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The Use of a Modified Penman Method for Estimating Evapotranspiration in a Hot and Arid Climate

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ABSTRACT To evaluate the modified Penman method of determining evapotranspiration, actual evapotranspiration was measured from an actively growing, 20 cm tall, full cover and well watered crop of alfalfa at the King Saud University Agricultural Experiment Station in Dirab, in 1981 and 1982. Since the modified Penman equation involves variations in the use of coefficients and methods for the calculation of vapor pressure deficit, estimated values of evapotranspiration (ET), with the equation, were determined separately for each method. The meteorological data were taken from an adjacent weather station.

The methods suggested by Walker and Wright were found to give close results to the ET from 20 cm tall alfalfa. Suitable wind coefficients are needed with the other methods to get reliable estimates of the ET. Using the actual data for ET, the wind function was derived in each case. Wind coefficients were then determined from the relationship of the wind function to the actual wind run. These coefficients can be used for obtaining more reliable estimates of ET in hot and arid regions in general and Saudi Arabia in particular.

The knowledge of consumptive use of crops or evapotranspiration (ET) plays an important role in efficient use of the scarce water for irrigation purposes in arid and semi-arid regions of the world. One of the methods for estimation of ET is the Penman equation. The original Penman equation (1948, 1956) was based on estimating evaporation from a free water surface and was found to underestimate the relatively large ET values under arid conditions (Evans and Thomas 1981). The modified form of the equation has been found to work well in some areas (Walker 1982). The equation, however, involves a number of parameters, which could be determined by different methods and appropriate coefficients. As a result, different values of the estimate are obtained for the same climatic conditions. With these variations in the resulting values of the estimates and lack of experimental support from other areas, especially with extreme climatic conditions, it is difficult to tell with any certainty which one of these would be an accurate and, hence, reliable estimate of the evapotranspiration.

The most recent form of the Penman equation (Hansen *et al.* 1980) is:

$$E_{tp} = \left[\frac{\Delta}{\Delta + \gamma}(R_n + G) + \frac{\gamma}{\Delta + \gamma} 15.36\, W_f(e_s - e_d)\right] L^{-1}$$

where

E_{tp} = Potential ET for the reference crop, mm/day.
Δ = Slope of the curve of saturation vapor pressure Vs temperature, mbar/C.
γ = Psychometric constant = $C_p\, P\, (0.622\, L)^{-1}$
C_p = Specific heat of air = 0.242 Cal $g^{-1}\, C^{-1}$
P = 1013 − 0.1055 EL, mbar (EL is elevation in meters)
L = Latent heat of vaporization = 595 − 0.51 T_a in Cal g^{-1} at any tempera ture T_a (degree C)
R_n = net radiation in cal/cm^2 per day (langleys/day).
G = soil heat flux in cal/cm^2 per day (langleys/days).
W_f = wind fuction, considered to be of the form a + bU, where U is the wind run in km/day at 2 m.
$e_s - e_d$ = vapor pressure deficit in mbars.
0.1 is a multiplying factor to convert units to mm/day.

The variations in ET estimates result mainly from the computation of the parameters involved in the second term (aerodynamic term), comprising of the advective energy due to wind and its movement. At least six variations exist in the computation of the vapor pressure deficit and wind coefficient (Cuenca and Nicholson 1982). Walker (1982) has suggested another method for the computation of vapor pressure deficit (V.P.D.) and adopted different wind coefficients.

An earlier modification of the Penman equation by Wright and Jensen (1972) consisted of an adjustment in the wind function and was claimed to give better estimates of the daily potential evapotranspiration (PET) rates for arid climates. Recently, Wright (1982, 1983) has given entirely different and time dependent values for the coefficients involved in the computation of the parameters of the modified Penman equation. The wind coefficients 'a' and 'b' are described by polynomials in D (day of the year) and the vapor pressure deficit is calculated from e_s as the average of the two saturation vapor pressures corresponding to the daily maximum and minimum air temperatures and e_d as the saturation vapor pressure for the measured dewpoint at 0800 hr.

These variations cause, consequently, differences in the estimates and it is difficult to regard one of them as the most accurate and hence a reliable estimate of the ET. Hence, this work was carried out to make a comprehensive evaluation of the method, by comparing the actual ET from 20 cm tall alfalfa with the various estimates and, hence, determine proper coefficients for use under arid conditions.

