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ASSESSMENT OF PENMAN-MONTEITH EQUATION AND VARIOUS METHODS OF MODELING REFERENCE EVAPOTRANSPIRATION FOR HYPER-ARID AREA

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By
A. A. Alazba

Agricultural Engineering Department, College of Agriculture, King Saud University, Riyadh, Saudi Arabia

ABSTRACT

The Penman-Monteith model was assessed for hyper-arid climate, which prevails in most areas of Saudi Arabia, particularly in the central regions. Also, four different forms of the Penman combination type-equation for the estimates of alfalfa reference evapotranspiration (ET_{ref}) have been investigated. The tested models, in addition to the Penman-Monteith, included the Penman 1982 Kimberly; the Penman 1972 Kimberly; the Penman uncorrected FAO-24; and the Penman equation locally calibrated for wind function. The results reveal that the Penman-Monteith is a good estimator of ET_{ref} under hyper-arid conditions. The model provided better ET_{ref} predictions with modification of the leaf area index (*LAI*) equation. In accordance with the modified *LAI* equation, the standard error of estimates (*SEE*) for the model reduced from 1.59 to about 1.0 mm/day. The results also showed that the locally calibrated Penman model is highly suitable for the central part of Saudi Arabia. The Penman 1982 and 1972 Kimberly models fairly estimated ET_{ref} with advantageous to the later one. The Penman uncorrected FAO-24 largely underestimated the alfalfa reference evapotranspiration and, inherently, has the largest *SEE* that equals 2.83 mm/day. It, however, was possible to reduce its *SEE* to 0.83 mm/day with using an alfalfa-grass conversion ratio of

1.55 in lieu of 1.15.

***Key words**: evapotranspiration, evapotranspiration methods, hyper-arid climate,reference evapotranspiration, Penman-Monteith model, Saudi Arabia.*

1.INTRODUCTION

1.1.General

Global increase of water demand has obviously become a fact due to the rapid increase in world population. Almost all of this population increase will be in the Third World, where there are already plenty of water and sanitation problems and where about 1400 people (mostly children) die every hour due to waterborne diseases (Bouwer, 2000). The demand of water that includes agriculture, municipal use, and industry, is anticipated to increase rapidly in the developing countries. Saudi Arabia, among other countries of the Arabian Peninsula, is one of the countries suffering most from rapid water demand and acute water shortage (Alazba, 1998). This is attributed to the scarcity of precipitation and limited water resources, in addition to the water demand augmentation. For agricultural purposes alone, the abstraction of ground water is expected to reach 20.31 billion m^3 and 22.2 billion m^3 in the years 2000 and 2010, respectively, (Abdulrazzak, 1995). This anticipated huge increase in agricultural definitely encourages efficient use of the irrigation water that is apparently accounting for 90 % of the total consumed agricultural water. The efficient use of the irrigation water can only be accomplished through proper irrigation project planning and management. The proper planning and management of the irrigation projects involve various aspects and numerous factors such that mathematical formulations and computer programming are essential. Irrigation planners need to analyze complex climate-soil-plant relations and apply mathematical optimization techniques to determine the optimally beneficial crop patterns and water allocations (Kuo *et al.*, 2000). Indeed, the aridity of the local climate of Saudi Arabia emphasizes the efficient use of the water in general and of the irrigation water in particular. This aridity can be seen from Figure

(1) that shows a 35-year statistical record of the annual rainfall for the central part of Saudi Arabia. As can be seen from this figure, the average annual rainfall is in the vicinity of 100 mm. This low amount of rainfall strongly supports the necessity of efficient water use to a maximum level. Undoubtedly, the key element of the efficient use of the irrigation water is the precise determinations of the crop water requirements (*CWR*), *i.e.*, the evapotranspiration (ET). In practice, *ET* determination is essential due to its involvement in many fields of applications such as hydrology, irrigation, watersheds, etc.

Achievement of the irrigation water conservation can be accomplished through efficient planning of the irrigation projects and proper scheduling of the irrigation water, which require knowledge of *ET*. It is unfortunate that *ET* is influenced by many climatic factors (temperature, humidity, radiation, and wind), by specific crop characteristics (height, resistance, reflectance or albedo, and emissivity), and by some management and environmental parameters (quantity and quality of water, control of weeds and diseases, etc.), which complicate its theoretical and experimental determination. The factors affecting *ET* include weather parameters, crop factors, and management and environmental conditions (Allen *et al.*, 1998). Many efforts have been made by numerous researchers to minimize differences between theoretical *ET* estimates using mathematical models and experimental *ET* measurements using field and laboratory apparatuses.

The crop *ET* is often estimated by computing *ET* for a reference crop, usually alfalfa or grass, and the crop coefficient K_c. While reference *ET* (ET_{ref}) reflects the impacts of climate factors, the crop coefficient incorporates the influencing factors of the targeted crop. When the effect of management and environmental conditions on crop *ET* is incorporated, the actual crop *ET* is attained. The initial step towards the computation of the actual crop *ET* is the determination of ET_{ref}.

