Fifty years of crop evapotranspiration studies in Puerto Rico

E.W. Harmsen

ABSTRACT: The water resources of Puerto Rico are currently being threatened by population pressure, development, pollution, and potentially adverse changes in the climate. Accurate determination of evapotranspiration is essential in managing water resources and practicing water conservation in Puerto Rico. In support of this goal, a review is presented covering the majority of research on crop water use and evapotranspiration estimation methods used in Puerto Rico during the last fifty years. Specifically, the review considers consumptive use determined from field water balance studies, calculation methods, and the pan evaporation method. Several studies also considered the estimation of reference evapotranspiration and the procedures for estimating climate parameter data needed as input to the reference evapotranspiration calculation methods. Recommendations for research priorities are provided.

Keywords: Crop water use, evapotranspiration, Hargreaves-Samani, pan evaporation, Penman-Monteith, Puerto Rico, reference evapotranspiration, U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS) Blaney-Criddle

The countries within the humid tropics contain almost one-third of the total world population (Bonell et al., 1993). Within this region there are many small islands that rely on agriculture to feed their populations and whose water resources are subject to an ever-increasing risk. Therefore, it is imperative to better understand the hydrology of small tropical islands with the goal of improving water conservation practices. Since irrigation is one of the largest consumers of water in society, special emphasis should be placed on the development of techniques for estimating crop water requirements. In support of this goal, this paper reviews the majority of crop evapotranspiration studies conducted during the last fifty years in Puerto Rico with the hope that this information may be useful in Puerto Rico as well as in other areas of the humid tropics.

This paper is organized under the following headings: evapotranspiration reference materials, consumptive use obtained from field studies, studies predicting consumptive use, studies predicting reference evapotranspiration, studies comparing the Penman-Monteith equation with other evapotranspiration methods, estimating climatic parameters for use with the Penman-Monteith equation, use of pan evaporation data for estimating consumptive use, and peak

Eric W. Harmsen is an associate professor in the Department of Agricultural and Biosystems Engineering at the University of Puerto Rico - Mayagüez Campus.

evapotranspiration estimates for irrigation system design. The paper ends with a list of priorities for future research.

Methods and Materials

Site description. Puerto Rico is an island between the Caribbean Sea and the North Atlantic Ocean, east of the Dominican Republic. It is located at geographic coordinates: 18 15 N, 66 30 W and has an area of 9,104 sq km, slightly less than three times the size of Rhode Island. The highest elevation in Puerto Rico is 1,338 m above mean sea level at Cerro de Punta, Puerto Rico (United States Central Intelligence Agency, 2002).

Many islands of the West Indies archipelago share similar characteristics with respect to climate. This is due in part to the influence of the trade winds and the islands' mountainous topography (Kent, 2002). Rainfall for these islands is generally greatest in the northeast and interior mountain areas. Due to orographic effects, the leeward side may be quite dry and even semiarid, as in the case of southwest Puerto Rico. The rainy season tends to be from June to November and the dry season from December to May. For a given location, air temperature variations throughout the year are small; however, air temperatures are highly correlated with elevation. An exception to this occurs within interior mountain valleys where warm air can become trapped. In some cases, average temperatures within interior mountain valleys may be higher than coastal areas at lower elevations (Capiel and Calvesbert, 1976).

Crop evapotranspiration. Crop evapotranspiration (ET_c) is defined as the combination of evaporation from soil and plant surfaces, and transpiration from plant leaves. Evaporation is the process where 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 evaporate water through small openings in their leaves called stomata. Evapotranspiration can be expressed in units of mm d^{-1} (in d^{-1}), or as an energy flux in units of MJ m^{-2} d^{-1} (cal ft^{-2} d^{-1}).

Evapotranspiration is often the largest component of the hydrologic cycle after rainfall. Under arid conditions, potential evapotranspiration can easily exceed rainfall. The following water balance equation illustrates the relationship between hydrologic variables at any location in the field:

$$S_2 = P + IRR - DP - RO - ET_c + S_1 \tag{1}$$

where: P is precipitation, IRR is irrigation, DP is deep percolation, ET_c is crop evapotranspiration, RO is surface runoff, and S is the amount 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 depth. All the terms in Equation 1 have units of mm (in). The subscripts 1 and 2 represent the beginning and end of the period under consideration. Equation 1 can be 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_c:

$$ET_c = (S_1 - S_2) + (P + IRR) - (DP + RO) \tag{2}$$

In Equation 2, the water balance has been separated into three components: stored water (S_1 - S_2), water input (P + IRR), and water losses (DP + RO).

Other general methods used to estimate evapotranspiration include the energy balance, micro-climatological, and weighing and nonweighing lysimeter methods (Goyal and González-Fuentes, 1990). In Puerto Rico, all of these methods have been used except for the weighing lysimeter method. Determination of evapotranspiration with a weighing lysimeter has been considered to be the most accurate of all methods. However, the major disadvantages of this method are its high cost and nonportability.

