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Simplified Estimation of Reference Evapotranspiration from Pan Evaporation Data in California

Richard L. Snyder¹; Morteza Orang²; Scott Matyac³; and Mark E. Grismer, M.ASCE⁴

Abstract: Evaporation pan (E_p) data are often used to estimate reference evapotranspiration (ET_0) for use in water resource planning and irrigation scheduling. This paper reviews equations to estimate ET_0 from E_p and provides a simpler method to make this conversion for arid climatic conditions like in California. The new method accounts for fetch differences by first adjusting the E_p rates to values expected for 100 m of grass fetch. Then it relies on an empirical relationship between ET_0 and the adjusted E_p to determine K_p values; thus, eliminating the need for relative humidity and wind speed data that are often unavailable. The method is conceptually simpler, easier to code into computer applications, and within California, it gave better results than methods based on relative humidity and wind speed. However, the method might require calibration in more humid or windier climates.

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CE Database subject headings: Evaporation; Evapotranspiration; Water consumption; Hydrologic models; Irrigation scheduling; California; Data analysis.

Introduction

Pan evaporation (E_p) data are often used to estimate reference evapotranspiration (ET_0) for a short canopy for use in irrigation scheduling and water resources planning. Commonly, ET_0 is estimated as the product of the E_p data and a pan coefficient (K_p)

$$ET_0 = K_p \times E_p \quad (1)$$

To our knowledge the most widely used table of K_p values to estimate ET_0 from E_p is that reported by Doorenbos and Pruitt (1977). This table of values is for National Weather Service (NWS) class "A" evaporation pans located over grass surfaces having a range of upwind grass fetch distances as described in Doorenbos and Pruitt (1977). More recently, Allen and Pruitt (1991) published the original K_p data (Table 1) used to develop the Doorenbos and Pruitt (1977) table. The K_p values in the table vary depending on the fetch, wind speed, and relative humidity.

When Table 1 was developed, ET_0 was determined using a large weighing lysimeter planted to 0.07–0.15 m tall, cool-season grass. Recently, the definition of ET_0 was changed from a grass canopy to using the Penman–Monteith equation to estimate the evapotranspiration from a hypothetical short $h=0.12$ m canopy

with a canopy resistance of 50 s m^{-1} when the net radiation is positive and 200 s m^{-1} when the net radiation is negative and the aerodynamic resistance is estimated as $208/U_2 \text{ m s}^{-1}$, where U_2 is the wind speed measured at 2 m height over the canopy (Walter et al. 2000).

While there is a strong correlation between E_p and ET_0 , there are differences in energy fluxes and heat storage in the pan water versus that from a short vegetation covered soil. One big difference is that much of the energy stored in the water of the NWS Class "A" pan during daylight hours will contribute to nighttime evaporation, whereas energy stored in the soil under short crop canopy with a high canopy resistance to water vapor transfer will exhibit little nighttime evaporation. Considering the K_p values for 100 m of fetch in Table 1, the maximum K_p value of about 0.85 occurs under low evaporative demand conditions (i.e., light wind and high humidity). As the evaporative demand increases (i.e., with lower humidity and higher wind speed), the difference

Table 1. K_p Values from Allen and Pruitt (1991) Corresponding to Mean Relative Humidity (%) and Wind Run (km day^{-1}) Data

Relative humidity (%)	Wind run (km day^{-1})	Fetch (m)			
		100	1	10	1,000
30	84	0.74	0.55	0.66	0.77
30	260	0.66	0.50	0.60	0.70
30	465	0.58	0.45	0.52	0.62
30	700	0.50	0.40	0.45	0.55
57	84	0.81	0.64	0.75	0.83
57	260	0.73	0.58	0.68	0.77
57	465	0.66	0.52	0.60	0.70
57	700	0.59	0.45	0.53	0.63
84	84	0.85	0.73	0.82	0.87
84	260	0.78	0.65	0.75	0.81
84	465	0.71	0.59	0.67	0.75
84	700	0.65	0.52	0.61	0.68

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Table 2. Location, Latitude, Longitude, Elevation, Fetch Distance of Grass Around Pan and Number of Data Pairs for Five California Evaporation Pan Locations

Location	Latitude (N)	Longitude (W)	Elevation (m)	Fetch (m)	Data pairs
Nicolaus	38°52'	121°32'	9.7	100	381
Manteca	37°50'	121°13'	10.0	330	386
Fresno	36°49'	119°44'	103.3	152	289
Shafter	35°31'	119°16'	109.7	100	553
El Centro	32°48'	115°27'	−15.2	33	558

between E_p and ET_0 increases and the K_p value decreases to near 0.50.

