Research Note

COMPUTER PROGRAM FOR ESTIMATING CROP EVAPOTRANSPIRATION IN PUERTO RICO[1,2]

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Estimates of crop evapotranspiration are useful for planning irrigation systems and scheduling irrigation applications. In Puerto Rico, irrigation is needed to supplement rainfall during certain months of the year. This need is especially great in southwest Puerto Rico, where the climate is considered to be semi-arid and evapotranspiration greatly exceeds rainfall. Estimation of the evapotranspiration is also important for hydrologic and environmental studies. A methodology is needed to provide reasonable estimates of evapotranspiration at locations within Puerto Rico where weather station data are not available.

The Puerto Rico EvapoTranspiration (PR-ET) estimation computer program was developed to estimate crop evapotranspiration in Puerto Rico. With only the site latitude and elevation, and specification of a climate division, the program calculates all the climate data necessary as input to the Penman Monteith reference evapotranspiration method. The Penman-Monteith method has been recommended by the United Nations Food and Agricultural Organization (FAO) as the single best method for estimating reference evapotranspiration (ET_0) throughout the world. A disadvantage of the method, however, is its relatively high data requirement. The FAO recommends using the Penman-Monteith method over all other methods even when local data are missing. Studies have shown that using estimation procedures for missing data with the Penman-Monteith equation will generally provide more accurate estimates of ET_0 than will other available methods requiring less input data (Allen et al., 1998). The FAO's recommendation to estimate missing climate data was the motivation for the present study.

The program operates in two modes: manual climate data input and automatic estimation of the climate input data. In the first case the user enters average monthly data. In this mode the program can be used anywhere in the world. In the second case the program estimates long-term average monthly climate data for locations within Puerto Rico. The program currently includes crop coefficient data for fifteen vegetable crops. Any other crops can be evaluated by manually entering crop coefficients into the program. PR-ET may be potentially valuable to agricultural extension specialists, hydrologists, water managers, climatologists, and to farmers who use irrigation.

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Crop evapotranspiration (ET) is defined as the product of the reference evapotranspiration (ET_o) and a crop coefficient (K_c):

$$ET = K_c ET_o \tag{1}$$

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 0.15-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 developed for ET_o. One such expression, which has been shown to have global validity, is the Penman-Monteith equation (Allen et al., 1998):

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \left(\frac{900}{T + 273}\right) \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{2}$$

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 2 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. PR-ET uses equation 2 to estimate reference evapotranspiration.

The basic parameters needed to use equation 2 are the monthly minimum and maximum air temperature, dew point temperature, wind speed and solar radiation. The procedures used in the PR-ET code are briefly described below. Details of the climate estimation procedures can be found in Harmsen et al. (2002), Harmsen and Torres-Justiniano (2001a and 2001b), and Harmsen et al. (2001). Harmsen et al. (2002) compared the reference evapotranspiration based on measured and estimated climate data at four locations in Puerto Rico, all of which indicated reasonably good agreement. In the same study, long-term average reference evapotranspiration was estimated for thirty-four locations in Puerto Rico.

In the climate data estimation procedure, minimum and maximum air temperatures are estimated from surface elevation data based on the regression equations developed by Goyal et al. (1988). Saturated and actual vapor pressures are estimated from the air temperature and dew point temperature, respectively. Dew point temperature is taken as the daily minimum air temperature plus or minus a temperature correction factor. Temperature correction factors and mean wind velocities, developed for the six Climate Divisions (NWS, 2004), established by the National Oceanic and Atmospheric Administration (NOAA) for Puerto Rico, were obtained from Harmsen et al. (2002). Net radiation was estimated from solar radiation (R_s) by using the method presented by Allen et al. (1998), involving the use of a simple equation for island locations (elevations <100 m) or by the Hargreaves' radiation equation (elevations ≥100 m), based on air temperature differences. The magnitude of the daily soil heat flux (G) is relatively small and therefore is assumed to be zero.

