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Evapotranspiration Measurement by Lysimeters in a Desert Climate

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ABSTRACT. Three identical drainage type lysimeters, 2x2x1 m in size, were installed at the Educational Farm of the College of Agriculture, King Saud University and planted with alfalfa to obtain reference crop evapotranspiration. The measured evapotranspiration was correlated with the evapotranspiration estimated from the Penman and Jensen - Haise methods using meteorological data from Dirab. The straight line correlation with intercept was not found to be significantly high under the local arid climatic conditions. A better correlation was obtained using a straight line correlation passing through the origin. The highest coefficient of correlation ($R^2 = 0.97$) was obtained between the measured evapotranspiration from alfalfa and the evaporation from class A pan.

Water is the most important resource and limiting factor for crop production in arid regions, and the agricultural sector is the largest consumer of water. As demand for water increases, it is essential that agriculture uses water more efficiently, particularly that, applied as irrigation, especially in areas where water resources are limited. The evapotranspiration (ET) is of considerable importance for estimating irrigation water requirements because of its relevance to irrigation scheduling (Stegman *et al.* 1980), drainage and leaching prediction (Turner *et al.* 1977) and because of its link with dry matter production (McAneney and Judd 1983). Evapotranspiration can be determined directly (through lysimeters) or indirectly (through the soil water balance), or it can be calculated using empirical formulae based on meteorological data. Extensive work has been done on evapotranspiration and reported by many researchers such as Pruitt and Angus (1960), Doorenbos and Pruitt (1977),Allen *et al.* (1989) and Jensen *et al.* (1990).

Almost all estimation methods involve some empirical relationship. Consequently, some local or regional verification is needed with the method selected.A method giving the highest precision over the shortest time period is preferred (Jensen *et al.* 1990). Generally the direct measurements are precise and accurate but are expensive and time consuming. They are mainly used to provide data to calibrate methods for estimating ET from climatic data (Burman *et al.* 1980).

The recent procedure for estimating crop water use in irrigation practice is based on a meteorologically related reference evapotranspiration, ET_r and a set of evapotranspiration crop coefficients. Crop coefficient could be developed for the local conditions. Alfalfa reference evapotranspiration, ET_r has been used for arid climates (Jensen *et al.* 1971, 1990, Wright and Jensen 1972, 1978, and Wright 1981, 1982), because it has high evapotranspiration rates in arid areas where there is considerable advective sensible heat input from the air. Therefore, it can be advantageously used as a referance crop in arid areas (Wright and Jensen 1972). The ET_r is defined as the evapotranspiration from an actively growing crop of alfalfa covering an extensive area, at least 20 cm tall and standing erect and well watered, so that soil water availability does not limit evapotranspiration (Jensen 1980).

The objectives of the study are:

(1) To obtain alfalfa reference evapotranspiration and calibrate some of the well known equations, using field data under desert conditions.
(2) To develop equations to be used as a basis for predicting reference crop evapotranspiration.

Materials and Methods

Three lysimeters, constructed of sheet steel, were installed at the Educational Farm of the College of Agriculture, King Saud University, Riyadh (altitude 650 m m.s.l and latitude 24.2°N). The lysimeters were of the drainage type. Each lysimeter had a surface area of 4 sq.m. (*i.e.* 2x2 m). All the three lysimeters were identical, having an effective soil profile depth of 1 m. The gravity drainage was achieved by slanting the bottom of the lysimeters towards one side where a screened outlet was provided to allow water to drain into containers. The lysimeters were provided with a gravel bed about 100 mm thick. They were then refilled with soil in layers of 150 mm successively, and carefully compacted. The soil bulk density was 1.55 gm/cm^3. The soil was sandy loam.

Each lysimeter was provided with a system of three perforated pipes for irrigation purposes and a flow meter to measure the amount of water applied in each irrigation during the entire period of experiment. Each lysimeter was provided with tensiometers, installed at a depth of 450 mm. The irrigation water was applied when the tension was in the range of 25-30 kPa. This threshold value was selected on the basis of soil properties such that the crop receives an ample supply of water and is not subject to any stress. The excessive water was collected as drainage water and measured. The lysimeters were surrounded with an alfalfa belt in 18 plots of equal size covering an area of 2500 sq. m. These plots were irrigated simultaneously with the lysimeters through a flow meter. The method of surface irrigation was used for these plots.