Crop evapotranspiration can also be estimated as the product of the reference evapotranspiration and crop coefficient:

$$ET_c = K_c \, ET_o \tag{3}$$

where: ET_c is crop evapotranspiration (mm), K_c is the crop coefficient (dimensionless) and ET_o is reference evapotranspiration (mm).

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 a reference crop (Allen et al., 1998). Reference evapotranspiration has been defined as the evapotranspiration from an extended surface height of 0.08 to 0.15 m (3.2 in to 5.9 in)—green grass cover of uniform height, actively growing, completely shading the ground, and not short of water (Doorenbos and Pruitt, 1977). Alternatively, reference evapotranspiration has been defined as the "upper limit or maximum evapotranspiration that occurs under given climatic conditions with a field having a well-watered agricultural crop with an aerodynamically rough surface, such as alfalfa with 12 in to 18 in of top growth" (Jensen et al., 1970).

Numerous mathematical equations have been developed for computing ET_o. One such expression, having global validity and recommended by the United Nations Food and Agriculture Organization (FAO), is the Penman-Monteith equation (Allen et al., 1998) given below:

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

where: Δ is the slope of the vapor pressure curve (kPa $°C^{-1}$), R_n is net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), γ is the psychrometric constant (kPa^{-1}), T is mean daily air temperature at 2 m height (°C), u_2 is wind speed at 2 m height, e_s is the saturated vapor pressure (kPa^{-1}) and e_a is the actual vapor pressure (kPa^{-1}). 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^{-1} and an albedo of 0.23. Note that the derivation of Equation 4 was based on SI units and therefore non-SI units should not be used.

Review of previous work in Puerto Rico. This literature review surveys the efforts to measure or estimate evapotranspiration in Puerto Rico. The majority of the literature indicates that before the late 1980s, Goyal or others in collaboration with him have made almost all of the currently available estimates of crop consumptive use and reference evapotranspiration. These studies are detailed in a compilation document, *Irrigation Research and Extension Progress in Puerto Rico* (Goyal, 1989a). Throughout the 1990s, there appears to have been a cessation in evapotranspiration research in Puerto Rico, except for the use of pan evaporation—estimated consumptive use for managing irrigation application amounts. Since 2000, some studies have been initiated involving comparisons between the Penman-Monteith method and other calculation methods (Harmsen et al., 2001a; Harmsen and Torres-Justiniano, 2001a; and Harmsen et al., 2002a). 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) provided a chapter on evapotranspiration in the book, *Manejo de Riego por Goteo,* published by the University of Puerto Rico Extension Service. The book provides basic definitions and descriptions of the following: three variations of the Penman method, three variations of the USDA-SCS Blaney-Criddle method, two Hargreaves methods, Jensen-Haise, Stephens-Stewart, Priestley-Taylor, Thornthwaite, Linacre, Makkink, pan evaporation, water balance, radiation and regression methods. Also covered are local calibration techniques and crop coefficients. Much of this material is also contained in a forty-five page extension document, *Evapotranspiración*, by Goyal and González (1989a).

Consumptive use obtained from field studies. The following five studies are significant because they represent a limited dataset in which actual field measurements were made to determine consumptive use:

1) Fuhriman and Smith (1951) conducted a study for the Aguirre area of southern Puerto Rico on the consumptive use of sugar cane using different types of irrigation treatments. At the time of this study between 1949 and 1950, sugarcane was the dominant crop in Puerto Rico, grown on 95% of the irrigated land. The experiment involved field studies using nonweighing lysimeters. Consumptive use was estimated using the water balance method, which accounted for rainfall, irrigation, percolation below the root zone, and changes in soil moisture. Daily water requirements varied between 2.5 and 4.6 mm d^{-1} (0.1 and 0.18 in d^{-1}). Soil moisture was estimated using tensiometers and nylon resistance blocks. Soil evaporation measured on several of the lysimeters was subtracted from consumptive use data on the sugar cane covered plots to determine plant transpiration rate.

2) Vázquez (1965) determined consumptive use using the 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 consumptive use values were determined for the two grasses and two grass mixtures over the fifteen-month study period. Annual water use by the guinea grass and para grass was 1,494 mm (58.8 in) and 1,466 mm (57.7 in), respectively. This was the only study found reporting consumptive use for grasses.

3) Vázquez (1970) used similar experimental methods to determine the consumptive use of sugar cane at Lajas, Puerto Rico. This study included use of a neutron probe method for soil moisture determination and was conducted from April 1965 through May 1966. Consumptive use was determined for various irrigation treatments. Average daily consumptive use varied between 2.5 and 4 mm d^{-1} (0.1 and 0.16 in d^{-1}). The study concluded that about 250 mm (9.84 in d^{-1}) 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 five months prior to harvest.

4) 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 was depleted by 20%, the average daily evapotranspiration was estimated to be 2.9 mm d^{-1} (0.11 in d^{-1}), and was found to be equivalent to 79% of pan evaporation. The minimum and maximum daily consumptive use was 1.5 and 3.6 mm d^{-1} (0.05 and 0.14 in d^{-1}), respectively, for September and December.