Material and Methods

The experiment was carried out at the Agricultural Research Station of the College of Agriculture, King Saud University, in Dirab, using lysimeters, 2m × 2m × 1.25 m in size. These were arranged in two rows and surrounded by a belt of alfalfa on all sides. The lysimeters were provided with a layer of pea gravel at the bottom and a clearance at the top. An underground passage was provided for access to the drainage water which was collected and measured with a graduated container. The experiment was started after having established a full cover of alfalfa in two of the lysimeters in March 1981 and the number was increased to four, in March 1982, in order to have a better control over the experiment. A couple of tensiometers were installed in each lysimeter to keep the tension about 20 centibars. The irrigation water was applied through calibrated meters. Soil moisture samples were regularly taken from the middle of the lysimeters and their moisture contents determined by the gravimetric method for changes in the soil profile. The values of ET were determined from the record of inputs and outputs to the lysimeters. The climatic data were taken from the meteorological station installed in the neighbourhood of the lysimeters.

The following equations and coefficients were used in arriving at the estimated values of ET by Penman method:

Δ = $33.8639[0.05904(0.00738\, t_a + 0.8072) - 3.42 \times 10^{-5}]$
t_a = mean air temperature
γ = $C_pP\,(0.622\,L)^{-1}$
C_p = the specific heat of air = $0.242\ \mathrm{cal\,g^{-1}c^{-1}}$
P = the atmospheric pressure = $1013 - 0.1055\,H$
H = elevation in meters
L = latent heat of water = $595 - 0.51\,t_a\ \mathrm{cal\,g^{-1}}$
R_n = $(1 - \alpha)R_s - R_b$ where
R_s = incident solar radiation, langleys/day
R_b = net outgoing longwave radiation, langleys/day.
α = the crop albedo (for most crops = 0.20 to 0.25)
R_b = $a'(R_s/R_{sc} + b')R_{bc}$ where R_{sc} = clear day solar radiation and
R_{bc} = net clear day outgoing longwave radiation
a' = 1.2 $b' = -0.2$
R_{bc} = $(a_1 - 0.044\sqrt{e_d})(11.71 \times 10^{-8}) \cdot 1/2 \cdot (T_{max}^4 + T_{min}^4)$
a_1 = 0.34, e_d = saturation vapor pressure at mean dewpoint. Walker (1982) uses $1/2 \cdot T_k^4$ instead of $1/2 \cdot (T_{max}^4 + T_{max}^4)$, where T_k is the average temp. (T_k, T_{max} and T_{min} are in degree Kelvin.

Wright (1982) has accounted for the sun angle effects on α and seasonal changes in the earth's net emissivity and takes:

$\alpha = 0.29 + 0.06 \sin 30(M + 0.0333 N + 2.25)$
M = No. of the month (1 to 12)
N = Day of the month
$a' = 1.126$; $b' = -0.07$ for R_s/R_{sc} greater than 0.7
$a' = 1.017$; $b' = -0.06$ for R_s/R_{sc} less than 0.7
$a_1 = 0.26 + 0.1 \exp[-\{0.0154(30 M + N - 207)\}^2]$

The soil heat flux was estimated from $G = C_s(t_a - t_p)$ where t_a = mean air temp for the current period, t_p = mean air temp for the preceding three days period and C_s = an empirical specific heat coefficient = 9.

The wind coefficients were taken as follows:

$a = 1.06$ $b = 0.0091$ for the first five methods listed below
$a = 1.0$ $b = 0.0081$ for the method given by Walker (1982).
$a = 23.8 - 0.7865 D + 9.7182 \times 10^{-3} D^2 + 5.4589 \times 10^{-5} D^3 + 1.42529 \times 10^{-7} D^4 - 1.41018 \times 10^{-10} D^5$ and
$b = -0.0122 + 5.2956 \times 10^{-4} D - 5.9923 \times 10^{-6} D^2 + 3.4002 \times 10^{-8} D^3 - 9.00872 \times 10^{-11} D^4 + 8.79179 \times 10^{-14} D^5$ ... (Wright 1982).

