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Evaluation Of Prediction Methods For Estimating Climate Data To Be Used With The Penman-Monteith Equation In Puerto Rico

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Abstract. *The United Nation's Food and Agriculture Organization (FAO) has recommended the Penman-Monteith method as the single calculation method that should be used for estimating reference evapotranspiration throughout the world. A disadvantage of the method, however, is its relatively high data requirement. Wind speed, humidity (or dew point temperature) and radiation tend to be the least available of the required parameters; therefore the FAO has presented estimation procedures for these parameters. The purpose of this study was to evaluate estimation procedures for climate data to be used in the Penman-Monteith method for estimating long-term daily reference evapotranspiration, and to verify the accuracy of the procedures at four locations within Puerto Rico. Comparison of reference evapotranspiration determined using the estimated and measured climate data show reasonably good agreement. The methods presented are potentially valuable for calculating the long-term average daily reference evapotranspiration at any location within Puerto Rico.*

Keywords. evapotranspiration, crop water use, Penman-Monteith, climate data.

Introduction

Water consumptive use or evapotranspiration (ET) by crops is affected by air temperature, solar radiation, wind speed, humidity, and crop characteristics. ET can be estimated from the relation ET = K_c ET_o, where K_c is a crop coefficient and ET_o is the reference evapotranspiration. The Penman-Monteith method has been recommended as the best method to use for estimating ET_o (Allen et al., 1998). Numerous estimates of evapotranspiration have been made in Puerto Rico using the Soil Conservation Service (SCS) Blaney-Criddle method (USDA-SCS, 1970) and the Hargreaves-Samani method (Hargreaves and Samani, 1985). Harmsen et al. (2001) reported large differences between the SCS Blaney-Criddle method (obtained from Goyal et al., 1989) and the Penman-Monteith method in a study that compared seasonal consumptive use for pumpkin and onion at two locations in Puerto Rico. The maximum observed differences were on the order of 100 mm per season. Inaccurate predictions of ET for an irrigated crop can lead to inefficient use of water and energy, increased potential for surface and groundwater contamination, and reduced profits for the grower.

The objectives of this study were 1) to evaluate prediction methods for estimating long-term average daily minimum temperature (T_{min}), maximum temperature (T_{max}), dew point temperature (T_{dew}), solar radiation (R_s) and wind speed (U_2, subscript refers to the height of the instrument above the ground in meters) for Puerto Rico; and 2) to verify the ability to estimate ET_o, using the Penman-Monteith method, at four locations where long-term measured climate data were available.

Materials and Methods

Estimation procedures for long-term daily climate data were derived from the literature. To evaluate the appropriateness of the procedures, comparisons were made of ET_o calculated using estimated and measured climate data (i.e., T_{min}, T_{max}, T_{dew}, R_s and U_2) at four locations within Puerto Rico: San Juan, Aguadilla, Mayagüez and Ponce. These sites represent the northeast, northwest, west, and south of Puerto Rico, respectively, and were selected because relatively complete climatic data sets exist for these locations.

Two primary sources of long-term climate data exist for Puerto Rico: Local Climatological Data (LCD) sheets published by the National Oceanic and Atmospheric Administration (NAAO) and the International Station Meteorological Climate Summary (ISMCS) (National Climate Data Center, 1992). The LCDs provide temperature data for approximately 40 locations in Puerto Rico. The LCDs also include detailed weather data for San Juan, which includes wind speed, relative humidity and hours of daily sunshine. This was the sole source of long-term average daily radiation data for Puerto Rico. The ISMCS provides long-term average daily T_{min}, T_{max}, T_{dew} and U_{10} for airports at Aguadilla, Mayaguez, Ponce, San Juan and the Roosevelt Road Navy Base at Ceiba. Unfortunately, the long-term Roosevelt Road T_{min}, T_{max} and T_{dew} data were determined to be in error and, therefore, could not be used in this study. Additional long-term average daily wind speed data ($U_{0.58}$) were available from the following sites: Aguirre, Lajas, Isabela, Rio Piedras, Gurabo, Corozal, Fortuna, Yabucoa and Adjuntas.

Results and Discussion

Proposed Climate Estimation Procedures For Puerto Rico

In this section, estimation procedures for T_{min}, T_{max}, T_{dew}, R_s and U_2 are presented.