5) Ravalo and Goyal (1988) estimated water requirements for rice during December through May of 1973 at the Lajas substation using a hydrologic balance approach that accounted 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. Daily water requirements varied between 6.9 and 11.8 mm d^{-1} (0.27 and 0.47 in d^{-1}). It is interesting to note that in none of the above studies was there an attempt to calculate crop coefficients from field data. The crop coefficient is calculated from rearrangement of Equation 3 (i.e. $K_c = ET_c/ET_o$). In future studies that derive crop coefficients in Puerto Rico, data from these studies should be evaluated.

Studies predicting consumptive use. Monthly water consumption by fifteen different vegetable crops for two locations in Puerto Rico (Fortuna and Isabela) was calculated by Goyal (1989b) (also see Goyal and González, 1988a). The USDA-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 USDA-SCS Blaney-Criddle equation is given as:

$$CU = (K_{crop}\, K_t\, p\, T\, H)/100 \quad (5)$$

where: CU is the monthly water consumptive use (in mo^{-1}), K_t is a climatic coefficient related to mean air temperature, p is a monthly percentage of annual daylight hours (percent), T is mean air temperature (°F), H is a 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 USDA-SCS Blaney-Criddle method are not equivalent to the evapotranspiration crop coefficient used in Equation 1 (Burman et al., 1981).

The purpose of the study was to estimate monthly consumptive use, and 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 (USDA-SCS, 1970). The gross irrigation requirement was calculated by dividing the monthly consumptive use by 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. Each crop was evaluated for growing seasons of various lengths with season starting dates at fifteen-day intervals through the year (e.g. Jan. 1, Jan.15, Feb. 1, Feb. 15, etc.), which further enhanced the applicability of the data.

Using the USDA-SCS Blaney-Criddle method, Goyal (1989c) estimated monthly consumptive use for papaya at seven agricultural experimental stations located at Adjuntas, Corozal, Fortuna, Gurabo, Isabela, Lajas, and Mayagüez. Average daily consumptive use varied between 2.8 mm d^{-1} (0.11 in d^{-1}) at Adjuntas and 3.7 mm d^{-1} (0.15

in d^{-1}) at Fortuna. In this report, the author cautioned that the consumptive use estimates have not been compared with experimental data, and that such experimental data are obtained with lysimeter studies, which are not available for Puerto Rico.

Goyal and González-Fuentes (1989b) used the USDA-SCS Blaney-Criddle method to estimate monthly consumptive use for sugar cane at four locations in Puerto Rico: Fortuna, Gurabo, Isabela, and Lajas. Monthly consumptive use was minimum in April and maximum in August at all four sites. Average daily consumptive use varied between 4.1 and 4.4 mm d^{-1} (0.16 and 0.17 in d^{-1}). Consumptive use estimates from this study compared reasonably well with the range for sugar cane determined by Fuhriman and Smith (1951) for a field project in the Aguirre area ("normally irrigated" treatment).

Several other studies were conducted using the USDA-SCS Blaney-Criddle method, which involved 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, consumptive use data were estimated for the Gurabo Experiment Station. These data can be compared with the September and December 1977 results (1.5 and 3.6 mm d^{-1} [0.06 and 0.14 in d^{-1}], respectively) from the water balance study by Abruña et al. (1979). For these same months Goyal and González (1988c) derived values of 3.8 and 5.1 mm (0.15 and 0.2 in d^{-1}), respectively. Assuming the field study data are accurate, the error in the USDA-SCS Blaney-Criddle method estimated minimum and maximum consumptive use was 30% and 60%, respectively. It should be noted that Goyal and González (1988c) based their calculations on mean monthly average climate data, whereas actual monthly data for the period were used by Abruña et al. (1979). Although these data were not available for comparison, inspection of the 1977 annual pan evaporation for the Gurabo Experimental Station (González and Goyal, 1989) indicates only a 6.4% deviation below the long-term average annual pan evaporation. Since pan evaporation is correlated with evapotranspiration, the 30% and 60% differences between the field and estimated data do not appear to be reasonable.

González-Fuentes and Goyal (1988) estimated consumptive use 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 10 and March 10, 1986. This was the only study found in which the Hargreaves-Samani method was used in combination with a crop coefficient to estimate consumptive use. Minimum and maximum consumptive use were 2 and 7 mm d^{-1} (0.08 and 0.28 mm d^{-1}) during December and March, respectively.