The following methods were used in computation of vapor pressure deficit, $e_s - e_d$:

1. Saturation vapor pressure at average temperature minus vapor pressure at minimum dewpoint temp = $e_{s(ave)} - e_{dp\ min}$.

2. Saturation vapor pressure at average temp minus vapor pressure at average dewpoint temp = $e_{s(ave)} - e_{dp(ave)}$.

3. Saturation vapor pressure at average temperature minus relative humidity times the vapor pressure at average temp. = $e_{s(ave)} - R.H. \times e_{s(ave)}$

4. Average of saturation vapor pressure at maximum and minimum temperatures minus vapor pressure at average dewpoint temp = $1/2\,(e_{smax} + e_{smin}) - e_{dp(ave)}$

5. Average saturation vapor pressure computed at maximum and minimum temperatures or

$$\frac{(e_{s\,max} - e_{max}) + (e_{s\,min} - e_{min})}{2}$$

6. $e_s - e_d = 1/2\,(e_{smax} + e_{smin}) - R.H. \times e_{smin}$ .... (Walker)

7. $e_s - e_d = 1/2\,(e_{smax} + e_{smin}) - e_{dp(0800\ Hr)}$ ..... (Wright)

For convenience, the number at the beginning of each method will be used for reference.

The saturation vapor pressures at different temperatures were computed from the following polynomial:

$$e_t = C_0 + C_1t + C_2t^2 + C_3t^3 + C_4t^4 + C_5t^5$$

t = temperature in degree Celsius.

$C_0 = 6.105$ $C_1 = 4.44 \times 10^{-1}$ $C_2 = 1.434 \times 10^{-2}$
$C_3 = 2.623 \times 10^{-4}$ $C_4 = 2.953 \times 10^{-6}$ $C_5 = 2.559 \times 10^{-8}$

Results and Discussion

The estimated values of ET from the modified Penman equation, based on different methods for vapor pressure deficit, over a period of two years (1981, 1982) are plotted in Fig. 1 (a and b). The actual values from 20 cm tall alfalfa are also shown. It is seen that method 6, suggested by Walker (1982) with vapor pressure deficit as $1/2(e_{smax} + e_{smin}) - R.H. \times e_{s\,min}$ gives the best results with its average values of wind coefficients (a = 1.0; b = 0.0081). A disadvantage of the method, that it does not work well in extended wet weather conditions, could be ignored as such conditions prevail only over a limited period of time (a few days) in winter in desert areas.

The estimates from the other methods follow the same pattern but a proportionate discrepancy is found to exist almost throughout. This indicates that the coefficients adopted for these are not suitable and result in underestimation of the evapotranspiration. These coefficients (*viz.* a = 1.06, b = 0.0091) were originally derived for method 4 of vapor pressure deficit. Hence, stronger wind functions are needed for estimation of ET by these methods. Since the same pattern is traced, any of the methods could be used to arrive at reasonably accurate estimate of ET by selecting proper values of the wind coefficients.

As seen from Fig. 1 (a and b), methods 2 & 3 and 4 & 5 result in estimates that are about the same throughout, hence these methods could be used interchangeably for most practical purposes.

Figure 2 shows the comparison of ET estimates computed by using the wind functions and methods given by different investigators with the actual ET from 20 cm tall alfalfa. The figure shows that the Wright's method (1982) underestimates by some 10-15%. It also suggests that the summer ET is greatly underestimated by using wind coefficients given earlier by Wright and Jensen (1972) with the modified Penman equation.

Evidently, there is a need for stronger wind coefficients with the Wright's method. Improved wind coefficients with lower term polynomials are now given by Wright (1983) as:

$$a = -3.896 + 6.43738 \times 10^{-2} D - 1.82917 \times 10^{-4} D^2$$
for $100 < D < 250$ and $a_{min} = 0.75$

$$b = 6.146 \times 10^{-3} - 1.93709 \times 10^{-5} D + 3.62901 \times 10^{-7} D^2 - 9.59398 \times 10^{-10} D^3$$
for $0 < D \leq 365$.

