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Evaluation of Five Methods for Estimating Class A Pan Evaporation in a Humid Climate

Suat Irmak[1] and

Dorota Z. Haman[2]

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SUMMARY. Evaporation pans continue to be used extensively throughout the world to measure free-surface water evaporation (E_{pan}) and to estimate evapotranspiration for irrigation scheduling and water management for agronomic and horticultural crops. E_{pan} is also being used extensively to estimate evaporation rates from lakes, wetlands, rivers, reservoirs, and other water bodies for management of wildlife and ecological habitat. A reliable method is needed to estimate missing daily E_{pan} data. Determination of a reliable method for the estimation of E_{pan} would also be useful in modeling of crop growth, and hydrological and ecological systems. Five methods [Penman (Penman, 1948), Kohler-Nordenson-Fox (KNF) (Kohler et al., 1955), Christiansen (Christiansen, 1968), Priestley-Taylor (PT) (Priestley and Taylor, 1972), and Linacre (Linacre, 1977)] for estimating E_{pan} were compared with the historical (23-year) measured daily values to determine the success of accurate and consistent E_{pan} estimations under humid climatic conditions in Florida. The root mean square error (RMSE) was used as the criteria to judge the accuracy and reliability of a given method. An RMSE value of <0.5 mm·d^{-1} (0.02 inches/d) between the measured and estimated E_{pan} was considered as an acceptable error for daily estimations. The standard deviation (SD) values, and percent error (%E) between the estimated and measured values were

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[1]Department of Agricultural and Biological Engineering, University of Florida, 234 Frazier Rogers Hall, P.O. Box 110570, Gainesville, FL 32611. To whom reprint requests should be addressed; e-mail sirmak@mail.ifas.ufl.edu.

[2]Department of Agricultural and Biological Engineering, University of Florida, Rogers Hall, P.O. Box 110570, Gainesville, FL 32611.

also considered in the performance evaluations. Performance evaluations of the E_{pan} estimates of the methods were made on a daily, monthly, and annual basis. Results indicated that the KNF method provided the best E_{pan} estimations. The Linacre method yielded the poorest estimates. The second, third, and fourth best methods were the Penman, PT, and Christiansen, respectively. The RMSE and SD of E_{pan} estimates were lowest when using KNF method. The mean value of the %E of daily, monthly, and annual estimations were 27%, 27%, and 26% for Christiansen; 6%, 6%, and 4% for KNF; 33%, 32%, and 26% for Linacre; 24%, 24%, and 21% for PT; and 19%, 17%, and 11% for Penman methods, respectively. The weekly, monthly, and annual total of E_{pan} estimates from KNF method were also compared to the measured values of the two selected years of data (1981 and 1983). The annual rainfall totals were significantly lower than the 23-year mean in 1981, and higher in 1983. The %Es of weekly, monthly, and annual total E_{pan} estimates were 9%, 9%, and –1% in 1981; and 11%, 5%, and 4% in 1983, respectively. The KNF method underestimated E_{pan} in 1981 (dry year) and the underestimations were higher in summer months. The underestimations in a dry year, especially in summer months, might be due to the fact that the sensible heat advection is not effectively accounted for in the KNF equation causing underestimations of E_{pan}. Overall results indicated that the KNF method should be the first choice, among the methods tested, for estimating daily E_{pan} for irrigation scheduling and for estimating the missing E_{pan} data in humid areas.

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature, and humidity on the evaporation from an open water surface (Allen et al., 1998). Pan evaporation data have been used in many different applications. E_{pan} has been used for irrigation scheduling of many horticultural and agronomic crops such as blueberries (*Vaccinium corymbosum*) (Byers and Moore, 1987), tomatoes (*Lycopersicum esculentum*) (Locascio and Smajstrla, 1996; Smajstrla and Locascio, 1990), snap beans (*Phaseolus vulgaris*) (Smittle et al., 1990), turfgrass (*Cynodon* spp.) (Carrow, 1995), wheat (*Triticum aestivum*) (Bandyopadhyay, 1997), french bean (*Phaseolus vulgaris*) (Nandan and Prasad, 1998), and rubber (*Hevea brasiliensis*) (Rao et al., 1998). Also, in another application of E_{pan} data, Rohwer (1931), Young (1945), Kohler (1954), Penman (1956), Sellers (1965), Hounam (1973), and (Abtew, 2001) have shown that E_{pan} can successfully be used to estimate evaporation from lakes, reservoirs, and other water bodies. Numerous studies have shown a high correlation between E_{pan} and reference evapotranspiration (ET_o) (Doorenbos and Pruitt, 1975; Jensen et al., 1961; Pruitt, 1966). de Wit (1958) developed a model which uses E_{pan} data as one of the input parameters to estimate crop dry matter production. Since E_{pan} value is measured as depth of water, it is also directly comparable with rainfall records. Since the evaporation rate from the Class A pan and the evapotranspiration (ET) rate from vegetated surface differ, the two rates are related by a pan coefficient (K_{pan}). The K_{pan} accounts for upwind fetch of low-growing vegetation, mean daily wind speed, and mean daily relative humidity were reported by Doorenbos and Pruitt (1977). In some cases, the term crop factor (CF) or crop coefficient (K_c) and K_{pan} have been used in the literature interchangeably. However, CF or K_c and K_{pan} are two different coefficients and are sometimes misused in the literature. The K_{pan} values mentioned in this paper represent the local coefficients that are used to convert pan evaporation values to reference evapotranspiration, and they do not represent the crop factors. The National Weather Service (National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.) has standardized evaporation pans, for their use in the U.S., to the Class A pan [1.21 m (47.638 inches) in diameter and 0.25 m (9.843 inches) deep set on a 0.15 m (5.906 inches) wooden platform] which has also been the most widely-used type of pan in many other countries.

