# Re-evaluation of pan evaporation coefficients at seven locations in Puerto Rico[1,2]

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**J. Agric. Univ. P.R. 88(3-4):109-122 (2004)**

**ABSTRACT**

**The goal of this project was to update pan evaporation coefficient ($K_p$) values for the seven University of Puerto Rico Experimental Substations, based on updated pan evaporation data and 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 or Corozal. A significant difference was found to exist between the mean $K_p$ values calculated with pan evaporation data from 1960 to 1980 and those with data from 1981 to 2000.**

**Key words: Pan evaporation, pan coefficient, evapotranspiration, crop water use, Puerto Rico**

**RESUMEN**

**Revaluación del coeficiente de evaporímetro en siete localidades en Puerto Rico**

**El objetivo de este proyecto es actualizar los valores del coeficiente de evaporímetro ($K_p$) en las siete subestaciones experimentales de la Universidad de Puerto Rico, basado en la ecuación de referencia de Penman-Monteith para la evapotranspiración. Como parte del estudio se evaluaron los datos históricos recolectados con evaporímetros en las siete subestaciones. Se observó una disminución significativa en la evaporación en Lajas y Río Piedras, mientras hubo un crecimiento significativo en la evaporación en Gurabo y Adjuntas; no hubo variación significativa en Fortuna, Isabela y Corozal. Se encontró diferencia significativa entre los valores de $K_p$ calcula-**

[1]Manuscript submitted to Editorial Board 21 January 2004.

[2]This material is based on research supported by University of Puerto Rico Agricultural Experiment Station Grant SP-368 and by NOAA-CREST and NASA-EPSCoR.

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**dos con datos del evaporímetro desde 1960 a 1980 y aquéllos con datos de 1981 a 2000.**

**Palabras claves: evaporímetro, coeficiente de evapotranspiración, Puerto Rico**

## INTRODUCTION

The pan evaporation method is widely used to schedule irrigation because it is easy and inexpensive. The University of Puerto Rico Agricultural Experiment Station (UPR-AES) is currently promoting this method in their "Conjunto Tecnológico" guidance publications for various crops (L. E. Rivera, UPR-Agricultural Experiment Station, personal communication). 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 (bananas 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., 2002a and 2003 (sweet peppers under humid conditions)]. Harmsen (2003) presented a summary of these studies.

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

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

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

where $ET_{pan}$ is actual 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. In the authors' experience, equations 1 and 2 are usually applied for periods of four to seven days in Puerto Rico. Most of the studies have recommended applying water to plants at a rate equal to 1 to 1.5 times the pan-estimated ET 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 because of 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. The magnitude of the crop coefficient depends on crop height, leaf area, crop color, stomatal resistance, and crop maturity. Although recommended irrigation application rates by this method may maximize crop yields, the method may also result in the over-application of water early in the crop season, 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, Juana Díaz (Fortuna), Gurabo, Isabela, Lajas, and Río Piedras. 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 on the basis of the ratio of long-term monthly average reference evapotranspiration (estimated from an equation) to pan evaporation:

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

where $K_p$ is the pan coefficient; $ET_o$ is reference or potential evapotranspiration; and $E_{pan}$ is the pan evaporation rate. Mean daily values of pan evaporation were derived from a University of Puerto Rico Agricultural Experiment Station document *Climatological Data from the Experimental Substations of Puerto Rico* (Goyal and González, 1989a). Goyal and González (1989b) estimated the potential evapotranspiration by using the Soil Conservation Service (SCS) Blaney-Criddle method (SCS, 1970). In a 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 (overestimation on average by 17% in humid regions and underestimation on average by 16% in arid regions). In a study that compared seasonal con-

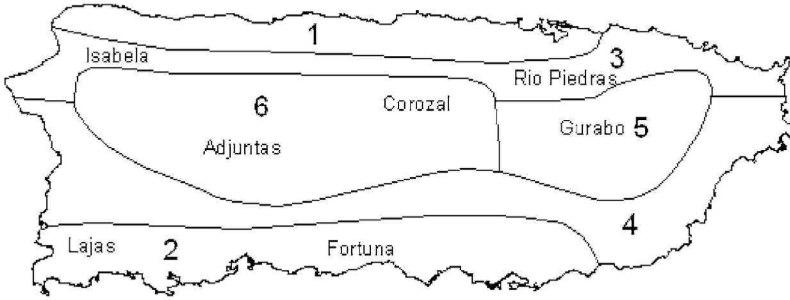


FIGURE 1. UPR Agricultural Experiment Substation locations and NOAA climate divisions of Puerto Rico: 1, North Coastal; 2, South Coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6, Western Interior.