Here, building on previous efforts (e.g., Snyder 1992; Grismer et al. 2002), we develop a model to estimate ET_0 where the E_p data are first adjusted to estimate evaporation from a pan with 100 m of fetch (E_{pa}) and then the K_p values are estimated as a function of the E_{pa} rate. This eliminates the need for wind speed and relative humidity data and simplifies the conversion of E_p to ET_0 .

Methods and Materials

Evaporation pan data from five sites maintained by the California Department of Water Resources (CDWR) were used in this analysis. Location and fetch distance characteristics of these sites are summarized in Table 2 along with the number of data pairs analyzed at each site. Monthly mean daily ET_0 rates for the five locations are given in Table 3. Eqs. (1)–(4) have been reported to estimate the K_p values in Table 1 from Allen and Pruitt (1991) or in the table of rounded K_p values (not provided) from Doorenbos and Pruitt (1977):

Allen and Pruitt (1991)

$$K_p = 0.108 - 0.000331U + 0.0422 \ln(F) + 0.1434 \ln(H) - 0.000631[\ln(F)]^2 \ln(H) \quad (2)$$

Cuenca (1989)

Table 4. California Immigration Management Information System Weather Stations Used to Characterize Daily Evapotranspiration Rates in Sacramento, San Joaquin, and Imperial Valleys

Valley	CIMIS stations
Sacramento	Davis, Colusa, Durham, Fair Oaks, Gerber, Nicolaus, Orland & Zamora
San Joaquin	Arvin, Blackwell, Firebaugh, WSFS, Fresno St, Fresno, Kesterson, Kettleman, Lindcove, Lodi, Madera, Manteca, McFarland, Mendota, Merced, Modesto, OrangeC, Panoche, Parlier, Paterson, Shafter, Visalia & Westlands
Imperial	Mulberry, Meloland, SaltSeaW, Seeley & Thermal

$$K_p = 0.475 - 0.00024U + 0.00516H + 0.00118F - 1.6 \times 10^{-5}[H]^2 - 1.01 \times 10^{-6}F^2 - 0.8 \times 10^{-8}H \cdot U - 1.0 \times 10^{-8}H^2F \quad (3)$$

Snyder (1992)

$$K_p = 0.482 + 0.024 \ln(F) - 0.000376U + 0.0045H \quad (4)$$

Orang (private communication 1998) and Grismer et al. (2002)

$$K_p = 0.512062 - 0.000321U + 0.002889H + 0.031886 \ln(F) - 0.000107H \ln(F) \quad (5)$$

Reference evapotranspiration (ET_0) data were obtained from the California Irrigation Management Information System (CIMIS), which is operated by the CDWR. The CIMIS ET_0 equations were described by Snyder and Pruitt (1992). Recently, a modified Penman–Monteith (PM) equation has been suggested to estimate ET_0 using hourly data (Walter et al. 2000). However, calculated CIMIS ET_0 values are similar to those from the modified PM equation (Ventura et al. 2001).

Monthly means of daily ET_0 rates from several stations in the Sacramento, San Joaquin, and Imperial Valleys, in California were used as an independent test of the model. The CIMIS stations used to calculate valley-wide ET_0 rates are shown in Table 4. The mean monthly total evaporation pan data for the three valleys came from CDWR (1977).

Table 3. Mean Monthly Total Evapotranspiration (mm) for Five Evaporation Pan Sites

Month	Nicolaus	Manteca	Fresno	Shafter	El Centro
January	22.1	22.8	21.6	31.8	62.6
February	39.9	44.1	41.4	52.7	82.3
March	81.7	85.8	82.0	97.7	139.8
April	123.4	128.1	132.9	144.6	189.3
May	159.6	163.8	176.7	189.9	226.5
June	190.8	191.5	202.3	202.6	233.0
July	202.8	203.6	219.1	209.1	229.1
August	175.7	180.6	194.0	188.1	215.0
September	131.0	131.9	137.4	146.7	172.0
October	86.2	84.6	91.1	104.5	134.7
November	38.3	40.5	42.6	51.8	78.6
December	22.6	21.9	21.7	29.9	56.4
Annual total	1,274.1	1,299.2	1,362.7	1,449.2	1,819.2