In some cases, continuous measurement of daily E_{pan} may not be possible due to practical, theoretical or financial reasons. Evaporation pans equipped with automated measurement devices (Asrar et al., 1982; Phene and Campbell, 1975) are relatively expensive and devices that rely on floats can often be subject to mechanical malfunctions, causing significant errors in readings. A less expensive system, a washtub method, 0.48 m (18.898 inches) in diameter and 0.25 m deep, with slightly sloping sides (Sims and Jackson, 1971; Westesen, 1978), has been used for irrigation scheduling of field and horticultural crops. A misuse of this method is often reported since other non-standard containers such as oil drums and other containers are used without calibration (Westesen and Hanson, 1981). However, Simonne et al. (1992) have shown that measurements of 3-d and 6-d cumulative pan evaporation using a washtub provided an accurate, easy, and inexpensive way to schedule irrigations. In Florida, only a few weather stations measure E_{pan} on a regular basis. In addition, in Florida, as is the case in many states in the U.S. and around the world, missing E_{pan} data can cause limitations to users and should be estimated with reasonable accuracy using physically or empirically based equations. For example, of the 29-year of E_{pan} data that were collected in Green Acres Agricultural Research Center (GAARC) near Gainesville, Fla., only 23-year of data are currently available to the researchers/users due to considerable amount of missing data for the other 6 years. The situation is similar or worse in other stations throughout Florida and southeastern U.S.

Equations developed to estimate E_{pan} give reliable results when applied to climatic conditions similar to those for which they were developed. Thus, the reliability and consistency of the methods for estimating E_{pan} should be tested against measured data for a given locality. In Florida and in other humid areas with a climate similar to that of Florida, not enough information is available to indicate which method gives the best estimates of E_{pan}. The objective of this study was to compare five E_{pan} estimation methods to select the best method for reliable and accurate E_{pan} estimations under humid climatic conditions in Florida.

Materials and methods

Climate characteristics of the study region. In any study that is related to the crop irrigation, water management, and climate, it is important to report long-term distributions of the basic climate variables so that the reader would be able to better interpret and compare the results of this study to their local climate and soil conditions. In Florida, the average annual rainfall ranges from 1,016 mm (40.0 inches) in the Keys to nearly 1,680 mm (66.1 inches) in the Panhandle and the statewide average is 1,372 mm (54.0 inches). About 60% of the total annual precipitation occurs during the period June through September (Clemens et al., 1984). In this study area (Gainesville), the 23-year mean monthly total rainfall ranged from 60 mm (2.4 inches) in November to 183 mm (7.2 inches) in August with a 23-year annual mean of 1,301 mm (51.2 inches) (Fig. 1A). The long-term daily mean values of the extraterrestrial radiation (R_a), clear-sky solar radiation (R_{so}), incoming solar radiation (R_s), and net radiation (R_n) throughout the year for the 23-year period are given in Fig. 1B. Daily maximum, mean, and minimum temperature, and daily mean and minimum relative humidity values are given in Fig. 1C and D, respectively. The pattern of the daily mean wind speed is given in Fig. 1E. In Fig. 1A–E, each data point represents an average of 23 measurements per day.

CLIMATIC DATASET, PROCEDURES, AND EQUATIONS USED TO ESTIMATE E_{pan}. The climate data used in this study consisted of 8,395 daily data points. Daily data for the 23-year period (1 Jan. 1978 to 30 Sept. 2000) were obtained from the GAARC weather station [(lat. 29°38' N, long. 82°22' W, elevation = 29.3 m (96.13 ft)] located near Gainesville, Fla. Daily weather variables measured at the station include rainfall, maximum and minimum air temperature, relative humidity, wind speed and direction, incoming solar radiation, and open Class A E_{pan}. The wind speed was measured at 0.61 m (24.016 inches) above the ground. At the GAARC, the E_{pan} readings were recorded on a daily basis and the depletion between yesterday's and today's evaporation rate had been calculated and reported to the users. It should be noted that the rainfall effect on E_{pan} readings had already been accounted for when the depletion was calculated. Therefore, in this study, the measured pan evaporation data reflect the rainfall effect in daily measured versus estimated E_{pan} comparisons.

The water management districts and other institutions who are responsible for designing and managing of water resources and granting water permits to the farmers/growers for irrigation of agronomic and horticultural crops need to project monthly and annual water consumption. Therefore, in every evaporation and/or evapotranspiration study, it would be very useful to report monthly and annual total or average E_{pan} or evapotranspiration estimates. The E_{pan} values from five methods were calculated using the 23-year measured daily weather data and then averaged over 23-year to obtain a long term daily, monthly, and annual average. The RMSE was used as the criteria to judge the accuracy and reliability of a given method. The SD and %E between estimated and measured values were also considered in the performance analyses. The RMSE between the measured and estimated E_{pan} was calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i^e - y_i^m)^2} \quad [1]$$

where n is the number of observations, y_i^e is the estimated E_{pan}, and y_i^m is the measured E_{pan}. Although in the literature, the minimum acceptable error of the E_{pan} estimations by different E_{pan} methods has not been reported, in this study, an RMSE value of <0.5 $mm \cdot d^{-1}$ (0.02 inches/d) between the measured and estimated E_{pan} was considered as an acceptable error for daily estimations. The %E of estimation was calculated as the difference between the estimated and measured E_{pan} divided by the measured E_{pan} and multiplied by 100. The plus (+) and minus (–) signs were used in %Es to indicate over and underestimations, respectively. Duncan's multiple range test (DMRT) was used to identify if the estimated E_{pan} values were significantly different from the measured values at the 5% significance level for a given period. The method providing the best estimates of E_{pan} (lowest RMSE between the measured and estimated E_{pan}) was further tested to evaluate the performance of the method during two selected years, which had rainfall distributions significantly different than the 23-year average.

The E_{pan} was estimated using five methods developed in various climatic regions. The methods evaluated were Penman (Penman, 1948), KNF, (Kohler et al., 1955), Christiansen (Christiansen, 1968), PT (Priestley and Taylor, 1972), and Linacre (Linacre, 1977). All of the methods used in this study, except for the Penman pan evaporation equation, were described by Burman and Pochop (1994). The form of the Penman E_{pan} equation given by Jensen et al. (1990) was used. The detailed description of each method is not given here and the reader is referred to the original sources.