Minimum and Maximum Air Temperature

Goyal et al. (1988) developed regression equations for minimum and maximum long-term average daily air temperatures for Puerto Rico based on surface elevation. Table 1 lists the regression coefficients for the daily average minimum and maximum temperatures in Puerto Rico by month. The regression equations have the following general form:

$$T = A+BZ \qquad (1)$$

where T is temperature (^oC), A and B are regression coefficients and Z is elevation (m) above mean sea level. Regression equations were derived with temperature data from Climatography of the United States No. 86-45 for Puerto Rico.

Table 1. Relationship among temperature (T) and elevation (Z) for Puerto Rico*

	Mean Daily Maximum Temperatures, ^oC			Mean Daily Minimum Temperatures, ^oC		
Month	A	B,-10^{-5}	R^2	A	B,-10^{-5}	R^2
Jan.	29.24	770	0.73	18.58	544	0.44
Feb.	29.37	752	0.72	18.37	558	0.46
Mar.	30.08	711	0.71	18.71	590	0.48
Apr.	30.59	687	0.71	19.9	686	0.63
May	31.16	707	0.76	21.23	608	0.63
Jun.	31.76	686	0.73	21.92	577	0.59
Jul.	32.07	717	0.64	22.14	591	0.58
Aug.	32.12	682	0.75	22.21	585	0.58
Sep.	32.12	696	0.79	21.95	586	0.62
Oct.	31.84	705	0.79	21.48	553	0.59
Nov.	30.89	706	0.75	20.68	562	0.55
Dec.	29.83	744	0.73	19.52	547	0.47

* T = A + BZ, where T = temperature, ^oC; Z = elevation above mean see level, m; A and B are regression coefficients and R^2 is the square of the coefficient of correlation. Table contents are from Goyal et al., 1988, Table 1.

Dew Point Temperature

The FAO (Allen et al., 1998) has reported that T_{dew} can be estimated based on the use of the daily minimum air temperature. A correction factor, which is added to the minimum temperature, is recommended based on local conditions. Therefore, T_{dew} can be estimated in Puerto Rico from the following equation:

$$T_{dew} = T_{min} + K_{corr} \qquad (2)$$

where K_{corr} is a temperature correction factor in degrees ^oC, listed in Table 2, and the other variables have been previously defined.

Based on the analysis presented in the next section, correction factors (K_{corr}) were calibrated for three of the six Climatic Divisions of Puerto Rico as defined by NOAA, and are presented in Table 2. Figure 1 shows the Climatic Divisions for Puerto Rico. The -2.5 ^oC correction factor for Division 2 is consistent with (T_{min}-T_{dew}) data for similar arid regions reported by Allen et al. (1998). No long-term average T_{dew} data were available for Climatic Divisions 3, 5 and 6. Therefore, these Divisions were assigned a value of 0 ^oC similar to Division 4 (humid conditions). Table 2 recommends using a value for K_{corr} of 0.5 if the T_{dew} is estimated using estimated T_{min} data and a value of –1.5 ^oC if T_{dew} is estimated using measured T_{min} data. The reason for this is that, for the four locations evaluated in this study, the regression equations (Table 1) underestimated T_{min}, causing an underestimation of T_{dew}. To correct this problem, a value of K_{corr} equal to 0.5^{o}C should be used when T_{dew} is estimated from estimated T_{min} data.

Table 2. Temperature correction Factor K_{corr} used in Equation 2 for Climatic Divisions within Puerto Rico.

Climatic Division	**1**	**2**	**3,4,5,6**
K_{corr} (^{o}C)	0.5 if T_{dew} is estimated using estimated T_{min} data -1.5 if T_{dew} is estimated using measured T_{min} data	-2.9	0