The lysimeters were planted with alfalfa (variety: local, Hassavi) on 20th December, 1991. The three lysimeters were managed in the same manner with respect to irrigation treatments, fertilizer application and cutting. The cutting of alfalfa in the lysimeters and plots was carried out when about 10% flowers appeared. The initial growth cycle from planting to cut was 100 days, while the subsequent growth cycles between consecutive cuts were of about 35 days each as shown in Fig. (1). The crop height was measured twice a week. The alfalfa reached the height of 200 mm on the 15th day after each cut. The cutting was carried out manually and the height after each cut was about 70 mm. The evapotranspiration, ET, from lysimeters was determined from the following water balance equation:

$$ET = I + R - D \pm dW \quad \text{.......} \quad (1)$$

where ET was the measured evapotranspiration in mm; I = the amount of irrigation water applied during the period of observation; R = rainfal in mm, if any, during the period; D = the drainage water during the same period in mm. and dW = is the change in stored water.

Initially, the water content was raised to the field capacity and ETwas calculated between successive periods when the water contents were at field capacity, *i.e.* on the days on which drainage water was obtained. Hence the change in water contents of the soil profile is approximately zero or dW could be neglected in the calculations.

The daily evaporation from a U.S. Weather Bureau class A pan (EA) was measured during the entire course of experiment from the meteorological station situated near the site of experiment. Other meteorological data used in the study were obtained from the meteorological station situated at Dirab (altitude = 300 m m.s.1 and latitude = 24.2° N), about 25 Km south of Riyadh.

Most of the crop coefficients are based on $ET_r = ET_{20}$ *i.e.* evapotranspiration from an actively growing alfalfa stand 20 cm tall, hence ET_{20} was determined from the measured evapotranspiration. In order to obtain ET_{20} values for all the growth period, the ratio of measured evapotranspiration to evaporation from class A pan (r = ET/EA) during each growth cycle was plotted versus growth period as shown in Fig. (1). The ET_{20} corresponding to any evapotranspiration was then obtained from these curves and EA data. Since the growth cycle was of 35 days, each graph was divided into 5 equal parts. ET_{20} was obtained by interpolation as follows:

$$r_1 = r_2 \cdot \frac{p_1}{p_2} \quad \text{(2a)}$$

or

$$(ET/EA)_{20} = (ET/EA)_{35} \cdot \frac{p_1}{p_2} \quad \text{(2b)}$$

by rearranging the above equation, $(ET)_{20}$ is obtained as:

$$(ET)_{20} = (EA)_{20} \, (ET/EA)_{35} \cdot \frac{p_1}{p_2} \quad \text{(2c)}$$

where p_1 is the time period from cutting to the time when 200 mm height is attained and p_2 is the period from cutting time to the time when the height under consideration, say 35, is attained and EA is the evaporation from class A pan corresponding to ET_{20}.

