A Review of Evapotranspiration Studies in Puerto Rico

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Abstract. *This paper presents a review of previously published efforts to estimate crop water use in Puerto Rico. Specifically the review considers consumptive use determined from field water balance studies, calculational methods and the pan evaporation method. Several studies also considered the estimation of reference evapotranspiration, and procedures for estimating climate parameter data, needed as input to the reference evapotranspiration calculation methods. Recommendations for research priorities are provided.*

Keywords. *evapotranspiration, reference evapotranspiration, crop water use, Blaney-Criddle, Hargreaves-Samani, Penman-Monteith, pan evaporation, Puerto Rico.*

INTRODUCTION

Evapotranspiration (ET_c) is defined as the combination of evaporation from soil and plant surfaces, and transpiration from plant leaves. Evaporation is the process whereby liquid water is converted to water vapor and removed from the evaporating surface (Allen et al., 1998). Transpiration is the vaporization of liquid water contained in plant tissues and its subsequent removal to the atmosphere. Crops predominately loss water through small openings in their leaves called stomata. Evapotranspiration can be expressed in units of mm/day (or in/day), or as an energy flux in units of MJ/m^2-day (or cal/ft^2-day).

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Evapotranspiration is important because it is often the largest component of the hydrologic cycle after rainfall. Under arid conditions, evapotranspiration can easily exceed rainfall. The following water balance equation illustrates the relationship between hydrologic variables within the soil profile:

$$S_2 = P + IRR – DP – RO – ET_c + S_1 \quad \text{equ 1}$$

where P is precipitation, IRR is irrigation, DP is deep percolation, ET_c is evapotranspiration, RO is surface runoff, and S is the depth of water in the soil profile, equal to $\theta_v z$, where θ_v is the average volumetric soil moisture content and z is the root zone thickness. The subscripts 1 and 2 represent the beginning and end of the period of consideration. Equation 1 can used over periods ranging from hours to many months or even years. A common approach for estimating evapotranspiration involves rearranging equation 1 and solving for ET:

$$ET_c = P + IRR – DP – RO + (S_1 – S_2) \quad \text{equ 2}$$

Other methods used to estimate evapotranspiration include the energy balance, micro-climatological, weighing and non-weighing lysimeter methods. In Puerto Rico, all of these methods have been used except for the weighing lysimeter method. Determination of evapotranspiration by using a weighing lysimeter has been considered to be the most accurate of all methods; the major disadvantage of the method, however, being its high cost.

Crop evapotranspiration (ET_c) can also be defined as the product of a reference evapotranspiration (ET_o) and crop coefficient (K_c):

$$ET_c = K_c\, ET_o \quad \text{equ. 3}$$

In much of the crop water use literature published in Puerto Rico, evapotranspiration has been referred to as consumptive use (CU). Therefore, in this review, ET_c and CU will be used interchangeably. The crop coefficient (K_c) accounts for the effects of characteristics that distinguish the field crop from the grass reference crop (Allen et al., 1998). The reference evapotranspiration is defined as the evapotranspiration from an extended surface of 0.08 to .15 m tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977). Numerous mathematical expressions have been develop for ET_o. One such expression, which has been shown to have global validity and is recommended by the United Nations Food and Agriculture Organization (FAO) is the Penman-Monteith equation (Allen et al., 1998):

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

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 an albedo of 0.23.

REVIEW OF PREVIOUS WORK IN PUERTO RICO

This literature review surveys the efforts to either measure or estimate evapotranspiration in Puerto Rico. The majority of the literature indicates that before the late 1980s, Dr. Megh R. Goyal or others in participation with him have made almost all of the currently available estimates of agricultural consumptive use and reference evapotranspiration. These studies are detailed in a compilation document called *Irrigation Research and Extension Progress in Puerto Rico* (Goyal, 1989a). Throughout the 1990s, however, there appears to have been a cessation in evapotranspiration research in Puerto Rico, except in the use of pan evaporation-estimated

CU for managing irrigation application rates. Since 2000, some studies have been started involving comparisons between the Penman-Monteith methods and other methods (Harmsen et al., 2001a; Harmsen and Torres-Justiniano, 2001a; and Harmsen et al., 2002). Also, one recent study has attempted to standardize and validate climate parameter estimation procedures for use with the Penman-Monteith method in Puerto Rico (Harmsen and Torrez Justiniano, 2001b).

Evapotranspiration Reference Materials

Goyal and González Fuentes (1990) published a chapter on evapotranspiration in the book *Manejo de Riego por Goteo* published by the University of Puerto Rico Extension Service. The document provided basic definitions and descriptions of the following: three variations of the Penman method; three variations of the SCS Blaney-Criddle method; two Hargreaves methods; Jensen-Haise, Stephens-Stewart, Priestly-Taylor, Thornthwaite, Linacre, Makkink, pan evaporation, water balance, radiation and regression methods. The document also covers local calibration techniques and crop coefficients. Much of this material is also contained in a forty-five page extension document called *Evapotranspiración* by Goyal and González (1989a).

Consumptive Use Obtained from Field Studies

The following five studies are significant because they represent a small group in which actual field measurements were made to determine CU.

Fuhriman and Smith (1951) conducted a study for the Aguirre area of southern Puerto Rico on the CU of sugar cane under differing irrigation treatments. At the time of this study, between 1949 to 1950, sugarcane was the dominant crop in Puerto Rico, grown on 95 percent of the irrigated land. The experiment involved field studies and non-weighing lysimeters. Consumptive use was estimated by a water balance method, which accounted for rainfall, irrigation, percolation below the root zone and changes in soil moisture. Soil moisture was estimated by tensiometers and nylon resistance blocks. The experiment measured soil evaporation on several of the lysimeters, which in combination with CU data from the sugar cane-covered plots, allowed for the determination of plant transpiration rate.