sumptive use for pumpkin and onion at two locations in Puerto Rico, Harmsen et al. (2001) reported large differences between the SCS Blaney-Criddle method (estimates obtained from Goyal, 1989) and the Penman-Monteith method. The Penman-Monteith approach used 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.

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 above-mentioned ASCE study (Jensen et al., 1990), with errors not exceeding ± 4 percent.

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

## MATERIALS AND METHODS

### *Pan Evaporation Data*

Historical pan evaporation data were evaluated to determine whether decreasing or increasing trends existed 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., for the 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's Climatological Data Sheets.

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

*Reference Evapotranspiration*

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

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

where $\Delta$ = slope of the vapor pressure curve; $R_n$ = net radiation; G= soil heat flux density; $\gamma$ = 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 grass 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. The FAO recommend using the Penman-Monteith method over all other methods even when local data are 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 data input (Allen et al., 1998).

Of the various climate parameters needed to calculate equation 4, only air temperature (T) and wind speed (u) were available for all seven experimental substations; however, wind speed was not measured consistently. For example, in the case of Lajas, wind speed data were available only during the following years: 1963, 1966 to 1969, 1971 to 1978, 1983 to 1985 and 1987 to 1990. Wind speeds were measured at 0.33 m above the ground and therefore needed to be adjusted to the two-meter value ($u_2$) using the logarithmic adjustment equation presented by Allen et al. (1998).

Relative humidity (needed to estimate actual vapor pressure) is measured at the substations by using a sling psychrometer, but only once in 24 hours; thus, these data do not represent daily average values. Therefore, the actual vapor pressure was derived from the dew point temperature ($T_{dew}$). Long-term average dew point temperature was estimated from the minimum air temperature plus or minus a temperature correction factor. Temperature correction factors, developed for the six NOAA Climate Divisions for Puerto Rico (Figure 1), were obtained previously from Harmsen et al. (2002b). Net radiation was estimated from solar radiation ($R_s$) by using the method presented by Allen et al. (1998) involving the use of a simple equation for island settings (elevations <100 m) or by the Hargreaves radiation equation (elevations ≥ 100 m), based on air temperature differences.

Pan coefficients were estimated from equation 3. Statistical comparisons were made between $K_p$ from average pan evaporation data collected between 1960 and 1980 and $K_p$ from data collected between 1981 and 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. Figures 3, 4 and 5,

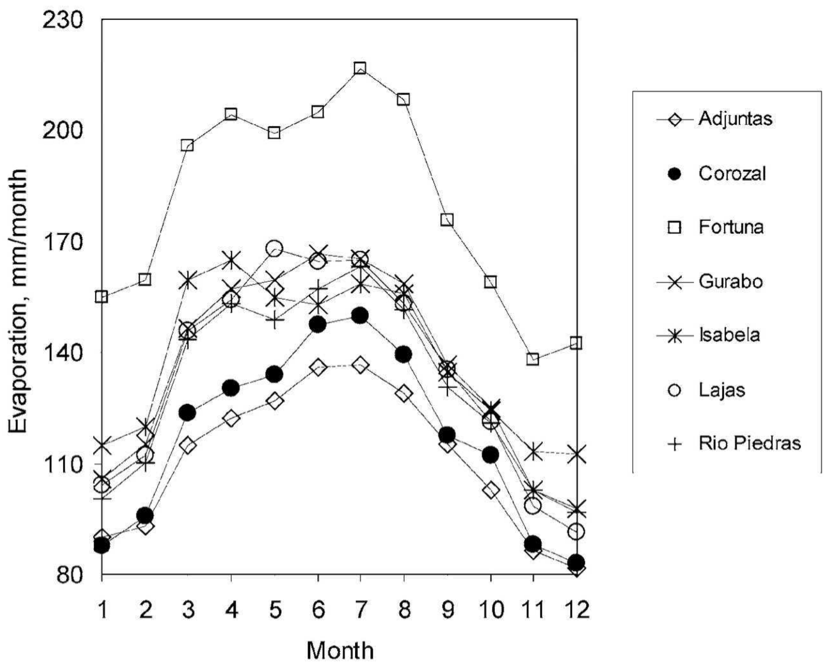


FIGURE 2. Long-term average monthly pan evaporation for the seven substations in Puerto Rico.

