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ESTIMATING LONG-TERM AVERAGE MONTHLY EVAPOTRANSPIRATION FROM PAN EVAPORATION DATA AT SEVEN LOCATIONS IN PUERTO RICO[1]

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ABSTRACT

The goal of this project is to update pan evaporation coefficients (K_p) values for the seven University of Puerto Rico Experimental Substations, based on the Penman-Monteith reference evapotranspiration. As a part of the study, historical pan evaporation data were evaluated from seven experimental substations. Significant decreasing pan evaporation was observed at Lajas and Río Piedras. Significant increasing pan evaporation was observed at Gurabo and Adjuntas, and no significant trends were observed at Fortuna, Isabela and Corozal. A significant difference was found to exist between the mean K_p values calculated with pan evaporation data from 1960-1980 and 1981-2000.

INTRODUCTION

Pan evaporation is a method widely used to schedule irrigation because it is easy and inexpensive to use. The University of Puerto Rico Agricultural Experiment Station (UPR AES) is currently promoting this method in their "Conjunto Tecnologico" guidance publications for various crops (e.g., Rivera, 2002). A number of studies have been performed to determine optimal irrigation rates based on pan evaporation data in Puerto Rico (e.g., Goenaga, 1994 [tanier]; Goenaga and Irizarry, 1998 [banana's under mountain conditions]; Goenaga and Irizarry, 1995; [bananas under semiarid conditions]; Goenaga et al. 1993 [plantains under semiarid conditions]; Santana Vargas, 2000 [watermelon under semiarid conditions]; Harmsen et al., 2002 [sweet peppers under humid conditions]).

The pan evaporation method estimates crop evapotranspiration from the following equations:

$$ET_{pan} = K_c \, ET_{o\text{-}pan} \quad (1)$$

$$ET_{o\text{-}pan} = K_p \, E_{pan} \quad (2)$$

where ET_{pan} is actual potential crop evapotranspiration, based on the pan-derived reference evapotranspiration, $ET_{o\text{-}pan}$; K_p is the pan coefficient; E_{pan} is the pan evaporation; and K_c is the crop coefficient. According to Allen et al. (1998), estimates of evapotranspiration from pan data are generally recommended for periods of 10 days or longer. However, in Puerto Rico equation 1 and 2 are usually applied for periods of 4 to 7 days. Most of the studies have recommended applying water to plants at a rate equal to 1 to 1.5 times the pan-estimated ET_c rate to maximize crop yield. Because this approach is easy and inexpensive, these studies represent valuable contributions to agricultural production in the tropics. Problems, however, may result from this approach owing to the inherent differences in water loss from an open water surface and a crop (Allen, et al., 1998). Another potential limitation is that only a single value of crop coefficient is commonly used, and by definition, the crop coefficient varies throughout the season. Although recommended irrigation application rates by this method may maximize crop yields, the method may also result in the over-application of water, leading to the degradation of groundwater resources from leaching of agricultural chemicals.

In Puerto Rico, the K_p values commonly used were derived from a study by Goyal and González (1989a) using data from the seven agricultural substations located at Adjuntas, Corozal, Fortuna, Gurabo, Isabela, Lajas, and Río Piedras, PR. Figure 1 shows the location of the substations and the Climate Divisions established by the National Oceanic and Atmospheric Administration (NOAA). These data were developed based on the ratio of long-term monthly average reference evapotranspiration, estimated from an equation, to pan evaporation:

$$K_p = ET_o / E_{pan} \quad (3)$$

[1] This material is based on research supported by the University of Puerto Rico Agricultural Experiment Station Grant SP-357.

