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Estimating Island-Wide Reference Evapotranspirations for Puerto Rico Using the Penman-Monteith Method

Eric Harmsen, Ph.D., P.E.

Assistant Professor, Department of Agricultural and Biosystems Engineering

University of Puerto Rico, Mayagüez, PR 00681

Salvio Torres Justiniano

Undergraduate Research Assistant

Department of Agronomy, University of Puerto Rico, Mayagüez, PR 00681

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Abstract. *This paper presents the application of a simple procedure for estimating long-term average daily reference evapotranspiration (ET_o) in Puerto Rico. With only two parameters, site latitude and surface elevation, it is possible to estimate all other input to the Penman-Monteith method. Minimum and maximum air temperatures are estimated from surface elevation data. Dew point temperature is estimated from the minimum temperature plus or minus a temperature correction factor. Temperature correction factors and average wind speeds are associated with six climatic divisions for Puerto Rico. Solar radiation is estimated from a simple equation for island settings or by the Hargreaves' radiation equation, based on air temperature differences. Estimated ET_o is presented for thirty-four locations within Puerto Rico. Comparisons are made with values of ET_o previously made using the Hargreaves-Samani method for the same locations.*

Keywords. evapotranspiration, crop water use, Penman-Monteith, climatology, Puerto Rico.

Introduction

Estimates of long-term average daily evapotranspiration (ET) and reference evapotranspiration (ET_o)[1] have been made for numerous agricultural crops in Puerto Rico (Goyal, 1989a). These data are essential for determining monthly irrigation volumes, sizing of pumps and water conveyance devices, and for determining irrigation system fixed and operating costs. Most of the estimates previously made were based on 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 (estimates obtained from Goyal, 1989b) 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. No comparisons have been made between the Hargreaves-Samani and Penman-Monteith methods at locations in Puerto Rico. 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.

In 1990 a committee of the United Nations Food and Agriculture Organization (FAO) recommended the Penman-Monteith method as the single approach to be used for calculating reference evapotranspiration (ET_o). This recommendation was based on comprehensive studies, which compared twenty ET calculation methods with weighing lysimeter data (Jensen et al., 1990). These studies found the Penman-Monteith method to produce superior results relative to all other methods (including the SCS Blaney-Criddle and Hargreaves-Samani methods). Therefore, it is imperative that improved estimates of long-term average daily reference evapotranspiration be made available for Puerto Rico at this time.

The objectives of this study were 1) to present a simplified procedure for estimating long-term average daily reference evapotranspiration for any location in Puerto Rico; and 2) to compare previous estimates of reference evapotranspiration using the Hargreaves-Samani method with the Penman-Monteith method.

Materials and Methods

Harmsen and Torres Justiniano (2001) presented procedures for estimating climate parameters to be used in the Penman-Monteith method for Puerto Rico. Their methodology was based on methods presented in the literature, which were then calibrated for Puerto Rico conditions. The study compared estimates of reference evapotranspiration at four locations (San Juan, Aguadilla, Mayagüez and Ponce) using measured and estimated climate data as input to the Penman-Monteith method. Figure 1 shows the results of their comparison of ET_o based on measured and estimated climate input data. Input to the Penman-Monteith method includes: maximum daily air temperature (T_{max}), minimum daily air temperature (T_{min}), dew point temperature (T_{dew}), wind speed, measured at 2 meters above the ground (U_2), and solar radiation (R_s). Although the methodology tended to overestimate slightly (Figure 1), for estimation purposes, it appears to provide reasonably good results. As noted by Harmsen and Torres Justiniano (2001), from an irrigation design standpoint, the fact that ET_o (based on all parameters being estimated) overestimates slightly is not a serious problem. The procedures presented by Harmsen and Torres Justiniano (2001) were used in this study for estimating Island-wide reference evapotranspirations. The procedures are summarized below.

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[1] Evapotranspiration (ET) is related to the reference evapotranspiration (ET_o) by the following relation: ET = K_c ET_o, where K_c is a crop coefficient.