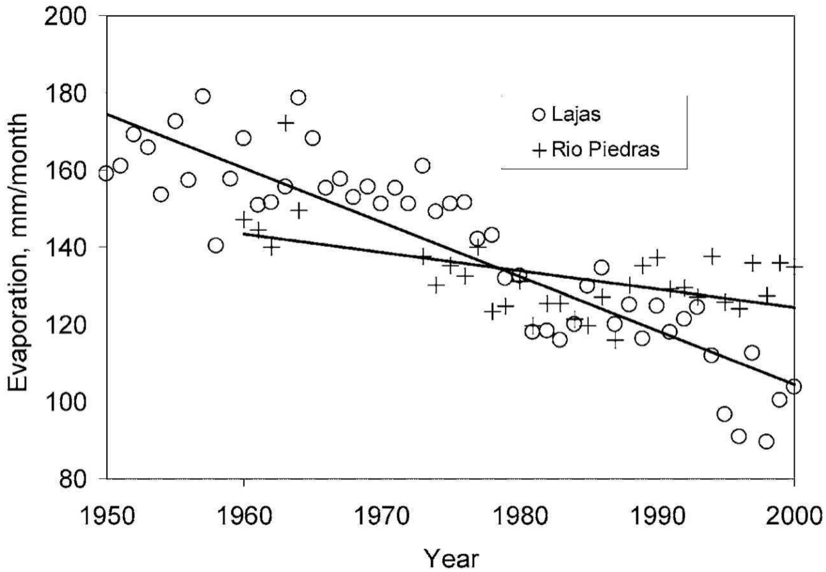


FIGURE 3. Average monthly pan evaporation with time at Lajas and Río Piedras, Puerto Rico.

show the average monthly pan evaporation with time. Figure 3 shows the sites that had significant decreasing pan evaporation with time; Figure 4 shows the sites that had significant increasing pan evaporation with time; Figure 5 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% probability 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.

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

°Lajas had the greatest decrease in the average monthly pan evaporation: 1.4 mm per month (average) per year. This amount is equivalent to a drop of 56 mm per month in the pan evaporation in forty years. This is a very significant reduction considering that the average pan evaporation in 2002 was only 103.9 mm per month in Lajas. It will be interesting to see whether this trend continues in the future or whether it begins to level off.

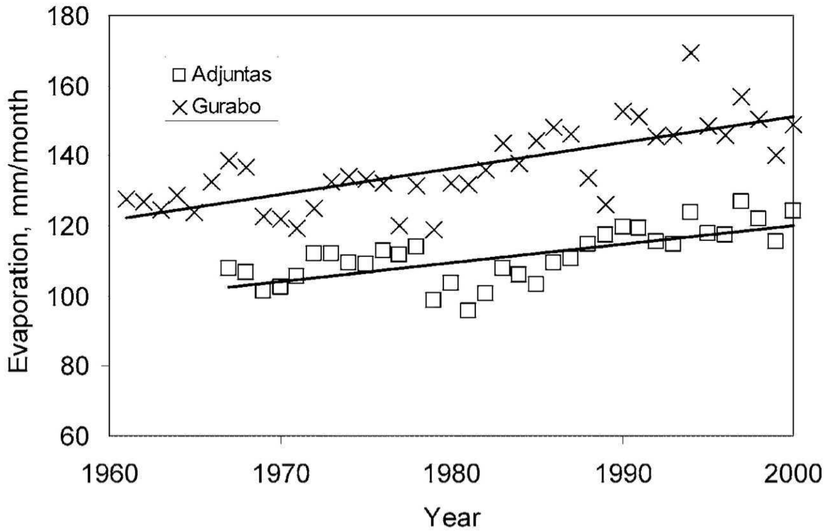


FIGURE 4. Average monthly pan evaporation with time at Adjuntas and Gurabo, Puerto Rico.