Vázquez (1965) determined CU by a water balance method for guinea grass, para grass and guinea grass-kudzu and para grass-kudzu mixtures at Lajas, Puerto Rico. Soil moisture content was estimated by means of tensiometers, gypsum resistance blocks and by gravimetric analysis of soil samples. The study was conducted from March 1959 through June of 1960. Sixty-day CU values were determined for the two grasses and two grass mixtures over the 15-month study period. This was the only study found in which CU was determined for grasses.

In a later study, Vázquez (1970) used similar experimental methods to determine the CU of sugar cane at Lajas, Puerto Rico. In this study he included a neutron probe method for soil moisture determination. The study was conducted from April 1965 through May 1966. Consumptive use was determined for various irrigation treatments. The study concluded that about 250 mm of water consumption could be saved under soil and climatic conditions similar to those existing at Lajas, if the crop is irrigated frequently during the early part of the growing season and no further irrigation is applied after 5 months prior to harvest.

Abruña et al. (1979) conducted a study of water use by plantains at the Gurabo Substation in Puerto Rico. Consumptive use was determined by a water balance procedure based on soil moisture measurements and rainfall data. The study was conducted from September 1976 through April 1977. For irrigations scheduled when available soil moisture depleted by 20%, the average daily evapotranspiration was estimated to be 2.9 mm/day, and was found to be equivalent to 79% of pan evaporation. The minimum and maximum daily CU were 3.6 and 1.5 mm, respectively, for September and December.

Ravalo and Goyal (1988) estimated water requirements for rice during December through May of 1973 at the Lajas Substation using a hydrologic balance approach, accounting for farm inflow from the irrigation canal, effective rainfall, evapotranspiration, deep percolation, seepage through borders, border overflow, depth of flooding and water for saturating soil. Monthly estimated water requirements varied between 6.9-11.8 mm/day.

It is interesting to note that none of the above studies attempted to calculate crop coefficients from their field data. The crop coefficient is calculated from rearrangement of equation 1 (i.e., $K_c = ET_c/ET_o$). Future studies that attempt to derive crop coefficients in Puerto Rico should consider evaluating the data from these studies.

Studies Which Predicted Consumptive Use

Monthly water consumption by fifteen different vegetable crops for two locations in Puerto Rico (Fortuna and Isabela) were calculated by Goyal (1989b) (also see Goyal and González, 1988a). The SCS Blaney-Criddle approach was used; based on monthly percentage of annual daylight, mean air temperature and a humid area factor for Puerto Rico. The SCS Blaney-Criddle equation is given as

$$CU = (K_{crop}\ K_t\ p\ T\ H)/100 \qquad \text{equ 5}$$

where CU is the monthly water consumptive use, K_t is a climatic coefficient related to mean air temperature, p = monthly percentage of annual daylight hours, T = mean air temperature, H = humid area factor, and K_{crop} is a crop growth coefficient reflecting the growth stage. It should be noted that the crop growth coefficients used in the SCS Blaney-Criddle method are not equivalent to the crop coefficient used in equation 1 (Burman, et al., 1981).

The purpose of the study was to estimate monthly water consumption, net and total gross irrigation requirements. The net irrigation requirement was based on the monthly consumptive use minus the monthly effective rainfall as determined by the Soil Conservation method (SCS, 1970). The gross irrigation requirement was calculated by dividing the monthly consumptive use by the irrigation efficiency (80% for drip, 60% for sprinkler and 40% for surface irrigation).

This study was valuable because it included a large number of crops and surveyed both humid and semiarid locations in Puerto Rico. The applicability of the data was further enhanced by the fact that each crop was evaluated for various lengths of growing season, and for season starting dates at fifteen day intervals throughout the year (e.g., Jan. 1, Jan.15, Feb. 1, Feb. 15, etc).

Using the same method (SCS Blaney-Criddle method) Goyal (1989c) estimated monthly CU for papaya at seven Agricultural Experimental Stations located at Adjuntas, Corozal, Fortuna, Gurabo, Isabela, Lajas and Mayagüez. Average daily CU varied between 2.8 mm/day at Adjuntas and 3.7 mm/day at Fortuna. In this report, the author cautioned that the CU estimates have not been compared with experimental data, and that such experimental data are obtained with lysimeters studies, which are not available for Puerto Rico.

Goyal and González-Fuentes(1989b) used the SCS Blaney-Criddle method to estimate monthly CU for sugar cane at four locations in Puerto Rico: Fortuna, Gurabo, Isabela and Lajas. The monthly CU was minimum in April and maximum in August at all four sites. Average daily CU varied between 4.1 to 4.4 mm/day. Consumptive use estimates from this study compared reasonably well with the range determined for sugar cane determined by Fuhriman and Smith (1951) for the Aguirre area (“normally irrigated fields” treatment).

Several other studies were conducted using the SCS Blaney-Criddle method involving sorghum at two locations (Goyal and González, 1988b), Plantain at seven locations (Goyal and González, 1988c), and bell and cubanelle peppers at two locations (Goyal and González, 1988d). In the Plantain study, CU data were estimated for the Gurabo Experiment Station, which can be compared with the results from the water balance study by Abruña et al. (1979). Abruña et al (1979) determined the minimum and maximum CU values to be 1.5 and 3.6 mm, respectively, for September and December. For these same months Goyal and González (1988c) derived values 3.82 and 5.1 mm, respectively. It should be noted that Goyal and

González (1988c) based their calculations on mean monthly average climate data, whereas non-average conditions may have been encountered by Abruña et al (1979) during their study.