Crop coefficients (K_c) for fifteen vegetable crops are provided within the PR-ET computer program. These crop coefficients were obtained from FAO Paper No. 56 (Allen et al., 1998). In the program, the value of the crop coefficient for the initial crop growth stage ($K_{c,ini}$) is calculated from a set of polynomial equations that account for type of irrigation used, soil type, depth of irrigation applied, and average reference evapotranspiration. The polynomial equations were derived from graphical data contained in Figures 29 and

30 of Allen et al. (1998). If drip irrigation is used, 40 percent of the surface is assumed to be wetted by the drip emitter. With flood and sprinkler irrigation, 100% of the surface is assumed to be wetted. Values of the crop coefficients for the mid season and late season crop growth stages ($K_{c,mid}$ and $K_{c,end}$, respectively) are adjusted for the monthly minimum relative humidity and wind speed by using equations 62 and 65, respectively, of Allen et al. (1998). If a desired crop is not included among the list of fifteen, the user can select a generic crop and then enter the K_c data manually. PR-ET calculates the crop and reference evapotranspiration using equations 1 and 2, respectively. Monthly average values of ET_o are interpolated to obtain the daily values throughout the crop season. The adjusted values of $K_{c,ini}$ and $K_{c,mid}$ are used during the initial and mid season crop growth stages, respectively. The K_c values used between the last day of the initial stage and the first day of the mid stage (i.e., the crop development stage) is a linear interpolation between the $K_{c,ini}$ and $K_{c,mid}$ values. The K_c values used between the last day of the mid season stage and the last day of the crop season (i.e., the late season) is a linear interpolation between the $K_{c,mid}$ and $K_{c,end}$ values. Daily values of K_c and ET_o are multiplied to obtain daily values of ET throughout the crop season.

An example is provided to illustrate the use of the PR-ET computer program. In this example, a hypothetical sweet pepper crop was planted on 1 February 2005 in Ponce, PR. The initial input data screen is shown in Figure 1. On this screen the user first enters the crop to be grown, the name of the city or town, and the site latitude and elevation. In the lower left corner, information on the number of days between irrigations, the total depth of irrigation and the soil type is entered. In this case the irrigation is applied every four days; the total irrigation depth is approximated to be 12 mm (based on the assumption

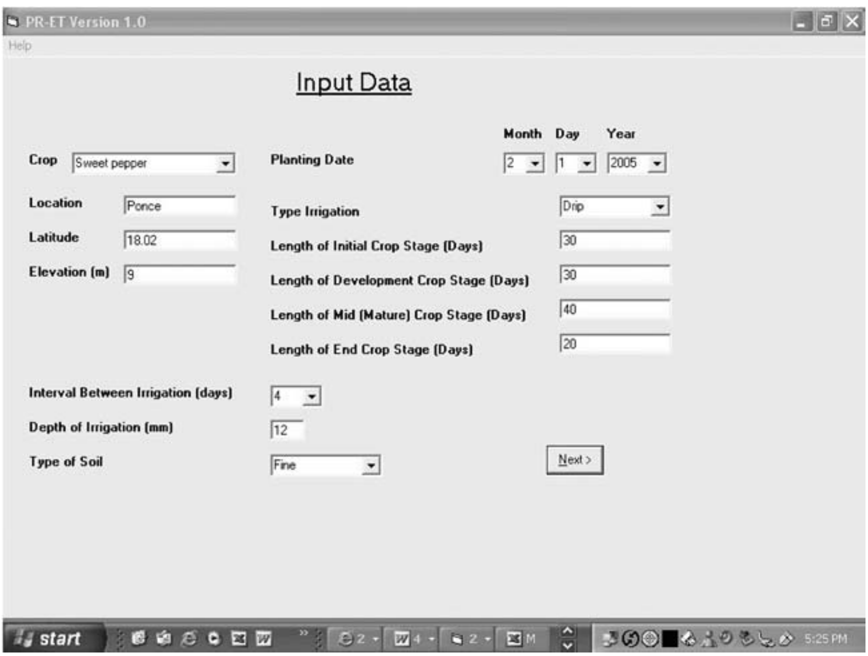

FIGURE 1. PR-ET initial input screen for a hypothetical sweet pepper crop planted 1 February 2005 in Ponce, PR.

of 3 mm of ET per day during the initial crop stage times four days), and soil type is fine. In PR-ET, soil type can be either fine or coarse and refers to the soil's texture. On the right side of the screen the user enters the planting date, the type of irrigation used (drip, sprinkler or flood), and the length in days of the initial, developmental, mid and end crop growth stages. In automatic climate data estimation mode, it is necessary to select the climate division within which the site is located; Ponce, PR, is located within climate division 2 (Figure 2). PR-ET's output includes a list of the input data for the site, the estimated long-term average monthly climate data (minimum, maximum and dew point temperatures, solar radiation and wind speed) and reference evapotranspiration. Figure 3 shows the daily estimated values of crop coefficient, reference evapotranspiration, and crop evapotranspiration in tabular format produced by PR-ET. In the computer program, these data can also be viewed graphically.