°The decreasing pan evaporation observed at Lajas and Río Piedras is 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 each substation. As with 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 that of Fortuna, whereas the Lajas pan evaporation (Figure 2) was lower than that of Fortuna. There are two possible explanations for this: (1) The local environment may have gradually changed in the vicinity of the evaporation tank in Lajas. For example, installation of new structures, establishment of trees, or relocation of the evaporation tank. Development of the Lajas Valley may also have influenced a change in pan evaporation at the substation. (2) Pan evaporation and

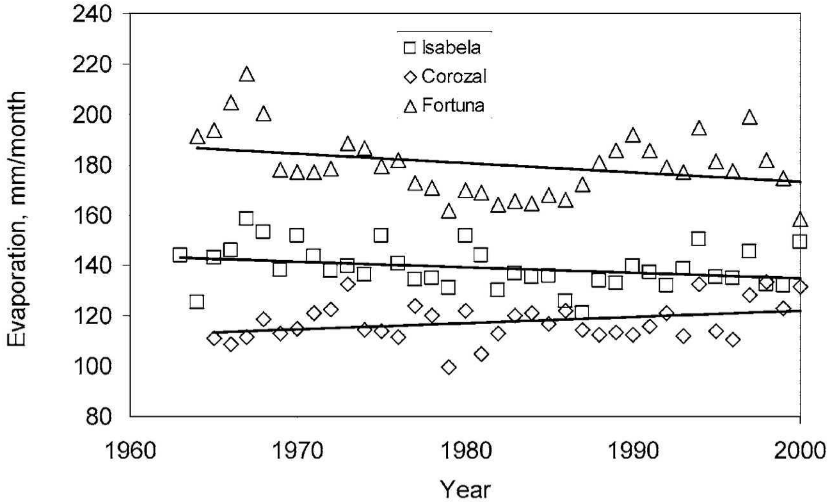


FIGURE 5. Average monthly pan evaporation with time at Corozal, Isabela and Fortuna, Puerto Rico.

reference 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 from 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.

°Heat transfer occurring through the sides of the pan can affect the energy balance.

Monthly average pan coefficients were estimated for each month at each of the seven experimental substations on the basis of pan evaporation data from 1960 (approximate) to 1980 and from 1981 to 2000. (For convenience, hereafter the earlier period will be referred to as 1960 to 1980 and the latter period as 1981 to 2000.) A Student t-Test analysis indicated that the difference between the mean $K_p$ based on the two time periods was highly significant. Table 2 presents the re-

TABLE 1. *Linear regression results for the pan evaporation data from the seven substations.*

| | Latitude | Elevation (m) | NOAA Climate Division | Regression Coefficient (slope of line) | $r^2$ | Significant at the 5% level | Trend |
|---|---|---|---|---|---|---|---|
| Gurabo | 18°15'N | 48 | 5 | 0.029 | 0.55 | Yes | Increasing |
| Adjuntas | 18°11'N | 549 | 6 | 0.021 | 0.47 | Yes | Increasing |
| Corozal | 18°20'N | 195 | 6 | 0.010 | 0.11 | No | Increasing |
| Isabela | 18°28'N | 126 | 3 | -0.008 | 0.08 | No | Decreasing |
| Fortuna | 18°01'N | 21 | 2 | -0.015 | 0.10 | No | Decreasing |
| Río Piedras | 18°24'N | 100 | 3 | -0.019 | 0.28 | Yes | Decreasing |
| Lajas | 18°03'N | 27 | 2 | -0.055 | 0.81 | Yes | Decreasing |