González Fuentes and Goyal (1988) estimated CU for sweet corn grown at the Fortuna Experiment Station using the Hargreaves-Samani method to calculate reference evapotranspiration, which was then multiplied by crop coefficients applicable to sweet corn. The data were used to determine net irrigation requirements between December 10th and March 10th, 1986. This was the only study found in which the Hargreaves-Samani method was used in combination with a crop coefficient to estimate CU. The next section will indicate that all other applications of the Hargreaves-Samani method were limited to estimating reference evapotranspiration.

Studies Which Predicted Reference Evapotranspiration

This section summarizes several studies in which reference evapotranspiration (ET_o) was estimated. It should be noted that a shift in the kind of information is being reported. That is, reference evapotranspiration (ET_o) instead of consumptive use (CU). The advantage of reporting ET_o is that it leaves one free to calculate CU for any crop. The disadvantage is that crop coefficients are not yet available for numerous crops in Puerto Rico.

Goyal (1988a) used the Hargreaves-Samani method to estimate monthly ET_o for Central Aguirre, Fortuna and Lajas substations, and for Magueyes Island located on the south coast of Puerto Rico. The Hargreaves-Samani equation for reference evapotranspiration is given by (Hargreaves and Samani, 1985):

$$ET_o = 0.0023\ R_a\ (T + 17.8)\ (T_{max} - T_{min})^{0.5} \qquad \text{equ 6}$$

Where ET_o is the reference evapotranspiration, R_a is the extra terrestrial radiation, T is the mean daily average temperature , and T_{min} and T_{max} are the mean daily minimum and maximum temperatures, respectively. Daily estimated values of ET_o varied between 3.68 to 5.37 mm/day.

The minimum estimated value of ET_o occurred in December and the maximum occurred in July. The same procedure was applied for Vieques Island, PR, with estimated monthly ET_o ranging between 3.29 in December to 4.94 mm/day in July (Goyal, 1988b).

Goyal et al. (1988) used the Hargreaves-Samani method (equ 6) to estimate ET_o for thirty-four locations within Puerto Rico. Average monthly minimum and maximum air temperatures were based on long term measured data. Average monthly values of R_a were based on the average latitude of Puerto Rico. This paper also describes a regression analysis in which several monthly climatic factors (mean daily minimum, maximum and average air temperature) were correlated with surface elevation in Puerto Rico.

Studies Comparing the Penman-Monteith with Other Evapotranspiration Methods in Puerto Rico

In 1990 a committee of the United Nations Food and Agriculture Organization (FAO, 1990) 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).

Harmsen et al. (2001a) 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 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, 1989b. 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 overestimation in other months. Figure 1 shows Differences (DELTA) in the seasonal consumptive use (CU) estimates between the SCS Blaney-Criddle (SCS BC) and Penman-Monteith (PM) methods for Pumpkin at Fortuna, PR. (DELTA = SCS Blaney-Criddle minus Penman-Monteith). In this example, the SCS Blaney-Criddle method overestimated the seasonal CU by approximately 90 mm for crop seasons beginning in June through August, and underestimated by approximately 60 mm for crop seasons beginning in December and January.

Goyal et al. (1988) estimated reference evapotranspiration at thirty-four locations in Puerto Rico using the Hargreaves-Samani method (equ 6). Harmsen et al. (2002) compared these data with ET_o estimates based on the Penman-Monteith method. The maximum positive and negative differences were observed at the Juncos 1E and Aguirre stations, 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 considered to have a humid climate, while Aguirre is considered to be semi-arid. The maximum underestimate of –0.75 mm/day at Aguirre (semi-arid) was equal to a -13% error, and the maximum overestimate of 0.92 mm/day at Juncos 1E (humid) was 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. Some of the observed differences in the two methods may be because equation 6 does not account for the affects of wind and humidity as does the Penman-Monteith method. According to Allen et al (1998), equation 6 tends to under-predict under high wind conditions and over-predict under conditions of high relative humidity Allen.

Table 1 summarizes the studies in Puerto Rico that have measured or predicted consumptive use, and/or have predicted reference evapotranspiration. The table shows that five studies have been conducted in which CU has been measured, that prior to the year 2000, computational approaches have been limited to only two methods, that CU has been estimated for a relatively large number of crops, and that reference evapotranspiration has been estimated for a large number of locations within Puerto Rico.

Estimating Climatic Parameters For Use with the Penman-Monteith Equation

Harmsen et al. (2002) evaluated climate parameter estimation procedures for use with the Penman-Monteith equation in Puerto Rico. With only two parameters, site latitude and surface elevation, they were able to estimate all other input to the Penman-Monteith method. Minimum and maximum air temperatures were estimated from surface elevation data. Dew point temperature was estimated from the minimum temperature plus or minus a temperature correction factor. Temperature correction factors and average wind speeds were associated with six climatic divisions in Puerto Rico. Solar radiation was estimated from a simple equation for island settings (elevation < 100 m) or by the Hargreaves' radiation equation (elevations > 100 m), based on air temperature differences. Comparisons of reference evapotranspiration using the climate parameter estimation procedures and measured climate parameters showed reasonable agreement (r^2 = 0.93) for four locations in Puerto Rico. The authors suggested the use of measured temperature data in lieu of the estimation procedure in the interior valleys of Puerto Rico.

Use of Pan Evaporation Data for Estimating Reference Evapotranspiration

A number of studies have been performed to determine optimal irrigation rates based on pan evaporation data in Puerto Rico during the 1990s (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]). The pan evaporation method estimates crop evapotranspiration from the following equation:

$$CU = K_c K_p E_{pan} \quad \text{equ 7}$$

where CU = crop evapotranspiration, K_c = crop coefficient and E_{pan} = pan evaporation. A slightly different form of the above equation is being recommended by the UPR Experiment Station (Rivera-Martínez, 2002):

$$CU = K_p K_c (E_{pan} – Rain) \quad \text{equ 8}$$

where Rain refers to rainfall.