where K_p is the pan coefficient, ET_o is reference evapotranspiration, and E_{pan} is the pan evaporation rate. Goyal and González (1989a) estimated the reference evapotranspiration using the Soil Conservation Service (SCS) Blaney-Criddle method (SCS, 1970). In recent study by the American Society of Civil Engineers (ASCE) (Jensen et al., 1990), the SCS Blaney-Criddle method was found to produce large errors relative to weighing lysimeter data (over estimation on average by 17% in humid regions and underestimation on average by 16% in arid regions). Harmsen et al. (2001) reported large differences between the SCS Blaney-Criddle method (estimates obtained from Goyal, 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 Penman-Monteith approach utilized crop coefficients as determined by the FAO procedure (Allen et al., 1998). Crop stage durations, used to construct the crop coefficient curves, were based on crop growth curve data presented by Goyal (1989). The maximum observed differences in the estimated seasonal consumptive use were on the order of 100 mm per season. The study concluded that large potential differences can be expected between the SCS Blaney-Criddle and the Penman-Monteith methods, with underestimations some months and overestimations in other months.

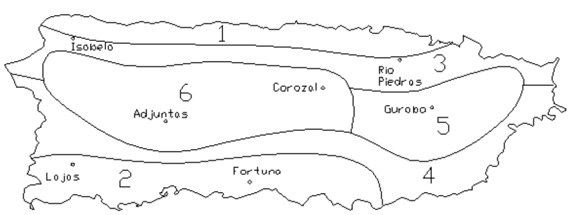

Figure 1. UPR Agricultural Experiment Substation Locations and NOAA Climate Divisions Of Puerto Rico: 1, North Coastal; 2, South Coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; And 6, Western Interior.

Because of inherent errors associated with the SCS Blaney-Criddle method, the published values of K_p for Puerto Rico may not be accurate. The United Nations Food and Agriculture Organization (FAO) currently recommend using the ratio of pan evaporation divided by the Penman-Monteith-estimated reference evapotranspiration for calculating the pan coefficient (Allen et al., 1998). The Penman-Monteith-based reference evapotranspiration was found to have a high degree of accuracy in the ASCE study mentioned above (Jensen et al., 1990), with errors not exceeding ± 4 percent.

The goal of this project was to update pan coefficients values for the seven Substations using the Penman-Monteith reference evapotranspiration, and to incorporate twenty years of additional pan evaporation data. As a part of the study, long-term trends in pan evaporation data were evaluated.

METHODOLOGY

Pan Evaporation Data

Historical pan evaporation data were evaluated to determine if decreasing or increasing trends exist in the data. Roderick and Farquhar (2002) and Ohmura and Wild (2002) have reported that pan evaporation rates have been decreasing globally. The cause of the decrease has been attributed to the observed decrease in solar irradiance (during the last decade) and changes in diurnal temperature range and vapor pressure deficit (Roderick and Farquhar, 2002). If in fact, pan evaporation is changing in Puerto Rico, then the more recent data (e.g. last 20 years) may provide better estimates of the pan coefficient than would longer term average data. Updated pan evaporation data were obtained from NOAA Climatological Data Summary Sheets, and from a UPR AES document called *Climatological Data from the Experimental Substations of Puerto Rico* (Goyal and González, 1989b).

To evaluate possible trends, pan evaporation data was plotted graphically, and regression analysis was used to determine if the regression coefficient (i.e., the slope) of the best-fit linear model was significantly different from zero. All statistical analyses were performed using the statistical software package StatMost Version 3.6 (Dat@xiom Software, Inc., 2001)

Reference Evapotranspiration

The long-term monthly reference evapotranspiration was estimated using the Penman-Monteith equations (Allen et al., 1998):

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \left(\frac{900}{T + 273}\right) \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \quad (4)$$

where Δ = slope of the vapor pressure curve, R_n = net radiation, G= soil heat flux density, γ = psychrometric constant, T = mean daily air temperature at 2 m height, u_2 = wind speed at 2 m height, e_s is the saturated vapor pressure and e_a is the actual vapor pressure. Equation 4 applies specifically to a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec/m and a solar reflectivity of 0.23.