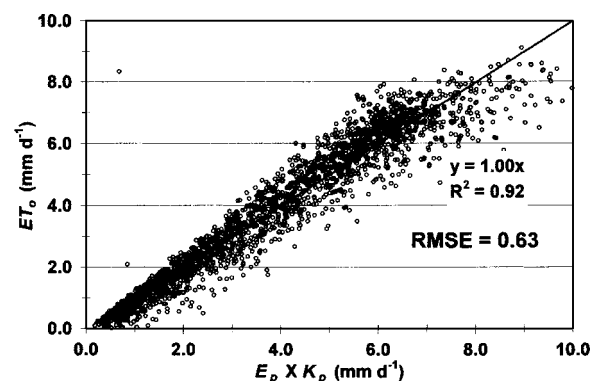


Fig. 1. Plot of California Irrigation Management Information System reference evapotranspiration versus product of pan evaporation and pan coefficient using Allen and Pruitt (1991) K_p equation

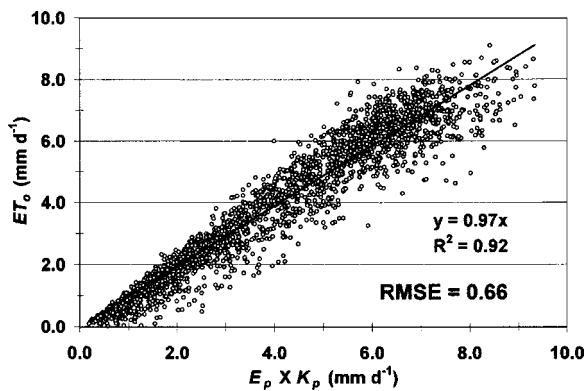


Fig. 2. Plot of California Irrigation Management Information System reference evapotranspiration versus product of pan evaporation and pan coefficient using Cuenca (1989) K_p equation

Results and Discussion

Using fetch, wind speed, and relative humidity, ET_0 and E_p data from the five California locations, a comparison was made between ET_0 from CIMIS and ET_0 estimated from pan evaporation. Plots of ET_0 versus $E_p \times K_p$ from the four K_p equations by Allen and Pruitt (1991), Cuenca (1989), Snyder (1992), Orang (private communication 1998) are shown in Figs. 1–4. Regression statistics and the root mean square error (RMSE) between predicted and CIMIS ET_0 values are provided. Because the four equations provide good estimates of the K_p values in Allen and Pruitt (1991), pan-based estimates of ET_0 closely matched ET_0 estimates from the CIMIS stations.

Although good results were observed, wind speed and relative humidity are sometimes unavailable at pan evaporation sites. Also, it is often difficult to conceptually explain the difference between E_p and ET_0 data in terms of relative humidity and wind speed. Consequently, a new method to estimate ET_0 was derived based on a two step process. The E_p data for a site with known fetch are first adjusted to estimate the evaporation expected if there were 100 m of fetch at the site (E_{pa}). Then ET_0 is estimated as an empirical function of E_{pa} . The assumption being that, under arid California conditions, the relationship between E_p and ET_0 is

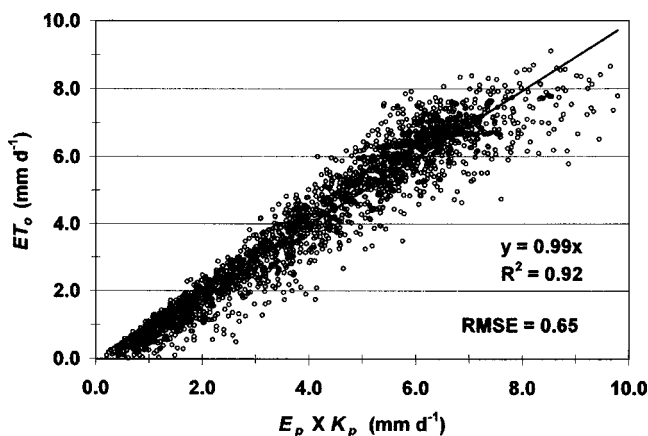


Fig. 3. Plot of California Irrigation Management Information System reference evapotranspiration versus product of pan evaporation and pan coefficient using Snyder (1992) K_p equation