Numerous methods have been developed to estimate ET_{ref} (Amatya *et al.*, 1995; Hatfield, 1990; and Allen *et al.*, 1989). The Penman (1948,1963) combined model is the most accurate widely used method based on metrological information for estimating reference evapotranspiration (Rosenberg *et al.*, 1983 and Weiss, 1982). Many derived forms of the Penman type equation are available in the literature. Allen *et al.* (1998) and Jensen *et al.* (1990) believe that the Penman-Monteith (Monteith, 1965) model is the most appropriately universal method for ET_{ref} determination. The Penman-Monteith equation is generally regarded as an accurate estimator of *ET* for a wide variety of climates and geographical locations (Jensen *et al.*, 1990). The work of Ben-Asher *et al.* (1989) points out that the Penman-Monteith equation can be a useful method, provided data on canopy resistance r_c and aerodynamic resistance r_a are available. These parameters, however, are complex and hard to obtain.

A refinement of Penman-Monteith model has been made by Allen *et al.* (1989). They developed general relationships expressed as linear and logarithmic functions of mean plant height for estimating daily average values of canopy and aerodynamic resistance parameters required by the Penman-Monteith equation. The development of relationships for canopy and aerodynamic resistances as functions of reference crop height allowed the use of the Penman-Monteith equation in an operational mode, and improved transferability of this resistance form of the Penman equation to a wide variety of climates (Allen *et al.*, 1989).

1.2.Previous assessments of ET_{ref} Models

The ET_{ref} models have been extensively tested and compared at many locations and for a variety of crops, alfalfa and grass. Jensen (1974) showed off the initial testing of various ET_{ref} models with lysimeters from different locations in the world and Jensen *et al.* (1990) updated those comparisons with more recent lysimeter data and improved crop coefficients. Allen (1986) compared nine different forms of the Penman-Monteith and a Priestley-Taylor model for three locations: Kimberly, Idaho; Davis, Calif.; and Coshocton, Ohio. He found that the Penman-Monteith with a resistance term provided the most reliable and consistent values of alfalfa and grass *ET*. To use this form of the Penman-Monteith model, an aerodynamic resistance as a function of surface roughness and wind speed was needed in addition to canopy resistance. Steiner *et al.* (1991) evaluated eight different potential *ET* equations for grain sorghum in the semiarid environment of Bushland, Tex., and found that the Penman-Monteith model with a canopy and aerodynamic resistance was the best estimator of potential *ET*. They used two different methods for the estimation of r_c, the method of Allen (1986) and that of Idso (1983) with equally good results. They also found that it was not possible to derive an empirical wind function for the original Penman model from their data.

Lemeur and Zhang (1990) evaluated the Penman-Monteith model by applying it to an arid river basin in Xinjiang, China, and found that the Penman-Monteith model is particularly sensitive to the canopy resistance r_c, but is not sensitive to the surface albedo. From this study, it was concluded that the Penman-Monteith model is applicable to arid regions, and that the Penman-Monteith model yields the best results.

Allen and Fisher (1990) designed and constructed cantilever load cells lysimeters at the Drainage Research Farm of Utah State University and found that Evapotranspiration from the fescue/forage grass mix agreed well with *ET*, ET_o, estimated with the Penman-Monteith method. Howell *et al.* (1995) measured *ET* for irrigated winter wheat (*Triticum aestivum* L.) at Bushland, Texas, in the semi-arid Southern High Plains for the 1989-1990, 1991-1992, and 1992-1993 winter wheat cropping seasons using weighing lysimeters. Weather data from a nearby station were used to compute daily *ET* values for a reference alfalfa crop (hypothetical) using the ASCE Manual and Reports No. 70 equations based on the Penman-Monteith equation and several other widely used "potential" or "maximum" *ET* models. The results of this study demonstrated that for obtaining correct results from such models, the variables R_n (net radiation), G (soil heat flux) and r_l (leaf resistance) need to be accurately modelled. It was also found that the reference *ET* methods responded differently to the climatic conditions in the area. Linear regressions between *ET* estimated from widely used equations and the reference alfalfa *ET* equation indicated that direct comparisons with computed *ET* values could not be reliably predicted with simple ratios.

In a field study, Farahani and Bausch (1995) assessed the seasonal performance of the Penman-Monteith model and found that the model performance at higher leaf area index (LAI>2) was satisfactory but performed poorly at low leaf area index ($LAI < 2$) and warned the application of the Penman-Monteith to partial canopy with the surface resistance defined solely by the canopy resistance and neglecting the influence of soil on evaporation.

Shouse *et al.* (1980) found that the Penman model with the wind function of Doorenbos and Pruitt (1977) provided the best estimate of potential *ET* in an arid environment that would be applicable to areas in which irrigation is required.

1.3.Objective

In irrigation scheduling, ET_{ref} is generally estimated by different equations. High agreement between estimated and measured ET_{ref} is a target, particularly in areas with limited water as the case of Saudi Arabia. The arid and hot climate of Saudi Arabia encourages use of more precise and reliable mathematical models that give theoretical ET_{ref} estimates that agree well with the measured ET_{ref}. In other words, the ET_{ref} prediction equations need to be tested for the dry-hot conditions prevailing in the Kingdom of Saudi Arabia. Therefore, The objective of this study was to investigate the ability of the Penman-Monteith model as well as other four methods of Penman equation to estimate ET_{ref} from meteorological data. The forms of the Penman equation include the Penman uncorrected FAO-24, the Penman 1972 Kimberly, the Penman 1982 Kimberly, and the Penman with the wind function locally calibrated.