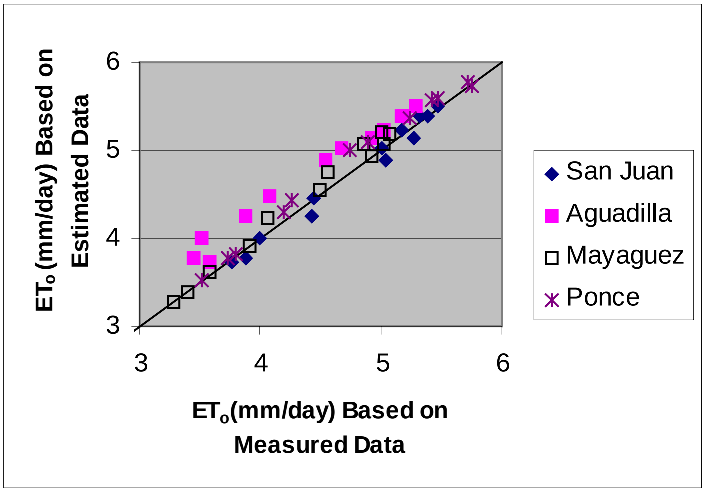

Figure 1. Comparison of long-term average daily reference evapotranspiration (ET_o) calculated with measured and estimated data. (Harmsen and Torres Justiniano (2001).

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:

$$T = A+BZ \tag{1}$$

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.

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:

$$T_{dew} = T_{min} + K_{corr} \tag{2}$$

where K_{corr} is a temperature correction factor in degrees ^oC, listed in Table 2, and the other variables have been previously defined. The correction factors (K_{corr}) are presented in Table 2. Figure 2 shows the Climatic Divisions for Puerto Rico.

Table 1. Relationship among temperature (T) and elevation (Z) for Puerto Rico (Goyal et al., 1988)*

	Mean Daily Maximum Temperatures, °C			Mean Daily Minimum Temperatures, °C		
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, °C; 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 2. Temperature correction Factor K_{corr} used in Equation 2 for Climatic Divisions within Puerto Rico. (Harmsen and Torres Justiniano, 2001)

Climatic Division	1	2	3,4,5,6
K_{corr} (°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

Wind Speed

For Puerto Rico, daily average wind speeds measured at 2 meters above the ground surface (U_2) were estimated based on averaging station data within the Climatic Divisions established by NOAA, and are presented in Table 3.

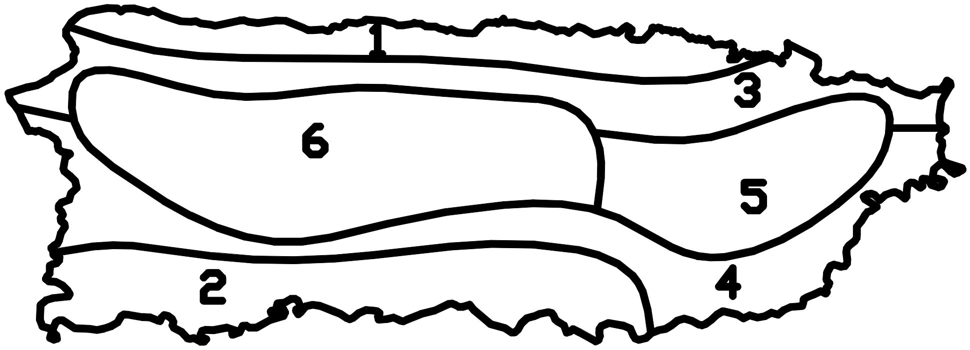

Figure 2. Climatic Divisions of Puerto Rico: 1 North Coastal, 2 South Coastal, 3 Northern Slopes, 4 Southern Slopes, 5 Eastern Interior, and 6 Western Interior.

Table 3. Average Daily Wind Speeds by Month and Climatic Division* with Puerto Rico. (Harmsen and Torres Justiniano, 2001)

	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. Table 4 lists values of R_a by month and for latitudes applicable to Puerto Rico. The equations used to develop Table 4 are presented in Allen et al., 1998.

Table 4. Extraterrestrial radiation by month and latitude within Puerto Rico

	Extraterrestrial Radiation, R_a (MJ/m^2-day)						
	Latitude (decimal degrees N)						
Month	17.90	18.00	18.10	18.20	18.30	18.40	18.50
Jan	27.90	27.85	27.80	27.74	27.69	27.64	27.58
Feb	31.36	31.32	31.27	31.23	31.19	31.14	31.10
Mar	35.33	35.30	35.28	35.25	35.23	35.20	35.18
Apr	38.03	38.02	38.02	38.02	38.01	38.01	38.01
May	39.02	39.03	39.04	39.06	39.07	39.09	39.10
Jun	39.07	39.09	39.12	39.14	39.16	39.19	39.21
Jul	38.91	38.93	38.95	38.97	38.99	39.01	39.03
Aug	38.30	38.31	38.31	38.32	38.32	38.33	38.33
Sep	36.38	36.36	36.35	36.33	36.32	36.31	36.29
Oct	32.91	32.88	32.84	32.81	32.77	32.74	32.70
Nov	29.10	29.05	29.01	28.96	28.91	28.86	28.81
Dec	26.89	26.84	26.78	26.73	26.67	26.61	26.56