Equation 4 was implemented in a recently developed computer program called PR-ET, which estimates the Penman-Monteith reference evapotranspiration at any location in Puerto Rico (Harmsen and González Pérez, 2002). The program uses estimation procedures to obtain long-term average monthly climate parameters required by the Penman-Monteith method. PR-ET estimates minimum and maximum air temperatures from surface elevation data. Dew point temperature is estimated from the minimum air temperature plus or minus a temperature correction factor. Temperature correction factors and average wind speeds are associated with six climatic divisions for Puerto Rico (Figure 1). Solar radiation is estimated from a simple equation for island settings or by the Hargreaves' radiation equation, based on air temperature differences.

Pan coefficients were estimated from equation 3. Statistical comparisons were made between K_p from average pan evaporation data from 1960 (approximately) to 1980 and 1981 through 2000.

Results and Discussion

Figure 2 shows the monthly average pan evaporation for the seven experimental substations, based on approximately forty years of pan evaporation data. Note that pan evaporation was highest for Fortuna and lowest for Adjuntas for most months of the year. Figure 3, 4 and 5, show the average monthly pan evaporation with time. Figure 3 shows the sites that had significant decreasing pan evaporation with time. Figure 5 shows the sites that had significant increasing pan evaporation with time; and Figure 4 shows the sites that had no significant increase or decrease in pan evaporation with time. Increases and decreases, as expressed by the linear regression coefficients, associated with Figures 3 and 4, were significant at or below the 5 percent confidence level. Regression coefficients associated with the linear regression lines shown in Figure 5 were not statistically significant. The linear regression results are summarized in Table 1.

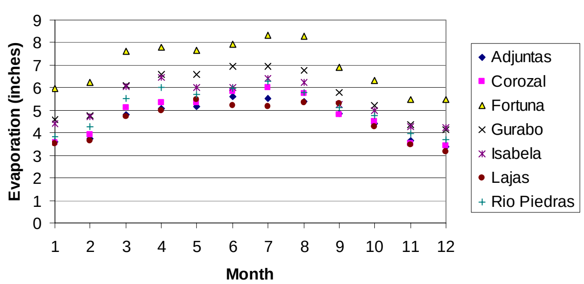

Figure 2. Long-Term Average Monthly Pan Evaporation for The Seven Experimental Substations in Puerto Rico.

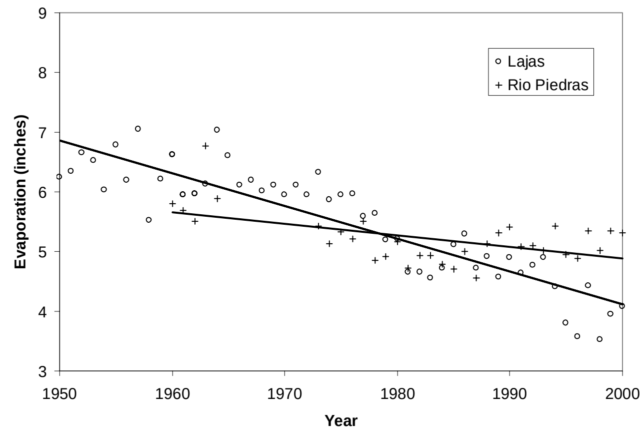

Figure 3. Average Monthly Pan Evaporation with Time At Lajas and Río Piedras, Puerto Rico.

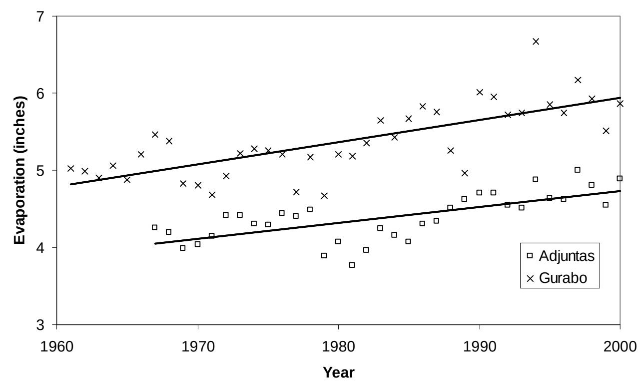

Figure 4. Average Monthly Pan Evaporation with Time at Adjuntas And Gurabo, Puerto Rico.