1.4.Generalized formulation of penman models

As previously mentioned, numerous mathematical models have been developed to theoretically determine the reference *ET*, ET_{ref}. Nonetheless, the mathematical formulations of the Penman type equation for ET_{ref} estimates differ from one model to another. A generalized form of the Penman models may be proposed as follows:

$$ET_{ref} = \frac{C}{\lambda}\left[\frac{\Delta}{\Delta+\gamma^{*}}(R_n - G) + \frac{\gamma}{\Delta+\gamma^{*}} K\,(e_s - e_a)\right] \tag{1}$$

or

$$ET_{r/o} = \frac{C}{\lambda}\left[\frac{\Delta}{\Delta+\gamma^{*}}(R_n - G) + \frac{\gamma}{\Delta+\gamma^{*}} K\,(e_s - e_a)\right] \qquad (2)$$

where:

ET_{ref} or $ET_{r\,o}$	reference evapotranspiration and the subscripts r/o refer to the type of reference crop, r for Alfalfa and o for Grass [mm/day];
C	adjustment factor, introduced by Doorenbos and Pruitt (1977) in the FAO-Penman equations to account for day and night weather conditions [dimensionless];
λ	latent heat of vaporization [MJ/kg];
Δ	slope of the saturation vapor pressure-temperature curve at mean air temperature [kPa/°C];
R_n	net radiation [MJ/(m^2.day)];
G	soil heat flux [MJ/(m^2.day)];
γ	psychrometric constant [kPa/°C];
γ*	modified psychometric constant [kPa/°C], equal to $\gamma(1-r_s/r_a)$, in which r_s= surface resistance [s/m] and r_a= aerodynamic resistance [s/m];
K	a parameter relevant to ET_{ref} models [MJ/(m^2.day.kPa)];
e_s	saturation vapor pressure at mean air temperature [kPa]; and
e_a	actual vapor pressure [kPa].

In (1 and 2), the adjusting parameter C is equal to one for all Penman models except for the corrected Penman FAO-24 in which it is obtained from tables provided by Doorenbos and Pruitt (1977) or, alternatively, computed from equations founded in Jensen *et al.* (1990). Recent refined equation for C can be obtained from Kotsopoulos and Babajimopoulos (1997).

For general use with the Penman-Monteith models, the K parameter is equal to $1.854x10^5\lambda/[(T+273)r_a$ that is an exact value of $(86400*0.622/1.01/0.287)$. For the Penman-Monteith FAO-56 model (Allen *et al.*, 1998), $K=900\,\lambda/(T+273)u_2$ and $\gamma^* = \gamma\,(1+0.34u_2)$. For that of the ASCE Manual and Reports No. 70 (Jensen *et al.*, 1990),

$K=(700-2.8T)\lambda/r_a$ and $\gamma^* = \gamma(1+r_s/r_a)$. For simplification and with insignificant errors, K can be approximated by $2x10^5 \frac{\lambda / r_a}{T+273}$. For models of the Penman type equation, the K parameter represents the wind function, W_f of the form $6.43(a_w+b_w u_2)$, where a_w and b_w are the empirical wind coefficients and u_2 is the wind speed measured at height of 2 m.

As can be seen from Eqs. 1 and 2, the generalized mathematical expression of all Penman equations would simplify calculations and facilitate programming of the models. Needless to say that the modified psychometric constant γ^* is equal to γ for models other than Penman-Monteith. This can be achieved by letting r_s equal to zero for the forms of Penman other than the Penman-Monteith models.

2. METHODOLOGY AND DATA AVAILABILITY

2.1.Calculated Parameters

The availability of weather data imposes use of the ASCE Manual and Reports No. 70 equations to closely compute the parameters in Eq. 1. As can be seen from Table 1, the average values of temperature and relative humidity, but not the maximum and minimum, were only provided. This is to say that some calculations of parameters in Eq. 1 are the same, most importantly the vapour pressure deficit (VPD), *i.e.*, $e_s - e_a$.

The wind coefficients for Penman 1972 and 1981 Kimberly don't differ from those presented in the ASCE Manual and Reports No.70. For Penman uncorrected FAO-24, it was a necessitate to modify the a_w and b_w coefficients such that they are numerically consistent with the generalized Penman form, Eq. 1. The values of the a_w and b_w coefficients were 0.41 and 0.363, respectively. From the best fit analysis, the values of the a_w and b_w coefficients for locally calibrated Penman model were 3.0 and 0.15, respectively.

2.2.Measured Data

The selected models for the estimation of ET_{ref} were assessed by comparing the estimates obtained from the theoretical models with the actual ET_{ref} for a 20 cm tall, well-watered, dense and actively growing stand of alfalfa crop. ET_{ref} data measured from lysimeters at the Educational farm of the College of Agriculture, King Saud University, were available for the months of January to November for the year of 1992. The three identical lysimeters were of the drainage type and have surface dimensions of 2 m by 2 m and a depth of 1 m. The three lysimeters were furnished with a gravel bed 10 cm thick. They were successively filled with a sandy loam soil that was carefully compacted in layers of 15 cm. The lysimeters were surrounded by alfalfa belt and carried a pea gravel layer at the bottom to facilitate drainage. The water was applied through calibrated meters and the drainage water was collected in cans and measured. More details of the experiment can be found in Abo-Ghobar and Mohammad (1995).