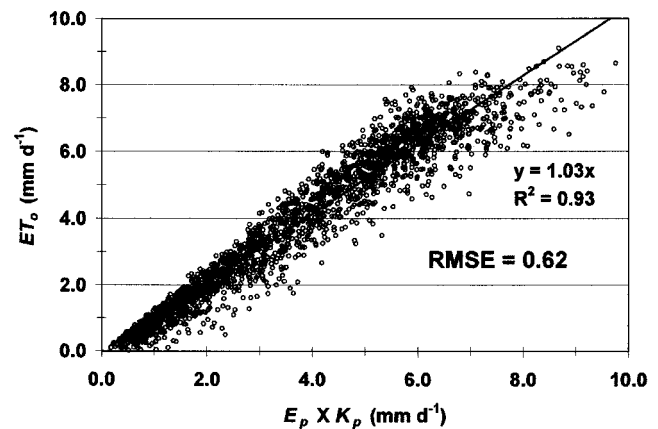


Fig. 4. Plot of California Irrigation Management Information System reference evapotranspiration versus product of pan evaporation and pan coefficient using Orang (private communication 1998) K_p equation

similar for evaporation pans with 100 m of fetch regardless of the microclimate.

Using the K_p data from Table 1, E_p data corresponding to $ET_0 = 5 \text{ mm day}^{-1}$ were computed as shown in Table 5. The resulting E_p data for fetches of 1, 10, and 1,000 m were plotted against the E_p data for 100 m fetch (Fig. 5). Slopes of regressions through the origin were computed for each fetch and the results are shown in Fig. 5. Using ET_0 rates different from 5 mm day^{-1} had no effect on the slopes observed for the three fetch distances. Since the goal is to convert the E_p rate from a site with known fetch to pan evaporation (E_{pa}) for 100 m of fetch, for any given fetch distance, E_{pa} is estimated as

$$E_{pa} = E_p \times F_{100} \quad (6)$$

where

$$F_{100} = \frac{1}{b} \quad (7)$$

and b = slope of the regression line through the origin from Fig. 5. If pan data from a site with 100 m of fetch were plotted in Fig. 5, the resulting regression line through the origin would have a slope

Table 5. E_p Estimates (mm day^{-1}) Corresponding to Reference Evapotranspiration Rate of 5 mm day^{-1} Estimated Using K_p Values from Table 1

Relative humidity (%)	Wind run (km day^{-1})	Fetch (m)			
		100	1	10	1,000
30	84	6.76	9.09	7.58	6.49
30	260	7.58	10.00	8.33	7.14
30	465	8.62	11.11	9.62	8.06
30	700	10.00	12.50	11.11	9.09
57	84	6.17	7.81	6.67	6.02
57	260	6.85	8.62	7.35	6.49
57	465	7.58	9.62	8.33	7.14
57	700	8.47	11.11	9.43	7.94
84	84	5.88	6.85	6.10	5.75
84	260	6.41	7.69	6.67	6.17
84	465	7.04	8.47	7.46	6.67
84	700	7.69	9.62	8.20	7.35

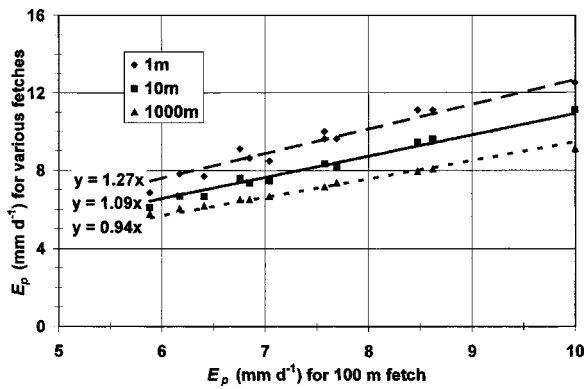


Fig. 5. Plot of E_p estimated using K_p values from Allen and Pruitt (1991) and assumed reference evapotranspiration = 5.0 mm day⁻¹

$b=1.0$. Using b values of 1.2675, 1.0811, 1.0000, and 0.9485 corresponding to fetch distances of 1, 10, 100, and 1,000 m, a plot of F_{100} versus the natural logarithm of the fetch (F) was determined (Fig. 6); from which the resulting quadratic equation can be used to estimate F_{100} as a function of $\ln(F)$

$$F_{100} = -0.0035[\ln(F)]^2 + 0.0622[\ln(F)] + 0.79 \quad (8)$$

where the y intercept was rounded to 0.79. Therefore, multiplying F_{100} by E_p will provide an estimate of pan evaporation (E_{pa}) for a pan surrounded by 100 m of fetch.