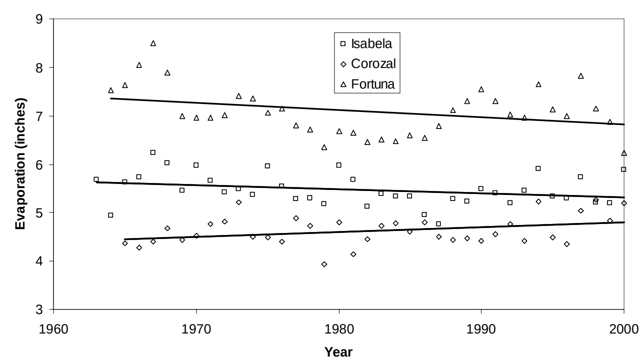

Figure 5. Average Monthly Pan Evaporation with Time at Corozal, Isabela and Fortuna, Puerto Rico.

Table 1. Linear Regression Results for the pan evaporation data from the seven experimental substations

	Latitude	**Elev. (m)**	**Regression Coefficient**	**R^2**	**Significant at the 5% level**	**Trend**
Gurabo	18° 15' N	48	0.029	0.55	**Yes**	**Increasing**
Adjuntas	18° 11' N	549	0.021	0.47	**Yes**	**Increasing**
Corozal	18° 20' N	195	0.010	0.11	No	Increasing
Isabela	18° 28' N	126	-0.008	0.08	No	Decreasing
Fortuna	18° 01' N	21	-0.015	0.10	No	Decreasing
Río Piedras	18° 24' N	100	-0.019	0.28	**Yes**	**Decreasing**
Lajas	18° 03' N	27	-0.055	0.81	**Yes**	**Decreasing**

There are several noteworthy results, which appear in Figure 3 through 5 and Table 1:

- Lajas had the greatest decrease in the average monthly pan evaporation; 0.055 inches per year. This is equivalent to a drop of 2.2 inches in the pan evaporation in forty years. This is a very significant reduction considering that the average monthly pan evaporation in 2002 was only 4.09 inches in Lajas. It will be interesting to see if this trend continues in the future or if it begin to level off.
- The decreasing pan evaporation observed at Lajas and Río Piedras are consistent with the observed decreasing trend globally.

Pan evaporation at two sites (Adjuntas and Gurabo) increased. These results are contrary to the observed global decrease in pan evaporation. Both sites are located in humid areas. It is interesting to note that Adjuntas is at a relatively high elevation (549 m), whereas, Gurabo is at a relatively low elevation (48 m).

Figure 6 shows the estimated long-term average monthly reference evapotranspiration for the seven experiment substations. Similar to pan evaporation (Figure 2), Fortuna shows the highest ET_o and Adjuntas shows the lowest values during most of the year. However, ET_o for Lajas was essentially identical to Fortuna, whereas the Lajas pan evaporation (Figure 2) was lower than for Fortuna. There are two possible explanations for this:

1. PR-ET-estimated reference evapotranspiration is insensitive for locations within the same Climate Division at approximately the same latitude and elevation, as was the case for Lajas and Fortuna.

2. Pan evaporation and evapotranspiration may not be directly comparable. Allen, et al. (1998) list the following factors that may cause significant differences in loss of water from a water surface and from a cropped surface:

- Reflection of solar radiation from the water surface might be different than the assumed 23% for the grass reference surface.
- Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime.
- There are differences in turbulence, temperature and humidity of the air immediately above the respective surfaces; and
- Heat transfer occurring through the sides of the pan can affect the energy balance.