In principal, the Penman and the KNF methods are similar with the exception of the psychrometric constant and the calculation of the aerodynamic function. The humidity coefficient (C_H) in the Christiansen equation which was modified by Burman (1976) was used here, and the Christiansen's monthly coefficient (C_M) was taken as 1 as suggested by Burman (1976). The daily soil heat flux term (G) in the PT equation was assumed to be zero. The daily values of R_n were calculated using the procedures described by Allen et al. (1998). Because equations used in this study require wind speed values at a 2 m (78.7 inches) height, daily wind speed measured at 0.61 m was converted to the 2 m standard height using the procedures described by Allen et al. (1998).

Equations to estimate Class A pan evaporation

PENMAN (1948) PAN EVAPORATION EQUATION. Penman (1948) stated that his experimental result showed that the aerodynamic approach is not adequate and an empirical expression is a better description of evaporation from open water surface. Penman derived an equation to estimate open water surface evaporation by plotting the ratio of daily measured pan evaporation and vapor pressure deficit [(E_{pan})/($e_s - e_a$)] versus wind speed measured at 2 m height (u_2) where E_{pan} was measured using 0.76 m (29.921 inches) diameter and 0.61 m (24.016 inches) deep ground evaporation pan surrounded by turf. The form of the Penman's linear equation given by Jensen al. (1990) for estimating E_{pan} in $mm \cdot d^{-1}$ is

$$E_{pan} = \frac{6.43(1+0.53u_2)(e_s - e_a)}{\lambda} \quad [2]$$

where λ is the latent heat of vaporization of water, 2.45 $MJ \cdot kg^{-1}$, and u_2 is the daily mean wind run ($m \cdot s^{-1}$) at 2 m.

KNF (1955) EQUATION. The KNF method (Kohler et al., 1955) is perhaps the most widely used method to estimate evaporation (Burman and Pochop, 1994). Kohler et al. (1955) conducted extensive experiments at Lake Hefner, Okla. and made computations from the pan evaporation relation for 21 Class A stations well distributed over the U.S. and one in Alaska. They adapted Penman (1948) evaporation equation by adjusting the psychrometric constant. Based on their results, they stated that the equation is universally applicable. Their combination-based equation is

$$E_{pan} = \frac{\Delta R_n + \gamma_p E_a}{\Delta + \gamma_p} \quad [3]$$

where E_{pan} is the pan evaporation ($mm \cdot d^{-1}$), R_n is net radiation ($mm \cdot d^{-1}$), Δ is the slope of the saturation vapor pressure versus air temperature curve (kPa/°C), γ_p is the psychrometric constant, 0.001568 P (kPa/°C), E_a is the aerodynamic function ($mm \cdot d^{-1}$), and P is the atmospheric pressure (100.9541 kPa for Gainesville, Fla.). The aerodynamic function, E_a, was evaluated by Kohler et al. (1955) by using pan evaporation data obtained from four locations in the U.S. and the relation is:

$$E_a = 25.4[0.296(e_s - e_a)^{0.88} (0.37 + 0.00255\ u_p)] \quad [4]$$

where E_a is expressed in $mm \cdot d^{-1}$, u_p is the wind speed at 15.2 cm (5.98 inches) above the rim of the Class A pan in $km \cdot d^{-1}$, e_s is saturation vapor pressure at the air temperature in kPa, and e_a is the vapor pressure at the dew point temperature in kPa ($e_s - e_a$ = vapor pressure deficit, kPa). Kohler et al. (1955), Lamoreux (1962), and Jensen (1974) suggested the following relationship to calculate effective net radiation ($R_n\Delta$) for a Class A pan accounting for the effects of sensible heat transfer through the sides and bottom of the pan (Burman and Pochop, 1994):

$$R_n\Delta = 154.4 \exp[(1.8T - 180)(0.1024 - 0.01066 \ln(0.239R_s)) - 0.01544] \quad [5]$$

where T is the mean daily air temperature (°C) and R_s is in $J \cdot cm^{-2} \cdot d^{-1}$.

Christiansen (1968) equation. Christiansen (1968) developed an equation by using a multiple correlation method to estimate Class A pan evaporation and tested it with 3,928 months of data from 80 weather stations from different locations in the world. Many different types of Christiansen's methods of estimating E_{pan} or ET are presented in the literature. The method used in this study was described by Christiansen (1968):

$$E_{pan} = 0.473\ R_a C_T C_W C_H C_S C_E C_M \quad [6]$$

where R_a is the extraterrestrial radiation ($mm \cdot d^{-1}$) and C_T, C_W, C_H, C_S, C_E, and C_M represent the coefficients for temperature, wind speed, humidity, sunshine percentage, elevation, and Christiansen's monthly coefficient, respectively, and the coefficients are given by the following relations:

$$C_T = 0.393 - 0.5592\left(\frac{T_c}{20}\right) + 0.04756\left(\frac{T_c}{20}\right)^2 \quad [7]$$

$$C_W = 0.708 + 0.3276\left(\frac{W}{96.6}\right) - 0.036\left(\frac{W}{96.6}\right)^2 \quad [8]$$

Burman (1976) modified the original equation for calculating C_H given by Christiansen (1968) and suggested the following relation for C_H:

$$C_H = 1.250 - 0.212\left(\frac{H_m}{57.4}\right) - 0.038\left(\frac{H_m}{57.4}\right)^2 \quad [9]$$

$$C_S = 0.542 + 0.64\left(\frac{S}{80}\right) - 0.4992\left(\frac{S}{80}\right)^2 + 0.3174\left(\frac{S}{80}\right)^3 \quad [10]$$

$$C_E = 0.970 + 0.030\ (E/305) \quad [11]$$

where T_c is the mean daily temperature (°C), W is the mean daily wind speed ($km \cdot d^{-1}$), H_m is the mean daily relative humidity (%), S is the sunshine percentage, and E is the elevation (m).

