	0.0160
4. FAO Penman C from Allen	1 $ET = -3.125 + 1.408\ ET_{est}$	1.750	0.724	0.0959
	2. $ET = 1.061\ ET_{est}$	1.880	0.678	0.0234
5. FAO Penman grass to alfalfa	1 $ET = -0.56 + 1.032\ ET_{est}$	1.635	0.759	0.0640
	2. $ET = 0.975\ ET_{est}$	1.634	0.757	0.0186
6. FAO Radiation	1 $ET = 0.129 + 1.081\ ET_{est}$	1.633	0.760	0.0670
	2. $ET = 1.095\ ET_{est}$	1.623	0.759	0.0207
7. J-H Method	1 $ET = 0.517 + 0.977\ ET_{est}$	1.751	0.724	0.0666
	2. $ET = 1.032\ ET_{est}$	1.748	0.722	0.0211
8. Turc Method	1 $ET = -0.429 + 1.220\ ET_{est}$	1.732	0.730	0.0819
	2. $ET = 1.169\ ET_{est}$	1.726	0.729	0.0236
9. Priestly-Taylor	1 $ET = 0.327 + 2.066\ ET_{est}$	2.434	0.467	0.2437
	2. $ET = 2.139\ ET_{est}$	2.421	0.466	0.0615
10. Thornthwaite	1 $ET = 7.12 + 0.184\ ET_{est}$	2.875	0.256	0.0347
	2. $ET = 0.577\ ET_{est}$	5.663	0.221	0.0466
11. Pan A Evap	1 $ET = -0.05 + 0.83\ E_p$	0.923	0.927	0.0256
	2. $ET = 0.82\ E_p$	0.917	0.927	0.0088

(1990). The Priesly-Taylor and Thornthwaite methods give the lowest correlation since these two methods were developed for humid areas where the advective effects are negligible.

From Table 1 it is also observed that almost the same correlation is obtained when the intercept is taken as zero. Thus almost the same resuts can be obtained by using the much simpler relation between the estimated and measured ET values.

Another trial was made to correlate separately the winter and summer measured values to the corresponding estimated values from the different methods. The results are tabulated in Tables 2a and 2b. These Tables show that the correlation coefficients

Table 2a. Results of the linear regression analysis of measured ET versus the estimated ET from different methods with and without intercept (winter data)

Method		Equation	Standard error	R^2	Standard error of coefficient
1. Original Penman	1	$ET = 0.397 + 0.970\,ET_{est}$	0.853	0.544	0.1710
1963	2.	$ET = 1.039\,ET_{est}$	0.840	0.541	0.0275
2. Kimberly Penman	1	$ET = 1.415 + 0.672\,ET_{est}$	0.880	0.509	0.1270
1972	2.	$ET = 0.880\,ET_{est}$	0.912	0.458	0.0250
3. Kimberly Penman 1982	1	Not valid			
4. FAO Penman, alf.	1	$ET = 0.458 + 0.791\,ET_{est}$	0.854	0.542	0.1398
C from Allen	2.	$ET = 0.857\,ET_{est}$	0.842	0.538	0.0227
5. FAO Penman	1	$ET = 0.538 + 0.748\,ET_{est}$	0.569	0.797	0.0730
grass to alfalfa	2.	$ET = 0.820\,ET_{est}$	0.569	0.789	0.0147
6. FAO Radiation	1	$ET = 2.629 + 0.570\,ET_{est}$	0.797	0.601	0.0900
	2.	$ET = 1.007\,ET_{est}$	1.087	0.531	0.0347
7. J-H Method	1	$ET = 3.455 + 0.417\,ET_{est}$	1.010	0.359	0.4170
	2.	$ET = 0.972\,ET_{est}$	1.434	0.340	0.0211
8. Turc Method	1	$ET = 3.580 + 0.410\,ET_{est}$	1.077	0.272	0.1290
	2.	$ET = 1.018\,ET_{est}$	1.452	0.270	0.0476
9. Priestly-Taylor	1	$ET = 4.517 + 0.395\,ET_{est}$	1.232	0.470	0.3440
	2.	$ET = 1.708\,ET_{est}$	1.512	0.480	0.0833
10. Thornthwaite	1	$ET = 7.13 + 0.081\,ET_{est}$	0.840	0.565	0.1356
	2.	$ET = 0.219\,ET_{est}$	4.373	0.320	0.0418
11. Pan A Evap.	1	$ET = 0.097 + 0.938\,E_p$	2.280	0.210	0.0418
	2.	$ET = 0.953\,E_p$	2.240	0.215	0.0950