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:

$$R_s = k_{Rs} (T_{max} - T_{min})^{1/2} R_a \qquad (4)$$

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

Example Application

To illustrate the use of the climate estimation procedures for calculating long-term average daily reference evapotranspiration, an example is presented. The following conditions apply, location: Dos Bocas, Arecibo County, PR; elevation: 60 m; latitude: $18^o20'$. The estimated climate data and reference evapotranspiration for January through December are given in Table 5. Minimum and maximum temperatures were calculated with data from Table 1. Dos Bocas is in Climate Division 6, therefore, per Table 2, the temperature correction factor (K_{corr}) is 0 ^oC and the estimated dew point temperature is equal to the minimum air temperature. Wind speeds were obtained from Table 3 for Climate Division 6. From Table 4 and equation 3, R_s values were determined. The latitude in decimal form (required to use Table 4) is determined as follows: 18 degrees + 20 minutes / 60 minutes per degree = 18.33 decimal degrees. Estimated R_s, along with Ra values obtained from Table 4 are presented in Table 5.

Table 5. Estimated Climate Data and Long-Term Average Daily 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

Definitions: maximum daily air temperature (T_{max}), minimum daily air temperature (T_{min}), dew point temperature (T_{dew}), wind speed, measured at 2 meters above the ground (U_2), extraterrestrial radiation (R_a) solar radiation (R_s) and long-term daily average reference evapotranspiration (ET_o).

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. Currently, a computer program is being developed by the Senior Author, which will perform the above procedure directly on the World Wide Web. This will increase accessibility to the public and greatly reduce the number of calculations required by the user.

Comparison of Estimated Reference Evapotranspiration at Thirty-Four Locations in Puerto Rico

Goyal et al. (1988) estimated reference evapotranspiration at thirty-four locations in Puerto Rico using the Samani-Hargreaves method. In this section estimates will be presented based on the Penman-Monteith method and a comparison of the two approaches will be discussed. The locations where estimates were made are shown in Figure 3.

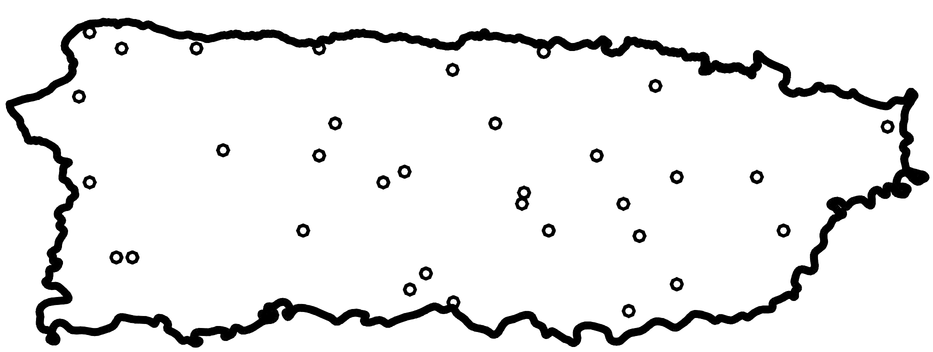

Figure 3. Locations within Puerto Rico where estimates of reference evapotranspiration have been made (see Table 6 for estimated values).

Table 6 lists the Penman-Monteith-estimated reference evapotranspirations for the thirty-four locations considered by Goyal et al. (1988). The table indicates the Climatic Division for each site, upon which the K_{corr} and U_2 values where selected from Tables 2 and 3. For locations with elevations less than or equal to 100 m and greater than 100 m, R_s was calculated using equations 3 and 4, respectively. Figure 4 shows the results of the comparison.