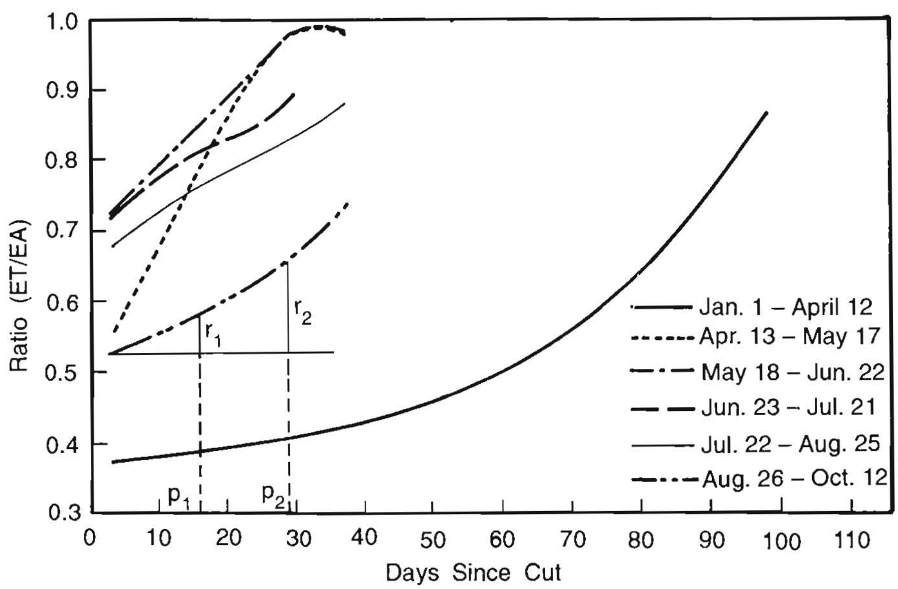

Fig. 1. The variation of the ratio ET/EA (measured ET to Pan evap.) during different seasons of growth.

The reference evapotranspiration was also estimated from Penman and Jensen - Haise methods (Jensen *et al.* 1990) as follows:

Penman Method: The modified Penman equation for estimating alfalfa based reference evapotranspiration used was:

$$ET_r = ET_{20} = \frac{\Delta}{\Delta + \gamma}(R_n + G_s) + \frac{\gamma}{\Delta + \gamma} f_u(e_s - e_d) \quad \ldots\ldots (3)$$

where ET_r is the reference crop (alfalfa) evapotranspiration in mm/day; Δ is the slope of the vapor pressure-temperature curve in mbar/C; γ is the psychrometric constant in mbar/C; R_n is the net radiation in mm/day, G_s is soil heat flux to the surface in mm/day and could be neglected (Gunston and Bachelor 1983); f_u is the wind function corresponding to wind speed at 2 m height (dimensionless); e_s is the saturation vapor pressure in mbar and e_d is the actual vapor pressure in mbar.

Jensen - Haise Method (J & H Method): The modified J & H method for alfalfa based reference evapotranspiration is as follows:

$$ET_r = ET_{20} = C_T = (T_X - T)\, R_S \quad \ldots\ldots (4)$$

where ET_r is the reference ET in mm/day; R_s is the incoming short wave solar radiation, mm/day; T is the air temperature in °C, C_T is the temperature coefficient and given by

$$C_T = \frac{1}{C_1 + C_2 C_H} \quad \ldots\ldots (5)$$

where $C_1 = 38 - (2\ \text{Elev}/305)$; $C_2 = 7.3$; and

$$C_H = \frac{5.0\text{kPa}}{(e_2 - e_1)} \quad \ldots\ldots (6)$$

where e_2 and e_1 are the saturation vapor pressures in kPa at the mean maximum and mean minimum temperatures respectively, for the warmest month of the year for the area. T_X is the intercept of the temperature axis. (Further details for both methods are given by Jensen *et al.* 1990).

Results and Discussions

The variation of the ratio ET/EA (the measured evapotranspiration to evaporation from class 'A' pan) during the six different periods is plotted in Fig. (1). As seen from this figure, the ratio increases from cold to hot weather conditions. It increases from

0.4 in January to 0.98 at 30 days after cut in June. This indicates that the measured evapotranspiration is closer to evaporation from a class A pan during summer, while it is far less than pan evaporation during the colder winter months. This was expected as transpiration increases during summer. The evaporation and transpiration of a crop are similar as long as the evaporative conditions are low and the upper soil is wet. When the climatic factors have high values and the upper soil layer becomes drier, the difference between evaporation and evapotranspiration increases (Jensen 1980).