PR-ET can be helpful to a grower who wishes to apply water to his or her crop at a rate equal to the long-term average crop water requirement. In the example given above, suppose the grower wishes to irrigate three hectares of sweet peppers on 11 February to replace water lost by evapotranspiration during the four days of 8 February through 11 February. In this example it is assumed that the irrigation will be applied to the field over an eight-hour period. From Figure 3, the estimated ET for 8, 9, 10 and 11 February was 2.24 mm, 2.25 mm, 2.26 mm and 2.28 mm, respectively. Therefore the total crop water requirement is approximately 9 mm of water. The total irrigation volume is 9 mm of water spread over the three-hectare area or 271 m^3 (71,560 gallons) of water. The required

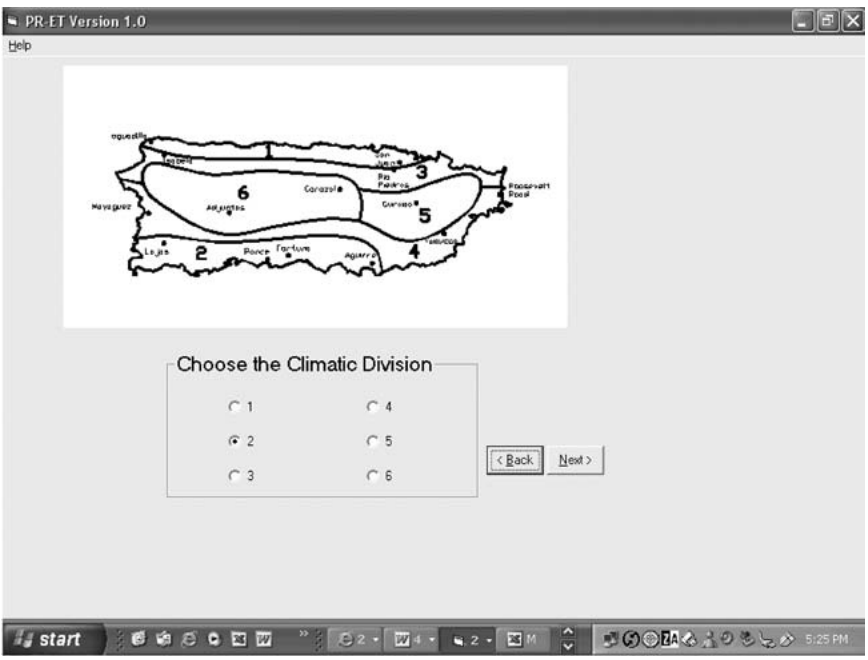

FIGURE 2. PR-ET climate division screen. In the example problem the sweet pepper crop is being grown in Ponce; therefore, climate division 2 is selected. Definitions of climate divisions: 1, North Coastal; 2, South Coastal; 3, Northern Slopes; 4, Southern Slopes; 5, Eastern Interior; and 6, Western Interior.