Figure 4 indicates positive and negative differences. The maximum positive difference (i.e., H-S minus P-M) was 0.92 mm/day during the month of November at the Juncos 1E station. On a monthly basis, this is equal to 27.5 mm or 1.1 inches of water. The minimum difference (i.e., negative difference) was –0.75 mm/day during the month of June at Aguirre. On a monthly basis this is –22.5 mm or –0.88 inches of water. Figure 4 indicates, that while there is agreement between the two methods during many months at many locations, there were also many estimates, which were not in agreement. One could reasonable ask the question: "Which method is more correct?" FAO recommends using the Penman-Monteith method over all other methods even when local data is missing. Studies have shown that using estimation procedures for missing data with the Penman-Monteith equation will generally provide more accurate estimates of ET_o than will other available methods requiring less input data (Allen et al., 1998).

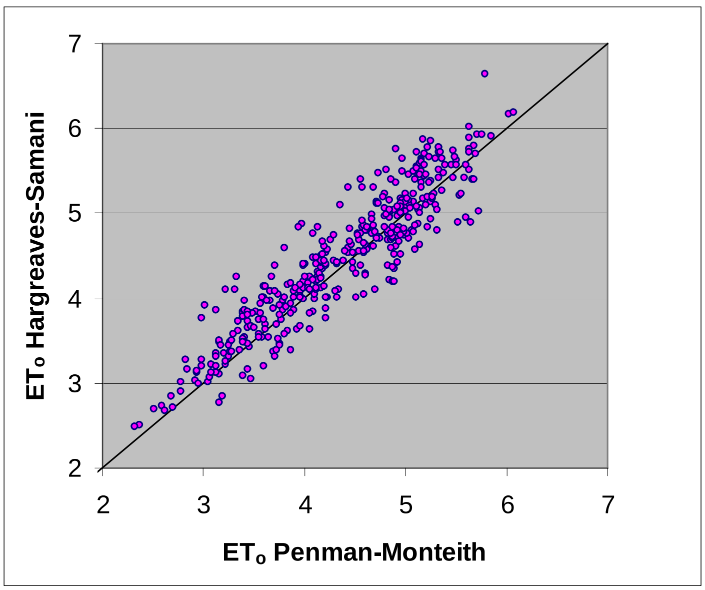

Figure 4. Comparison of reference evapotranspiration estimated by the Penman-Monteith (P-M) and Hargreaves-Samani (H-S) Methods for thirty-four locations in Puerto Rico.

Figure 5 shows a plot of the differences between ET_o calculated by the two methods (H-S minus P-M) by month, for the Juncos 1E and Aguirre stations. Maximum positive and negative differences were observed at these sites, respectively. If the Penman-Monteith method is taken as the standard ("correct") ET_o, then it can be stated that the Hargreaves-Samani method overestimated ET_o at Juncos 1E and underestimated ET_o at Aguirre. Juncos 1E is in Climate Division 5, which is humid, while Aguirre, in Climate Division 2, is semi-arid. The maximum

Table 6. Reference Evapotranspiration Estimates using the Penman-Monteith (P-M) and Hargreaves-Samani (H-S) Methods for Thirty-Four Locations in Puerto Rico. *