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 equations 8 and 9 are usually applied for periods of 2 to 4 days.

In Puerto Rico, the K_p values commonly used were derived from a study by González and Goyal (1989). These data were developed based on the ratio of long-term average pan evaporation and the estimated evapotranspiration using the SCS Blaney-Criddle method. Because of inherent errors associated with the SCS Blaney-Criddle method, the recommended K_p values may also be somewhat in error. The FAO currently recommends using the ratio of pan evaporation divided by the Penman-Monteith-estimated reference evapotranspiration for calculating pan coefficient (Allen et al., 1998).

Most of the studies have recommended applying water to plants at a rate equal to 1 or greater times the pan-estimated CU rate. 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.

Recently, a water use study was conducted on pumpkin at the University of Puerto Rico Experiment Station at Lajas, PR (Harmsen, 2001). The purpose of the study was to evaluate the potential for over-application of irrigation water based on irrigation scheduling recommendations from pan-derived ET rates. Irrigation treatments included 0.5, 0.75, 1.0 and 1.25 times the pan-derived ET rate (ET_{pan}). Weekly soil moisture was measured using a Time Domain Reflectometry (TDR) method. Evapotranspiration was estimated using the Penman-Monteith method and an FAO-derived crop coefficient curve for pumpkin. Climate data, including air temperature, wind speed, solar radiation and humidity were obtained from a weather station located at the edge of the experimental plots. Runoff was assumed to be negligible. Deep percolation was estimated using a rearrangement of the water balance equation (equ 4). Some deep percolation was estimated to have occurred in each of the four irrigation treatments. The deep percolation rate correlated well with the irrigation treatments (i.e., the estimated volumes of deep percolation were from lowest to highest the 0.5 ET_{pan}, 0.75 ET_{pan}, 1.0 ET_{pan} and 1.25 ET_{pan} treatments, respectively).

Peak Evapotranspiration

Design of irrigation systems requires knowledge of the peak evapotranspiration (ET_{peak}). The Soil Conservation Service (currently the Natural Resource Conservation Service) has published values of ET_{peak} for various crops grown in Puerto Rico in its Irrigation Guide (SCS, 1969). To the author's knowledge, this document is the most widely used source of peak evapotranspiration values in Puerto Rico.

Harmsen et al. (2002) compared ET_{peak} for six vegetable crops for three locations in Puerto Rico, obtained using the SCS Irrigation Guide (SCS, 1969), the SCS Blaney-Criddle method (Goyal,1989b) and the Penman-Monteith method. It should be noted that the SCS Irrigation guide recommends a single value of ET_{peak} for the entire Island for a given crop. The peak ET for the SCS Blaney-Criddle method was obtained by using the maximum monthly consumptive use divided by the number of days in the month. The SCS Blaney-Criddle-estimates of ET_{peak} were not available for the Aibonito location. The input data for the Penman-Monteith-determined reference evapotranspiration were estimated by using the procedure described Harmsen et al. (2002) (see next section of this paper). Estimates of ET_{peak} were based on the maximum daily reference evapotranspiration (ET_o) times the published value of the crop coefficient (K_c) for the mature (or mid) growth stage. The crop coefficients were obtained from Allen et al. (1998). Table 2 presents the comparison of the peak ET data.

For the three methods considered, estimates of ET_{peak} were, lowest to highest, as follows: SCS Irrigation Guide, the SCS Blaney-Criddle method and the Penman-Monteith method, respectively. The implications of these results are important because designers of irrigation systems in Puerto Rico may be under-designing systems at this time. Normally, an under-designed system can be compensated for by operating the system longer; for example, a system could be operated for eight hours instead of six hours. However, if the system was designed to run more hours per day (e.g., 22 hours, which is the maximum recommended by the American Society of Agricultural Engineers (ASAE 1999), then increasing the operating time may not be an option.

RECOMMENDATIONS FOR FUTURE EVAPOTRANSPIRATION RESEARCH IN PUERTO RICO

Several areas of evapotranspiration research are needed in Puerto Rico at this time. Some of the suggested research will be of direct benefit to the Caribbean Region as well as in Puerto Rico, and may be of benefit to other tropical regions of the world.

- Development of Crop Coefficients (K_c). To date, no crop coefficients have been derived in Puerto Rico. Although crop coefficients derived in other parts of the world can used to provide approximate estimates of evapotranspiration, the K_c is in fact depend on the crop cultivar and other local conditions. Perhaps more importantly, no crop coefficients are available in the literature for many of the local crops grown in Puerto Rico. The Natural Resource Conservation Service (NRCS) in Puerto Rico has given high priority for developing crop coefficients for the following cultivars (Martínez, 2000): Acerola, Tannier, Guanabana, Malanga, Parcha, Star Grass, Recao, Pangola Grass, Ñame, and Buffel Grass.

  As noted above (see Table 1 for summary of studies), water balance and non-weighing lysimeter studies performed during the 1960s and 70s in Puerto Rico did not determine crop coefficients. A study could be performed to reevaluate these data for this purpose. The crops considered in these studies included: sugar cane, guinea grass, para grass and guinea grass-kudzu, para grass-kuduz mixtures, plantains, rice and pumpkin.

- Validation of the pan evaporation method for scheduling irrigation. This method has become popular in Puerto Rico in recent years because it is easy of use. However, the method may result in over- or under-application of water relative to the crop water requirements when a single value of the crop coefficient (K_c) for the entire season is used. It is preferable to use data from an evapotranspiration crop coefficient curve, which takes into account the development of the crop. Allen et al. (1998) provide an excellent discussion on the construction of crop coefficient curves. Another potential source of error is the use of published values of K_p derived from the study of González and Goyal (1989), which were based on evapotranspiration estimates from the SCS Blaney-Criddle method. Future efforts should be made to update the K_p values for Puerto Rico using the Penman-Monteith reference evapotranspiration.