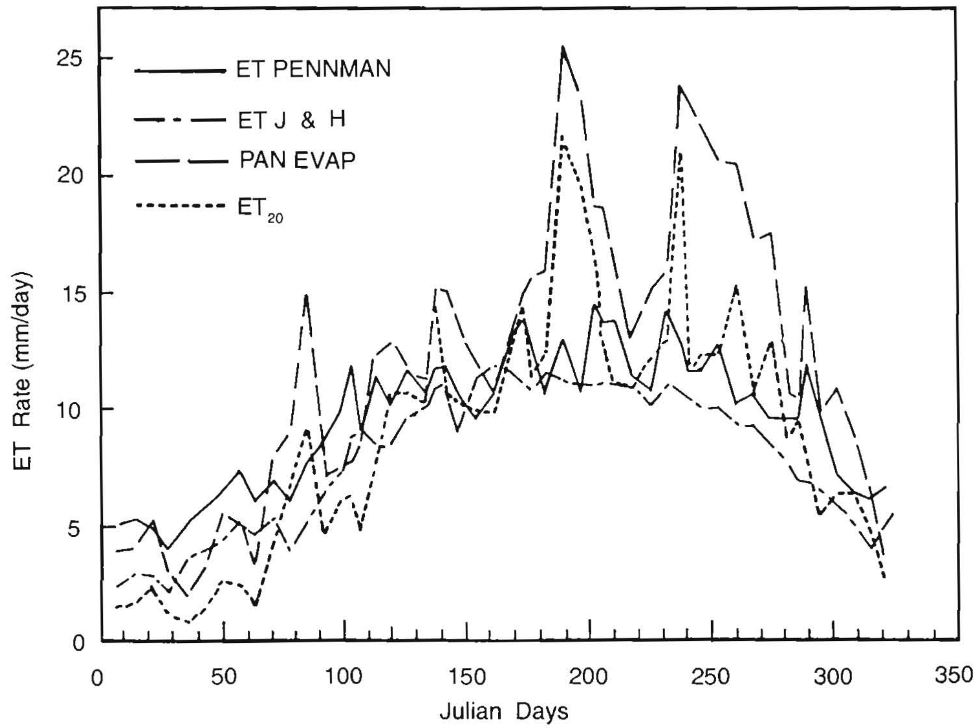

Fig. 2. The measured ET_{20} as compared to evap. from "A" Pan, ET estimated from penman and J&H method.

The measured and predicted evapotranspiration by the modified Penman and J&H methods are presented in Fig. (2). The evaporation from a class A pan is also shown on the same figure. As seen from this figure, the class A pan evaporation is the highest during the year except for the first 65 days and then from 90-110 days. The Penman estimates were the maximum during these periods. During the rest of the period, the Penman evapotranspiration followed almost the same pattern as the ET_{20} from measured values. The J&H predicted estimates are close to the pan evaporation values during the colder months and comparatively less during summer. This shows that the J&H method underestimates the evapotranspiration during summer season since it does not consider the advective energy transfer in hot summer months in desert areas.

The measured evapotranspiration was the lowest during the first 65-70 days and 90-110 days and was found to be very close to evaporation from a classA pan. It also followed almost the same pattern as the evaporation from a classA pan.

The differences taking place in Fig. 2 in the predicted values and those given by measured methods are due to different methods of accounting for the effects of many factors influencing evapotranspiration. These factors include air temperature, wind speed and distribution, relative humidity (RH), net solar radiation, and the advected energy. The J&H method is based on air temperature and solar radiation while the Penman method is based on the combination of the energy balance and aerodynamic equations. Fig. 2 shows that neither of the methods is in close agreement with either the measured evaporation or measured evapotranspiration. However, the Penman equation gave close values to the measured evapotranspiration during the hot summer months.