In some locations data are available for sky cover (SC), cloud cover (CC) or cloudiness, but not for S. Christiansen (1968) made a comparison between S and SC for 12 months at 32 weather stations in different locations in the U.S. and reported the following equation for computing S:

$$S = 1 - 0.016\ SC - 0.0084\ SC^2 \quad [12]$$

where SC is the sky cover, scale 0 to 10. Unfortunately, in this study, the daily values of SC were not available from the weather station. However, Doorenbos and Pruitt (1977) proposed an equation to calculate the ratio between actual measured bright sunshine hours and maximum possible sunshine hours (n/N ratio) using incoming solar radiation (R_s) and extraterrestrial radiation (R_a) and they provided a table to calculate SC using n/N ratio. Their equation to calculate n/N ratio is

$$R_s = (0.25 + 0.50\ n/N)\ R_a \quad [13]$$

where both R_s and R_a are in $MJ \cdot m^{-2} \cdot d^{-1}$. The values of n/N ratio was calculated from the above equation using measured R_s and computed R_a. A linear regression was conducted to estimate the daily values of SC using the table (n/N ratio versus SC) provided by Doorenbos and Pruitt (1977). In this study, the resulting linear regression equation between n/N ratio and SC was found to be

$$SC = (0.9691 - n/N)/0.0842 \quad [14]$$

PT (1972) equation. Priestley and Taylor (1972) expressed the evaporation rate from uniformly saturated surfaces as a function of the equilibrium conditions, i.e. when the air in contact with a wet surface is vapor saturated. They introduced an empirical coefficient (α) that is defined as the ratio of evaporation from a uniformly saturated surface when conditions of minimal advection exist to evaporation under equilibrium conditions (Burman and Pochop, 1994). The PT equation has been used to estimate evapotranspiration as well. The equation is

$$E_0 = \alpha\left(\frac{\Delta}{\Delta + \gamma}\right)(R_n - G) \quad [15]$$

where E_0 is the evaporation rate from free water surface ($mm \cdot d^{-1}$), α is the empirical coefficient (dimensionless), γ is the psychrometric constant (0.06711 kPa/°C for Gainesville, Fla.), and G is the soil heat flux ($mm \cdot cm^{-2} \cdot d^{-1}$), assumed to be zero, and R_n is in $mm \cdot d^{-1}$. Priestley and Taylor (1972) used several sets of data from different uniformly saturated surfaces and found an average of $\alpha = 1.26$. The daily values of R_n are calculated as the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net longwave radiation (R_{nl}).

Linacre (1977) equation. Linacre (1977) simplified the Penman (1948) formula by reducing climatic data input to only air temperature for estimating evaporation rate. The resulting expression for free water evaporation is:

$$E_0 = \frac{\frac{700T_m}{(100 - A)} + 15(T - T_{dp})}{80 - T} \quad [16]$$

where A is the latitude (deg), T is the daily mean air temperature (°C), T_{dp} is the daily mean dew point temperature (°C), and T_m is defined as

$$T_m = T - 0.006\ h \quad [17]$$

where h is elevation (m). Data input for Equation 16 is reduced to temperature, humidity, elevation, and latitude.

Linacre (1977) recommended two methods for eliminating the need for humidity measurements. The term ($T - T_{dp}$) can be estimated either from tabulated data developed using data from Australia and New Zealand, or by the following expression developed using the data from the regions where the monthly precipitation is at least 5 mm/month (0.2 inches/month) and ($T - T_{dp}$) is at least 4 °C (39.2 °F):

$$(T - T_{dp}) = 0.0023\ h + 0.37\ T + 0.53\ R + 0.35\ R_{ann} - 10.9 \quad [18]$$

where R is the average difference between mean daily maximum and minimum temperature (°C), and R_{ann} is the difference between the mean temperatures of the hottest and coldest months (°C). Thus, the evaporation rate can be estimated simply from values of the elevation, latitude, and daily maximum and minimum temperatures.

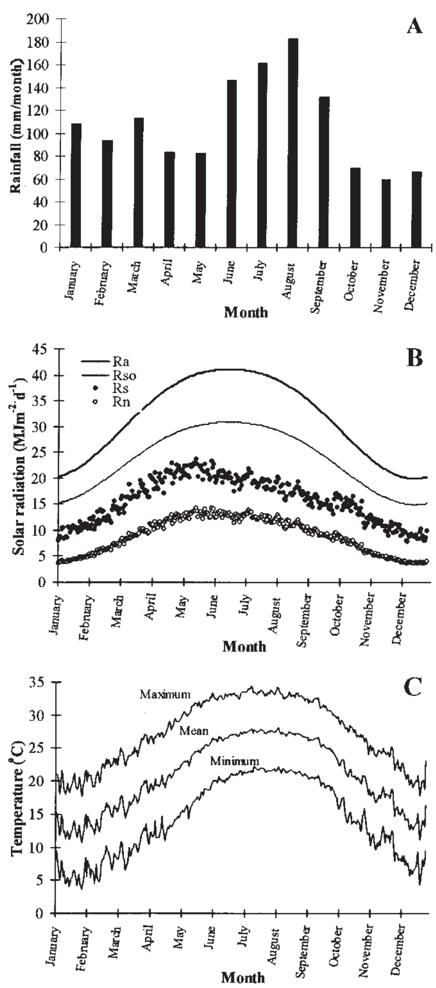
Results and discussion

DAILY COMPARISONS OF E_{PAN} ESTIMATES. The 23-year mean daily measured E_{pan} values and E_{pan} values estimated using the equations of Penman, KNF, Christiansen, PT, and Linacre are given in Fig. 2A–E, respectively. The 23-year mean daily values of measured E_{pan} in Fig. 2A shows that the peak values of E_{pan} in north-central Florida occurs in May. This period is also associated with the highest values of R_s (Fig. 1B). The E_{pan} values in summer months (June, July, and August) are lower than those in April-May due to cloud cover during normal summer rainy periods. Figure 2A shows that daily E_{pan} values range from about 2 mm·d^{-1} (0.1 inches/d) in January and December to about 7 mm·d^{-1} (0.3 inches/d) in peak month.