- Harmsen et al. (2002) (also Harmsen and Torres-Justiniano, 2001b) proposed procedures for estimating input to the Penman-Monteith method in Puerto Rico. A geographic information system (GIS) could be developed for Puerto Rico, incorporating the estimation procedures. This GIS consumptive use system could be made available on the internet or on a CD-ROM.

- The use of remote sensing techniques for estimating evapotranspiration. Satellite data can be used to estimate evapotranspiration over relatively large areas. Examples of this technique include the Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen, 2000); or by estimating biophysical processes using remotely sensed data (e.g., Choudhury and DiGiolamo, 1998; Kite and Droogers, 2000).

- Instead of using the crop coefficient and the reference evapotranspiration to estimate evapotranspiration (equ 4), evapotranspiration can be defined in a "one-step" method as

  $ET = ET(r_a,r_b)$ equ 9

  where $ET(r_a,r_b)$ represents the general form of the Penman-Monteith equation, which is a function of the aerodynamic resistance (r_a) and the bulk surface resistance (r_s). For convenience, the other parameters/varaibles used in the Penman-Monteith equation are not shown. At this time, the parameters r_a and r_s are not easily obtained. However, through research efforts, it is hoped that in the not to distant future it will be possible to apply equation 9 directly.

The Expert Consultation on the revision of FAO methodologies for crop water requirements (Smith et. al., 1990) has suggested the following areas of research (which could be supported in Puerto Rico):

1. To evaluate the effect of advective conditions on crop resistance factors (i.e., r_a and r_b);
2. To make a systematic effort reviewing various research results, in developing sound values for crop resistance factors for a range of crops;
3. To review the effect on crop resistance factors of reduced evapotranspiration under soil moisture stress and adverse growth conditions.

CONCLUSIONS

This paper presented a review of the majority of crop water use studies performed in Puerto Rico. Areas reviewed included: reference materials; consumptive use obtained from field studies; studies which predicted consumptive use and reference evapotranspiration; studies comparing the Penman-Monteith with other evapotranspiration methods; estimation of climate parameters for use with the Penman-Monteith method; use of pan evaporation data for estimating reference evapotranspiration; and the comparison of peak evapotranspiration estimates. Recommendations for research priorities were also provided.

REFERENCES

Abruña, F. J. Vicente-Chandler, H. Irizarry and S. Silva. 1980. Evapotranspiration with Plantains and the Effect of Frequency of Irrigation on Yields. J. Agric. U.P.R. 64(2):204-10.

Allen, R. G., L. S. Pereira, Dirk 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.

ASAE, 1999. Design and Installation of Microirrigation System. American Society of Agricultural Engineers, ASAE EP405.1 DEC99.

Bastiaanssen, W. G. W., 2000. SEBAL-based sensible and latent heat fluxes in the irrigated Gediz Basin, Turkey. Journal of Hydrology 229:87-100.

Burman, R.D., P.R. Nixon, J. L. Wright, W. O. Pruitt, 1981. Water Requirments, Chapter 6 in Design and Operation of Farm Irrigation Systems. American Society of Agricultural Engineers, Edited by Marvin E. Jensen, St. Joseph, Michigan.

Choudhury, B. J. and N. E. DiGirolamo. 1998. A biophysical process-based of global land surface evaporation using satellite and ancillary data. I. Model description and comparison with observations. Journal of Hydrology 205:164-185.

Doorenbos, J. and W.O. Pruitt, 1977. Guidelines for Predicting Crop Water Requirements. FAO Irrigation and Drainge Paper 24, Revised. United Nations, Rome.

FAO, United Nations, 1990, Expert consultation Italy, on revision of FAO methodologies, 28-31 May for crop water requirements, Annex V. Rome.

Fuhriman, D. K. and r. M. Smith, 1951. Conservation and consumptive use of water with Sugar Cane under irriation in the south coastal area of Puerto Rico. J. of Agric. University of Puerto Rico, Vol. 35(1):1-45.

Goenaga, R., H. Irizarry and E. Gonzalez. 1993. Water requirement of plantains (Musa acuminata X Musa balbisiana AAB) grown under semiarid conditions. Trop. Agric. (Trinidad) vol. 70 No. 1, January.

Goenaga, R. 1994. Growth, nutrient uptake and yield of tanier (Xanthosoma spp.) grown under semiarid conditions. J. Agric. Univ. P.R. vol. 78, No. 3-4, July/October, pp 87-989.

Goenaga, R and H. Irizarry, 1995. Yield Performance of Banana Irrigated with Fractions of Class A pan Evaporation in a Semiarid Environment. Agronomy Journal, Vol. 97, March –April.

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

González-Fuentes E. A. and M. R. Goyal, 1988. Estimación de los requisitos de riego para maiz dulce (Zea mays cv. Suresweet) en la costa sur de Puerto Rico. J. of Agric. University of Puerto Rico. 72(2):277-84.

González, E. and M. R. Goyal, 1989. Coeficiente de Evaporímetro para Puerto Rico. J. Agric. Univ. P.R. 73(1):00.

Goyal, M. R. 1988a. Research Note. Potential evapotranspiration for the south coast of Puerto Rico with the Hargreaves-Samani technique. J. Agric. U.P.R. 72(1):57-63.

Goyal, M. R. 1988b, Potential Evapotranspiration for Vieques Island, Puerto Rico, With the g and Samani Model, Research Note. Journal of Agriculture, U.P.R. 72(1): 177-78.