Studies predicting reference evapotranspiration. This section summarizes several studies in which reference evapotranspiration (ET_o) was estimated. It should be noted that the information reported has shifted from consumptive use (CU) to reference evapotranspiration (ET_o). The advantage of reporting ET_o is that it allows for calculation of consumptive use 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 below (Hargreaves and Samani, 1985):

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

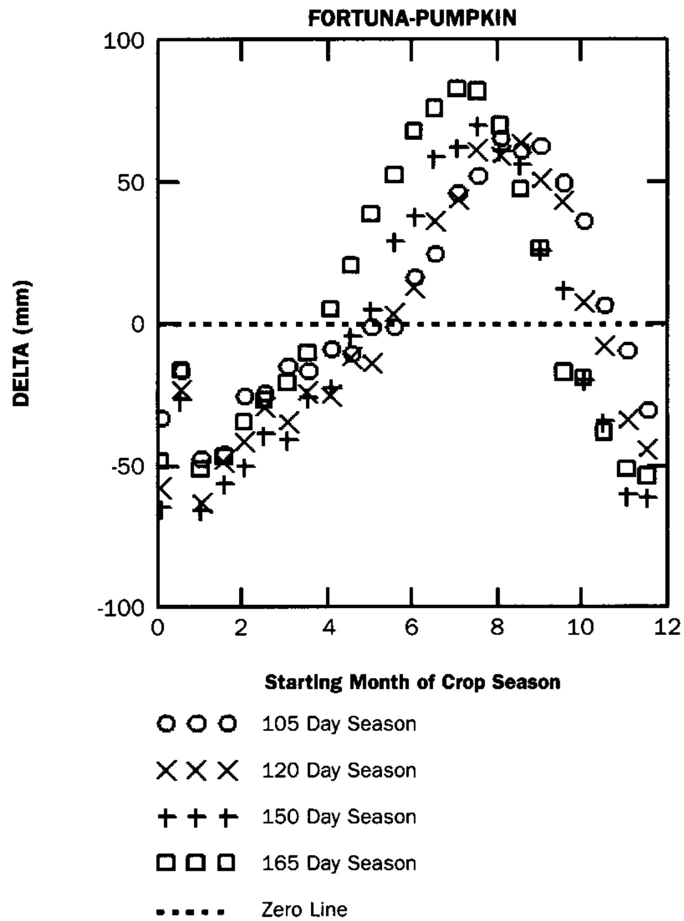
where: ET_o (mm d^{-1}) is the reference evapotranspiration, R_a (mm d^{-1}) is the extra terrestrial radiation, T is the mean daily average temperature (°C), and T_{min} and T_{max} are the mean daily minimum and maximum temperatures (°C), respectively. Daily estimated values of reference evapotranspiration varied between 3.68 to 5.37 mm d^{-1} (0.15 to 0.21 in d^{-1}). The minimum estimated value of reference evapotranspiration occurred in December while the maximum occurred in July. The same procedure was applied for Vieques Island, Puerto Rico, with estimated monthly reference evapotranspiration ranging between 3.29 mm d^{-1} (0.13 in d^{-1}) in December to 4.94 mm d^{-1} (0.19 in d^{-1}) in July (Goyal, 1988b).

Goyal et al. (1988) used the Hargreaves-Samani method (Equation 6) to estimate reference evapotranspiration 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 the extra terrestrial radiation (R_a) were based on the average latitude of Puerto Rico. They also developed 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 evapotranspiration methods in Puerto Rico. In 1990 a committee of the United Nations Food and Agriculture Organization (FAO) (FAO, 1990 and Smith et al., 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 numerous calculation methods with weighing lysimeter data (Jensen et al., 1990 and Choisnel et al., 1992). The study of the American Society of Civil Engineers (Jensen et al., 1990) found the Penman-Monteith method to produce superior results relative to all other methods (including the USDA-SCS Blaney-Criddle and Hargreaves-Samani methods).

Harmsen et al. (2001a) reported large differences between the USDA-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). Average monthly minimum and maximum air temperatures and wind speed for the experiment stations were obtained from the National Oceanic and Atmospheric Administration (NOAA) climatological data sheets. Long-term average monthly humidity and radiation were not available for the experiment stations; therefore these data were estimated by procedures recommended by the FAO (Allen et al., 1998). Crop growth stage durations, needed 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 approximately 100 mm per season (3.94 in d^{-1}). The study concluded that large potential differences can be expected between the USDA-SCS Blaney-Criddle and the

Figure 1
Differences (DELTA) in the seasonal consumptive use (CU) estimates between the USDA-SCS Blaney-Criddle (BC) and Penman-Monteith (PM) methods. (DELTA = BC − PM)



Source: Harmsen et al. 2001a.

Penman-Monteith methods, with underestimations in some months and overestimation in others. Figure 1 shows differences (DELTA) in the seasonal consumptive use (CU) estimates between the USDA-SCS Blaney-Criddle (BC) and Penman-Monteith (PM) methods for pumpkin at Fortuna, Puerto Rico. In this example, the USDA-SCS Blaney-Criddle method over-estimated the seasonal consumptive use by approximately 90 mm (2.54 in) for crop seasons beginning in June through August, and underestimated consumptive use by approximately 60 mm (2.36 in) for crop seasons beginning in December and January.