Table 2b. Results of the linear regression analysis of measured ET versus the estimated ET with and without intercept (summer data)

Method		Equation	Standard error	R^2	Standard error of coefficient
1. Original Penman 1963	1	$ET = -1.912 + 1.479\, ET_{est}$	1.579	0.704	0.1316
	2.	$ET = 1.260\, ET_{est}$	1.607	0.688	0.0253
2. Kimberly Penman 1972	1	$ET = 0.410 + 0.981\, ET_{est}$	1.671	0.669	0.0948
	2.	$ET = 1.019\, ET_{est}$	1.658	0.668	0.0211
3. Kimberly Penman 1982	1	$ET = 1.199 + 0.930\, ET_{est}$	1.209	0.827	0.0585
	2.	$ET = 1.041\, ET_{est}$	1.240	0.814	0.0160
4. FAO Penman, alf. C from Allen	1	$ET = -1.362 + 1.256\, ET_{est}$	1.930	0.558	0.1530
	2.	$ET = 1.116\, ET_{est}$	1.927	0.551	0.0270
5. FAO Penman grass to alfalfa	1	$ET = 1.680 + 0.860\, ET_{est}$	1.726	0.650	0.0870
	2.	$ET = 1.001\, ET_{est}$	1.726	0.625	0.0220
6. FAO Radiation	1	$ET = 0.211 + 1.091\, ET_{est}$	1.824	0.605	0.121
	2.	$ET = 1.112\, ET_{est}$	1.808	0.605	0.0252
7. J-H Method	1	$ET = -0.142 + 1.056\, ET_{est}$	1.901	0.571	0.1260
	2.	$ET = 1.042\, ET_{est}$	1.884	0.570	0.0246
8. Turc Method	1	$ET = -0.871 + 1.297\, ET_{est}$	1.735	0.643	0.1327
	2.	$ET = 1.201\, ET_{est}$	1.728	0.639	0.0260
9. Priestly-Taylor	1	$ET = 3.419 + 1.546\, ET_{est}$	2.440	0.294	0.329
	2.	$ET = 2.256\, ET_{est}$	2.526	0.229	0.0720
10. Thornthwaite	1	$ET = 8.50 + 0.320\, ET_{est}$	2.326	0.356	0.0597
	2.	$ET = 1.106\, ET_{est}$	5.887	0.320	0.0954
11. Pan A Evap	1	$ET = 3.0 + 0.5\, E_p$	1.754	0.720	0.0340
	2.	$ET = 0.76\, E_p$	2.379	0.480	0.0210

cients drop in all cases both during summer and winter. Only the FAO Penman has a good correlation with the observed ET_r during winter. Since these equations are developed from yearly data, hence the seasonal analysis does not give good results.

For accurate irrigation scheduling under hot arid climatic conditions prevailing in this area, it is preferable to use combination methods such as Penman with different versions rather than those with radiation term alone or based on temperature.

Calibration of the wind function: To obtain better estimates, wind function under local conditions was developed for all the combination methods using equation (27). Since different expressions for the correction factor C are given with the FAO Penman method, the wind function was obtained corresponding to each C as shown in Table 3.