* See Figure 1 for Climate Divisions

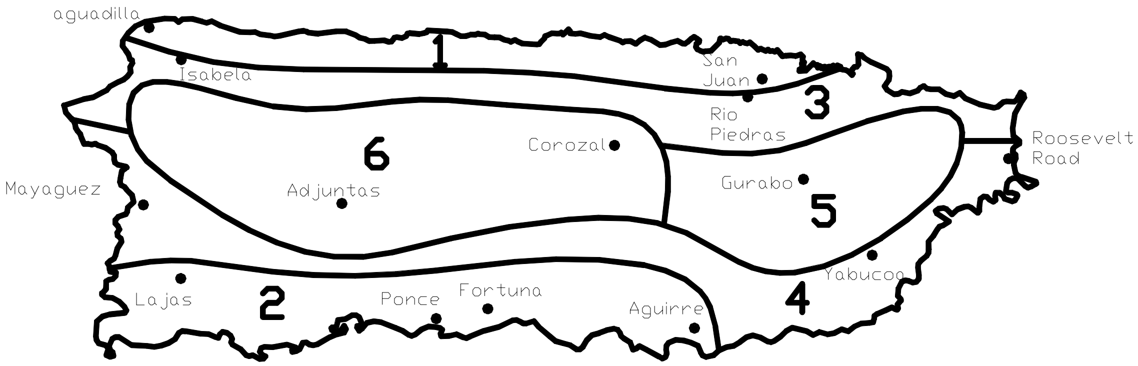

Figure 1. Climatic Divisions of Puerto Rico.

Wind Speed

No equation exists for estimating wind speed. The FAO recommends that wind speed be estimated from nearby weather stations or as a preliminary measure, use of the worldwide average of 2 m/sec can be used. Wind speeds that are collected at heights above the ground other than 2 m can be adjusted to the U_2 value using an exponential relationship. For Puerto Rico, daily average wind speeds were estimated based on averaging station data within the Climatic Divisions established by the NOAA, and are presented in Table 3.

Table 3. Average Daily Wind Speeds by Month and Climatic Division* with Puerto Rico.

	Average Daily Wind Speeds (m/s)**											
Climatic Division*	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
1	2.7	2.8	3.0	2.9	2.6	2.6	2.9	2.7	2.1	1.9	2.2	2.6
2	1.8	2.0	2.2	2.1	2.2	2.4	2.4	2.1	1.7	1.5	1.4	1.5
3	2.2	2.4	2.6	2.4	2.2	2.4	2.7	2.5	2.0	1.8	2.0	2.3
4	1.8	2.0	2.1	2.1	2.0	2.0	2.0	1.8	1.6	1.6	1.6	1.6
5	1.1	1.3	1.4	1.5	1.6	1.7	1.6	1.3	1.1	0.9	0.9	0.9
6	1.3	1.5	1.5	1.5	1.6	1.8	1.8	1.5	1.2	1.1	1.0	1.0

* See Figure 1 for Climate Divisions

** Averages are based on San Juan and Aguadilla for Div. 1; Ponce, Aguirre, Fortuna and Lajas, for Div. 2; Isabela and Rio Piedras for Div. 3; Mayagüez, Roosevelt Rd. and Yabucoa for Div. 4; Gurabo for Div. 5; and Corozal and Adjuntas for Div. 6.

Radiation

The FAO recommends that solar radiation be estimated using the following equation for islands:

$$R_s = (0.7 R_a - b) \qquad (3)$$

where R_s is solar radiation, b is an empirical constant, equal to 4 MJ m^{-2} day^{-1} and R_a is the incoming extraterrestrial radiation given by the following equation:

$$R_a = (24*60/\pi) G_{sc} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \qquad (4)$$

where G_{sc} is a solar constant equal to 0.0820 MJ m^{-1} min^{-1}, and d_r is the inverse relative distance Earth-Sun equal to

$$d_r = 1+0.033\cos(2\pi J / 365) \qquad (5)$$

where J is a number of the day in the year between 1 (1 January) and 365 or 366 (31 December). For estimating the long-term average daily reference evapotranspiration by month, J is equal to 15 for January, 45 for February, 75 for March, and so on. The sunset hour angle ω_s is give by

$$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)] \qquad (6)$$

The solar declination (radians) is given by

$$\delta = 0.409 \sin[(2\pi J / 365) - 1.39] \qquad (7)$$

In the above equations, the latitude φ must be in radians. The conversion from decimal degrees to radians is

$$[\text{Radians}] = (\pi/180)\ [\text{decimal degrees}] \qquad (8)$$

It should be noted that the only input required to use equation 4 is the day of the year (J) and the site latitude (φ). For a more detailed discussion of the calculation of R_a, the reader is referred to Allen et al., 1998.

Equation 3 is limited to elevations less than 100 m above sea level. Therefore, for higher elevations, in the interior areas of Puerto Rico where the ocean does not moderate air temperatures as much as along the low altitude coastal areas, the Hargreaves' radiation formula can be used:

$$R_s = k_{Rs}\,(T_{max} - T_{min})^{1/2}\,R_a \qquad (9)$$

where k_{Rs} is an adjustment factor equal to 0.19, and the other variables have been previously defined.