Harmsen et al. (2002a) compared the Penman-Monteith and Hargreaves-Samani methods for estimating reference evapotranspiration at thirty-four locations in Puerto Rico (Figure 2). The Hargreaves-Samani results were obtained from Goyal et al. (1988). Generally, the two methods were in reasonable agreement (r^2 = 0.86). Mean monthly climate data, needed as input to the Penman-Monteith method, were estimated using procedures derived for Puerto Rico (see Results and Discussion). 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 underpredict with high wind conditions and overpredict with conditions of high relative humidity. Differences in the two methods might also be attributable to the fact that Goyal et al. (1988) used an average single value for latitude when estimating extra terrestrial radiation (R_a).

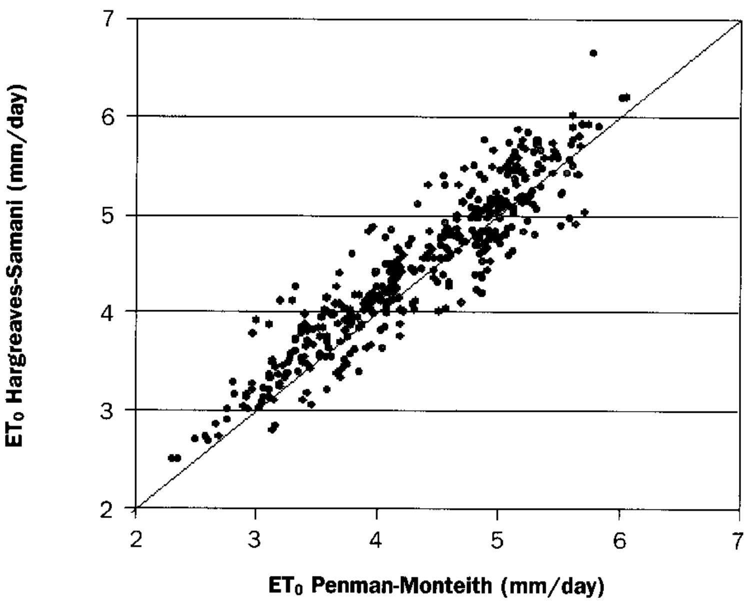
The maximum positive and negative differences were observed at the Juncos 1E and Aguirre stations, respectively. If the Penman-Monteith method is thought to be the best estimator of reference evapotranspiration, then it can be stated that the Hargreaves-Samani method overestimated reference evapotranspiration at Juncos 1E and underestimated it at Aguirre. Juncos 1E is considered to have a humid climate, while Aguirre is considered to be semiarid. The maximum underestimate of -0.75 mm d^{-1} (0.03 in d^{-1}) occurred during May at Aguirre (semiarid) was equal to a -13% error, and the maximum overestimate of 0.92 mm d^{-1} (0.04 in d^{-1}) occurred during December at Juncos 1E (humid) was equal to a 28% error. These results are consistent with the findings of the American Society of Civil Engineers' 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.

The assumption that the Penman-Monteith method is the best estimator of reference evapotranspiration may be inappropriate under nonreference conditions (Allen et al., 1998). Reference conditions imply that the weather data are measured above an extensive grass crop that is actively evapotranspiring, or in a well-watered environment with healthy vegetation.

A summary of studies in Puerto Rico that have measured or predicted consumptive use, and/or have predicted reference evapotranspiration is presented in Table 1. Five studies have been conducted in which consumptive use has been measured. Prior to the year 2000, computational approaches used were limited to only two methods. Consumptive use has been estimated for a relatively large number of crops and reference evapotranspiration has been estimated for a large number of locations within Puerto Rico.

Figure 2

Comparison of reference evapotranspiration estimated by the Penman-Monteith (PM) and Hargreaves-Samani (HS) methods for thirty-four locations in Puerto Rico.



Source: Harmsen et al. 2001a.

Results and Discussion

Estimating climatic parameters for use with the Penman-Monteith equation. Harmsen et al. (2002a) evaluated climate parameter estimation procedures for use with the Penman-Monteith equation in Puerto Rico. With only site latitude, surface elevation, and specification of the site's NOAA Climate Division, they were able to estimate all other needed inputs to the Penman-Monteith method. Mean monthly 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 [328 ft]) or by the Hargreaves' radiation equation (elevations > 100 m [328 ft]) based on air temperature differences.

Comparisons of reference evapotranspiration using the climate parameter estimation procedures and measured climate parameters showed good agreement ($r^2 = 0.93$) for four locations in Puerto Rico. Recently, Harmsen and González (2002) developed a Windows®-based computer program for implementing the climate estimation procedures. The computer program includes a database of information for the fifteen vegetable crops analyzed by Goyal (1989b).

Use of pan evaporation data for estimating consumptive use. 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]; Harmsen et al., 2002b [sweet pepper]). The pan evaporation method estimates crop water requirement from the following equation:

$$CWR = K_c K_p E_{pan} - P \qquad (7)$$

where: CWR is crop water requirement (mm d^{-1}), K_c is the crop coefficient, K_p is the pan coefficient, E_{pan} is pan evaporation (mm) and P is precipitation (mm). The product $K_p E_{pan}$ is an estimate of ET_o.