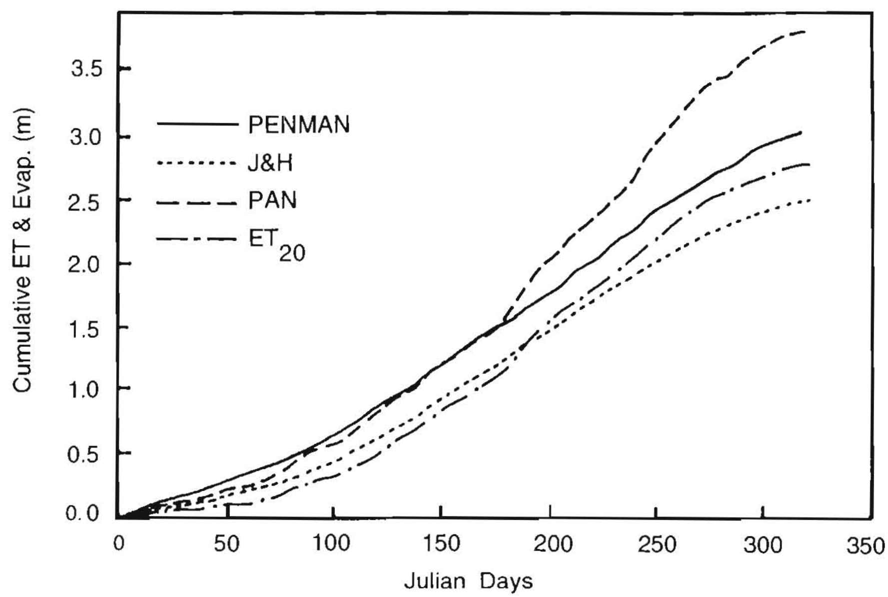

Fig. 3. Cumulative ET by different methods versus time in Julian Days.

Cumulative evapotranspiration values determined from measured values and predicted by Penman and J&H methods are given in Fig. 3. The measured evaporation from a class A pan consistently exceeded the measured and predicted values from the J&H method during the entire period. The cumulative Penman evapotranspiration values exceeded the pan evaporation for the first 150 Julian days. This may be due to the reason that the Penman equation was derived for evaporation for wet surfaces and it has a tendency to overestimate the evapotranspiration in arid areas (Phene *et al.* 1986). During the rest of the period, the cumulative pan evaporation was more.At the end, the cumulative pan evaporation exceeded the cumulative Penman, ET_{20} and J&H by 20.2%, 26.9% and 34.4% respectively, while the cumulative ET_{20} was greater than cumulative J&H by 10.2% and less than cumulative Penman by 9.2%.

Analysis of variance using the SAS system, was carried out and the measured evapotranspiration for the 320 days period from the lysimeters was correlated with the evapotranspiration estimated from different methods. The results of the analysis are given in Table (1). In the first case a linear regression with an intercept was assumed and the measured evapotranspiration was taken as dependent variable as shown in Fig. 4 (a,b,c,). The following relationship, shown in Fig. 4(a), was obtained between ET_{20} and the evapotranspiration estimated from Penman method:

$$ET_{20} = 1.5\ ET_{Penman} - 5.7 \qquad R^2 = 0.67 \quad \text{(7)}$$

where ET_{Penman} is the evapotranspiration estimated by Penman method. Similarly a straight line relationship between ET_{20} and the evapotranspiration estimated from J&H equation is shown in Fig. 4(b) with the following equation:

$$ET_{20} = 1.44\ ET_{J\&H} - 2.55 \qquad R^2 = 0.71 \quad \text{(8)}$$

Method		a	b	Prob. >T	F	Prob. >F	R^2	Standard Error
Case 1	Penman	−5.72		.0002	108.9	0.0001	0.67	1.45
			1.45	.0001				0.144
	J&H	−2.55		.0196	132.2	0.0001	0.71	1.057
			1.44	.0001				0.125
	Pan Evap.	−0.74		.1886	372.3	0.0001	0.88	0.554
			0.79	.0001				0.041
Case 2	Penman		0.96	.0001	428.5	0.0001	0.89	1.046
	J&H		1.16	.0001	591.8	0.0001	0.92	1.048
	Pan Evap.		.755	.0001	1543.4	0.0001	0.97	0.019