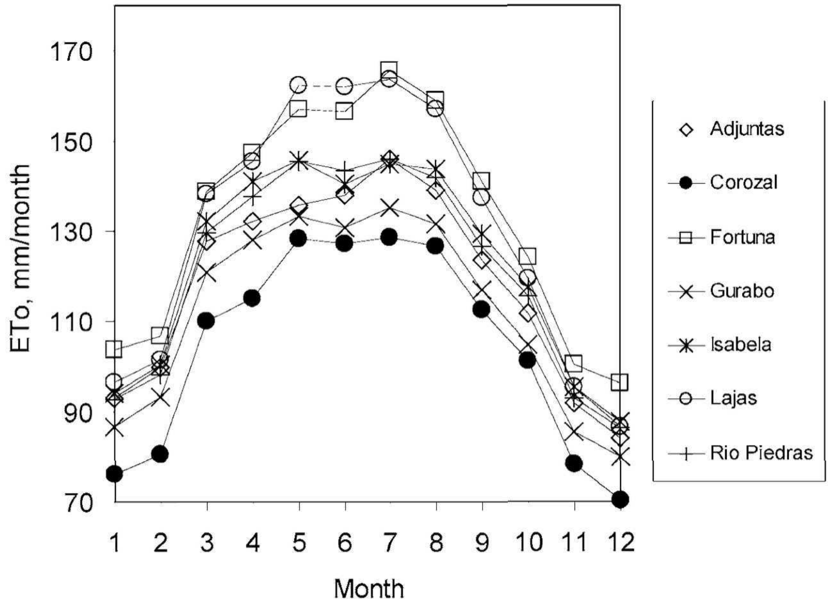


FIGURE 6. Long-term average monthly reference evapotranspiration for the seven substations.

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 [Two Tail Test]

1960 to 1981 vs. 1981 to 2000:

| | 1960 to 1981 | 1981 to 2000 | | |
|---|---|---|---|---|
| Sample Size | 84 | 84 | | |
| Number of Missing | 0 | 0 | | |
| Minimum | 0.5694 | 0.6732 | | |
| Maximum | 1.1579 | 1.2473 | | |
| Standard Deviation | 0.1398 | 0.1319 | | |
| Standard Error | 0.0153 | 0.0144 | | |
| Coeff of Variation | 18.5924 | 14.5441 | | |
| Mean | 0.7520 | 0.9067 | Difference = 0.1547 | |
| Variance | 0.0196 | 0.0174 | Ratio = 1.1242 | |
| | t-Value | Probability | DF | Critical t-Value |
| Paired | 9.5097 | 6.24516E-015 | 83 | 1.9890 |
| | Co-Variance = 0.0074, | | Std Deviation = 0.0163 | |

sults of the t-Test. The difference in the mean $K_p$ for all locations for the two time periods was 0.15. The average $K_p$ equaled 0.75 for 1960 to 1980 and 0.91 for 1981 to 2000. A comparison was also made between the $K_p$ values of Goyal and González (1989a) and the 1981 to 2000 $K_p$ values from this study (Table 5). A significant difference was observed between the two data sets at the 0.01% probability level, with a difference in the mean $K_p$ of 0.08. The average value of the $K_p$ of Goyal and González (1989a) was 0.82.

To understand whether the difference in the mean pan evaporation between the two periods (1960 to 1980 and 1981 to 2000) 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 1500 mm; then the $K_p$ difference of 0.15 is equivalent to $0.15 \times 1500$ mm = 225 mm in the annual reference evapotranspiration. On a farm having an area of 18 hectares (average farm size in Puerto Rico, 1998 Census of Agriculture) this is equivalent to 40,500 $m^3$ of water (or 10.7 million gallons).

Because there was a significant difference between the mean $K_p$ for the last 20 years and that of 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.

## CONCLUSIONS

Historical pan evaporation data were evaluated to determine whether increasing or decreasing trends existed 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

TABLE 3. *Long-term average reference evapotranspiration ($ET_o$) in mm/month for the seven experimental substations.*