Table (1): Averaged daily climatic data for central area of Saudi Arabia for 1992 at Deerab Station.

Month	**Average temperature T_a(°C)**	**Average relative humidity RH_a (%)**	**Wind speed u_2(m/s)**	**Net radiation R_n (MJ/m^2)**
January	10.75	44.10	2.21	5.78
February	14.47	32.89	2.64	8.90
March	18.94	36.59	2.09	10.39
April	25.77	17.91	2.54	13.95
May	31.66	12.39	2.46	15.96
June	33.88	9.08	2.82	16.77
July	34.30	8.82	3.16	16.27
August	34.06	9.86	2.44	15.26
September	30.43	11.09	2.30	13.38
October	24.27	13.99	2.52	10.02
November	22.02	29.95	1.64	7.21
Yearly Average	**25.50**	**20.61**	**2.44**	**12.17**

The meteorological data were obtained from a weather station at Deerab. The Deerab weather station (latitude of 24.2° and altitude of 300 m) is about 25 km apart from the experiment field. The weather data at Deerab consisted of the average temperature (T_a), the average relative humidity (RH_a), the wind speed (u_2), and the net radiation (R_n). Table 1 provides the values of the weather variables used in the study.

Appendix I. NOTATION

The following symbols are used in this paper:

C = adjustment factor in the FAO-Penman equations to account for day and night weather conditions;
CRW = crop water requirement
e_a = actual vapor pressure.
ET = evapotranspiration;
ET_{ref} = reference evapotranspiration;
e_s = saturation vapor pressure at mean air temperature;
G = soil heat flux;
K = parameter in Penman equations;
r_a = aerodynamic resistance;
r_c = canopy resistance;
R_n = net radiation;
r_l = leaf resistance;
R_n = net radiation;
r_s = surface resistance;
α = correlation parameter.
Δ = slope of the saturation vapor pressure-temperature curve;
γ = psychometric constant;
γ^* = modified psychometric constant; and
λ = latent heat of vaporization.

3.RESULTS AND DISCUSSION

3.1. ET_{ref} estimates *versus* measurements

The measured ET_{ref} and that estimated by the different methods are depicted in Figures 2-7. As shown in each figure, the measured and estimated values of ET_{ref} were fitted using polynomial equation of the same degree for ease of tracing. Figure 2 illustrates the good agreement between the measured ET_{ref} and that estimated by the Penman-Monteith model. Nonetheless, It was possible to improve the model estimates by modifying the *LAI* equation that has the following form:

$$LAI = 1.5\ln(hc) + 5.5 \qquad (3)$$

where, *hc* is the crop height in meters. The adjusted *LAI* equation is as follows:

$$LAI = 1.5\ln(hc) + 10.5 \qquad (4)$$

Figure 3 depicts that ET_{ref} estimates with the modified Penman-Monteith model are well agreed with the measured values. In fact, the results of the modified Penman-Monteith model were highly identical with those obtained with the Penman model that was locally calibrated as shown in Figure 7. It is obvious from Figure 7 that the locally calibrated Penman model gives ET_{ref} estimates that are in a good agreement with the measured data.

Figures 4 and 5 show that the Penman 1972 and 1982 Kimberly models fairly predict the daily ET_{ref} with advantageous to the Penman 1972 Kimberly. In contrast, the Penman uncorrected FAO-24 model highly underestimates daily ET_{ref}, Figure 6. This low estimate of the Penman uncorrected FAO-24 might be attributed to the low humidity prevailing in the region.

3.2.Correlations and standard errors of estimates

Different mathematical expressions can be used to relate measured and estimated ET_{ref}. The following equation was selected for this study:

$$ET_{ref\ (lysimeter)} = \alpha ET_{ref\ (method)} \qquad (5)$$

where, $ET_{ref(lysimeter)}$ = ET_{ref} measured with lysimeters, **α** = correlation parameter, and $ET_{ref(method)}$ = ET_{ref} estimated with models. The correlation between ET_{ref} measurements and ET_{ref} estimates was tested for two choices of the parameter **α**. The first option was to let **α** equalsunity. The second option was to allow **α** be according to its best fit using a regression analysis. The two options of **α** have been tested using the statistical parameter of standard error of estimates (*SEE*). The mathematical expression for *SEE* calculations used in this study was of the following form:

Table (2): Average ET_{ref}, SEE and R^2 for different reference ET models with α equal to unity.