Comparison of ET_o with Measured and Estimated Data

In this section, calculated ET_o based on measured and estimated climate parameters are compared. The ET_o based on measured data will be referred to as ET_{om} and the ET_o based on estimated data will be referred to as ET_{oe}. Figures 2 through 5 show the calculated ET_o based on measured and estimated T_{min} and T_{max}, T_{dew}, U_2 and $R_{s,}$ respectively. Estimated parameters were obtained from Table 1, 2 and 3 and equations 1, 2 and 3. Equation 3 was used (instead of equation 9) because all of the locations being considered are at elevations less than 100 m. Ponce airport wind speeds were markedly higher than the nearby Fortuna University Experiment Station wind speeds, even after adjustment for measurement height and converting 24-hour measurements, taken at the Experiment Station, to daytime wind speeds. Therefore, measured wind speeds for Ponce were taken as the arithmetic mean of the Ponce airport and the Fortuna Experiment Station.

The comparisons of ET_{om} and ET_{oe}, shown in Figures 2 through 5, indicate reasonably good agreement with some under (-) and overestimations (+) as noted below:

- Values for ET_{oe} for Ponce, based on estimated T_{min} and T_{max} values, resulted in slight underestimations relative to ET_{om} at high values of ET_o(Figure 2). The maximum error was -0.44 mm/day (underestimate) for Ponce in June. The maximum overestimate was +0.3 mm/day for Aguadilla during November.

- Values of ET_{oe}, based on estimated T_{dew}, were in fairly good agreement with ET_{om} for all locations (Figure 3). The maximum error was +0.35 mm/day for Mayagüez during January. The maximum underestimate was -0.23 mm/day for San Juan during the months of March and April. Note that, based on instructions given in Table 2, the K_{corr} value used was –1.5 ^{o}C, because the values of T_{min} were measured (not estimated).
- ET_{oe} based on estimated values of wind speed (U_2), generally were in good agreement relative to ET_{om} (Figure 4). The maximum observed error was -0.27 mm/day (underestimate) for Ponce in January. The maximum overestimate was +0.13 mm/day for San Juan in November.
- Measured radiation was only available for San Juan. Figure 5 indicates good agreement between ET_{oe}, based on equation 3, and ET_{om}. The maximum under and overestimates were -0.14 mm/day (February) and +0.21 mm/day (May), respectively.

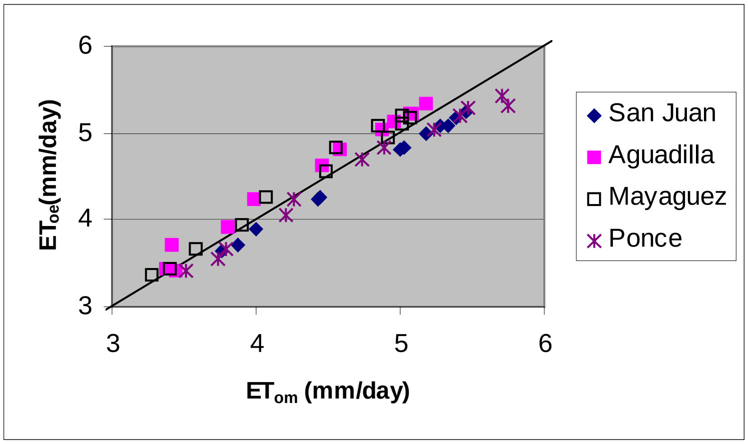

Figure 2. Comparison of ET_o calculated with measured data (ET_{om}) and estimated T_{min} and T_{max} data (ET_{oe}).