Most of the studies have recommended applying water to plants at a rate equal to 1 or greater times the pan-estimated consumptive use rate. Because this approach is easy and inexpensive, these studies represent valuable contributions to agricultural production in the tropics. However, problems may result from this approach due 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 overapplication of water, contributing to the degradation of groundwater resources from leaching of agricultural chemicals.

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 7 is usually applied for periods of 2 to 4 days. The shorter-than-recommended periods used in Puerto Rico may be due to the widespread use of microirrigation systems, in which smaller and more frequent applications of water are common.

In Puerto Rico, the pan coefficient 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 USDA-SCS Blaney-Criddle method (USDA-SCS, 1970). Because of inherent errors associated with the USDA-SCS Blaney-Criddle method and observed long-term changes in pan evaporation, the recommended pan coefficient 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 determining pan coefficients (Allen et al., 1998).

Harmsen et al. (2003) evaluated historical pan evaporation data to determine if statistically significant increasing or decreasing trends existed for data from seven University of Puerto Rico experimental stations. 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

Table 1. Summary of studies that measured or predicted consumptive use (ET_c), and/or predicted reference evapotranspiration (ET_o) in Puerto Rico.

Number	Method	Number of Locations	Crop	Source
	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. 2002a

to exist between the mean pan coefficient calculated with pan evaporation data from 1960 to 1980 and 1981 to 2000. An updated table of monthly average pan coefficients was provided that can be used to estimate reference evapotranspiration for the seven agricultural experiment stations.

Peak evapotranspiration. Design of irrigation systems requires knowledge of the peak evapotranspiration (ET_{peak}) rate. The U.S. Department of Agriculture-Natural Resources Conservation Service (USDA-NRCS) has published values of peak evapotranspiration for various crops grown in Puerto Rico in its irrigation guide (USDA-SCS, 1969), which is a widely used source of peak evapotranspiration values in Puerto Rico.

Harmsen et al. (2002a) compared estimated peak evapotranspiration by using three methods for six vegetable crops at three locations in Puerto Rico. The three methods used were the USDA-SCS irrigation guide (USDA-SCS, 1969), the USDA-SCS Blaney-Criddle method (Goyal, 1989b) and the Penman-Monteith method. A comparison of the peak evapotranspiration data is presented in Table 2. It should be noted that the USDA-SCS irrigation guide recommends a single value of peak evapotranspiration for the entire Island for a given crop. Peak evapotranspiration for the USDA-SCS Blaney-Criddle method was obtained by using the maximum monthly consumptive use divided by the number of days in the month. The USDA-SCS Blaney-Criddle estimates of peak evapotranspiration were not available for the Aibonito location. Input data for Penman-Monteith estimates of reference evapotranspiration were determined using procedures described by Harmsen et al. (2002a). Estimates of peak evapotranspiration were based on the maximum daily reference evapotranspiration (ET_o) times the published value of the crop coefficient (K_c) for the mid-season growth stage. The crop coefficients were obtained from Allen et al. (1998).

For the three methods, estimates of peak evapotranspiration ranked from the lowest to highest were: USDA-SCS irrigation guide, the USDA-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 underdesigning systems at this time (assuming the Penman-Monteith method is the most accurate method). Normally, an underdesigned drip irrigation system will be corrected 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.

Summary and Conclusion

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, crop coefficients have not been developed for Puerto Rican conditions. Although crop coefficients derived in

Table 2. Comparison of peak evapotranspiration estimates determined by three different methods for six vegetable crops at three locations in Puerto Rico.

	Peak Evapotranspiration (mm d^{-1})		
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

Source:* *Harmsen et al., 2002a

[1] **From USDA-Soil Conservation Service, 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, Puerto Rico.**

[3] **Input to the Penman-Monteith equation for reference evapotranspiration were determined using the method Harmsen et al. (2002a). Crop coefficients for the mature growth stage were obtained from Allen et al. (1998).**

[4] **NA Not Available.**

other parts of the world can be used to provide approximate estimates of evapotranspiration, they are dependant upon the crop cultivar and other local conditions. Perhaps more importantly, crop coefficients are not available in the literature for many of the local crops grown in Puerto Rico. The Natural Resources Conservation Service in Puerto Rico has given high priority to developing crop coefficients for the following cultivars (Martínez, 2000): Acerola, Tannier, Guanabana, Malanga, Parcha, Star Grass, Recao, Pangola Grass, Ñame, and Buffel Grass.

Water balance and nonweighing lysimeter studies performed during the 1960s and 70s in Puerto Rico did not determine crop coefficients. A study should be performed to re-evaluate these data for this purpose. The crops considered in these studies included sugar cane, guinea grass, para grass, guinea grass-kudzu and 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 of its ease of use. However, the method may result in over or underapplication 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) provides an excellent discussion on the construction of crop coefficient curves. Another potential source of error is the use of published values of the pan coefficient derived from the study of González and Goyal (1989), which estimated evapotranspiration using the UDSA-SCS Blaney-Criddle method, based on pre-1980 climate data. Work has recently begun to update the pan coefficient values for Puerto Rico using the Penman-Monteith reference evapotranspiration (Harmsen et al., 2003).