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adjuntas | 93 | 100 | 128 | 132 | 136 | 138 | 146 | 139 | 124 | 112 | 92 | 84 |
| Corozal | 76 | 80 | 110 | 115 | 128 | 127 | 129 | 127 | 112 | 101 | 78 | 70 |
| Fortuna | 104 | 107 | 139 | 147 | 157 | 156 | 166 | 159 | 141 | 124 | 100 | 96 |
| Gurabo | 87 | 93 | 121 | 128 | 133 | 131 | 135 | 132 | 117 | 105 | 85 | 80 |
| Isabela | 94 | 100 | 132 | 141 | 146 | 141 | 145 | 144 | 129 | 118 | 95 | 88 |
| Lajas | 97 | 102 | 138 | 145 | 162 | 162 | 164 | 157 | 137 | 120 | 95 | 87 |
| Río Piedras | 93 | 98 | 130 | 138 | 145 | 143 | 146 | 142 | 127 | 116 | 93 | 86 |
| Average | 93 | 100 | 128 | 132 | 136 | 138 | 146 | 139 | 124 | 112 | 92 | 84 |

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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adjuntas | 92 | 95 | 122 | 129 | 131 | 143 | 141 | 136 | 124 | 112 | 93 | 86 |
| Corozal | 91 | 100 | 130 | 136 | 136 | 148 | 152 | 146 | 122 | 114 | 90 | 87 |
| Fortuna | 152 | 159 | 193 | 199 | 194 | 202 | 212 | 210 | 176 | 161 | 139 | 139 |
| Gurabo | 117 | 121 | 155 | 167 | 168 | 177 | 176 | 172 | 147 | 133 | 110 | 105 |
| Isabela | 112 | 120 | 154 | 164 | 153 | 153 | 163 | 158 | 134 | 126 | 108 | 108 |
| Lajas | 89 | 92 | 120 | 127 | 139 | 133 | 131 | 135 | 135 | 108 | 89 | 81 |
| Río Piedras | 97 | 109 | 141 | 153 | 145 | 152 | 160 | 147 | 130 | 122 | 100 | 94 |

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 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Adjuntas | 1.02 | 1.05 | 1.05 | 1.03 | 1.04 | 0.97 | 1.04 | 1.02 | 1.00 | 1.00 | 0.99 | 0.98 |
| Corozal | 0.84 | 0.80 | 0.85 | 0.85 | 0.94 | 0.86 | 0.85 | 0.87 | 0.92 | 0.88 | 0.87 | 0.81 |
| Fortuna | 0.68 | 0.67 | 0.72 | 0.74 | 0.81 | 0.78 | 0.78 | 0.76 | 0.80 | 0.77 | 0.72 | 0.69 |
| Gurabo | 0.74 | 0.77 | 0.78 | 0.77 | 0.80 | 0.74 | 0.77 | 0.77 | 0.80 | 0.79 | 0.77 | 0.76 |
| Isabela | 0.84 | 0.84 | 0.86 | 0.86 | 0.95 | 0.92 | 0.89 | 0.91 | 0.97 | 0.93 | 0.88 | 0.82 |
| Lajas | 1.08 | 1.10 | 1.15 | 1.14 | 1.17 | 1.22 | 1.25 | 1.16 | 1.02 | 1.10 | 1.08 | 1.07 |
| Río Piedras | 0.95 | 0.90 | 0.92 | 0.90 | 1.00 | 0.95 | 0.91 | 0.96 | 0.97 | 0.95 | 0.93 | 0.92 |

were observed at Fortuna, Isabela or Corozal. A significant difference was found to exist between the mean $K_p$ calculated with pan evaporation data from 1960 to 1980 and that with data from 1981 to 2000. An updated table of monthly average pan coefficients is provided (Table 5) that can be used to estimate $ET_{pan}$ for the seven substations.

Additional research is needed to help explain the significant reduction in the pan evaporation observed at Lajas as compared to that of other locations. The $K_p$ data presented in Table 5 are valid for data obtained from the pan located at the Lajas Experiment Station. However, if pan evaporation is obtained from another source in the vicinity of Lajas, these data should be compared with the experiment station evaporation data to verify consistency between the two data sources. If large differences exist, then an adjustment should be made in the Lajas $K_p$ values presented in Table 5. Further research is also needed to investigate the reason for the observed variations in the trends in pan evaporation (i.e., increasing at some locations and decreasing at other locations).

## LITERATURE CITED

Allen, R. G., L. S. Pereira, D. Raes and M. Smith, 1998. Crop Evapotranspiration Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome.

