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Estimation of reference evapotranspiration for southern region of Saudi Arabia

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Abstract The reference crop evapotranspiration (ET_r) for four areas in Saudi Arabia was estimated using five different methods: FAO-Penman, Jensen-Haise, Blaney & Criddle, pan evaporation, and calibrated FAO-Penman under local conditions (Penman$_{-SA}$). Comparison was also made between the estimated ET_r and the measured ET_r of alfalfa grown in lysimeters in the Riyadh area. Regression analysis revealed that estimated ET_r values were highly correlated with measured ET_r values. In addition, linear regression relationships between ET_r values estimated by the Penman$_{-SA}$ method and other methods were determined. The results of this study indicated that the calibrated Penman$_{-SA}$ method can be transferred successfully to other locations, and this method could be used for the estimation of ET_r values in all areas in the southern region of Saudi Arabia.

Introduction

With growing population, urbanization and irrigated agriculture in arid regions in general and in Saudi Arabia in particular, water shortages are increasing. As a result of increasing demand for water resources, competition for existing water supplies is becoming more critical each year, calling for wiser use of the limited available water. In Saudi Arabia, the agriculture sector accounts for more than 80% of the total annual water consumption. As demand intensifies the effective conservation of water is of primary importance to agricultural development. Finding methods that increase water use efficiency and reduce the excessive application of water are of importance for conserving water. The knowledge of crop evapotranspiration (ET) is one of the most important factors in irrigation scheduling, proper water management and water conservation.

The estimation of ET involves calculating the potential ET or the reference crop ET (ET_r), and then applying a suitable crop coefficient (K_c). Potential ET is defined as the rate at which water would be removed from wet soil and plant surfaces expressed as the rate of latent heat transfer per unit area, or as a depth of water per unit time. ET_r is defined as the rate at which water would be removed from the soil and plant surfaces expressed as the rate of latent heat transfer per unit area, or as a depth of water per unit time evaporated and transpired from a reference crop. The use of ET_r for a specified crop surface has largely replaced the use of the more general potential crop ET. This is because of the ambiguities involved in the interpretation of potential ET. Also, the use of a reference crop ET permits a physically realistic characterization of the effect of the microclimate of a field on the evaporative transfer of water from the soil-plant system to the atmospheric air layers overlying the field (Wright 1996). Alfalfa and grass are commonly used as reference ET surfaces, and the alfalfa ET_r has been used more for arid climates (Wright and Jensen 1972, 1978; Allen et al. 1989; Jensen et al. 1990; Abo-Ghobar and Mohammad 1995). Alfalfa has higher ET_r rates in arid areas where there is considerable advective sensible heat input from the air. ET_r obtained with such an alfalfa surface will usually be greater than that for a clipped grass surface, particularly in windy arid areas (Burman et al. 1981). Therefore, it can be advantageously used as a reference crop in arid areas (Wright and Jensen 1972).

Numerous scientists and specialists worldwide have developed many methods for estimating ET_r over the last 50 years. These methods were subject to rigorous local calibration and proved to have limited global validity (Smith et al. 1996). Doorenbos and Pruitt (1977) adopted the concept ET_r and adjusted several existing methods to yield identical ET_r estimates varying from

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complex energy balance techniques requiring detailed meteorological data to simpler methods with limited data requirements. The accuracy of ET_r estimates depends primarily on the ability of the methods being used to describe the physical laws governing the processes and the accuracy of the meteorological and cropping data (Jensen et al. 1990). Since the existing methods of estimating ET_r from meteorological data involve empirical relationships, some local or regional verification or calibration is advisable with any selected method. Tanner (1967) emphasized that any empirical equation for estimating ET_r needs to be calibrated, particularly in arid and semi-arid regions, because of the increased ET_r due to the advective energy from dry surroundings.