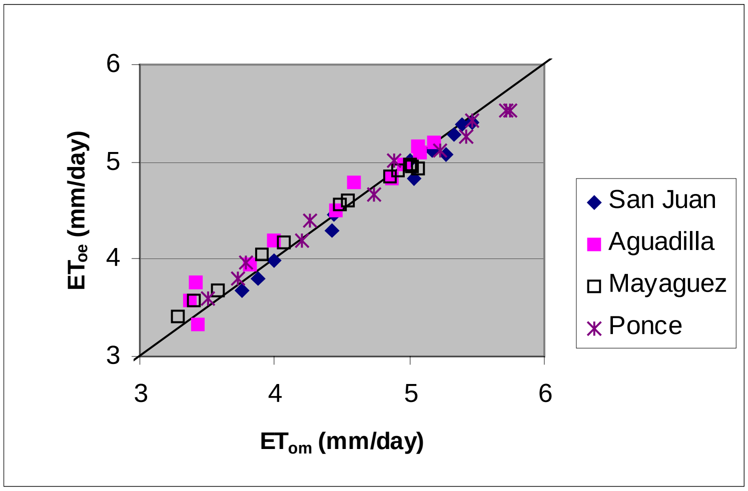

Figure 3. Comparison of ET_o calculated with measured data (ET_{om}) and estimated T_{dew} data (ET_{oe}). K_{corr} was set to –1.5 for Climate Division 1 Sites.

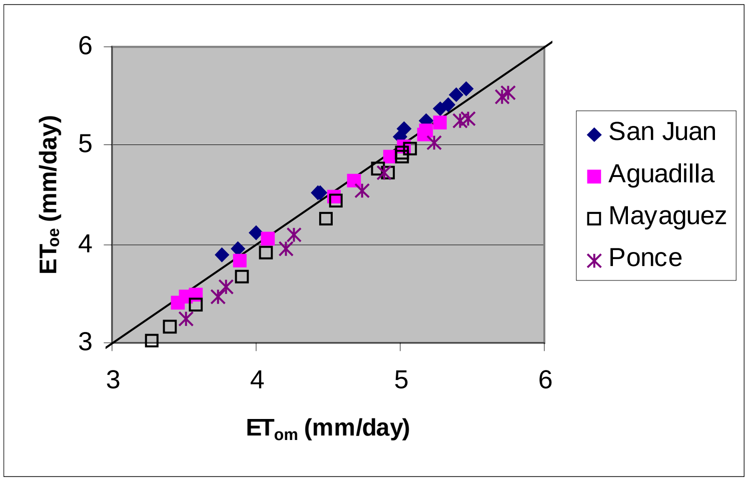

Figure 4. Comparison of ET$_o$ calculated with measured data (Et$_{om}$) and estimated U$_2$ data (ET$_{oe}$).

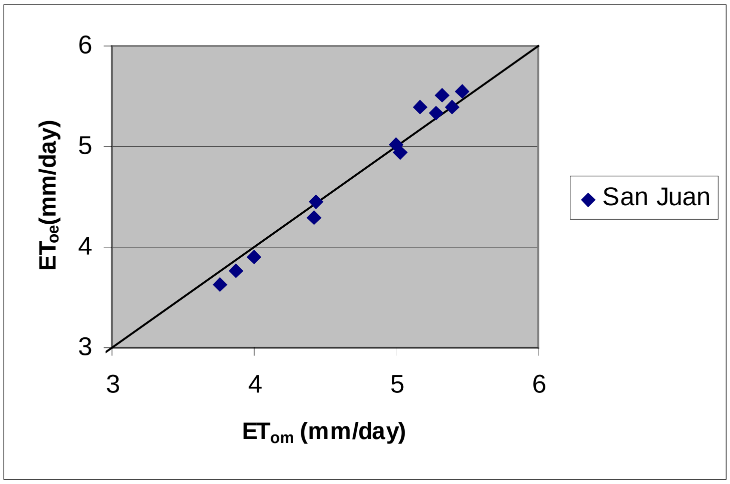

Figure 5. Comparison of ET$_o$ calculated with measured data (ET$_{om}$) and estimated R$_s$ data (ET$_{oe}$).

Figure 6 compares ET$_{om}$ and ET$_{oe}$ based on all parameters estimated simultaneously. In general the ET$_{oe}$ tended to overestimate relative to ET$_{om}$. However, data for San Juan, Maygüez and Ponce showed very good agreement. ET$_{oe}$ for Aguadilla was overestimated for all months relative to ET$_{om}$. The maximum error was 0.47 mm/day for Aguadilla during November. One potential application of this data is for irrigation design, which relies on the peak ET. Therefore, from an irrigation design standpoint, the fact that ET$_{oe}$ (based on all parameters being estimated) overestimates, is not a serious problem.