Location	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m)	Climatic Division	ET_o Method**	Reference Evapotranspiration (mm/day)											
						Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Aguirre	17.97	66.48	15.0	2	P-M	3.8	4.3	4.9	5.3	5.5	5.6	5.7	5.6	5.1	4.5	3.9	3.6
					H-S	3.6	4.0	4.5	4.8	4.9	4.9	5.0	5.0	4.9	4.4	3.9	3.5
Aibonito	18.13	66.27	690.0	5	P-M	2.6	3.1	3.7	4.3	4.4	4.5	4.5	4.4	4.1	3.6	2.9	2.6
					H-S	2.5	2.9	3.6	4.5	4.2	4.2	4.1	4.0	3.9	3.4	2.7	2.5
Arecibo 2 ESE	18.47	66.70	4.5	1	P-M	3.8	4.2	4.9	5.2	5.4	5.6	5.7	5.5	5.1	4.6	4.1	3.8
					H-S	3.6	4.0	4.7	5.1	5.3	5.4	5.4	5.2	5.1	4.5	3.9	3.5
Barranquitas	18.18	66.32	540.0	6	P-M	2.7	3.2	3.8	4.2	4.4	4.5	4.5	4.4	4.1	3.6	3.0	2.6
					H-S	2.9	3.2	3.9	4.3	4.4	4.4	4.3	4.3	4.1	3.7	3.2	2.7
Caguas	18.23	66.03	75.0	5	P-M	3.1	3.7	4.3	4.8	5.0	5.1	5.1	5.0	4.6	4.0	3.3	3.0
					H-S	3.9	4.4	5.1	5.5	5.5	5.5	5.6	5.5	5.3	4.9	4.1	3.8
Canovanas 2N	18.40	65.08	9.0	3	P-M	3.3	3.8	4.4	4.8	5.0	5.0	5.0	4.9	4.6	4.0	3.4	3.1
					H-S	3.5	4.0	4.6	5.0	5.2	5.1	5.0	4.8	4.8	4.4	3.7	3.3
Carite Camp Tunnel	18.07	66.10	600.0	6	P-M	2.9	3.4	3.9	4.3	4.4	4.5	4.5	4.5	4.2	3.7	3.1	2.7
					H-S	3.1	3.5	4.1	4.3	4.2	4.1	4.1	4.2	4.2	3.8	3.4	3.0
Cayey 1 NW	18.12	66.15	420.0	4	P-M	3.5	4.2	4.9	5.2	5.1	5.0	5.0	5.0	4.8	4.3	3.8	3.4
					H-S	3.6	4.1	4.8	5.2	5.1	5.1	5.1	5.0	5.0	4.4	3.9	3.5
Cidra 3 E	18.18	66.13	420.0	4	P-M	3.2	3.8	4.4	4.6	4.7	4.7	4.8	4.8	4.3	4.1	3.6	3.1
					H-S	3.3	3.8	4.8	4.8	4.8	4.8	4.8	4.7	4.7	4.3	3.7	3.2
Coloso	18.38	67.15	15.0	3	P-M	3.6	4.1	4.7	5.1	5.1	5.2	5.3	5.2	4.7	4.1	3.6	3.4
					H-S	4.0	4.5	5.1	5.5	5.5	5.7	5.7	5.5	5.3	4.8	4.2	3.8
Comerio Falls	18.27	66.18	150.0	5	P-M	3.0	3.5	4.2	4.5	4.6	4.7	5.2	4.5	4.2	3.7	3.2	2.8
					H-S	3.3	3.7	4.4	4.8	4.8	4.9	5.4	4.7	4.5	4.0	3.5	3.2
Corozal 4 W	18.33	66.37	120.0	6	P-M	3.3	3.9	4.6	5.0	5.1	5.2	5.1	4.9	4.7	4.2	3.5	3.1
					H-S	3.6	4.1	4.8	5.2	5.4	5.4	5.2	5.0	5.0	4.5	3.8	3.5