- Harmsen et al. (2002a) (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. In combination with the GIS consumptive use system, a rainfall and soil database for Puerto Rico could be included which would permit irrigation planning by means of a water balance analysis.

- 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 estimating biophysical processes using remotely sensed data (e.g.: Choudhury and DiGiolamo, 1998; Kite and Droogers, 2000). Numerous remote sensing projects are already being conducted at the University of Puerto Rico and collaborations exist between the Agricultural and Biosystems Engineering Department and the NOAA Cooperative Remote Sensing Science and Technology Center.

- Instead of estimating crop evapotranspiration using a crop coefficient and reference evapotranspiration (Equation 4), crop evapotranspiration can be determined using a "one-step" method as follows:

$$ET_c = f(r_a, r_b) \tag{9}$$

where: $f(r_a,r_b)$ represents the general form of the Penman-Monteith equation, which is a function of the aerodynamic resistance (sec m^{-1}) and the bulk surface resistance (sec m^{-1}). For convenience, the other parameters/variables 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.

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 to review 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.

This paper has presented a review of the majority of crop water use studies performed in Puerto Rico during the last fifty years. Areas reviewed include: 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 crop water requirements, and comparison of peak evapotranspiration estimates. Recommendations for research priorities were also provided.

Acknowledgements

This material is based on research supported by the U.S. Department of Agriculture-Cooperative State Research, Education, and Extension Service (USDA-CSREES) Grant No. CBAG-82 in Tropical/ Subtropical Agriculture Research; the University of Puerto Rico Agricultural Experiment Station Grant SP-368; and the National Oceanic and Atmospheric Administration-Cooperative Remote Sensing Science and Technology Center (NOAA-CREST).

References Cited

Abruña, F., J. Vicente-Chandler, H. Irizarry, and S. Silva. 1979. Evapotranspiration with plantains and the effect of frequency of irrigation on yields. Journal of Agriculture of the University of Puerto Rico 64(2):204-10.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration guidelines for computing crop water requirements. Food and Agriculture Organization irrigation and drainage paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy.

American Society of Agriculture Engineers (ASAE). 2000. Standard practices for the design and installation of microirrigation systems. ASAE EP405.1 DEC99. Pp. 189-232. *In:* ASAE Standards 2000, Standards and Engineering Practices Data, 47th edition. American Society of Agricultural Engineers, St. Joesph, Michigan.

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

Bonell, M., M.M. Hufschmidt, and J. S. Gladwell (eds.). 1993. Hydrology and water management in the humid tropics. Cambridge University Press. 620 pp.

Burman, R.D., P.R. Nixon, J.L. Wright, and W.O. Pruitt. 1981. Water requirements, Pp. 189-232. *In:* Marvin E. Jensen (ed.). Design and operation of farm irrigation systems, Chapter 6. American Society of Agricultural Engineers, St. Joseph, Michigan.

Capiel, M. and R.J. Calvesbert. 1976. On the climate of Puerto Rico and its agricultural water balance. Journal of Agriculture of the University of Puerto Rico LX(2):139-153.

Choisnel, E., O. De Villele, and F. Lacroze. 1992. "Une approache uniformisée du calcul de l' évapotranspiration potentielle pour l'ensemble des pays de la Communauté Européenne. Com. Commun. Européennes, Luxembourg. 176 pp.

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. Food and Agriculture Organization irrigation and drainage paper 24, revised. United Nations, Rome, Italy.

Food and Agriculture Organization, United Nations. 1990. Expert consultation on revision of Food and Agriculture Organization methodologies for crop water requirements. May. Pp. 28-31. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fuhriman, D.K. and R.M. Smith. 1951. Conservation and consumptive use of water with sugar cane under irrigation in the south coastal area of Puerto Rico. Journal of Agriculture of the University of Puerto Rico 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. Tropical Agriculture. (Trinidad) 70(1):3-7.

Goenaga, R. 1994. Growth, nutrient uptake, and yield of tanier (Xanthosoma spp.) grown under semiarid conditions. Journal of Agriculture of the University of Puerto Rico 78(3/4):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 97(2).

Goenaga, R. and H. Irizarry. 1998. Yield of banana grown with supplemental drip irrigation on an Ultisol. Experimental Agriculture 34(4):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. Journal of Agriculture of the University of Puerto Rico 72(2):277-84.

González, E. and M.R. Goyal. 1989. Coeficiente de evapórimetro para Puerto Rico. Journal of Agriculture of the University of Puerto Rico 73(1):00.

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

Goyal, M.R. 1988b. Potential evapotranspiration for Vieques Island, Puerto Rico, with the Hargreaves and Samani model. Research note. Journal of Agriculture of the University of Puerto Rico 72(1): 177-78.

Goyal, M.R. (ed.). 1989a. Irrigation research and extension progress in Puerto Rico. Prepared for the First Congress on "Irrigation in Puerto Rico," March 8th, 1989, Ponce, Puerto Rico. Agricultural Experiment Station, University of Puerto Rico.