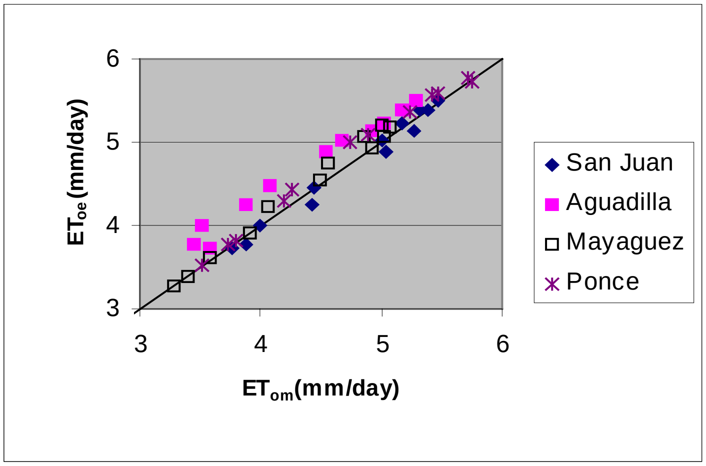

Figure 6. Comparison of ET_o calculated with measured data (ET_{om}) and estimated data (ET_{oe}) for all climate parameters. K_{corr} was set to 0.5 for Climate Division 1 locations.

Example Application

To illustrate the use of the climate estimation procedures for calculating reference evapotranspiration, an example is presented. The following conditions apply, location: Dos Bocas, Arecibo County, PR; elevation: 60 m; latitude: 18°20'. The estimated climate data and reference evapotranspiration for January through December are given in Table 4. Minimum and maximum temperatures were calculated with data from Table 1. Dos Bocas is in Climate Division 6, therefore, per Table 2, dew point temperature was taken as the minimum temperature (i.e., K_{corr} = 0 °C). Wind speeds were obtained from Table 3 for Climate Division 6. From equation 8, the site latitude in radians is 0.32 and the resulting R_a values have been included in Table 4.

Table 4. Estimated Climate Data and Reference Evapotranspiration for Dos Bocas, PR.

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**
T_{max}, °C	29.2	29.4	30.1	30.6	31.2	31.8	32.1	32.1	32.1	31.8	30.9	29.8
T_{min}, °C	18.6	18.4	18.7	19.9	21.2	21.9	22.1	22.2	21.9	21.5	20.7	19.5
T_{dew}, °C	18.6	18.4	18.7	19.9	21.2	21.9	22.1	22.2	21.9	21.5	20.7	19.5
U_2, m/s	1.1	1.3	1.4	1.5	1.6	1.7	1.6	1.3	1.1	0.9	0.9	0.9
R_a, MJ m^{-2} day^{-1}	27.7	31.2	35.2	38.0	39.1	39.2	39.0	38.3	36.3	32.8	28.9	26.7
R_s, MJ m^{-2} day^{-1}	15.4	17.8	20.7	22.6	23.4	23.4	23.3	22.8	21.4	18.9	16.2	14.7
ET_o, mm/day	3.1	3.6	4.3	4.7	5.0	5.1	5.1	4.9	4.6	3.9	3.3	2.9

Reference evapotranspiration was calculated using the Penman Monteith method as described in Allen et al. (1998). The calculation procedure was implemented via an Excel spreadsheet. Alternatively, the reference evapotranspiration could have been calculated using the computer program CROPWAT (Clark, 1998). This program is available free of charge on the Internet.

Method Limitations

The approach presented in this paper should be considered only approximate for estimating reference evapotranspiration. Some potential limitations are:

- The data presented in Tables 1, 2 and 3 are only valid for Puerto Rico.
- The approach has not been validated using measured T_{dew} data from Climatic Divisions 3, 5 and 6.
- Equation 3b has not been verified to be accurate for areas within Puerto Rico where elevations exceed 100 m.
- The climate estimation procedures are daily averages for month-long periods. Therefore, it is not appropriate to use these estimation procedures for estimating ET_o for daily or weekly periods.

Conclusion

This study evaluated procedures for estimating climate data to be used as input to the Penman-Monteith reference evapotranspiration calculation method in Puerto Rico. Comparison of reference evapotranspiration based on estimated and measured data showed reasonably good agreement. The methods described in this paper can be used to estimate reference evapotranspiration at any location within Puerto Rico. It is evident from this study that additional long-term climate data are needed in Puerto Rico, especially in the interior mountain regions of the island.

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