Table 6. Continued

Location	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m)	Climatic Division	ET_o Method**	Reference Evapotranspiration (mm/day) Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dorado 4 W	18.47	66.28	7.5	1	P-M	3.4	3.9	4.6	4.9	5.0	5.2	5.1	5.1	4.9	4.3	3.7	3.4
					H-S	3.2	3.6	4.3	4.6	4.7	4.8	4.6	4.6	4.6	4.1	3.5	3.1
Dos Bocas	18.33	66.67	60.0	3	P-M	3.5	4.0	4.7	5.1	5.1	5.3	5.8	5.2	4.7	4.1	3.6	3.4
					H-S	3.8	4.4	5.1	5.6	5.6	5.9	6.6	5.5	5.5	4.8	4.1	3.8
Fajardo	18.33	65.65	12.0	4	P-M	3.2	3.6	4.2	4.6	4.8	4.9	4.9	4.9	4.6	4.1	3.5	3.0
					H-S	3.1	3.5	4.0	4.3	4.4	4.4	4.4	4.4	4.4	4.0	3.4	3.0
Garzas Dam	18.13	66.73	745.5	2	P-M	3.1	3.5	4.1	4.6	4.5	4.7	4.8	4.6	4.3	3.8	3.3	2.9
					H-S	3.1	3.6	4.1	4.6	4.5	4.7	4.8	4.6	4.4	3.9	3.4	3.0
Guayama	17.98	66.12	58.5	4	P-M	3.4	3.9	4.5	4.9	5.0	5.1	5.1	5.0	4.7	4.2	3.6	3.2
					H-S	3.4	3.8	4.4	4.7	4.8	4.8	4.8	4.8	4.7	4.1	3.6	3.2
Guineo Reservoir	17.98	66.12	900.0	4	P-M	2.7	3.1	3.7	4.0	4.0	4.0	4.1	4.1	3.9	3.4	2.9	2.6
					H-S	2.7	3.1	3.7	4.0	4.0	4.1	4.2	4.1	3.9	3.5	3.0	2.7
Humacao 1 SW	18.13	65.83	30.0	4	P-M	3.2	3.8	4.4	4.8	4.9	4.9	5.0	4.9	4.6	4.1	3.5	3.1
					H-S	3.5	3.9	4.6	4.8	4.7	4.7	4.8	4.8	4.6	4.2	3.7	3.3
Isabela 4 SW	18.47	67.07	126.0	3	P-M	3.4	3.9	4.5	4.9	4.9	4.9	5.0	4.9	4.7	4.2	3.5	3.3
					H-S	3.5	3.4	4.6	5.0	5.0	5.2	5.1	5.0	4.9	4.4	3.8	3.4
Jayuya	18.22	66.58	420.0	6	P-M	2.9	3.6	4.5	4.8	4.8	5.0	5.0	5.0	4.6	4.1	3.3	3.0
					H-S	3.2	3.7	4.6	5.0	5.0	5.2	5.2	5.1	4.9	4.4	3.6	3.3
Juana Diaz Camp	18.05	66.50	60.0	2	P-M	3.7	4.2	4.8	5.1	5.2	5.4	5.5	5.3	4.8	4.2	3.7	3.4
					H-S	4.0	4.5	5.1	5.5	5.4	5.5	5.6	5.4	5.2	4.6	4.1	3.8
Juncos 1 E	18.23	65.88	81.0	5	P-M	3.2	3.8	4.4	4.9	5.1	5.2	5.2	5.0	4.6	3.9	3.3	3.0
					H-S	4.1	4.6	5.3	5.8	5.7	5.8	5.9	5.7	5.4	4.8	4.3	3.9
Lajas	18.03	67.08	30.0	2	P-M	3.7	4.2	4.9	5.2	5.3	5.5	5.6	5.4	4.8	4.2	3.7	3.4
					H-S	4.1	4.6	5.4	5.6	5.6	5.7	6.0	5.7	5.2	4.7	4.3	4.0

Table 6. Continued

Location	Latitude (decimal degrees)	Longitude (decimal degrees)	Elevation (m)	Climatic Division	ET_o Method**	Reference Evapotranspiration (mm/day)											
						Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lares	18.28	66.88	360.0	6	P-M	3.6	4.2	4.9	5.3	5.5	5.7	5.6	5.5	5.1	4.2	3.8	3.3
					H-S	3.9	4.4	5.1	5.5	5.7	5.8	5.8	5.6	5.4	4.5	4.2	3.7
Maniti	18.43	66.45	75.0	1	P-M	3.7	4.3	4.9	5.3	5.5	5.6	5.7	5.5	5.1	4.6	4.0	3.7
					H-S	3.5	4.1	4.8	5.2	5.4	5.5	5.4	5.2	5.1	4.6	3.8	3.4
Mayaguez	18.22	67.13	24.0	4	P-M	3.6	4.1	4.8	5.2	5.2	5.3	5.3	5.2	4.9	4.3	3.7	3.4
					H-S	3.9	4.5	5.2	5.6	5.7	5.8	5.8	5.6	5.4	4.7	4.1	3.8
Patillas Dam	18.03	66.03	72.0	4	P-M	3.2	3.8	4.4	4.7	4.9	4.9	4.9	4.9	4.6	4.0	3.4	3.1
					H-S	3.3	3.8	4.4	4.7	4.8	4.7	4.7	4.8	4.7	4.1	3.8	3.1
Ponce 4 E	18.02	66.53	12.0	2	P-M	3.6	4.0	4.6	4.9	5.1	5.2	5.3	5.2	4.8	4.2	3.6	3.3
					H-S	3.8	4.3	4.8	5.1	5.1	5.1	5.2	5.2	5.0	4.5	4.0	3.7
Quebradillas	18.47	66.93	111.6	1	P-M	3.7	4.2	4.9	5.1	5.1	5.3	5.3	5.3	5.0	4.5	4.0	3.7
					H-S	3.4	3.9	4.5	4.9	5.0	5.1	5.1	4.9	4.8	4.3	3.7	3.3
Ramey Air Force Base	18.50	67.13	71.1	1	P-M	3.2	3.6	4.2	4.5	4.7	4.8	4.9	4.9	4.6	4.1	3.5	3.1
					H-S	2.8	3.2	3.8	4.0	4.1	4.2	4.2	4.2	4.0	3.6	3.1	2.8
Rio Piedras	18.40	66.07	30.0	3	P-M	3.3	3.8	4.4	4.8	4.9	5.0	5.0	5.0	4.6	4.0	3.4	3.2
					H-S	3.5	4.0	4.7	5.1	5.1	5.2	5.1	5.0	4.9	4.4	3.8	3.4
San German	18.08	67.05	114.0	4	P-M	4.1	4.7	5.3	5.6	5.5	5.6	5.8	5.7	5.2	4.7	4.2	4.0
					H-S	4.1	4.6	5.2	5.6	5.6	5.7	5.9	5.7	5.3	4.8	4.2	4.0
Utuado	18.27	66.70	129.0	6	P-M	3.9	4.5	5.4	5.6	5.7	6.0	6.1	5.8	5.3	4.7	4.0	3.6
					H-S	4.2	4.8	5.6	5.9	5.9	6.2	6.2	5.9	5.7	5.1	4.4	4.0