Goyal, M. R. (editor) 1989a. *Irrigation Research and Extension Progress in Puerto Rico*. Prepared for the First Congress on “Irrigation in Puerto Rico,” March 8th, 1989, Ponce, Pr. UPR-Ag. Experiment Station.

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

Goyal M. R., 1989c. Reseach Note: Monthly consumptive use of papaya at seven regional sites in Puerto Rico. J. Agric. U.P.R. 73(2):00

Goyal, M. G., and E. A. Gonzalez Fuentes, 1989a. Riego pro Goteo – Evapotranspiración. University of Puerto Rico Agricultural Extension Service. Serie 14, IA-72. 45 pages.

Goyal, M. R. and E. A. González-Fuentes, 1989b. Estimating Water Consumptive Use by sugarcane at four regional sites in Puerto Rico. J. Agric. U.P.R. 73(1):00

Goyal, M. R. and E. A. González Fuentes, 1990. "Evapotranspiration" in the book: Manejo de Riego por Goteo, Universidad de Puerto Rico Recinto Mayaguez, Colegio de ciencias Agricolas, Servico de Extension Agricola. Edited by Megh R. Goyal. SEA IA 80, ISBN 0-9621805-2-3, Library of Congress Catalog No. 89-50060.

Goyal, M. R. and E. A. González, 1988a. Water Requirements for Vegetable Production in Puerto Rico. ASCE Symposium on Irriation and Drainage, July.

Goyal M. R., and E. A. González (1988b). Requisitos de riego para sorgo en las costas Sur y Norte de Puerto Rico. J. Agric. University of Puerto Rico. 72(4)585-98.

Goyal, and E. A. González (1988c). Requisitos de riego para plátano en siete regions ecológicas de Puerto Rico. J. Agric. University of Puerto Rico. 72(4):599-608.

Goyal and González (1988d). Seasonal consumptive use of water by bell and Cuanelle peppers in semiarid and humid coastal sites in Puerto Rico. J. Agric. U.P.R., 72(4):609-14.

Goyal, M. R., E. A. Gonzalez and C. Chao de Baez. 1988. Temperature versus elevation relationships for Puerto Rico, Journal of Agriculture U.P.R., 1988 72(3):440-67.

Hargreaves, G. H. and Z. A. Samani, 1985. Reference crop evapotranspiration from temperature. J. Appl. Eng. Agric. 1(2):96-9.

Harmsen, E. W. 2001. Evaluation of Irrigation Scheduling Recommendations Based on the Pan Evaporation Method. Annual Report for Project CBAG-71. University of Puerto Rico Experiment Station, Rio Piedras, PR.

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

Harmsen, E. W. and S. Torres-Justiniano, 2001a. Estimating Island-Wide Reference Evapotranspirations for Puerto Rico Using the Penman-Monteith Method. ASAE Paper 01-2174. 2001 American Society of Agricultural Engineering Annual International Meeting. Sacramento Convention Center, Sacramento, California, USA. July 30-August 1, 2001.

Harmsen, E. W. and S. Torres-Justiniano, 2001b. Evaluation of Prediction Methods for Estimating Climate Data to be Used with the Penman-Monteith Equation in Puerto Rico. ASAE Paper 01-2048. 2001 American Society of Agricultural Engineering Annual International Meeting. Sacramento Convention Center, Sacramento, California, USA. July 30-August 1, 2001.

Harmsen, E. W., M. R. Goyal and S. Torres-Justiniano, 2002. Estimating Evapotranspiration in Puerto Rico. University of Puerto Rico Journal of Agriculture. (in press).

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.

Kite, G. and P. Droogers. 2000. Comparing Estimates of Actual Evapotranspiration from Satellites, Hydrologic Models, and Field Data: A Case Study from Western Turkey. International Water Management Institute, Research Report 42. pp 41.

Martínez, J. 2000. Personal communication. Meeting with the author and the representatives of the NRCS at the Juan Diaz, PR, Field Office. May, 2000.

Ravalo, E. J. and M. R. Goyal, 1988. Water Requirement of rice in Lajas Valley, Puerto Rico. Dimension, Año 2, Vol. 8, Enero-Febrrero-Marzo.

Rivera-Martínez, L. 2002, Draft Revisión de las secciones de dos conjuntos technológicos nuevos (berenjena y pimiento) por colegas revisores dentro del Colegio de Ciencias Agrícolas. University de Puerto Rico Estación Experimental Agrícola, Río Piedras, PR.

Santana Vargas, J. 2000. Patrones de humedecimiento bajo el sistema de micro riego subterraneo. Tesis de Maestía, Agronomía y suelos. Universidad de Puerto Rico Recinto Universitario de Mayagüez.

SCS, 1969. Technical guide for Caribbean Area, Section IV-Practice Standards and Specifications for Irrigation System, Sprinkler. Code 443. U.S. Department of Agriculture Soil Conservation Service.

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

Smith, M., Allen, R., J. L. Monteith, A. Perrier, L. Santos Pereira, and A. Segeren. 1990. Report on the Expert Consultation on Revision of FAO Methodologies for Crop Water Requiements. Held in FAO, Rome, Italy, 28-31 May, 1990.

Vázquez, Roberto, 1965. Effects of Irrigation and nitrogen levels on the yields of Guinea Grass, Para Grass, and Guinea Grass-Kudzu and Para Grass-Kudzu Mixtures in Lajas Valley. Journal of Agriculture of the University of Puerto Rico. Vol. XLLIX, No. 4:389-412.

Vázquez, Roberto, 1970. Water Requirements of Sugarcane under irrigation in Lajas Valley, Puerto Rico. Bulletin 224, University of Puerto Rico Agricultural Experiment, Rio Piedras, PR.