The Penman equation usually overestimated E_{pan} (Fig. 2A). The annual mean percent error (%E) of daily estimates for this method was quite high (19%). Although the estimated values were similar to the measured E_{pan} values between the first of May and mid September, statistical analyses showed that the estimated E_{pan} values were significantly different ($P < 0.05$, n = 366) from the measured values for one year period. The RMSE and SD between the measured and estimated E_{pan} values were 0.75 and 1.22 mm·d^{-1} (0.029 and 0.048 inches/d) for 1-year period, respectively. At first glance, these RMSE and SD values seem quite low, but if monthly or annual total E_{pan} were to be considered, the daily RMSE and SD values would be significantly higher. The poor performance of the Penman method might be because the equation does not account for variations in solar radiation or cloudiness, which play an important role when calculating E_{pan} in humid regions. Because, in humid climates, variations in E_{pan} are more often due to variations in solar radiation, relative humidity, or sunshine percentage than to variations in temperature and wind pattern. However, it is not expected for an empirical equation to perform well in estimating E_{pan} in different climatic conditions over all months because of the variability in climate with space and time. Therefore, it would be appropriate to analyze the performance of a given equation for specific time periods. Thus, the performance of the Penman equation to estimate E_{pan} between early May and mid-September was also evaluated. Based on the RMSE and %E values, the Penman equation provided reasonable estimates of E_{pan} between early May and mid-September with relatively low RMSE and SD values of 0.35 and 0.55 mm·d^{-1} (0.014 and 0.022 inches/d), respectively. Statistical analyses showed that the estimated and measured E_{pan} values for this time period were not significantly different ($P > 0.05$, n = 138).

Figure 2B shows the daily measured E_{pan} values and E_{pan} values estimated by the KNF method. The KNF method provided better estimates compared to the Penman method with a lower RMSE value of 0.37 mm·d^{-1} (0.015 inches/d). The SD value was lower [1.1 mm·d^{-1} (0.04 inches/d)] than for Penman method [1.22 mm·d^{-1} (0.048 inches/d)]. The annual mean value of the %E of daily estimates was low (6%). For a 1-year period, the measured and estimated E_{pan} values were not significantly different ($P > 0.05$, n = 366). However, the KNF method overestimated E_{pan} between 1 Jan. through the end of February and from November through the end of December. Burman (1976) evaluated the KNF and Christiansen methods to estimate E_{pan} for different climatic conditions and reported that none of the methods provided satisfactory estimates for all locations. He indicated that the KNF method performed best overall.

Daily measured E_{pan} versus estimated E_{pan} by the Christiansen method is given in Fig. 2C. Although the Christiansen method accounts for several climatic variables, Fig. 2C shows that this method significantly and consistently underestimated E_{pan} throughout the year with RMSE and SD values of 1.21 and 1.37 mm·d^{-1} (0.048 and 0.054 inches/d), respectively. The mean annual %E of daily estimates was also higher (–27%) compared to the Penman and KNF methods. The magnitude of the underestimations was not constant and showed variations from one season to another. The magnitude of the underestimations was found to be higher in summer months (from late April through late June). The estimated values ranged from 1.5 mm·d^{-1} (0.06 inches/d) in January and December to about 4.7 mm·d^{-1} (0.18 inches/d) in June and were about 2 mm·d^{-1} (0.1 inches/d) lower than the measured values. The



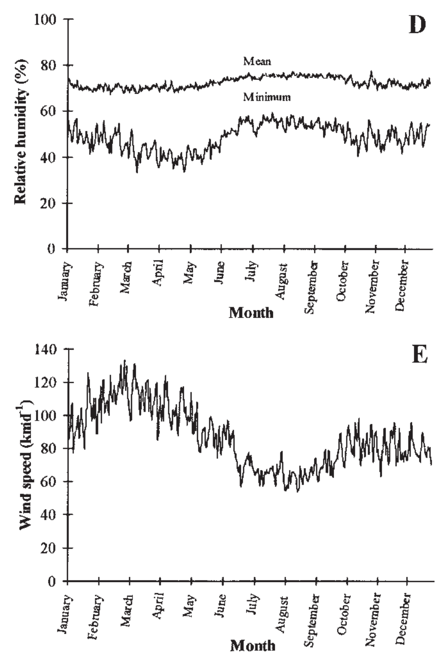
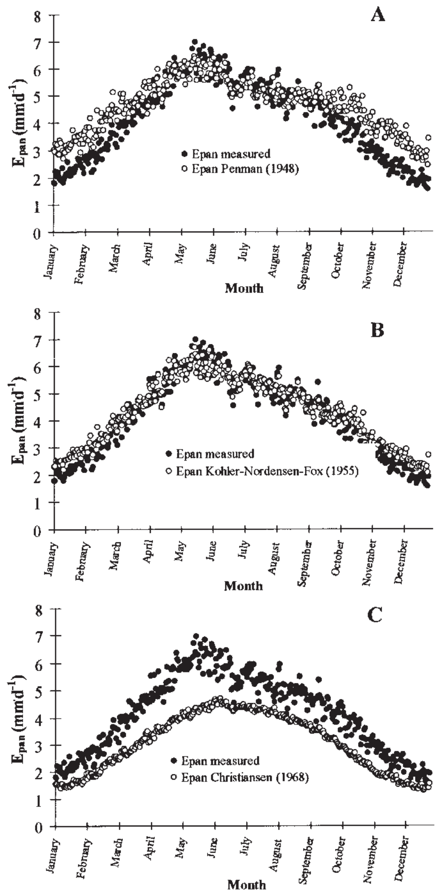


Fig. 1. The 23-year daily mean climate characteristics for Gainesville, Fla., including (A) rainfall (1 inch = 25.4 mm), (B) solar radiation (0.0864 MJ·m^{-2}·d^{-1} = 1 W·m^{-2}), (C) temperature [(°F = 1.8(°C) + 32)], (D) relative humidity (RH), and (E) wind speed (0.625 km·d^{-1} = 1 mile/d). Each data point represents an average of 23 measurements per day. R_a, R_{so}, R_s, and R_n represent extraterrestrial radiation, clear-sky radiation, total incoming radiation, and net radiation, respectively.