A few studies have been conducted to calculate ET_r for some selected areas in Saudi Arabia (Salih and Sendil 1985; Saeed 1986; Mustafa et al. 1989; Al-Omran and Shalaby 1992; Mohammad and Abo-Ghobar 1994; Abo-Ghobar and Mohammad 1995). The previous studies have concentrated on the central and eastern regions and the literature lacks the estimation of ET_r in the southern region of Saudi Arabia, which is considered to be one of the main agricultural regions in the country. Accordingly, the objective of this study was to determine ET_r for three major locations: namely, Najran (semi-mountainous inland), Asir (mountainous inland) and Jizan (coastal area), in the southern region of Saudi Arabia using five different methods. In addition, estimated ET_r for the different locations were compared with that estimated and measured for Riyadh, located inland.

Materials and methods

The availability of meteorological data is a major consideration in the selection of a method for calculating ET_r. Selection of the appropriate method for a specific location is a difficult task because unique guidelines are not available for defining the method of application most likely to give the best estimates. The methods considered in this study include those ranging from temperature-based methods to the more data-intensive combination methods. The methods are (1) FAO-modified Penman method; (2) Jensen-Haise (J-H) method; (3) modified Blaney & Criddle (B & C) method; (4) pan evaporation method and (5) the modified Penman method for Saudi Arabia climatic conditions (Abo-Ghobar and Mohammad 1995). The last method was used in this study, because experience has shown that most equations developed are not universally applicable without modification, or local calibration to all climatic or crop situations, especially in a dry and hot climate. These methods were chosen for this study to estimate the ET_r for each area and also to make a comparison among them in order to select the most suitable method for each area. The following is a review of the selected methods used in this study.

FAO-modified Penman method

The FAO-24 publication by Doornbos and Pruitt (1975, 1977) presented a modified Penman equation for estimating ET_r for grass (FAO-Penman method). However, this modified equation tends to overestimate ET_r at many locations (Jensen et al. 1990). Frevert et al. (1983) modified this method by introducing the polynomial equation for the adjustment factor (C), which compensates for the effect of day and night local weather conditions. This factor is a function of the maximum relative humidity (Rh_{max}), the solar radiation (R_s), the daytime wind speed (U_{day}), and the day/night wind ratio (U_{day}/U_{night}). The FAO modified Penman equation used is:

$$ET_r = C[w \cdot R_n + (1 - w)f(u) \cdot (\mathrm{VPD})] \quad (1)$$

where ET_r = reference crop evapotranspiration in mm/day (grass reference) C = adjustment factor = $0.6817006 + 0.0027864\ Rh_{max} + 0.0181768\ R_s - 0.0682501\ U_{day} + 0.0126514\ (U_{day}/U_{night}) + 0.0097297\ U_{day}\ (U_{day}/U_{night}) + 0.43025 \times 10^{-4}\ Rh_{max}\ R_s\ U_{day} - 0.92118 \times 10^{-7}\ Rh_{max}\ R_s\ (U_{day}/U_{night})$

w = temperature-related weighting factor = $\Delta/(\Delta + \gamma)$
Δ = rate of change of saturation vapour pressure with temperature in mbar/C
$\Delta = 2\ (0.00738\ T_{ave} + 0.8072)^7 - 0.00116$
γ = psychometric constant = 0.378 Pa/L
P_a = atmospheric pressure, given for any altitude = $(1013 - 0.1093E)$, where E is the elevation above mean sea level
L = latent heat of vaporization = $596 - 0.51\ T$
R_n is the net radiation (mm/day), T is the monthly mean air temperature in °C
$f(u)$ wind function = $0.27(1 - U_2/100)$, where U_2 is the wind speed in km/day