The relationship between ET_{20} and evaporation from class A pan is shown in Fig. 4(c) and given as follows:

$$ET_{20} = 0.79\ EA - 0.74 \qquad R^2 = 0.88 \quad \text{(9)}$$

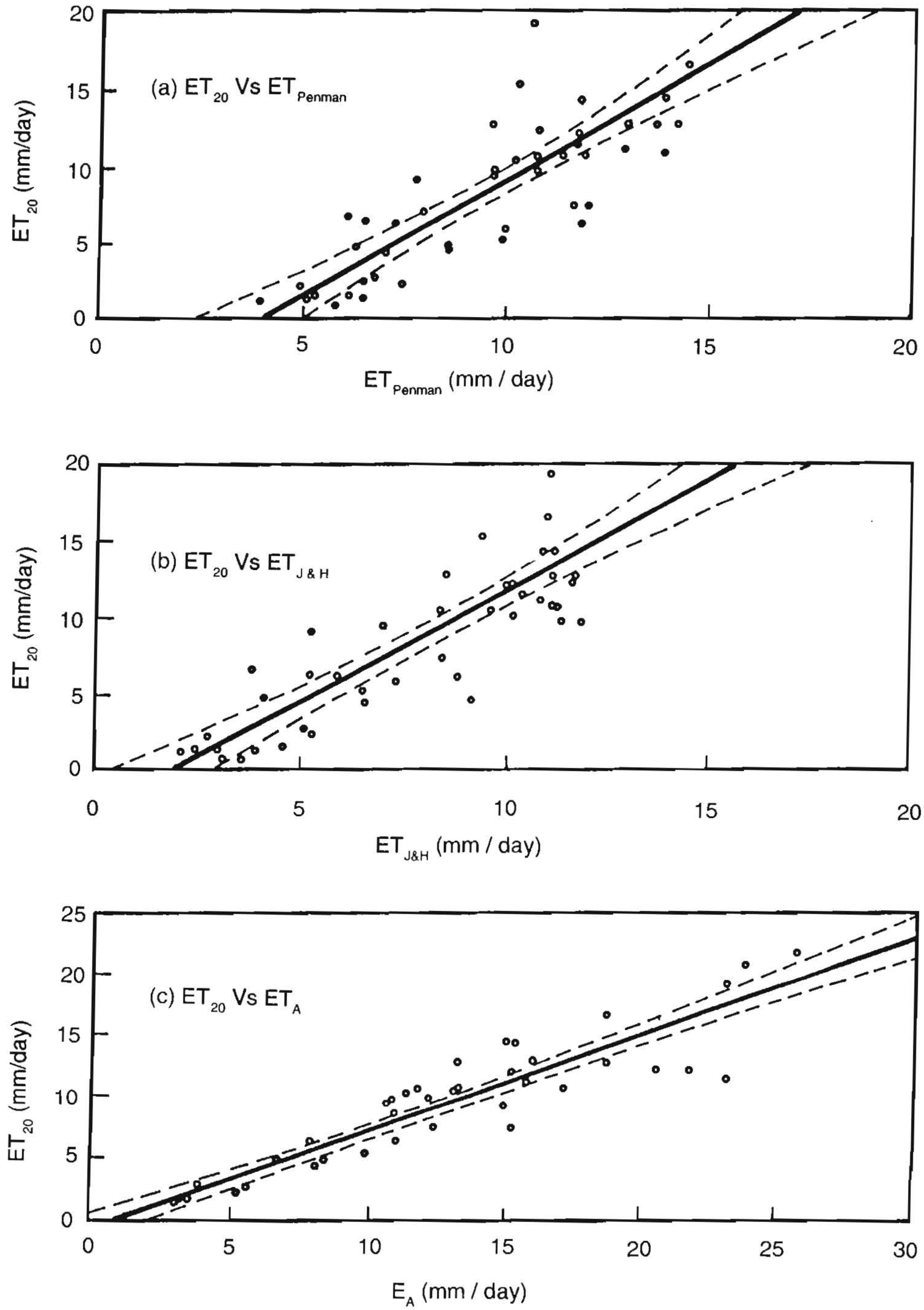

Fig. 4. The relationship between ET_{20} and Evapotranspiration estimated from different methods (Case 1: with intercept)