* Hargreaves-Samani values of reference evapotranspiration were obtained from Goyal et al. (1988).

** P-M Penman-Monteith method; S-H Hargreaves-Samani method.

underestimate of –0.75 mm/day at Aguirre (semi-arid) is equal to a 13% error, and the maximum overestimate of 0.92 mm/day at Juncos 1E (humid) is equal to a 28% error. These results are consistent with the findings of the ASCE study (Jensen et al., 1990), which found the Hargreaves-Samani method to underestimate on average by 9% in arid regions and overestimate on average by 25% in humid regions. It should be noted that Goyal et al. (1988) used estimated monthly values of R_a based on a single latitude equal to 18 degrees, which may account for some of the differences. In this study, actual site latitudes were used to obtain R_a.

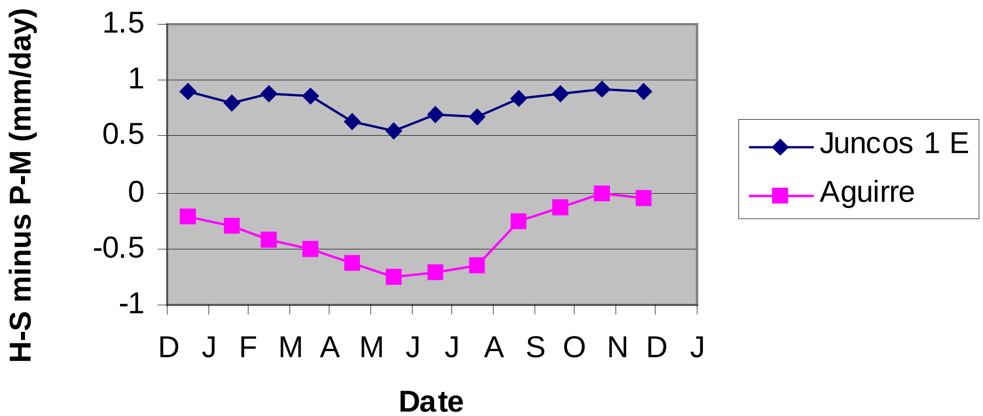

Figure 5. Estimated difference between ETo calculated by the Hargreaves-Samani (H-S) and Penman-Monteith (P-M) methods at the Juncos 1E and Aguirre stations.

Method Limitations

The approach presented in this paper should be considered only approximate for estimating long-term average daily 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, nor has Equation 4 been verified to be accurate for areas within Puerto Rico where elevations exceed 100 m. (see Harmsen and Torres Justiniano, 2001).
- The data in Tables 1, 2 and 4 are based on monthly averages of daily data. Therefore, it should be understood that the method presented in this paper, provides a monthly average of the daily value for reference evapotranspiration.

Conclusion

This study presented a simple method for estimating long-term average daily reference evapotranspiration in Puerto Rico. The only data needed to use the method is the site latitude and surface elevation. With these two parameters, it is possible to estimate all other input to the Penman-Monteith method. Comparisons of long-term average daily reference evapotranspiration calculated using the Penman-Monteith method were compared with estimates made using the Hargreaves Samani method for thirty-four locations in Puerto Rico. Maximum and minimum differences between the two methods (H-S minus P-M) were 0.92 and –0.75 mm/day, respectively.

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