Goyal, M.R. 1989b. Estimation of monthly water consumption by selected vegetable crops in the semiarid and humid regions of Puerto Rico. Agriculture Experiment Station Monograph. 99-90, June. Agricultural Experiment Station, University of Puerto Rico, Rio Piedras, Puerto Rico.

Goyal, M.R. 1989c. Reseach note: Monthly consumptive use of papaya at seven regional sites in Puerto Rico. Journal of Agriculture of the University of Puerto Rico 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 pp.

Goyal, M.R. and E.A. González-Fuentes. 1989b. Estimating water consumptive use by sugarcane at four regional sites in Puerto Rico. Journal of Agriculture of the University of Puerto Rico 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. Pp. 385-392. *In:* D.R. Hay (ed.). Planning Now for Irrigation and Drainage in the 21st Century. Proceedings of the Irrigation and Drainage Division Specialty Conference, Lincoln, Nebraska., July 1988. American Society of Civil Engineers.

Goyal M.R. and E.A. González. 1988b. Requisitos de riego para sorgo en las costas sur y norte de Puerto Rico. Journal of Agriculture of the University of Puerto Rico 72(4)585-98.

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

Goyal, M.R. and E.A. González. 1988d. Seasonal consumptive use of water by bell and cuanelle peppers in semiarid and humid coastal sites in Puerto Rico. Journal of Agriculture of the University of Puerto Rico 72(4):609-14.

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

Hargreaves, G.H. and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Journal of Applied Engineering in Agriculture 1(2):96-9.

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, Puerto Rico.

Harmsen, E.W. and S. Torres-Justiniano. 2001a. Estimating island-wide reference evapotranspirations for Puerto Rico using the Penman-Monteith method. American Society of Agricultural Engineers paper 01-2174. 2001 American Society of Agricultural Engineering Annual International Meeting. Sacramento Convention Center, Sacramento, California. 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. Amercian Society of Agricultural Engineers paper 01-2048. 2001 American Society of Agricultural Engineering Annual International Meeting, Sacramento Convention Center, Sacramento, California. July 30-August 1, 2001.

Harmsen, E.W., M.R. Goyal, and S. Torres-Justiniano. 2002a. Estimating evapotranspiration in Puerto Rico. Journal of Agriculture of the University of Puerto Rico 86(1/2):35-54

Harmsen, E.W., J. Colón Trinidad, C. Arcelay, and E. Sarmiento Esparra. 2002b. 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. Volume 38.

Harmsen, E.W. and A. González. 2002. Puerto Rico evapotranspiration estimation computer program PR-ET version 1.0 users manual. University of Puerto Rico Experiment Station-Rio Piedras. Grant SP-347. August 2002. Pp 44. www.uprm.edu/abe/PRAGWATER

Harmsen, E.W., A. González Pérez, and A. Winter. 2003. Estimating long-term average monthly evapotranspiration from pan evaporation data at seven locations in Puerto Rico. Proceedings of the NOAA-CREST/NASA-EPSCoR Joint Symposium for Climate Studies, January 10-11, 2003. University of Puerto Rico-Mayagüez Campus, Mayagüez, Puerto Rico.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and irrigation water requirements. American Society of Agricultural Engineers manuals and reports on engineering practice No. 70. 332 pp.

Jensen, M.E., D.C. N. Robb, and C.E. Franzoy. 1970. Scheduling irrigations using climate-crop-soil data. Proc. American Society of Civil Engineers. Journal of Irrigation and Drain Division 96(IR1):25-38.

Kent, R.B. 2002. West Indies. Microsoft® Encarta® online encyclopedia. 2002.

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 Natural Resources Conservation Service at the Juan Diaz, Puerto Rico Field Office. May, 2000.

Ravalo, E.J. and M.R. Goyal. 1988. Water requirement of rice in Lajas Valley, Puerto Rico. Dimension, Año 2. 8(1).

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

U.S. Central Intelligence Agency. 2002. The World Fact Book 2002. (http://www.cia.gov/cia/publications/factbook/geos/rq.html)

U.S. Department of Agriculture-Soil Conservation Service (USDA-SCS). 1969. Technical guide for Caribbean area. Section IV-practice standards and specifications for irrigation system, sprinkler. Code 443.

(USDA-SCS). 1970. Irrigation water requirements. Technical release no. 21. U.S. Department of Agriculture-Soil Conservation Service, Engineering Division.

Smith, M., R. Allen, J. L. Monteith, A. Perrier, L. Santos Pereira, and A. Segeren. 1990. Report on the expert consultation on revision of Food and Agriculture Organization methodologies for crop water requirements. Held in Food and Agriculture Organization, Rome, Italy, May 28-31, 1990.

Vázquez, R. 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 XLLIX(4):389-412.

Vázquez, R. 1970. Water requirements of sugarcane under irrigation in Lajas Valley, Puerto Rico. Bulletin 224. University of Puerto Rico Agricultural Experiment, Rio Piedras, Puerto Rico.