VPD is the vapour pressure deficit = $(e_s - e_d)$, where e_s is the saturation vapour pressure at T (mbar), and e_d is the the mean actual vapour pressure of the air (mbar), and can be calculated by:

$$e_s = 6.1078\,e^{(17.27T)/(T+237.3)}$$

$$e_d = \mathrm{Rh} \cdot e_s$$

Since the FAO-modified Penman method gives ET_r for grass, the estimated values by this method should be multiplied by 1.15, which is the factor for converting the grass ET_r to the alfalfa ET_r as suggested by Pruitt and Doorenbos (1977) for arid climate. The adjustment factor (C) was calculated for each area by using the equation developed by Frevert et al. (1983). C values were varied between the maximum and minimum, and the averages of all the values are 0.91, 0.96, 1.03 and 1.07 for Riyadh, Najran, Asir and Jizan, respectively. It can be noticed that the value of C is higher for humid areas (Jizan and Asir) than for dry areas (Riyadh and Najran).

Jensen-Haise method

The modified Jensen-Haise equation (J-H method) is used to estimate ET_r for alfalfa. This equation is based on air temperature, solar radiation, and vapour pressure as follows:

$$ET_r = C_T(T - T_x)R_s \quad (2)$$

where T = monthly mean temperature (°C)

R_s = incident solar radiation (mm/day)
$C_T = (1/C_1 + 7.3C_h)$; with $C_1 = 38 - (2E/305)$; where E = site elevation in m
C_h = 50 mbar/$(e_2 - e_1)$ where e_1, e_2 are the saturation vapour pressure over water, in mbar, at the mean monthly maximum and minimum air temperatures of the warmest month in the year, respectively.
$T_x = -2.5 - 0.14(e_2 - e_1) - (E/550)$.

Modified Blaney & Criddle method

Doorenbos and Pruitt (1977) presented the most fundamental revision of the B & C method since its introduction in 1945 in the United States of America. This modification is generally referred to as the FAO-24 B & C method. In this modification, other variables have been introduced such as Rh_{min}, U_{day}, and sunshine ratio (n/N, the ratio of actual to maximum possible sunshine hours). Doorenbos and Pruitt (1977) suggested using this method to estimate ET_r for 1 month or longer. The modified B & C method has been used throughout the world, and is written as follows:

$$ET_r = a + b\,p(0.46\,T + 8.13) \quad (3)$$

where ET_r = reference evapotranspiration in mm/day

T = monthly mean temperature in °C
p = mean daily percentage of total annual day hours for the period
a, b = adjustment factors
$a = 0.0043\ Rh_{min} - (n/N) - 1.41$
$b = 0.81917 - 0.0040922\ Rh_{min} + 1.0705(n/N) + 0.065649\ U_{day} - 0.0059684Rh_{min} \cdot (n/N) - 0.0005967Rh_{min} \cdot U_{day}$

The adjustment factors (a, b) are used because the equation without these factors was found to give ET_r values that are high at low temperatures and low at high temperatures. These factors take into consideration the effect of the three most important climatic factors.

Pan evaporation method

Evaporation pans provide a measurement of the integrated effects of radiation, wind, temperature and humidity on evaporation from a specific open water surface. This method was also used to estimate ET_r with reference to evaporation from class A pan (E-pan method). Evaporation pan data are relatively easy to obtain and can be very reliable if the evaporation site is maintained in a suitable and consistent manner. Evaporation data collected in poorly maintained locations will not produce estimates as accurate as those based on good meteorological data. Evaporation pan data can provide a simple independent check of the ET_r estimates and is given as:

$$ET_r = K_p \cdot E_p \quad (4)$$

where K_p is the pan coefficient, which is dependent on the type of pan involved and other factors, E_p is evaporation from class A pan. The values of K_p were determined from Table 18 on page 34 of FAO-24 by Doorenbos and Pruitt (1977). These values were 0.7 for Riyadh and Najran, and 0.8 for Asir and Jizan.