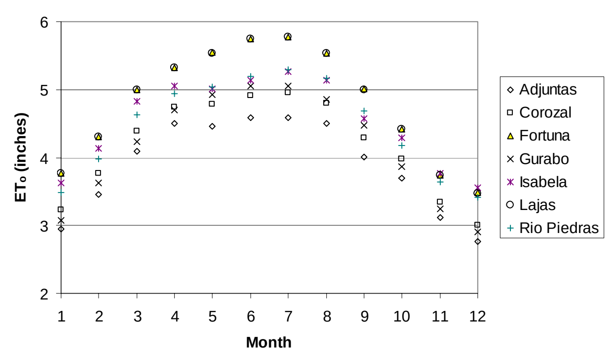

Figure 6. Long-Term Average Monthly Reference Evapotranspiration For The Seven Experimental Substations. Reference Evapotranspiration Was Estimated Using The Computer Program Pr-Et (Harmsen And González Pérez, 2002).

Monthly average pan coefficients were estimated for each month at each of the seven experimental substations based on pan evaporation data from 1960 (approximate) to 1980 and 1981 to 2000. (For convenience, hereafter the earlier period will be referred to as 1960-1980 and the latter period as 1981-2000.) A Student t-Test analysis indicated a significant difference between the mean K_p based on the two time periods. The results of the t-Test are presented in Table 2. Although a significant difference existed between the means of the two datasets, the difference was quite small in real terms: 0.04.

To understand whether the difference in the mean pan evaporation between the two periods is significant on a practical level (independent of statistical significance), we will use equation 2 and estimate the difference in the reference evapotranspiration for a given amount of pan evaporation. Suppose the annual pan evaporation for a certain location was 60 inches, then the K_p difference of 0.04 is equivalent to 0.04 x 60 inches = 2.4 inches in the annual reference evapotranspiration. On a 50 acre farm this is approximately equivalent to 3.26 million gallons of water.

Because there was a significant difference between the mean K_p for the last 20 years and the subsequent 20 year period, we recommend that crop water use estimates utilize K_p values from the most recent 20 years. Tables 3, 4 and 5 give the average monthly, reference evapotranspiration, pan evaporation and pan coefficients, respectively.

Table 2. Results of a Student t-test comparing monthly pan coefficients based on pan evaporation data from 1960 (approximate) to 1980 and 1981 to 2000.

****** t-Test Analysis Results ********
Confidence Level = 0.95 [One Tail Test]

1960 to 1981 vs. 1981 to 2000

		1960-1981	1981-2000
Sample Size		84	84
Number of Missing Samples		0	0
Minimum		0.62	0.63
Maximum		1.03	1.18
Standard Deviation		0.0854	0.1214
Standard Error		0.0093	0.0132
Coefficient of Variation		10.5462	14.2835
Mean		0.8099	0.8499
	Difference	=	-0.04
Variance		0.0073	0.0147
	Ratio	=	0.4951

	t-Value	Probability	DF	Critical t-Value
General	-2.4699	0.0073	166	1.6541

Summary and Conclusions

Historical pan evaporation data were evaluated to determine if increasing or decrease trends exist for data from the seven UPR Experimental Substations. Significant decreasing pan evaporation was observed at Lajas and Río Piedras. Significant increasing pan evaporation was observed at Gurabo and Adjuntas. No significant trends were observed at Fortuna, Isabela and Corozal.

A significant difference was found to exist between the mean K_p calculated with pan evaporation data from 1960-1980 and 1981-2000. An updated table of monthly average pan coefficients is provided (Table 5) that can be used to estimate ET_{pan} for the seven Agricultural Experiment Substations. Recommendations for future research:

- An investigation is needed to help explain the significant decrease in the evaporation at Lajas as compared to other locations.
- A future study should investigate the reason for the increasing pan evaporation rates in Gurabo and Adjuntas, which contradict the global trend in pan evaporation.
- The climate estimation procedures used in PR-ET are based on pre-1990 data. An effort should be made to verify that the estimation procedures are accurate.