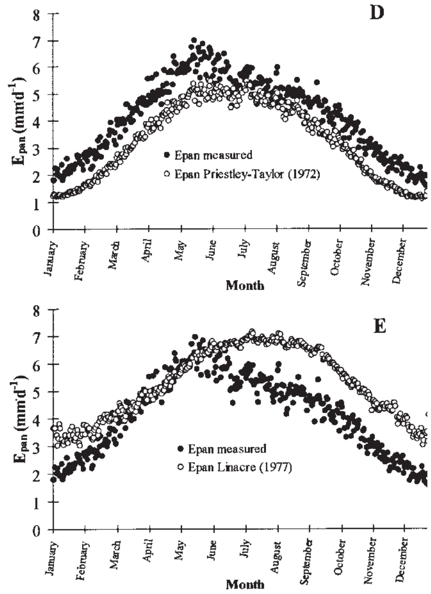


Fig. 2. The 23-year mean daily measured and estimated pan evaporation (E_{pan}) values using five methods: (A) Penman, (B) Kohler-Nordenson-Fox, (C) Christiansen, (D) Priestley-Taylor, and (E) Linacre. Each data point represents an average of 23 measurements per day.

Christiansen method was developed using data obtained mainly from stations located at high altitudes. Burman (1976) evaluated three E_{pan} methods, including the Christiansen method, for high and low altitudes, ranging from –30 to 960 m (–98.4 to 3,149.6 ft), and concluded that the Christiansen method was the only one that provided close estimates to the measured values for a location at 960 m altitude (Ruzizi Valley, Africa). For low altitudes, as in our study, the Christiansen method underestimated E_{pan}. Several researchers, including Rohwer (1931), Blaney (1956), and Peck (1967), investigated the effect of altitude and/or the change in atmospheric pressure on E_{pan}.

Figure 2D shows that the PT method consistently underestimated E_{pan}. The RMSE and SD values of daily estimates for a one year period were 0.97 and 1.48 mm·d^{-1} (0.038 and 0.058 inches/d), respectively. The annual mean value of the %E for daily estimate was -24%. The estimated values ranged from 1.2 mm·d^{-1} (0.05 inches/d) in January to 5.5 mm·d^{-1} (0.22 inches/d) in late May, and were 0.8 and 1.14 mm·d^{-1} (0.03 and 0.045 inches/d) lower than the measured values for the same periods, respectively. Priestley and Taylor (1972) proposed the value of $\alpha = 1.26$ or $0 < \alpha < 1.26$, where the lower limit represents the case of no evaporation, and the upper limit represents potential evaporation. They reported that the value of $\alpha = 1.26$ can be used for many different saturated surfaces because of the assumption that the ratio of actual to equilibrium evaporation is equal to 1.26. However, Fig. 2D indicates that this assumption is not valid for these climatic conditions.

The Linacre method (Fig. 2E) significantly overestimated E_{pan} throughout the year [$P < 0.05$, RMSE = 1.33 mm·d^{-1} (0.052 inches/d), SD = 1.44 mm·d^{-1} (0.057 inches/d), n = 366]. The annual mean %E of daily estimates was highest among all methods (32%). The estimated and measured values were in a good agreement only between mid-March and late May and had low RMSE and SD values of 0.33 and 0.67 mm·d^{-1} (0.013 and 0.026 inches/d), respectively. The estimated values during these periods were not significantly different ($P > 0.05$, n = 68) than the measured values. The estimated E_{pan} values ranged from a minimum value of 3.5 mm·d^{-1} (0.14 inches/d) in January and December to a maximum value of 7 mm·d^{-1} (0.3 inches/d) in mid-July. These values were significantly higher than the measured values. Thus, this method resulted in the highest RMSE and SD of daily E_{pan} estimates throughout the year among all methods. Although the peak evaporation was measured in May, this method estimated the maximum E_{pan} value in July. Reducing the climatic input data to only temperature in the Linacre method did not produce accurate estimates of $E_{pan.}$

MONTHLY AND ANNUAL TOTAL COMPARISONS. The monthly and annual totals of estimated and measured E_{pan} and the average %E values are given in Table 1. The KNF method resulted in good monthly E_{pan} estimates that were in a close agreement with the measured values in most months. The measured monthly E_{pan} values ranged from 63 mm·month^{-1} (2.5 inches/month) in December to 191 mm/month (7.5 inches/month) in May. The estimated monthly E_{pan} values varied among the methods. All methods estimated minimum E_{pan} value in December, except for Linacre method, which agreed with the measured values. The minimum E_{pan} estimate using Linacre method occurred in January. The maximum estimated E_{pan} varied among methods while maximum monthly measured E_{pan} value occurred in May. The Penman and KNF methods had the estimated maximum monthly E_{pan} values in May whereas the PT and Linacre methods had the estimated maximum value in July and Christiansen method in June. All methods underestimated E_{pan} in May. Although the Linacre method estimated E_{pan} value in May very close to the measured value, it significantly overestimated E_{pan} in all other months.

The %E in monthly E_{pan} estimates varied among the methods (Table 1). The KNF method had the lowest monthly average absolute %E (6%) whereas the Linacre method had the highest %E (32%). The monthly average absolute %E values for Penman, Christiansen, and PT methods were 17, 27, and 24%, respectively. Annual E_{pan} estimates by the KNF method were within 4% [1,580 mm/year (62.2 inches/year)] of measured total values [1,525 mm/year (60.0 inches/year)]. The annual estimated E_{pan} and absolute %E values of other methods were 1,696 mm/year (66.8 inches/year) and 11% for Penman, 1,121 mm/year (44.1 inches/year) and 26% for Christiansen, 1,199 mm/year (47.2 inches/year) and 21% for PT, and 1,921 mm/year (75.6 inches/year) and

Table 1. Monthly and annual total of the measured and estimated pan evaporation (E_{pan}) (mm) and percent errors of estimates (%E).