In the second case, a regression through the origin was used to evaluate the goodness of fit between the evapotranspiration measured from lysimeters and that estimated from equations, as shown in Fig. 5(a,b,c). This was assumed as both values should theoretically approach the origin when actual evapotranspiration is zero.The equations obtained from this regression are as follows:

$$ET_{20} = 0.96\ ET_{Penman} \qquad R^2 = 0.89 \quad \text{.......} (10)$$

$$ET_{20} = 1.16\ ET_{J\&H} \qquad R^2 = 0.92 \quad \text{.......} (11)$$

$$ET_{20} = 0.75\ EA \qquad R^2 = 0.97 \quad \text{.......} (12)$$

Equations (7,8,9) can be used to estimate reference evapotranspiration in Riyadh area. However, they give a negative value when evapotranspiration is small. Hence, these equations should be used with caution in colder months.The equations 10,11 and 12 can be used for evapotranspiration estimation throughout the year with more reliable results since R^2 is higher in this case for all methods.

A trial was made to find out the wind function from lysimeter evapotranspiration data to modify the Penman equation under the local conditions. Wind speed measurements at 2 m height above the ground from Dirab were used with the lysimeter measured ET_{20} values and the corresponding wind function f(U) was obtained according to the following equation, derived from equation (3):

$$f(U) = [ET_{20} - (\frac{\Delta}{\Delta + \gamma} R_n)] / [(\frac{\gamma}{\Delta + \gamma})(e_s - e_d)] \quad \text{.......} (13)$$

where ET_{20} is the lysimeter evapotranspiration from alfalfa in mm/day R_n is the radiation in mm/day. Assuming a straight line relationship between the wind function and wind speed in km/day at 2 m height, U, *i.e.*

$$f(U) = a + b\ U \quad \text{.......} (14)$$

the constants 'a' (intercept) and 'b' (slope) of correlation with wind speed were obtained as 0.33 and 0.0026 respectively. For comparison purposes, these values and those given by Wright (1982) were separately used in equation (3) and correlated to the measured ET_{20} values from lysimeters and the following correlation was obtained:

Intercept = 0, slope of line = 0.98 and R^2 = 0.76

when equation 12 was used the following correlation was obtained between the estimated and measured reference evapotranspiration:

Intercept = 0, slope of line = 0.96 and R^2 = 0.76

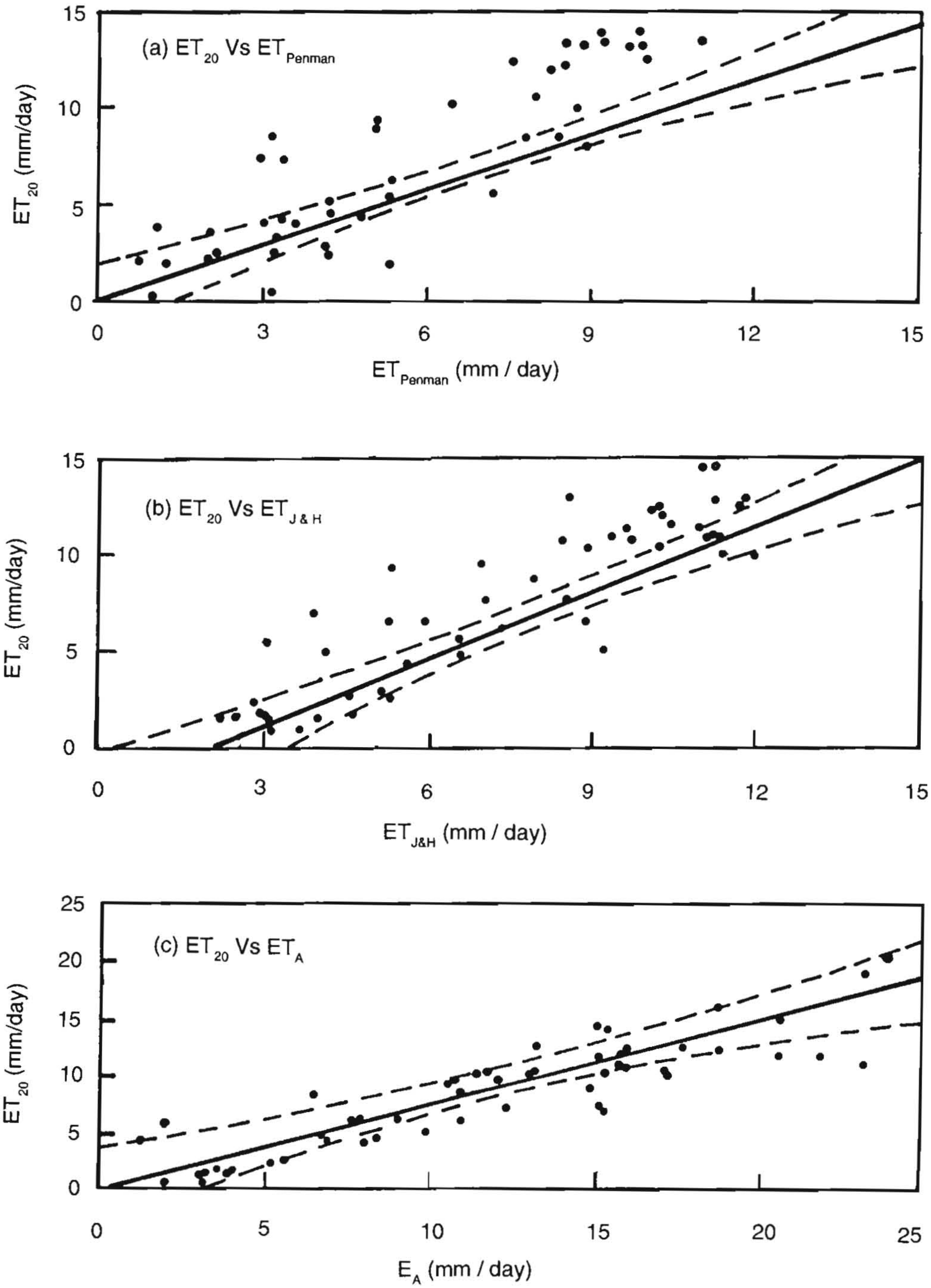

Fig. 5. The relationship between ET_{20} and Evapotranspiration estimated from dif ferent methods (Case 2: without intercept)

Since the correlations were the same in both cases and the wind function constants were close to each other, therefore, either of these wind functions could be used for predicting evapotranspiration using the Penman equation. The correlation between the measured ET_{20} and that estimated with the J&H method was obtained which also didn't give a higher value of R^2 (*i.e.* 0.67). However, a good correlation was found between the class A pan evaporation and the measured values. This may be due to the weather parameters obtained from Dirab which is 25 Km away from the site, the nearest meteorological station with full measuring sensors, while the pan evaporation measurements were taken near the site.

Conclusions

The evapotranspiration data from 3 lysimeters, under hot arid conditions, were used to obtain the reference evapotranspiration for alfalfa. A correlation between the measured ET_{20} was established with the evapotranspiration estimated by Penman and J&H Methods and class A pan evaporation and given in equations 7,8 and 9. A straight line passing through the origin gave a better correlation as compared to a straight line with intercept in all cases. The correlation between the measured reference ET and Penman and J&H was not very high due possibly to the non-availability of meteorological data near the site. The ET values by J&H method in summer underestimated the reference evapotranspiration under the extreme hot and dry conditions prevailing in this area.

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قياس البخر ـ نتح الفعلي بواسطة الليسميترات في المناطق الصحراوية

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استخدمت ثلاثة ليسميترات متشابهة في الحجم والشكل لقياس البخر ـ نتح الفعلي لمحصول البرسيم في المزرعة التعليمية بكلية الزراعة ، جامعة الملك سعود ، أبعاد كل منها (٢×٢×١متر) ، وقد تم إيجاد معامل الارتباط بين كل من البخر - نتح المقاس وذاك المحسوب من معادلة بنمان وجينسين ـ هيز التجريبيتين وكذلك مع معدلات التبخر من حوض البخر صنف أ .

أظهرت النتائج بأن هناك معامل إرتباط جيد بين البخر ـ نتح الفعلي وحوض البخر ، بينما وجد معامل الارتباط معتدل بين البخر ـ نتح الفعلي والمعادلات التجريبية تحت الظروف المحلية الصحروية .