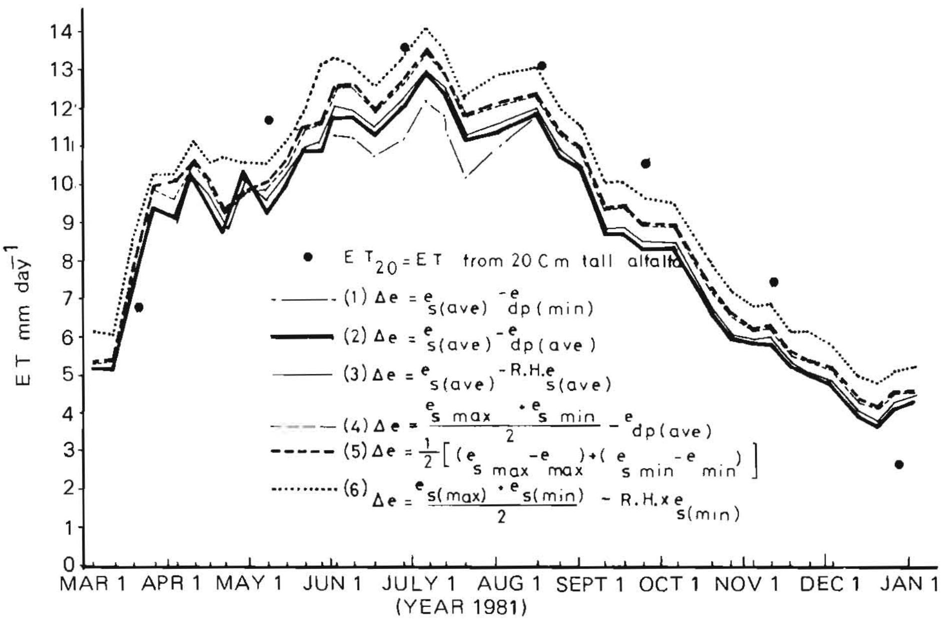

Fig. 1(a). Evapotranspiration from 20 cm tall alfalfa as compared to that estimated from Penman using different vapor-pressure-deficit methods.

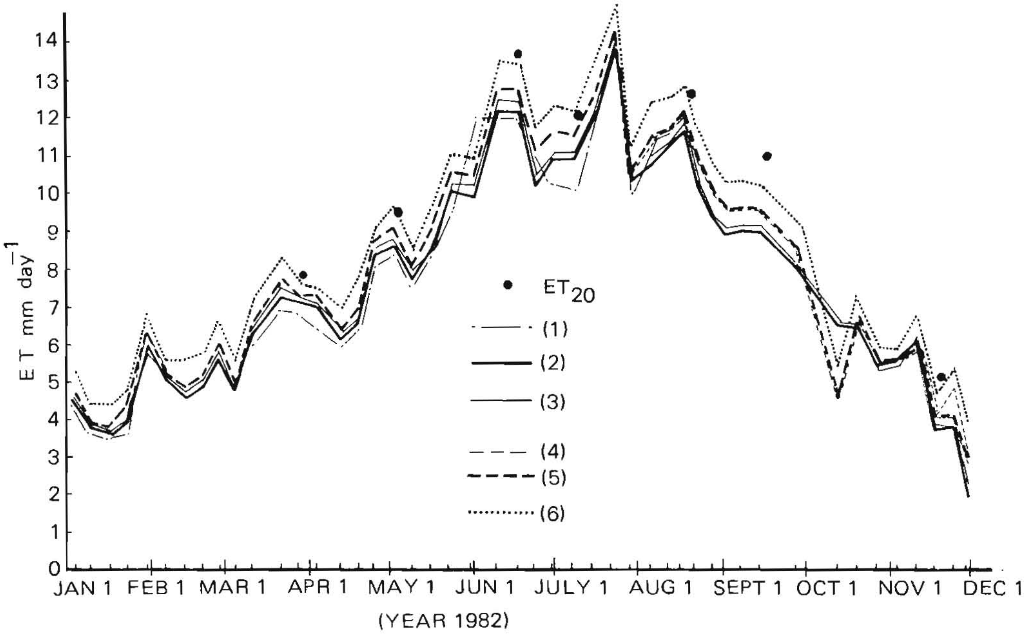

Fig. 1(b). ET from 20 cm alfalfa as compared to that estimated from Penman using different vapor-deficit methods.