	Method										
	Penman		KNF		Christiansen		PT		Linacre		Measured[z]
Month	E_{pan}[z]	%E[y]	E_{pan}	%E	E_{pan}	%E	E_{pan}	%E	E_{pan}	%E	E_{pan}
January	100	43	82	17	49	–30	42	–40	105	50	70
February	115	32	97	11	62	–29	57	–34	110	26	87
March	147	12	135	3	90	–31	94	–28	138	5	131
April	164	3	161	1	109	–31	123	–23	155	–3	159
May	186	–3	187	–2	132	–31	152	–20	190	–1	191
June	169	–3	171	–1	134	–22	150	–13	200	16	172
July	163	–3	170	1	134	–20	154	–8	213	27	168
August	154	0	155	1	123	–20	139	–10	210	36	154
September	146	10	130	–2	103	–23	109	–18	190	43	133
October	142	23	123	7	82	–29	87	–24	165	43	115
November	114	41	92	14	57	–30	53	–35	133	64	81
December	96	52	77	22	46	–27	39	–38	112	78	63
Average[y]		17		6		–27		–24		32	
Annual	1,696	11	1,580	4	1,121	–26	1,199	–21	1,921	26	1,525

[z]Each estimated and measured E_{pan} value represents an average of 23 estimates or measurements per month (1 inch = 25.4 mm). The methods evaluated were Penman (Penman, 1948), Kohler-Nordenson-Fox, KNF, (Kohler et al., 1955), Christiansen (Christiansen, 1968), Priestley-Taylor, PT, (Priestley and Taylor, 1972), and Linacre (Linacre, 1977).
[y]Percent error (%E) is calculated by [((E_{pan} estimated – E_{pan} measured)/(E_{pan} measured)) × 100].

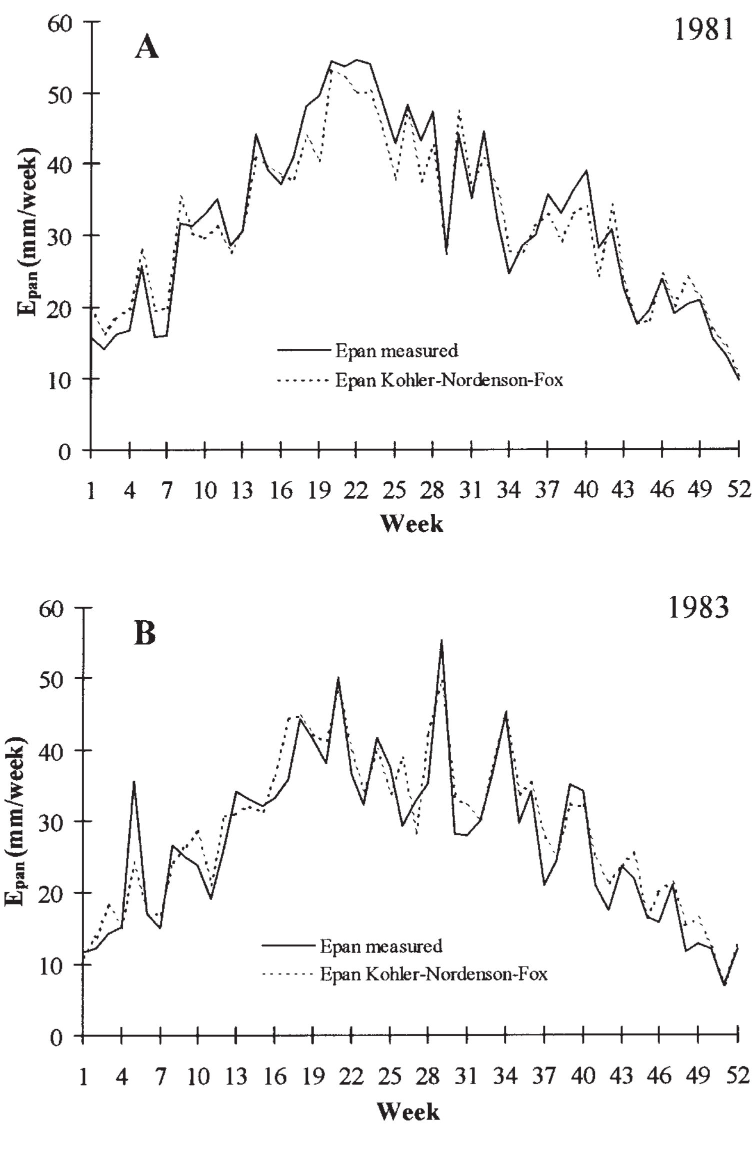


Fig. 3. **Measured and estimated weekly pan evaporation (E_{pan}) values for individual years: (A) 1981 and (B) 1983. Each data point represents an average of 23 measurements per week.**

26% for Linacre methods, respectively.

FURTHER EVALUATION OF THE KNF METHOD FOR INDIVIDUAL YEARS. The daily, monthly, and annual E_{pan} values estimated by the KNF showed good agreement with the measured values. However, the method should also be evaluated for individual years that have weather characteristics different than the 23-year mean. For this purpose, data for the years 1981 and 1983 were used to calculate weekly, monthly, and annual E_{pan} estimates using the KNF method. The annual rainfall totals for 1981 and 1983 were 890 mm (35.0 inches) [(482 mm (19.0 inches) lower than the long-term average (1,372 mm) (54.0 inches)] and 1,630 mm (64.2 inches) [(258 mm (10.2 inches) higher than the long-term average)], respectively.

Weekly E_{pan} estimates for 1981 and 1983 are given in Fig. 3A and B, respectively. In 1981, the weekly estimated E_{pan} values were closely related to measured values with an average %E of 8%. The minimum E_{pan} estimate [10 mm/week (0.4 inches/week)] occurred in December and the maximum value [53 mm/week (2.1 inches/week)] occurred in May which were in good agreement with the measured values of 10 and 54 mm/week (0.4 and 2.1 inches/week), respectively.