Calibrated Penman for Riyadh area in Saudi Arabia (Penman$_{-SA}$)

This equation was used to estimate $ET_{r\text{-}SA}$ under local climatic conditions of Riyadh, as suggested by Abo-Ghobar and Mohammad (1995). They suggested that the FAO-modified Penman equation (Eq. 1) should be corrected since the Eq. (1) is not expected to give the same values as obtained experimentally at all locations. Hence, it should be calibrated under Riyadh or other areas. The relationship between the estimated values (ET_r) from the Penman method and the actual values ($ET_{r\text{-}SA}$) is as follows:

$$ET_{r\text{-}SA} = A + B\ ET_r \quad (5)$$

where ET_r is the reference crop ET in mm/day (grass reference) estimated by Eq. (1); $ET_{r\text{-}SA}$ is the reference crop ET estimated under local conditions, the constants A and B include the necessary adjustments for local conditions. The values are $A = 0$ (the regression line passing through the origin) and $B = 0.96$, so that the equation could be written as:

$$ET_{r\text{-}SA} = 0.96ET_r \quad (6)$$

The mean monthly meteorological data over the last 20 years for the four areas were collected from the meteorological stations in each location. These data were maximum, minimum and average of air temperature, relative humidity, and also the data on radiation, wind speed, vapour pressure, rainfall and evaporation. The four study areas vary in their meteorological data and latitude, as can be seen from Table 1. Najran is semi-mountainous, and situated in the middle of the southern region (900 km south of Riyadh) and Asir is mountainous and located about 250 km west of Najran, whereas Jizan is situated about 200 km south west of Asir on the Red Sea.

The measured alfalfa ET_r data in Riyadh area obtained by Abo-Ghobar and Mohammad (1995) from three lysimeters were used to evaluate and compare the estimated ET_r by these methods. They installed three lysimeters at the Educational Farm of the College of Agriculture, King Saud University, Riyadh. The lysimeters were planted with alfalfa and surrounded with an alfalfa belt in 18 basins (plots) of equal size covering an area of 2500 m^2. These plots were irrigated simultaneously with the lysimeters. Each lysimeter had a surface area of 4 m^2, having an effective soil profile depth of 1.5 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 a sandy loam excavated from the lysimeter site in layers of 150 mm and carefully compacted. Irrigation water was measured by flow meters and applied by surface irrigation; also drainage water was collected and measured with graduated cylinders. Adequate water supply and full cover conditions were maintained throughout, and the ET was obtained by balancing the inputs and the outputs to the lysimeters. Tensiometers were installed in each lysimeter at different depths and the tension was kept within 25 kPa (corresponding to moisture depletion of 35%) to ensure that adequate water was always available.

The three lysimeters were managed in the same manner with respect to irrigation treatments, fertilizer application and cutting. The experiment was conducted for 2 years and the lysimeters were planted with alfalfa in December 1991. The daily evaporation from a class A pan was measured during the entire course of the experiment from the meteorological station situated near the site of the experiment. The alfalfa in the lysimeters and basins was cut when about 10% of the flowers appeared. The initial growth cycle from planting to cuts was 100 days, while the subsequent growth cycles between consecutive cuts were of about 35 days each. The crop height was measured twice a week. The alfalfa reached a height of 20 cm on the 15th day after each cut. The cutting was carried out manually and the height after each cut was about 70 mm.

Results and discussion

A computer program was written to calculate the ET_r values on a monthly basis for each method using the meteorological data for each area. The mean monthly ET_r estimated by the different methods for each of the

Table 1 Mean meteorological data of the four areas under the study [W_s wind speed, *Rain* (mm/month), R_s solar radiation (mm/day), n sunshine duration (h/day)]