	Average alfalfa reference evapotranspiration (mm/day)						
	Estimated						
	Penman-Monteith		Penman-kimberly		Original Penman		
Month	ASCE-70	Modified	1972	1982	Uncorrected FAO 24	Local calibration	Measured
1	3.07	3.71	3.82	2.88	2.84	4.11	3.88
2	4.59	5.57	5.62	4.18	4.02	5.65	6.46
3	4.78	5.51	5.64	4.46	4.33	6.21	6.60
4	8.18	9.37	9.43	7.91	6.96	9.67	8.84
5	10.45	11.65	11.75	11.46	8.92	12.14	11.75
6	12.27	13.78	13.77	14.65	10.29	13.50	12.78
7	13.08	14.81	14.62	15.46	10.61	13.65	13.62
8	11.23	12.41	12.50	12.57	9.46	12.93	13.70
9	9.93	11.05	11.19	10.44	8.54	11.82	12.40
10	8.04	9.29	9.33	8.12	6.77	9.53	8.44
11	4.50	5.00	5.21	4.21	3.84	6.41	6.18
Average	8.19	9.29	9.35	8.76	6.96	9.60	9.51
Statistical parameters							
SEE	1.59	1.02	0.93	1.66	2.83	0.66	
α	1.000	1.000	1.000	1.000	1.000	1.000	
R^2	0.790	0.915	0.929	0.771	0.336	0.964	

Table(3): Average ET_{ref}, SEE and R^2 for different reference ET models with α allowed to vary.

	Average alfalfa reference evapotranspiration (mm/day)						
	Estimated						
	Penman-Monteith		Penman-kimberly		Original Penman		
Month	ASCE-70	Modified	1972	1982	Uncorrected FAO 24	Local Calibration	Measured
1	3.48	3.73	3.82	2.94	3.83	4.07	3.88
2	5.21	5.60	5.62	4.27	5.41	5.59	6.46
3	5.42	5.53	5.65	4.56	5.83	6.14	6.60
4	9.28	9.42	9.44	8.08	9.36	9.57	8.84
5	11.84	11.71	11.77	11.71	12.01	12.01	11.75
6	13.91	13.85	13.79	14.97	13.84	13.36	12.78
7	14.83	14.88	14.65	15.79	14.28	13.51	13.62
8	12.73	12.47	12.52	12.84	12.73	12.80	13.70
9	11.26	11.11	11.21	10.66	11.49	11.70	12.40
10	9.11	9.33	9.34	8.30	9.11	9.43	8.44
11	5.10	5.02	5.22	4.30	5.17	6.34	6.18
Average	9.29	9.33	9.37	8.95	9.37	9.50	9.51
Statistical parameters							
SEE	1.00	1.01	0.93	1.65	0.83	0.65	
α	1.134	1.005	1.002	1.021	1.346	0.989	
R^2	0.918	0.915	0.929	0.775	0.943	0.965	

$$SEE = \sqrt{\frac{\sum_{1}^{n}\left(ET_{ref\,(lysimeter)} - ET_{ref\,(method)}\right)^{2}}{n-2}} \qquad (5)$$

Tables(2) and (3) show *SEE* associated with ET_{ref} models under consideration for the two aforementioned options of **α**. As can be seen from these tables, the results of the Penman-Monteith model were highly improved with the use of modified *LAI* equation, Eq. 4. The *SEE* for the Penman-Monteith model has declined from 1.59 to 1.02 mm/day as shown in Table 2. Nonetheless, it can be noticed form Tables 2 and 3 that the modified Penman - Monteith model requires no further modification since the two *SEE* values are almost the same. The two SEE values are 1.02 and 1.01 as seen in Tables (2 and 3), respectively. Needless to say that the modified Penman-Monteith is subjected to more studies before ultimate judgment is stated. This is particularly important because the effect of modifying other parameters on ET_{ref} was not investigated. In other words, the modification of the *LAI* equation may not be the only alternative to improve the ET_{ref} estimates with the Penman-Monteith model. In fact, the model may need no modification if the measurements of the reference alfalfa ET were taken at a height greater than 20 cm, specifically between 30 and 80 cm.

Table (2) illustrates that the Penman model with wind function locally calibrated and with **α** equal to one gave the lowest *SEE*, 0.66 mm/day. When the correlation parameter **α** be according to its best fit, the *SEE* decreased only from 0.66 to 0.65 mm/day as shown in Tables 2 and 3, respectively. This insignificantly small change in *SEE* implies that the model doesn't require any further modification. Similar explanation can be stated on the Penman 1972 Kimberly model where there were no changes in *SEE* values, which equal 0.93 mm/day for the two cases of **α** as depicted in Tables 2 and 3.

As for comparison, the grass based reference *ET* calculated from the Penman uncorrected FAO-24 was multiplied by 1.15 to get alfalfa based reference *ET* (Jensen, 1990). This multiplication value led to low ET_{ref} estimates as reflected by the high *SEE* value that was equal to 2.83, Table (2). It, however, was possible to get better ET_{ref}

estimates when α be according to its best fit. The *SEE* reduced to 0.83 as shown in Table 3. The multiplication factor needed to convert from grass to alfalfa estimates was about 1.55 that resulted from 1.15 times 1.35. This ratio is relatively close to the maximum value founded by Allen *et al.* (1989). They pointed out that the ratio of computed alfalfa to grass reference, ranged from 1.12 to 1.43 with an average value of 1.32, can cause a great difference and hence better results with this model can be obtained.