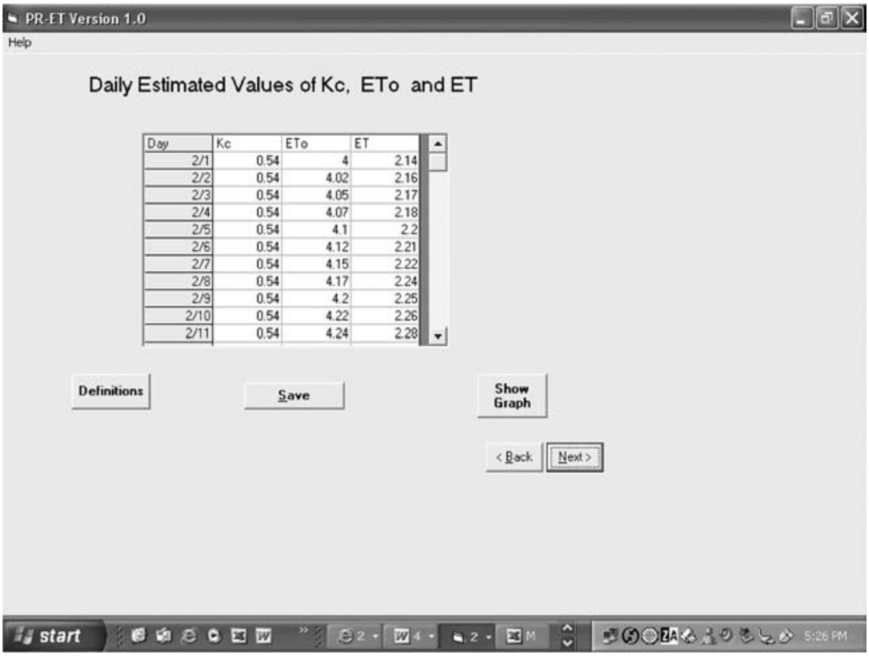

FIGURE 3. Screen output for daily average crop coefficient, reference evapotranspiration and crop evapotranspiration.

flow rate which must be pumped to the sweet pepper area is 271 m^3 divided by eight hours, or 34 m^3/h (149 gallons per minute). It should be noted that in any given year, the actual ET may vary significantly from the long-term average ET calculated by PR-ET. Furthermore, this example problem does not consider the additional water required to account for inefficiencies in the irrigation system.

The climate estimation procedure used in the PR-ET computer code should be considered only approximate for estimating reference evapotranspiration. Some of its potential limitations include:

- The coefficient of determination (r^2) values reported by Goyal et al. (1988) for the regression equations relating elevation and temperature in some cases were low, especially for minimum air temperature. Capiel and Calvesbert (1976) showed, for example, that Utuado at elevation 130 m above mean sea level (amsl), located within an interior valley, had higher average temperatures during every month of the year than did Manatí at elevation 75 m amsl. The average temperature data for Utuado even exceeded average temperatures for Ponce (elevation 12 m amsl) for nine months of the year. Therefore, within interior valleys, measured temperature data should be used if possible, rather than the temperature regression equations.
- Air temperature estimated from surface elevation data should be considered only approximate. Temperatures at the same elevation but at different locations may be different because of micro-climatic effects. For example, air temperatures on the windward and leeward sides of mountains may differ.

Air temperatures on the northern and southern faces of mountains may also differ because of different exposure to solar radiation.

- The approach has not yet been validated by using measured dew point temperature data from climate divisions 3, 5 and 6.
- The Hargreave's radiation equation has not yet been validated for areas within Puerto Rico where elevations exceed 100 m.
- The values used for wind speed in PR-ET are based on averages of historical data within each climate division (Harmsen et al., 2002). Generally, average wind speeds varied between 1 and 3 m/s for all climate divisions in Puerto Rico over all months. Wind speed can vary markedly within a climate division, and therefore is a potential source of error in the estimated reference evapotranspiration. According to Allen et al. (1998), the worldwide average wind speed is 2 m/s and could be used if no wind speed data is available. We believe, however, that using the averages of the measured wind speeds within the six climate divisions of Puerto Rico is preferable to using the worldwide average wind speed of 2 m/s. The user of PR-ET is encouraged to use site-specific wind speed data if available.

PR-ET is a computer program that provides estimates of evapotranspiration at any location within Puerto Rico. Estimation of the reference evapotranspiration depends only on the site latitude and elevation, and specification of a climate division. Because the methodology used for estimating climate parameters depends only on spatially oriented data, the method can potentially be used in a geographic information system (GIS) to estimate reference evapotranspiration distribution throughout Puerto Rico.

Numerous enhancements could be incorporated into the PR-ET computer program, including:

- Rainfall and soil data so that a soil water balance could be performed. This algorithm would allow estimating any one of the components of the water balance (e.g., percolation, soil moisture, or surface runoff). With incorporation of the water balance, irrigation scheduling could be performed by using the "checkbook" method.
- Additional crop coefficient data could be included. FAO Paper No. 56 contains data for approximately ninety crops, all of which could be incorporated into the PR-ET database.
- Currently the program can be downloaded from the Internet (www.uprm.edu/abe/PRAGWATER) and run on a personal computer. The Visual Basic code could be modified so that simulations could be run directly from the Internet.

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