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Table 3. Long-term average reference evapotranspiration (ET_o) by month for the seven experimental substations. Reference evapotranspiration was estimated using the computer program PR-ET (Harmsen and González Pérez, 2002).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Adjuntas	2.95	3.45	4.09	4.50	4.46	4.58	4.59	4.50	4.01	3.70	3.11	2.77	3.89
Corozal	3.23	3.76	4.39	4.74	4.78	4.91	4.95	4.80	4.29	3.98	3.34	3.01	4.18
Fortuna	3.76	4.31	4.99	5.32	5.55	5.74	5.78	5.54	5.01	4.42	3.74	3.48	4.80
Gurabo	3.08	3.62	4.24	4.70	4.92	5.05	5.05	4.86	4.47	3.87	3.24	2.90	4.17
Isabela	3.62	4.13	4.82	5.05	5.01	5.14	5.26	5.14	4.57	4.29	3.76	3.55	4.53
Lajas	3.76	4.30	4.99	5.32	5.54	5.74	5.77	5.54	5.00	4.41	3.74	3.47	4.80
Río Piedras	3.48	3.98	4.63	4.94	5.04	5.19	5.30	5.17	4.69	4.18	3.64	3.42	4.47
Average	3.41	3.94	4.59	4.94	5.04	5.19	5.24	5.08	4.58	4.12	3.51	3.23	4.41

Table 4. Average monthly pan evaporation (E_{pan}) based on 1981 through 2000 pan evaporation data for seven experimental substations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Adjuntas	3.60	3.76	4.79	5.07	5.15	5.63	5.53	5.37	4.87	4.41	3.64	3.39	4.60
Corozal	3.57	3.94	5.13	5.36	5.36	5.83	6.00	5.73	4.79	4.50	3.53	3.41	4.76
Fortuna	5.97	6.24	7.60	7.82	7.64	7.94	8.33	8.27	6.91	6.33	5.49	5.46	7.00
Gurabo	4.60	4.77	6.09	6.57	6.60	6.97	6.94	6.77	5.78	5.22	4.35	4.14	5.73
Isabela	4.40	4.71	6.06	6.45	6.03	6.02	6.41	6.23	5.26	4.97	4.27	4.23	5.42
Lajas	3.52	3.64	4.72	5.01	5.48	5.22	5.17	5.33	5.31	4.26	3.49	3.18	4.53
Río Piedras	3.83	4.29	5.55	6.01	5.70	5.97	6.30	5.79	5.12	4.79	3.95	3.71	5.08

Table 5. Pan Coefficients (K_p) based on 1981 through 2000 pan evaporation data, for seven experimental substations.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Adjuntas	0.82	0.92	0.85	0.89	0.87	0.81	0.83	0.84	0.82	0.84	0.85	0.82	0.85
Corozal	0.91	0.95	0.86	0.88	0.89	0.84	0.83	0.84	0.89	0.88	0.95	0.88	0.88
Fortuna	0.63	0.69	0.66	0.68	0.73	0.72	0.69	0.67	0.72	0.70	0.68	0.64	0.68
Gurabo	0.67	0.76	0.70	0.72	0.75	0.72	0.73	0.72	0.77	0.74	0.75	0.70	0.73
Isabela	0.82	0.88	0.80	0.78	0.83	0.85	0.82	0.83	0.87	0.86	0.88	0.84	0.84
Lajas	1.07	1.18	1.06	1.06	1.01	1.10	1.12	1.04	0.94	1.03	1.07	1.09	1.06
Río Piedras	0.91	0.93	0.83	0.82	0.88	0.87	0.84	0.89	0.92	0.87	0.92	0.92	0.88
Average	0.83	0.90	0.82	0.83	0.85	0.85	0.84	0.83	0.85	0.85	0.87	0.84	0.85