Referring to Figures (2-7), the largest difference between the two curves occurs at the begining of the year. It is fortunate that this is a short period and has low consumptive water use. This would imply that the error in using the Penman-Monteith model, as well as other models with exceptional to the Penman uncorrected FAO-24, is small such that it can be locally used in computing ET_{ref} with high confidence. Consequently, the Penman-Monteith model may provide good estimates of ET_{ref} without local calibration. Needless to say that avoiding local calibration of the ET_{ref} models is a preferably aimed target.

3.3.Limitations

Certain limitations are associated with the current research. One of the limitations is that the measured ET_{ref} values were taken when the alfalfa height was equal to 20 cm. This is some what less than the recommended values, which should be falling between 30 and 80 cm (Jensen *et al.*, 1990). Another limitation is that the climatic data were taken from a weather station that was not located in the same field of the experiment where ET_{ref} measurements were obtained.

Nevertheless, the necessarily calculations of parameters in Eq. 1 were accomplished according to the procedures presented in the ASCE Manual Report No. 70 (Jensen *et al.*, 1990) as a restriction caused by the data availability. The proper procedures would be as recommended by the FAO-56 (Allen *et al.*, 1998), particularly the calculations of the slope of the saturation vapor pressure-temperature curve and the vapor pressure deficit, $(e_s\text{-}e_a)$.

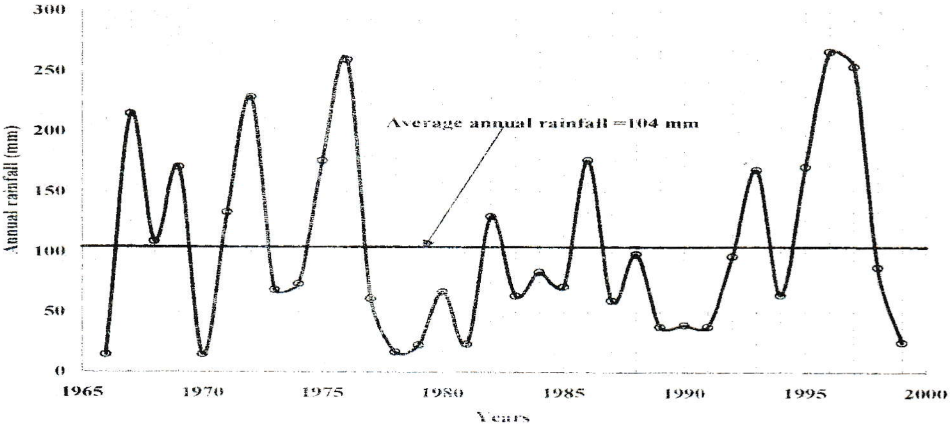

Fig. (1): Statistically recorded annual rainfall for the central part of Saudi Arabia.

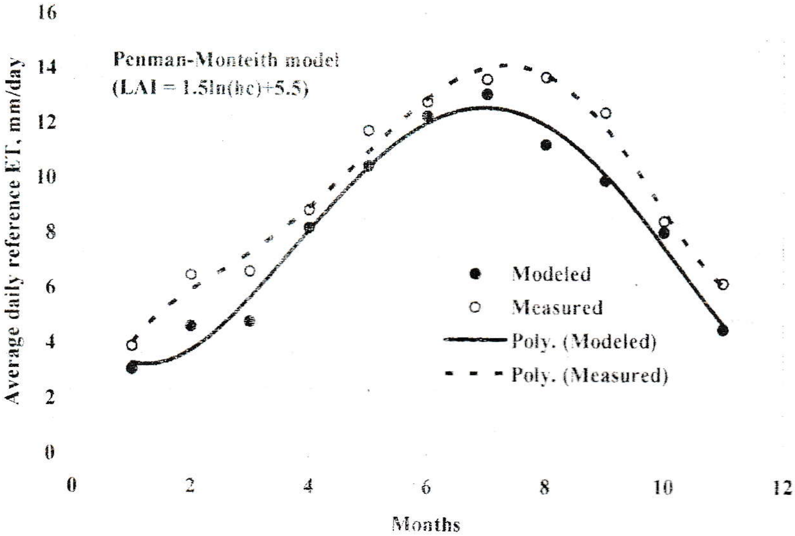

Fig. (2): Measured ET_{ref} with lysimeters and estimated ET_{ref} with Penman-Monteith model.

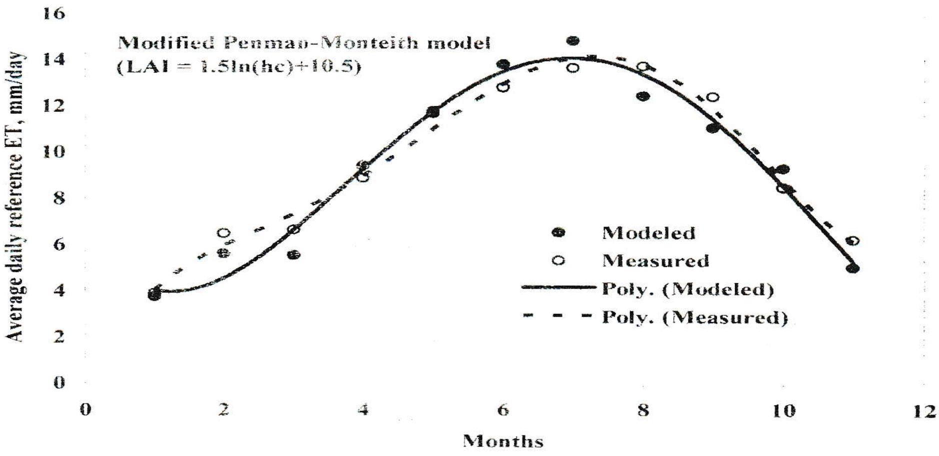

Fig. (3): Measured ET_{ref} with lysimeters and estimated ET_{ref} with modified Penman-Monteith model