Dat@xiom Software, Inc., 2001. User's Guide StatMost Statistical Analysis and Graphics. Fourth Edition. Dataxiom Software, Inc., 3700 Wilshire Blvd. Suite 1000, Los Angeles, CA 90010. (http://www.dataxiom.com)

Goenaga, R., H. Irizarry and E. González, 1993. Water requirement of plantains (*Musa acuminata* × *Musa balbisiana* AAB) grown under semiarid conditions. *Trop. Agric.* (Trinidad) 70(1):3-7.

Goenaga, R., 1994. Growth, nutrient uptake and yield of tanier (*Xanthosoma* spp.) grown under semiarid conditions. *J. Agric. Univ. P.R.* 78(3-4):87-98.

Goenaga, R. and H. Irizarry, 1995. Yield performance of banana irrigated with fractions of Class A pan evaporation in a semiarid environment. *Agron. J.* 87:172-167.

Goenaga, R. and H. Irizarry, 1998. Yield of banana grown with supplemental drip irrigation on an Ultisol. *Expl. Agric.* 34:439-448.

Goyal M. R., 1989. Estimation of Monthly Water Consumption by Selected Vegetable Crops in the Semiarid and Humid Regions of Puerto Rico. AES Monograph 99-90, Agricultural Experiment Station, University of Puerto Rico, Río Piedras, PR.

Goyal, M. and E. A. González-Fuentes, 1989a. Coeficiente de Evaporímetro para Puerto Rico. *J. Agric. Univ. P.R.* 73 (1):89-92.

Goyal, M. R. and E. A. González, 1989b. Datos climatológicos de las subestaciones experimentales de Puerto Rico. Estación Experimental Agrícola-UPR-RUM, Río Piedras. Páginas 1-87.

Harmsen, E. W., J. Caldero and M. R. Goyal, 2001. Consumptive Water Use Estimates for Pumpkin and Onion at Two Locations in Puerto Rico. *In:* Proceedings of the Sixth Caribbean Islands Water Resources Congress. Silva Araya, W. F. (ed). University of Puerto Rico, Mayagüez, PR 00680.

Harmsen, E. W., J. Colón-Trinidad, C. Arcelay and E. Sarmiento-Esparra, 2002a. Evaluation of the Pan Evaporation Method for Scheduling Irrigation on an Oxisol in Puerto Rico. Proceedings of the Caribbean Food Crops Society, Thirty Eighth Annual Meeting, 2002. Martinique. Vol. 38.

Harmsen, E. W., M. R. Goyal, and S. Torres-Justiniano, 2002b. Estimating evapotranspiration in Puerto Rico. *J. Agric. Univ. P.R.* 86(1-2):35-54.

Harmsen, E. W., J. Colón-Trinidad, C. L. Arcelay and D. Cádiz-Rodríguez, 2003. Evaluation of Percolation and Nitrogen Leaching from a Sweet Pepper Crop Grown on an Oxisol Soil in Northwest Puerto Rico. Proceedings of the 39th Annual Meeting of the Caribbean Food Crops Society, 2003. Grenada. Vol. 39.

Harmsen, E. W. and A. González-Pérez, 2002. Puerto Rico EvapoTranspiration Estimation Computer Program PR-ET Version 1.0 USER'S MANUAL. Prepared for the University of Puerto Rico Experiment Station-Río Piedras. Grant SP-347. August 2002. (http://www.uprm.edu/abe/PRAGWATER/)

Harmsen, E. W., 2003. Fifty years of crop evapotranspiration studies in Puerto Rico. *J. Soil Water Conserv.* 58(4):214-223

Jensen, M. E., R. D. Burman and R. G. Allen, 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice No. 70. 332 pp.

Ohmura, A. and M. Wild, 2002. Is the hydrologic cycle accelerating? *Science* 298:1345-1346.

Roderick, M. L. and G. D. Farquhar, 2002. The cause of decreased pan evaporation over the past 50 years. . 298:1410-1411.

Santana-Vargas, J., 2000. Patrones de humedecimiento bajo el sistema de micro riego subterráneo. M.S. Thesis, Department of Agronomy and Soils. University of Puerto Rico- Mayagüez Campus.

SCS, 1970. Irrigation Water Requirements, Technical Release No. 21. USDA Soil Conservation Service, Engineering Division.