Table 3. Wind function constant for use with FAO Penman (Different C's)

Method	Wind function constants		R^2
	a	b	
1. Original Penman (1963)	− 2.24	0.020	0.30
2. Kimberly Penman (1972) (1972 & 1982)	3.20	0.024	0.32
3. FAO Penman with C from:			
i. Allen & Pruitt	1.48	0.035	
ii. Cuenca	1.89	0.033	
iii. Frevert *et al.* 1982	3.27	0.020	

The wind functions calculated using the above constants and the measured ET were correlated to the given wind functions for the methods. Correlations with and without intercept were made. The results obtained were tabulated in Table 4.

The R^2 values are in good agreement with those reported by Phenc *et al.* [21] who found out that his R^2 value of 0.454 is better than those reported in literature. Hence, these values of wind functions can be used under local conditions.

For simplicity it is recommended to use the wind functions given in literature for the various methods and multiply the results by the slope in each case (taking intercept as 0), e.g. 1.05 for Allen & Pruitt 'C' (FAO method) as shown in Table 4. In the same way multiply by the relevant coefficient in other cases.

Since the class A pan evaporation gives the best correlation, it is recommended to estimate the reference evapotranspiration from pan evaporation under the local conditions. The class A pan is cheaper and easy to install anywhere. The reference ET can be determined from the following equations:

1. $ET = -0.05 + 0.83\,E_p$ $(R^2 = 0.923)$
2. $ET = 0.83\,E_p$ $(R^2 = 0.917)$; neglecting the intercept

Table 4. The relationship between the wind functions determined under local conditions and that given by FAO

Method	Constant a	Constant b	Standard error of Y estimate	R^2	No. of observations	Standard error of coefficient
1. Penman	−0.98	3.33	2.02	0.29	84	0.56
1963	0	2.79	2.01	0.28	84	0.099
2. Kimberly	0.94	1.74	0.02	0.29	84	0.302
1972	0	2.04	0.28	0.28	84	0.072
3. Kimberly	2.32	2.2	1.60	0.64	59	0.220
1982	0	2.96	1.75	0.55	59	0.078
4. Cuenca	−1.45	1.24	2.74	0.39	84	0.17
	0	1.06	2.74	0.37	84	0.037
5. Allen Pr.	−1.99	1.29	2.85	0.39	84	0.18
	0	1.05	2.86	0.37	84	0.039*
6. Frevert	1.23	0.75	2.41	0.23	84	0.154
	0	0.90	2.41	0.22	84	0.032

Conclusions

In general, the ET_r estimated with different versions of Penman equation gives good correlation with the measured ET than the other methods. This could be due to the fact that this equation involves all the climatic variables affecting the ET process. The Thornthwaite method showed the poorest correlation because it is based only on temperature in predicting crop ET. The Jensen-Haise, Turc, Priestly Taylor and FAO radiation methods underestimate the ET during the entire period of observations.

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معايرة معادلات البخر ـ نتح المرجعي للبرسيم تحت الظروف المناخية الجافة

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ملخص البحث. تم قياس البخر ـ نتح المرجعي (الفعلي) لمحصول البرسيم من ثلاثة لايسميترات لفترة عامين متتاليين، كما تم تقدير البخر ـ نتح باستخدام عشر معادلات شائعة الاستعمال للفترة الزمنية نفسها بدلالة بعض البيانات المناخية المتحصل عليها من محطات الأرصاد الموجودة ضمن منطقة الدراسة، وكذلك تم قياس البخر من حوض البخر «صنف أ». وبعد ذلك تم إيجاد معامل الارتباط بين كل من البخر ـ نتح الذي تم تقديره من المعادلات والبخر المقاس من حوض البخر مع البخر ـ نتح الفعلي المقاس لغرض المعايرة. فوجد أن أفضل معامل ارتباط تم الحصول عليه هو من حوض البخر «صنف أ». كما وجد أن معادلة بنمان هي الأفضل، لأن معامل الارتباط لهذه المعادلة هو الأعلى خلال السنتين. بالإضافة إلى ذلك تم تقدير معامل الرياح تحت الظروف المحلية، والقيم المتحصل عليها يمكن أن تستخدم بدقة لتقدير البخر ـ نتح المرجعي تحت الظروف المناخية المحلية الجافة.