Area	Altitude (m)	Latitude (N)	Longitude (E)	Mean Annual					
				TC	Rh (%)	W_s (m/s)	Rain	R_s	n
Riyadh	564	24°34′	46°43′	25.5	30.4	1.56	8.5	7.4	8.3
Najran	1250	17°33′	44°14′	23.2	36.2	1.12	5.4	7.0	8.2
Asir	2200	17°10′	42°37′	18.1	55.4	1.13	18.2	6.9	8.0
Jizan	40	18°12′	42°29′	31.0	66.8	1.72	9.3	7.1	7.6

four areas are plotted in Figs. 1–4. Taking each figure separately, it can be seen that there are some differences in the ET_r values estimated by the various methods in one area. This variation increases or decreases between the methods depending on the type of method used and the weather parameters included in the method. Also, there is variation between the values of ET_r estimated by the different methods when compared among areas; this can be attributed to the different methods of estimation used and to the natural variation in climatic conditions influencing ET that occur in each area. In general, it can be seen that the Riyadh area (inland) has the higher

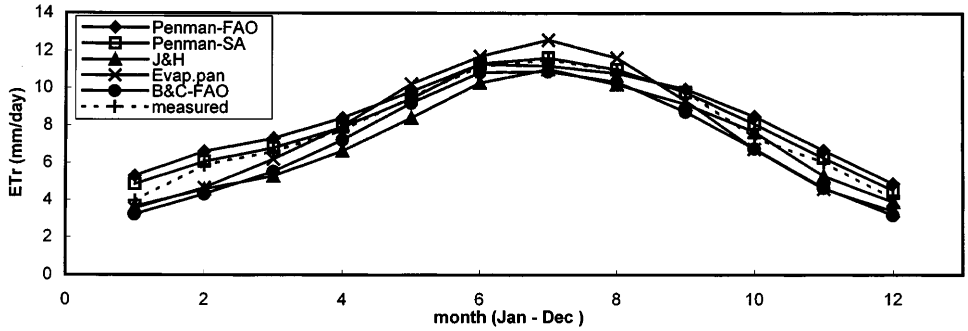

Fig. 1 Comparison between average monthly reference crop evapotranspiration (ET_r) estimated by various methods in addition to measured ET_r for Riyadh area

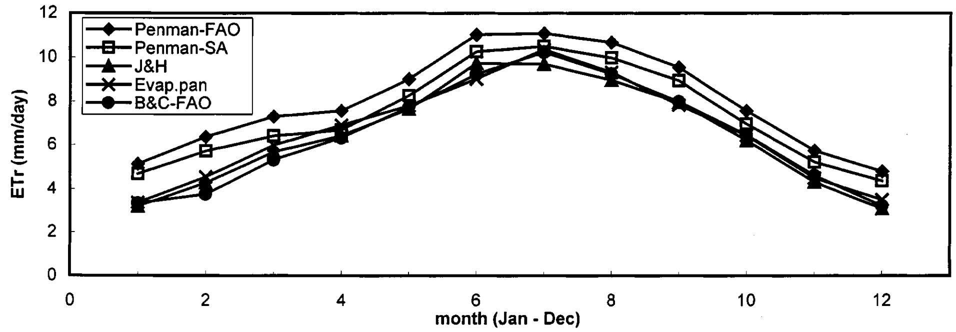

Fig. 2 Comparison between average monthly ET_r estimated from various methods for Najran area

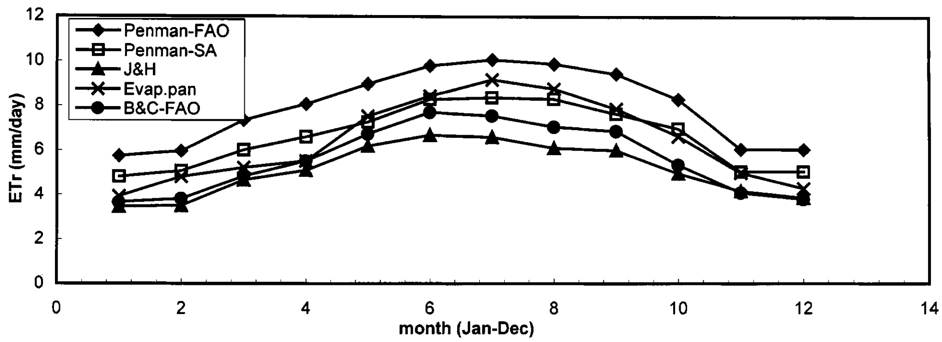

Fig. 3 Comparison between monthly average ET_r estimated by various methods for Asir area