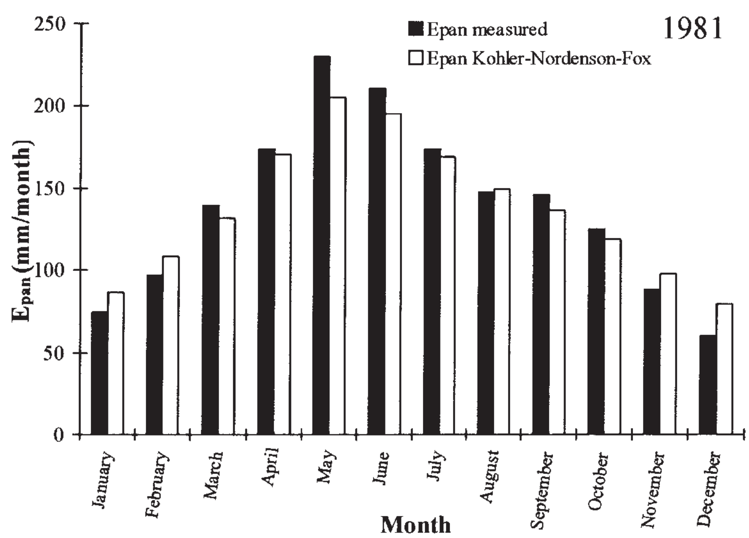
Similar results were obtained for 1983 where estimated E_{pan} values were in close agreement with the measured values (Fig. 3B). The average %E (11%) was greater than that for 1981 (8%). The minimum E_{pan} estimate occurred in December [7 mm/week (0.3 inches/week)] and the maximum was in July [50 mm/week (2.0 inches/week)]. The minimum and maximum measured E_{pan} values occurred during the same weeks [7 and 55 mm/week (0.3 and 2.2 inches/week), respectively]. The greatest %E occurred at the end of June when the estimated E_{pan} value was 34% higher than the measured value [39 versus 29 mm/week (1.5 versus 1.1 inches/week)]. The minimum %E occurred in week 43 (21 Oct.) when the estimated and measured values were the same [24 mm/week (0.9 inches/week)].

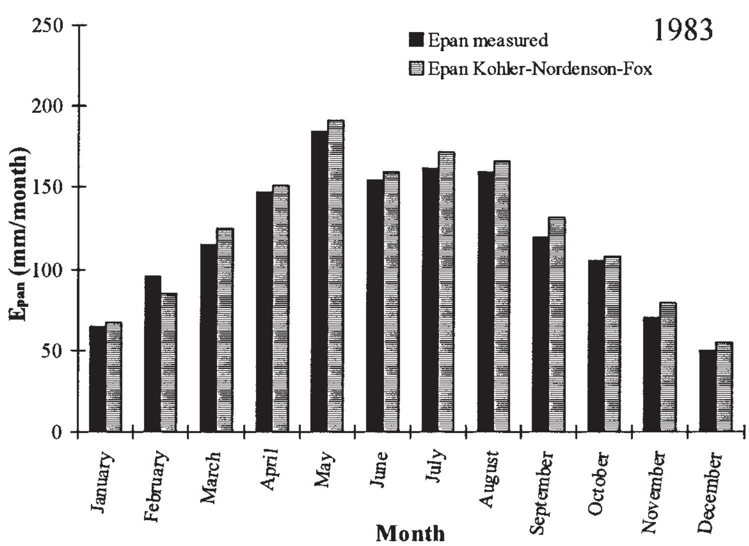
Figure 4A and B show the monthly estimated and measured E_{pan} for 1981 and 1983, respectively. The KNF method provided monthly E_{pan} estimates for the 2 years that were in good agreement with measured values for most months in both years. The measured monthly E_{pan} values ranged from 80 to 205 mm/month (3.1 to 8.1 inches/month) (Fig. 4A) and from 55 to 190 mm/month (2.2 to 7.5 inches/month) (Fig. 4B) in 1981 and 1983, respectively. In both years, the minimum and maximum monthly estimated E_{pan} values occurred in December and May, respectively, the same month when the minimum and maximum measured E_{pan} values occurred. In 1981, monthly %E values ranged from a low of -11% in May to a high of 32% in December with an overall average %E of 9%. In 1983, %E values ranged from a low of -11% in February to a high of 13% in November with an average %E of 5%. The KNF method underestimated E_{pan} in 1981 (dry year) and overestimated it in 1983 (wet year), and the underestimated values during the dry year tended to be greater in summer months. This may indicate that more sensible heat occurs from advection in summer months of dry years. During summer months, both advection and radiant energies are primary sources of latent heat for evaporating water (Mukammal and Neumann, 1977; Rosenberg et al., 1983), whereas only radiant energy is considered in the KNF equation, which may cause underestimations of E_{pan}. In 1981 and 1983, the estimated annual E_{pan} values [1,666 and 1,427 mm/year (65.6 and 56.2 inches/year), respectively] were closely related to the measured values [1,648 mm/year and 1,430 mm/year (64.9 and 56.3 inches/year), respectively]. The %E of estimates were –1% and 4% in 1981 and 1983, respectively.

Conclusion

Five different E_{pan} estimation methods (Penman, KNF, Christiansen, PT, and Linacre) were compared with long-term average (23-year) measured values under humid climatic conditions in Florida. The root mean square error was used as the criteria to judge the accuracy and reliability of a given method. Performance evaluations of the E_{pan} estimates of the methods were made on a daily, monthly, and annual basis. The KNF method provided the closest E_{pan} estimates to the measured values. The Linacre method provided the poorest estimates while the second, third, and fourth best methods were Penman, PT, and Christiansen, respectively. Some of the methods that provided poor E_{pan} estimates required less input data than other methods. For example, the Linacre method requires only mean air temperature and dew point, but its application for this and similar climatic conditions is not recommended. The KNF method requires total solar radiation that may not be readily available for some locations. However, for many applications, availability of these input data should not limit the method's application because solar radiation can often be estimated with sufficient accuracy for a given location. It is concluded that the KNF method should be preferred and recommended method among those evaluated for estimating daily E_{pan} for irrigation scheduling and for estimating the missing E_{pan} data in humid areas.

Fig. 4. Measured and estimated monthly pan evaporation (E_{pan}) values for individual years; (A) 1981 and (B) 1983. Each bar represents an average of 23 measurements per month.





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