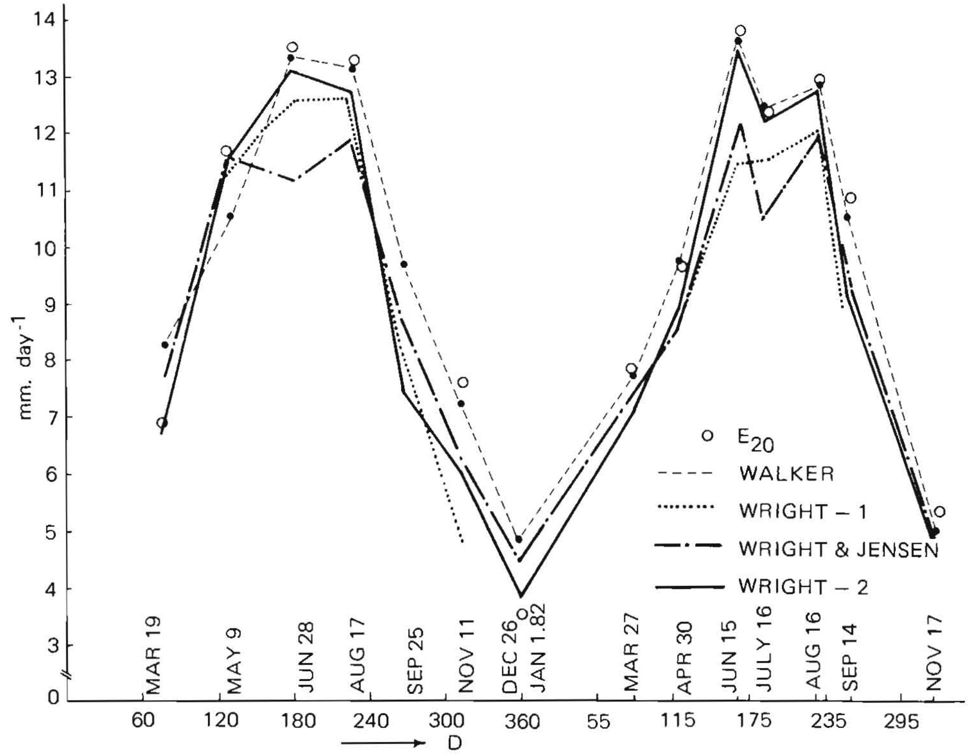

Fig. 2. Potential ET from 20 cm tall alfalfa as compared to the estimated values based on different wind functions.

The estimates based on these new values were also plotted in Fig. 2 and called Wright 2. It is seen that good results are obtained in summer and the estimated ET falls within 5% of the actual values. However, a great discrepancy is noted between the estimated and actual values as D exceeds 225. The discrepancy tends to narrow down again with a further increase in D and at D about 320, the estimated value falls within 10% of the actual value. Since 'a' assumes its minimum value of 0.75 from $D = 250$, the values of 'a', given by the quadratic equation in the range $225 < D < 250$, and the value of 0.75 in the range $250 < D < 320$ are not satisfactory and need improvement. If a linear rate of decrease for 'a' is assumed from its value of 1.33 at $D = 225$ to 0.75 at $D = 320$ and ET determined, the results obtained are close to 5% of the actual values. In winter ($320 < D < 365$ and $0 < D < 100$), the values of 'a' taken as 0.75 render satisfactory results.

In Fig. 3, actual values of U (km/day) are plotted against the wind function, W_f, derived from:

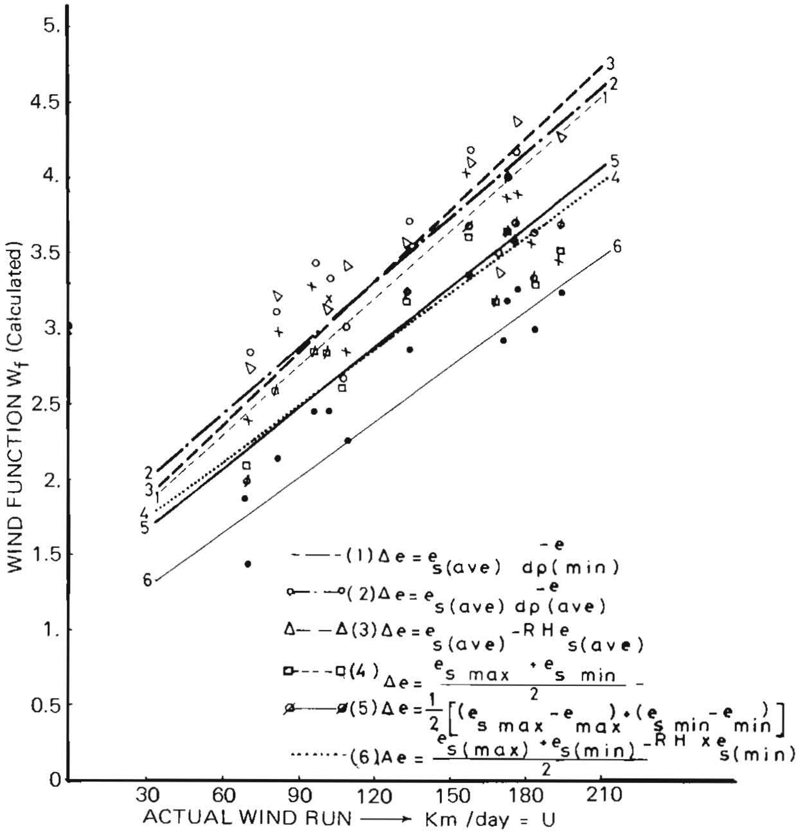

Fig. 3. The relationship between wind-run and actual wind function.

$$W_f = \frac{E_{tp} - \dfrac{\Delta}{\Delta + \gamma}(R_n + G)}{15.36\,\dfrac{\gamma}{\Delta + \gamma}(e_s - e_d)}$$

Consequently, the values of 'a' and 'b' obtained are given in Table 1. These values are based on straight line relationship between the wind function and wind run. It was observed that different values of the wind function, are obtained, from summer to winter, even with the same wind speed. The values are maximum in summer and minimum in winter. Thus, the wind function has some kind of relationship to the air temperature, an important factor in advective energy transfer. To arrive at this relationship, a number of equations were tried, with the vapor pres-

Table 1. Wind coefficients for the various methods.

V.P. Deficit Method	Wind Coefficients		r*
	a	b	
Method 1	1.4	0.015	0.79
Method 2	1.5	0.0125	0.79
Method 3	1.4	0.016	0.82
Method 4	1.35	0.013	0.91
Method 5	1.25	0.0136	0.91

* Coefficient of correlation.

sure deficit method as $e_s - R.H.\ e_s$, and finally it was found that the best results were obtained by taking the constants as:

$$a = 0.5 + 0.001\, t^2 \quad \text{(t in degree C)}$$

$$\text{and} \quad b = 0.0115$$

These temperature-dependent coefficients can be used with the modified Penman method to arrive at more accurate estimates of ET in arid regions.

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الاستهلاك المائى للنبات بطريقة بنهان المعدلة تحت ظروف المناطق الحارة الجافة (منطقة الرياض)

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يعتــبر هذا البحث واحـداً فى سلسلة الأبحـاث المنشـورة والحـارية والتى تهتم بإيجاد أنسب معادلة لحساب معدلات الاستهـلاك المـائى للنبـاتات المختلفة تحت ظروف المناطق الحارة الجافة (منطقة الرياض).

وقـد اهتمت هذه الـدراسـة بمقـارنـة معـدلات الاستهلاك المائى المحسوبة بطريقة بنهان المعدلة والتى تعتمد على عدة تصحيحـات لمعاملات الرياح والنقص فى ضغط بخـار المـاء مع تلك المعـدلات الفعلية والمقـاسة لمحصول البرسيم الحجازى بواسطة ليسومترات بمحطة المقننات المائية.

وقـد وجـد نتيجة لهذه الدراسة أن التصحيحات فى معامل النقص فى ضغط بخار الماء الذى أوجد بواسطة ووكر ١٩٨٢ ورايت ١٩٨٣ تتنـاسب مع الـظروف الجافة الحارة بعكس التصحيح فى معامل الرياح.

وقـد تمكن البـاحثـان من استنبـاط المعامل المناسب للرياح بحيث يتفق والظروف المناخية لمنطقة الرياض.