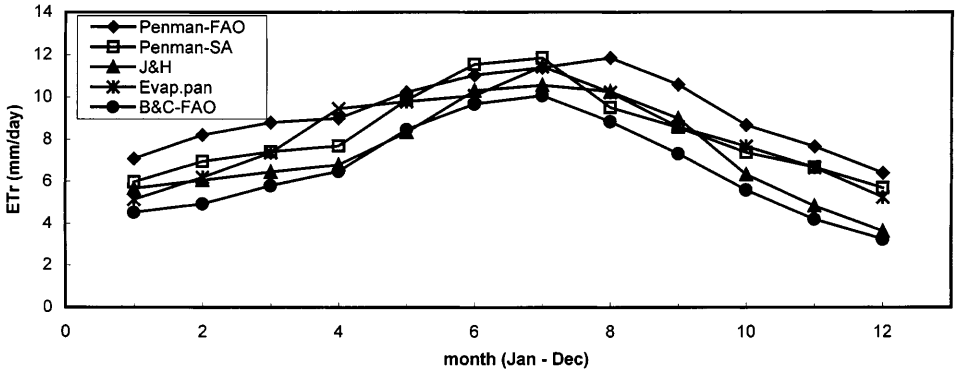

Fig. 4 Comparison between average monthly ET_r estimated by various methods for Jizan area

mean monthly ET_r values in summer, but Jizan (coastal area) has the highest ET_r in winter, while Asir (mountainous area) gave the lowest values of ET_r. Almost all estimation methods involve some empirical relationships and are subject to local calibration; hence they render limited global validity (Smith et al. 1996). Consequently, there will be differences in the ET_r values as can be seen in the figures. Thus, some equations overestimate the ET while others underestimate it. This is due to different methods of accounting for the effects of many factors influencing ET. These factors include air temperature, wind speed and direction, relative humidity, net solar radiation and advective energy. Also, the ET_r measured for alfalfa from the three lysimeters were averaged, and the results are presented graphically in Fig. 1. It can be seen that the variations between the measured and estimated values are small, and the calibrated Penman$_{\text{-SA}}$ gave the results closest to the measured values.

Since the values of ET_r as given by the different methods vary even in one area, the main concern was to determine which of these methods should be used to estimate ET_r for a given area. To resolve this matter, a comparison was made between average monthly ET_r values measured for alfalfa with those estimated by the five methods for the Riyadh area. The ET_r values measured in Riyadh were used as a standard for comparison purposes for the other areas in the southern region due to the difficulties of measuring ET_r values in these areas; also, the Riyadh area is the closest location with measured ET_r data. There is a need, despite the differences in climatic conditions, to transpose the measured data obtained under local conditions (Riyadh area) to other areas, where there is no measured data or local calibration of the various methods. Although this may result in some expected errors and the results obtained may be less precise due to climatic variations, but it is still of considerable value in order to estimate water use for agricultural crops in these areas. Therefore, linear regression analyses were made between the measured ET_r from three lysimeter values and the estimated ET_r values from the selected methods for each area, and the results of these regressions are given in Table 2.

There is a high degree of correlation (R^2) between measured and estimated ET_r values for all the areas. This implies that the measured ET_r from Riyadh could be transposed to these areas. It can be concluded that the modified Penman for local climate (Penman$_{\text{-SA}}$) ranked first, and it had the highest correlation with lower absolute intercept values of the regression lines for the four areas compared with the other methods, which for the most part gave comparable results. Fig. 1 shows that Penman$_{\text{-SA}}$ method gives the closest estimates to the measured values in comparison to the other methods. Therefore, from these results, the Penman$_{\text{-SA}}$ method was thought the most suitable for computing ET_r for all areas.