Table 1. Summary of Studies that Measured or Predicted Consumptive Use (ET_c), and/or Predicted Reference Evapotranspiration (ET_o)

in Puerto Rico.

No.	Method	Number of Locations	Crop	Source[1]
	Measured Consumptive Use			
1	Water balance	1	Sugar Cane	Fuhriman and Smith, 1951
2	Water balance	1	Guinea Grass, Para Grass and Guinea Grass-Kudzu and Para Grass-Kudzu Mixutures	Vázquez, 1965
3	Water balance	1	Sugar Cane	Vázquez, 1970
4	Water balance	1	Plantain	Abruña et al., 1979
5	Water balance	1	Rice	Ravalo and Goyal, 1988
	Predicted Consumptive Use (K_cET_o)			
6	SCS Blaney-Criddle	2	Green Beans, Cabbage, Carrots, Cucumber, Egg Plant, Lettuce, Melons, Okra, Onion, Potatoes, Pumpkin, Sweet Peppers, Sweet Potato and Tomotoes	Goyal, 1989b; Goyal and González, 1988a; Harmsen et al. 2001a (Onion and Pumpkin)
7	SCS Blaney-Criddle	7	Papaya	Goyal M. R., 1989c.
8	SCS Blaney-Criddle	4	Sugar Cane	Goyal, M. R. and E. A. González-Fuentes, 1989b
9	SCS Blaney-Criddle	2	Sorhgam	Goyal and González, 1988b
10	SCS Blaney-Criddle	7	Plantain	Goyal and González, 1988c
11	SCS Blaney-Criddle	2	Bell and Cubanelle peppers	Goyal and González, 1988d
12	Hargreaves-Samani with crop coefficient	1	Sweet Corn	González-Fuentes and Goyal, 1988
	Predicted Reference Evapotranspiration (ET_o)			
13	Hargraeves and Samani	4	N/A	Goyal, 1988a
14	Hargraeves and Samani	1	N/A	Goyal, 1988b
15	Hargraeves and Samani	34	N/A	Goyal et al., 1988; Harmsen et al. 2001a; and Harmsen et al. 2002

Table 2. Comparison of peak evapotranspiration estimates determined by three different methods for six vegetable crops at three locations in Puerto Rico (From Harmsen et al., 2002).

	Peak Evapotranspiration (mm/day)		
Crop	**SCS Irrigation Guide for Caribbean Area[1]**	**SCS Blaney-Criddle Method[2]**	**Penman-Monteith Method[3]**
	Fortuna		
Cabbage	4.1	5.3	6.1
Eggplant	4.1	5.3	6.1
Cucumbers	4.1	5.1	5.8
Melons	4.1	4.8	5.8
Sweet Potatoes	5.3	6.4	6.7
Tomatoes	5.3	5.8	6.7
	Isabela		
Cabbage	4.1	5.1	5.7
Eggplant	4.1	5.3	5.7
Cucumbers	4.1	4.6	5.4
Melons	4.1	4.6	5.4
Sweet Potatoes	5.3	6.1	6.2
Tomatoes	5.3	5.6	6.2
	Aibonito		
Cabbage	4.1	NA	5.5
Eggplant	4.1	NA	5.5
Cucumbers	4.1	NA	5.3
Melons	4.1	NA	5.3
Sweet Potatoes	5.3	NA	6.0
Tomatoes	5.3	NA	6.0

[1] From SCS, 1969. Technical guide for Caribbean Area, Section IV-Practice Standards and Specifications for Irrigation System, Sprinkler. Code 443. U.S. Department of Agriculture Soil Conservation Service.

[2] From Goyal M. R., 1989b. 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.

[3] Input to the Penman-Monteith equation for reference evapotranspiration were determined using the method described in this paper. Crop coefficients for the mature growth stage were obtained form Allen et al. (1998).

[4] NA Not Available.