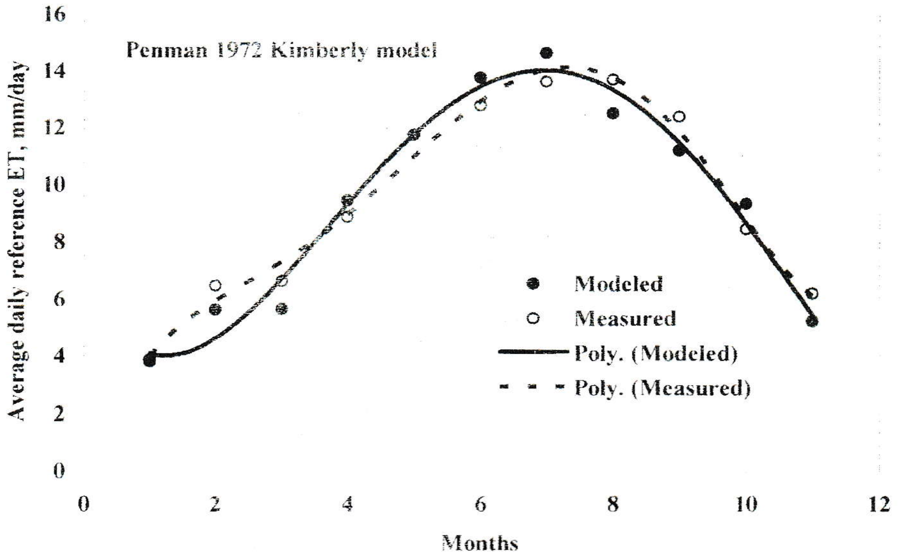

Fig. (4): Measured ET_{ref} with lysimeters and estimated ET_{ref} with Penman 1972 Kimberly model.

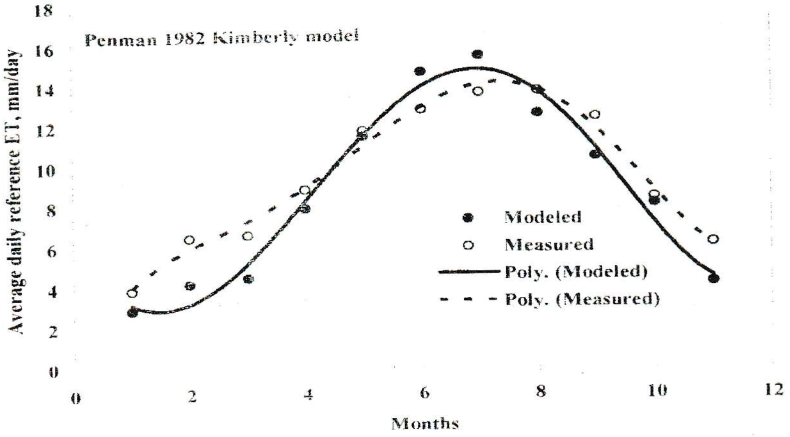

Fig. (5): Measured ET_{ref} with lysimeters and estimated ET_{ref} with Penman 1982 Kimberly model.

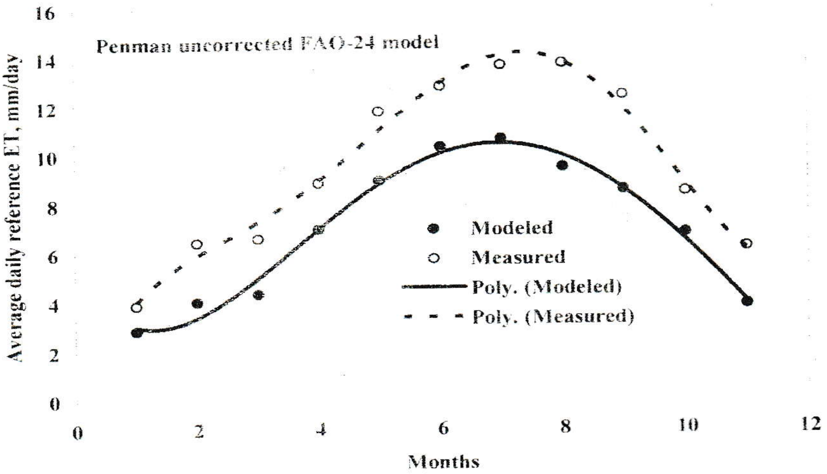

Fig. (6): Measured ET_{ref} with lysimeters and estimated ET_{ref} with Penman uncorrected FAO-24 model.