To judge the correlation between Penman$_{\text{-SA}}$ method and the other methods, the regression analysis was made between the ET_r values estimated by the Penman$_{\text{-SA}}$ method and those estimated by the other methods in each area, as shown in Table 3. It can be seen that there are highly significant correlations between Penman$_{\text{-SA}}$ values and those estimated by the other four methods. The best correlation was between the Penman$_{\text{-SA}}$ and FAO-Penman methods for Riyadh and Najran areas, and the Penman$_{\text{-SA}}$ and B & C methods for Asir and Jizan, since their regression lines gave highest R^2 values. This may be due to the locations of these two areas, since the B & C equation was originally developed for humid areas where the advective effect is usually negli-

Table 2 Simple linear regression ($y = a + bx$) between measured ET_r of alfalfa at Riyadh (y) and ET_r estimated by other equations (x) from different areas

Area	Method	Intercept (a)	Slope (b)	Correl. Coeff. (R^2)
Riyadh	Penman	−2.06	1.19	0.99
	Penman$_{\text{-SA}}$	−0.84	1.07	0.99
	J-H	0.72	1.001	0.97
	E-Pan	1.76	0.80	0.98
	B & C	1.40	0.92	0.99
Najran	Penman	−1.48	1.17	0.97
	Penman$_{\text{-SA}}$	−0.94	1.21	0.98
	J-H	0.74	1.11	0.99
	E-Pan	0.35	1.14	0.97
	B & C	0.90	1.08	0.98
Asir	Penman	−4.37	1.54	0.95
	Penman$_{\text{-SA}}$	−0.72	1.87	0.97
	J-H	−3.21	2.18	0.93
	E-Pan	−1.17	1.49	0.95
	B & C	−1.58	1.70	0.96
Jizan	Penman	−5.92	1.49	0.94
	Penman$_{\text{-SA}}$	−2.36	1.24	0.96
	J-H	−0.35	1.12	0.92
	E-Pan	−2.47	1.28	0.95
	B & C	0.35	1.14	0.93

Table 3 Simple linear regression ($y = a + bx$) between mean monthly ET_r (mm/day) estimated by Penman$_{\text{-SA}}$ equation (y) and those estimated by other equation (x)

Areas	Method	Intercept (a)	Slope (b)	Correl. Coeff. (R^2)
Riyadh	Penman	−1.12	1.10	0.99
	J-H	1.42	0.94	0.98
	E-Pan	2.45	0.74	0.98
	B & C	2.10	0.85	0.99
Najran	Penman	−0.42	0.97	0.99
	J-H	1.48	0.91	0.98
	E-Pan	1.18	0.93	0.96
	B & C	1.18	0.89	0.97
Asir	Penman	−3.70	1.46	0.94
	J-H	−2.16	2.02	0.93
	E-Pan	−0.31	1.32	0.97
	B & C	−0.68	1.58	0.96
Jizan	Penman	1.45	1.05	0.82
	J-H	2.16	0.83	0.87
	E-Pan	0.89	0.90	0.85
	B & C	0.44	0.88	0.95

gible. Table 3 may prove useful for conversion purposes from one method to another.

Conclusion

Five methods for the estimation of crop ET_r were evaluated under a hot and arid climate, by using over 20 years of meteorological data for each of the four areas under study. The results indicated that no one method provided the best results under all conditions. However, it was found that the ET_r estimated by the different methods was closely correlated with the ET_r measured from the lysimeters in the Riyadh area. Thus, a measured ET_r from Riyadh could be transposed to areas in the southern region of Saudi Arabia. In addition, the calibrated Penman$_{\text{-SA}}$ method gave the estimates closest to the values measured in comparison to the uncalibrated methods. Therefore, from these results, it is concluded that the Penman$_{\text{-SA}}$ method can be recommended for computing ET_r for all areas in the southern region of Saudi-Arabia.

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