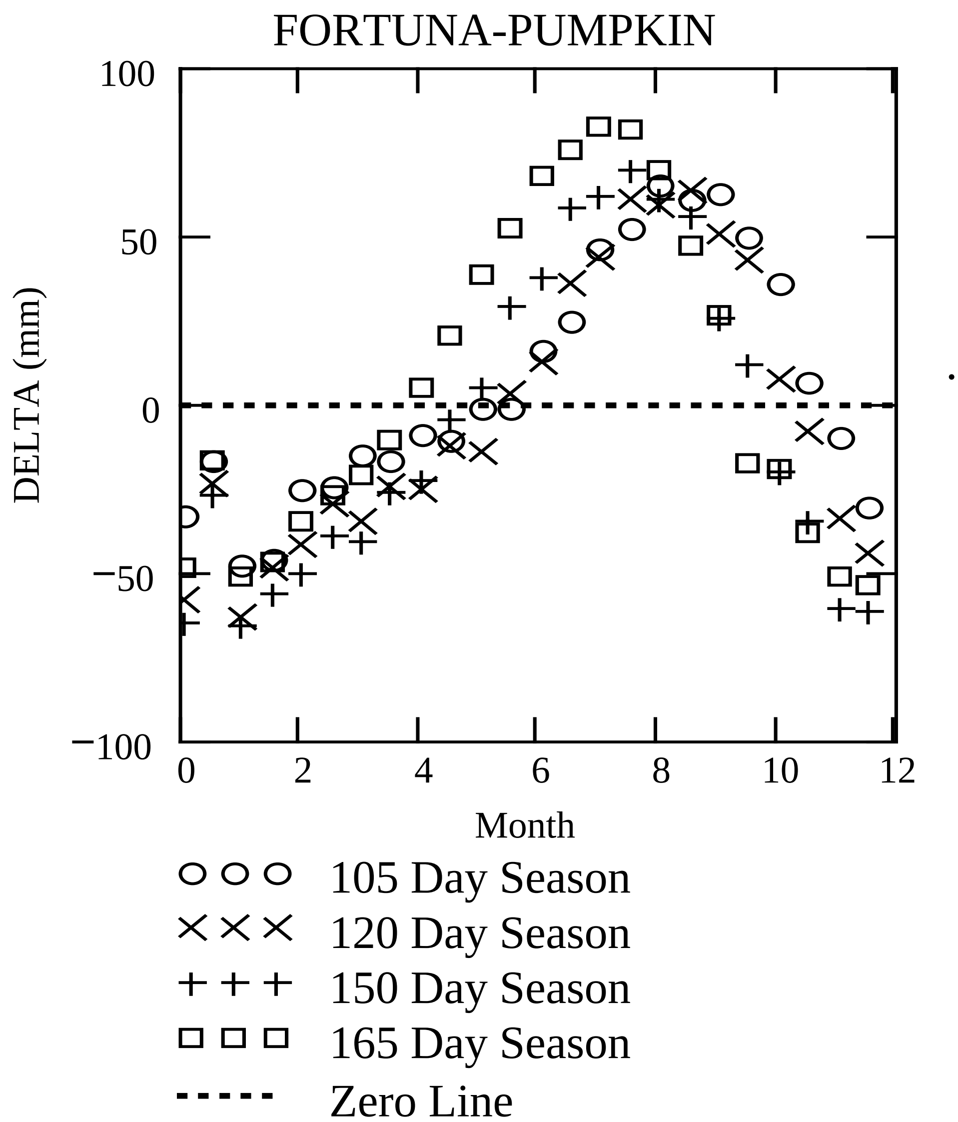

Figure 1. Differences (DELTA) in the seasonal consumptive use (CU) estimates between the SCS Blaney-Criddle (SCS BC) and Penman-Monteith (PM) methods. (DELTA = SCS Blaney-Criddle minus Penman-Monteith) (From Harmsen et al. 2001a).

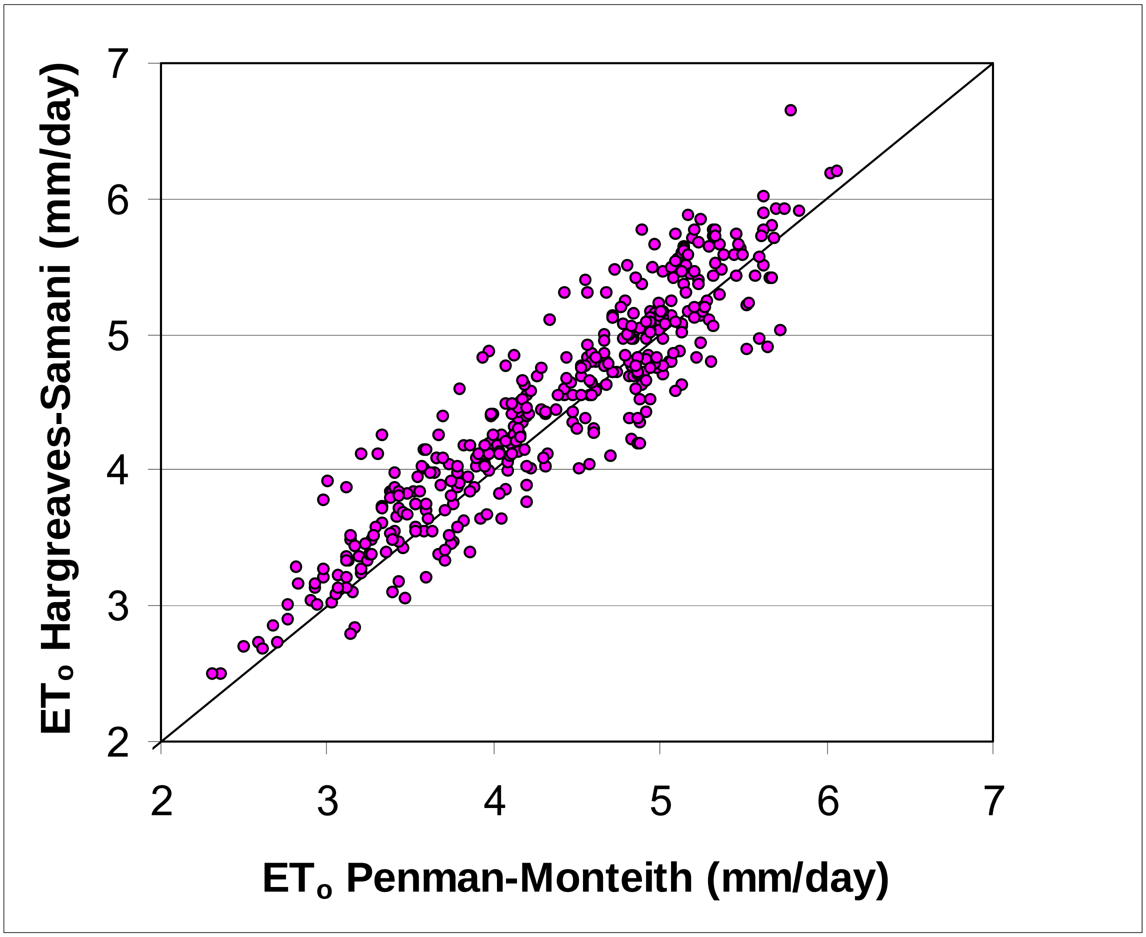

Figure 2. Comparison of reference evapotranspiration estimated by the Penman-Monteith (P-M) and Hargreaves-Samani (H-S) Methods for thirty-four locations in Puerto Rico. (From Harmsen et al. 2002).