Fig. 7 shows a plot of ET_0 versus E_p for Nicolaus, Shafter, Manteca, Fresno, and El Centro where the pans had fetch distances of 100, 100, 330, 152, and 33 m, respectively. Linear regressions through the origin gave pan coefficients of 0.78, 0.78, 0.79, 0.77, and 0.64 for Nicolaus, Shafter, Manteca, Fresno, and El Centro, respectively. The RMSE = 0.85 for the observed data versus the quadratic equation shown in Fig. 7 was not as good as predictions for the four models from the literature (Figs. 1–4). Next, Eq. (8) was used to determine the F_{100} correction for sites with fetch different from 100 m and the product of F_{100} and the E_p data were computed to estimate pan evaporation adjusted to 100 m (E_{pa}) for those locations. A plot of ET_0 versus E_{pa} for all locations is shown in Fig. 8. An attempt was made to fit various types of regression equations to the plot of ET_0 versus E_{pa} , but the equations tended to underpredict ET_0 for $E_{pa} < 10$ mm day⁻¹. Ultimately, a sine-wave equation

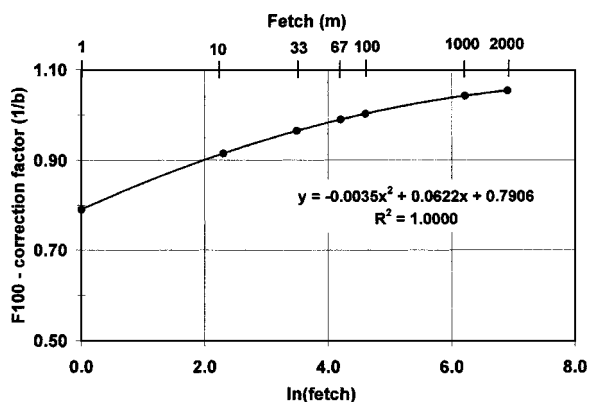


Fig. 6. Plot of correction factor (F_{100}) versus natural log of fetch in meters

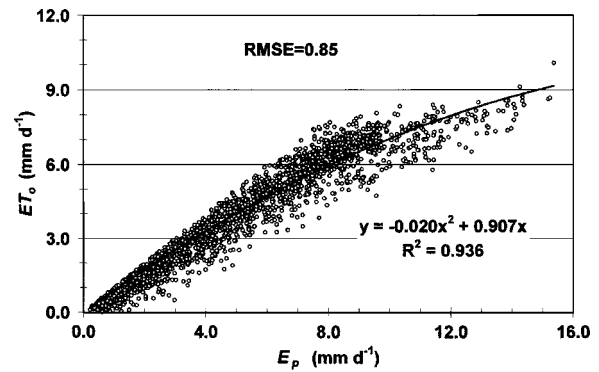


Fig. 7. Plot of reference evapotranspiration from California Irrigation Management Information System versus evaporation pan (E_p) data from five pan evaporation sites

$$ET_0 = 10 \sin \left[\left(\frac{E_{pa}}{19.2} \right) \frac{\pi}{2} \right] \quad (9)$$

was found to give a good estimate of the observed ET_0 rates. The RMSE = 0.59 mm day⁻¹ between the model and observed ET_0 was better than predicted by any of the other four models evaluated (Figs. 1–4). A plot of the 100 m pan coefficient K_{pa} as a function of E_{pa} , where $ET_0 = E_{pa} \times K_{pa}$, is shown in Fig. 9.

As an independent test of the sine-wave conversion equation, monthly total evaporation pan data from the Sacramento, San Joaquin, and Imperial–Coachella Valleys were compared with mean ET_0 data from the same valleys. A plot of observed ET_0 versus ET_0 calculated using Eq. (9) and the valley-wide estimated evaporation pan data showed excellent results (Fig. 10).

Although the method presented does not require wind speed and humidity data, it did provide more accurate estimates of ET_0 than the models by Allen and Pruitt (1991), Cuenca (1989), Snyder (1992), and Orang (private communication 1998). However, it should be noted that only data from California were used in the analysis and the results might be different in a more humid or windier climate. For example, the model presented by Snyder (1992) performed well using California data, but gave poor results in a humid Florida climate (Irmak et al. 2002). However, similar procedures as presented here might provide an ET_0 versus E_{pa} curve for more humid climates.