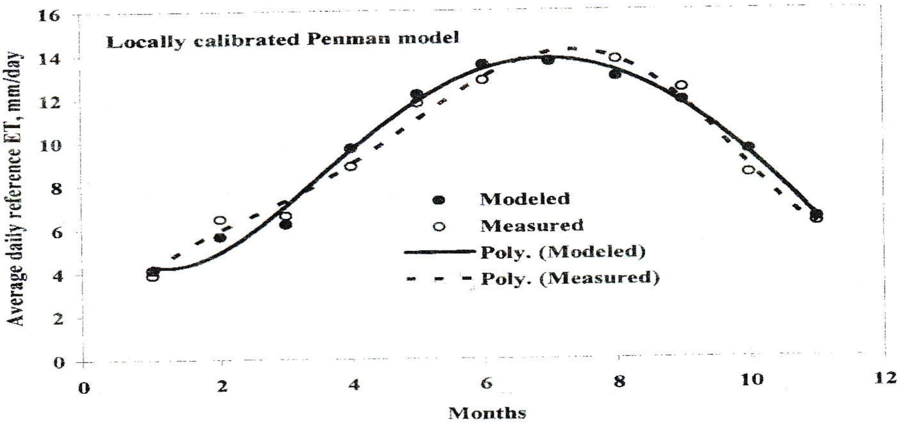

Fig. (7): Measured ET_{ref} with lysimeters and estimated ET_{ref} with locally calibrated Penman model.

Despite of these limitations, the Penman-Monteith model showed a high competition and can be used as an ET_{ref} estimator for local hyper-arid climate of Saudi Arabia. Furthermore, the Penman-Monteith model should be considered as a promising ET_{ref} estimator in hyper-arid area since it may directly be used to estimate crop *ET*. This is likely to be true, especially when the characteristics of a certain crop, any crop, such as emissivity, reflectance, resistance, and leaf area index are well described through mathematical equations or tabulated values. Eventually, the Penman-Monteith model is expected to provide best predictions of ET_{ref} if the lysimeters measurements and climatic parameters are obtained according to standardized procures.

CONCLUSIONS

The Penman-Monteith model has been tested for hyper-arid area as the climate conditions prevailing of most area of Saudi Arabia. The Penman-Monteith model provided good estimates of ET_{ref} compared with measured ET_{ref}. The model performance was noticeably improved when using a modified equation of the leaf area index. The Penman model with local wind calibration gave the best ET_{ref} estimates as compared with measured ET_{ref}. Also, the Penman 1972

Kimberly model provided good estimates of ET_{ref}. The worst ET_{ref} estimator was the Penman uncorrected FAO-24 model when it highly underestimated alfalfa ET_{ref}. The Penman 1982 Kimberly showed fair alfalfa ET_{ref} estimates.

Finally, it should be emphasized that despite that the Penman-Monteith model is apparently a good estimator of ET_{ref} for local climate of Saudi Arabia that is a hyper-arid region, ultimate judgment requires further studies.

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التحقق من ملائمة معادلة بنمان-مونتيث وطرق مختلفة لنمذجة البخر - نتح تحت ظروف المناخ شديد الجفاف

عبد الرحمن على العذبة

قسم الهندسة الزراعية- كلية الزراعة- جامعة الملك سعود-
الرياض- المملكة العربية السعودية

ملخص

تم في هذا البحث التحقق من مدى ملائمة نموذج بنمان-مونتيث للظروف المناخية شديدة الجاف السائدة في أغلب مناطق المملكة العربية السعودية، وخاصة في المنطقة الوسطى. كما تم اختبار أربع طرق مختلفة من طرق قياس البخر-نتح، وهي بنمان-كمبرلي ١٩٧٢، وبنمان-كمبرلي ١٩٨٢، وبنمان-فاو غير المعدلة، وبنمان المعايرة محليا. وقد أعطت معادلة بنمان-ومنيث نتائج جيدة تحت ظروف المناخ شديد الجفاف، وقد أمكن تحسين نتائج النموذج من خلال تعديل قيمة مؤشر مساحة الورقة LAI، حيث انخفضت قيمة الخطأ المعياري SEE من ١,٥٩ مم/يوم إلى ١,٠ مم/يوم. كما تبين من النتائج أن معادلة بنمان الأصلية المعايرة محليا هي الأفضل. وأعطت بنمان-كمبرلي ١٩٧٢ و١٩٨٢ نتائج جيدة، خاصة بنمان-كمبرلي ١٩٧٢. أما بالنسبة لنموذج بنمان-فاو غير المعدل، فقد أعطى أعلى قيمة للخطأ المعياري SEE الذي كان ٢,٨٣ مم/يوم، مما يعني عدم ملائمته للبيئة شديدة الجفاف، مع العلم أنه حصل تحسن في نتائج النموذج عندما استخدمت قيمة أكبر لمعامل التحويل من عشب إلى برسيم (١,٥٥ بدلا من ١,١٥).

المجلة العلمية لكلية الزراعة – جامعة القاهرة – المجلد (٥٥) العدد الأول (يناير ٢٠٠٤) : ١-٢٤.