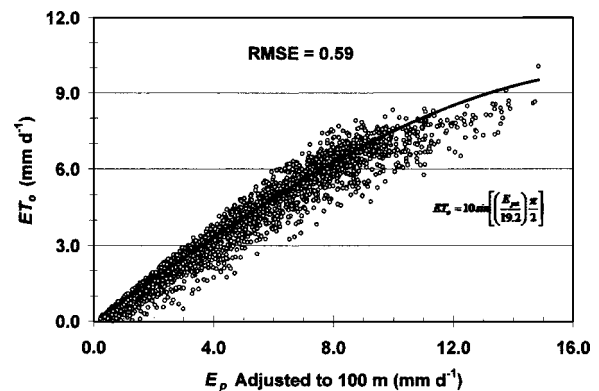


Fig. 8. Plot of reference evapotranspiration versus adjusted evaporation (E_{pa}) data for all five locations and sine wave approximation of evapotranspiration from E_{pa}

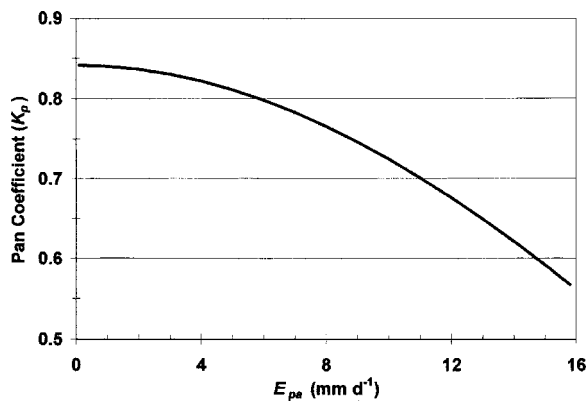


Fig. 9. Plot of 100 m pan coefficient (K_{pa}) versus 100 m pan evaporation (E_{pa})

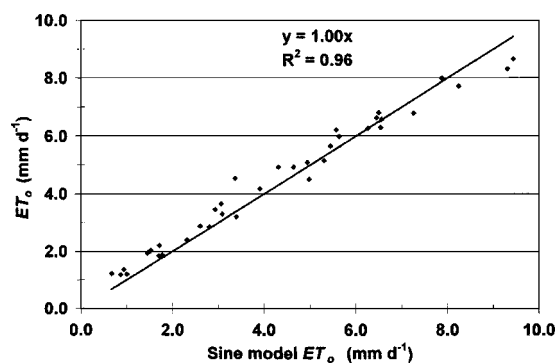


Fig. 10. Plot of observed mean daily reference evapotranspiration rates by month from the Sacramento, San Joaquin, and Imperial-Coachella Valleys versus evapotranspiration estimated from daily mean pan evaporation rates using Eq. (9) from same valleys

Table 6. Sample Calculation of Reference Evapotranspiration (ET_0) for Site with Fetch $f=50$ m and Given Values for Pan Evaporation (E_p). F_{100} was Calculated Using Eq. (8) and E_{pa} Values were Computed as Product of E_p and F_{100} . Reference Evapotranspiration was Elaborated Using Eq. (9) and E_{pa} Data

E_p (mm)	E_{pa} (mm)	ET_0 (mm)
4	3.9	3.1
8	7.8	6.0
12	11.8	8.2

$F_{100}=0.98$.

Sample Calculation

Given pan evaporation with rates of $E_p=4, 8$, and 12 mm day^{-1} from a site with fetch $f=50$ m, The F_{100} correction is calculated as $F_{100}=0.98$ using Eq. (8). Then the values for E_{pa} are calculated as the product of F_{100} and E_p . ET_0 was calculated using Eq. (9). The results are shown in Table 6.

Conclusions

For the California pan evaporation data in this study, the approach to adjust E_p data to estimate evaporation for 100 m fetch distances (E_{pa}) using Eq. (8) and then to estimate ET_0 from the E_{pa} data using Eq. (9) gave better estimates than other equations in the literature that also require wind speed and humidity data. A sine-wave approach was used to estimate ET_0 from the adjusted E_{pa} data. The model worked well in an arid climate like California; however, adjustments might be needed for more humid or windier climates.

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