EVALUATION OF REFERENCE EVAPOTRANSPIRATION METHODOLOGIES AND AFSIRS CROP WATER USE SIMULATION MODEL

(Final Report)

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1. INTRODUCTION

1.1. BACKGROUND

The Division of Water Supply Management at the St. Johns River Water Management District determined that there is a need to properly assess the various methodologies used to calculate evapotranspiration (ET) and to evaluate how crop water use is calculated using the Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model. The AFSIRS model was developed for the water management districts by Dr. Allen G. Smajstrala of the University of Florida's IFAS (Smajstrala, 1990). The model estimates irrigation requirements for Florida crops, soils, irrigation systems and climate conditions. The model was last revised in 1990. Over the past decade, two significant advances have affected the viability of the existing AFSIRS model: 1) additional research on crop water requirements has been conducted and 2) computer technology has significantly changed. In particular, there are opportunities to improve the estimates and projections of evapotranspiration for permitting and planning purposes. An evaluation of the model is essential to identify updates necessary to improve the accuracy and utility of AFSIRS.

At the present time, there are significant differences among the Water Management Districts (WMDs) regarding evapotranspiration (ET) estimates for various crops. For example, differences exist between citrus ET estimates at coincident locations made by South Florida Water Management District (SFWMD) versus those estimated by the St. Johns River Water Management District (SJRWMD) and Southwest Florida Water Management District (SWFWMD).

Additionally, the operational use requirements and computer platforms have changed over the past decade. The current AFSIRS model is an MS-DOS based program written in Fortran that can be run in an interactive mode or a batch mode. The interactive mode prompts the user for input while the batch mode processes an ASCII input file created by the user. An evaluation of the user interface, reporting capabilities and program platform is required to identify and prioritize potential improvements. A windows version of AFSIRS is also available (Moraga et al., 1995) but not used by SJRWMD.

1.2. TASKS

The investigation consisted of four tasks:

Reviewing the evapotranspiration literature;
Comparing water requirements for consumptive use permitting;
Reviewing the AFSIRS software; and
Preparing the final report.

1.2.1. Task One: Evapotranspiration Literature Review

A detailed literature review was conducted to identify existing models available to estimate reference crop ET losses in consumptive use permitting and to determine the advantages and disadvantages of the existing models. The models reviewed were compared to identify the approaches that: 1) best represent the physics of water losses from irrigated crops, 2) are easiest to use in terms of parameters needed and input, 3) consistently and accurately capture ET losses in growing regions of Florida, and 4) are acceptable to the general scientific community.

1.2.2. Task Two: Compare Reference Crop Evapotranspiration Losses in Florida Consumptive Use Permitting

The purpose of this task was to identify the differences in evapotranspiration losses in consumptive use permitting across the WMDs. The various irrigation water requirement models currently used by SJRWMD, SFWMD, and SWFWMD were accessed, reviewed and analyzed in detail to determine the basis of discrepancies in ET estimates. A quantitative comparison was conducted by analyzing the results of model runs to predict crop water requirements for each of the three models at the same site.

1.2.3. Task Three: AFSIRS Software Review

An evaluation of the operational use of the AFSIRS software was conducted. The objective of this task was to identify the limitations to the operational use of the AFSIRS software and to develop a list of proposed model modifications. This task included a peer review of the software and meetings with SJRWMD personnel who have an interest in using AFSIRS for consumptive use permitting. This review focused on data entry and reporting limitations as well as user interface and software issues. The evaluation of the user interface status sought to identify opportunities to develop a more user-friendly interface.

1.2.4. Task Four: Preparation of Technical Report

This technical report (meeting SJRWMD publications requirements) containing the results for Tasks one to three will be prepared and submitted to SJRWMD. The final report contains: 1) a detailed literature review of the existing models available to estimate reference crop ET for application in Florida, 2) a comparison of the methods used by SJRWMD, SFWMD, and SWFWMD to estimate reference crop ET, 3) recommendations on the most suitable method of estimating ET, 4) recommendations for future work towards modifying or replacing the existing AFSIRS for consumptive use permitting and planning, and 5) a prioritized list of proposed software modifications and enhancements. In order to assure participation by a group of peers and to assure that the scientific community supports any recommendations contained in this report, Appendix C contains a list of all technically/scientifically involved individuals, their affiliation, and their contact information will be submitted.

2. EVAPOTRANSPIRATION LITERATURE REVIEW

2.1. INTRODUCTION

A detailed literature review was conducted to identify the existing models to estimate reference crop ET. Fourteen models were documented and used to estimate reference crop ET losses in consumptive use permitting. The models were reviewed and compared to identify the approaches that: 1) best represent the physics of water losses from irrigated crops, 2) are easiest to use in terms of parameters needed, 3) consistently and accurately capture ET losses in growing regions of Florida, and 4) are acceptable to the general scientific community.

Reference crop ET is "the rate at which water, if available, would be removed from the soil and plant surface of a specific crop, arbitrarily called a reference crop" (Jensen et al., 1990). The reference crop is typically grass or alfalfa under well-watered conditions. In Florida, the standard reference crop is grass. The height of the grass reference should be at least 8 and no more than 15 cm (Doorenbos and Pruitt, 1977). A 12 cm grass reference is assumed for the most recent grass reference crop standards established by the American Society of Civil Engineers (ASCE) and the Food and Agricultural Organization (FAO). The reference crop ET provides a standard response of a plant to the given atmospheric conditions. The reference crop is often coupled with crop coefficients to determine the potential ET for a specific crop under a range of weather conditions.

ASCE and FAO have independently reviewed and recently established new standard methodologies for calculating reference ET (Allen et al., 1998; Walters et al., 2000). ASCE's primary objective was "to establish a methodology for calculating uniform ET estimates and thereby enhance the transferability of crop coefficients and the comparison of ET demands in various climates." The development of a standard reference crop ET facilitates the creation of crop coefficients that can be transferred from one location to the next. A large number of methods are available to calculate reference ET. However, the equations' ability to replicate the reference crop may perform differently depending on the region, season or atmospheric conditions. This work focuses on the application of reference crop ET methods using Florida climate data. The AFSIRS model combines daily reference ET with crop coefficients to determine the crop water demand on a daily basis. An important consideration in the selection of the reference crop ET method for SJRWMD is the availability of crop coefficients for that model.

2.2. METHODS TO ESTIMATE REFERENCE EVAPOTRANSPIRATION

Three general approaches to estimating reference crop ET were considered: temperature methods, radiation methods and combination methods. The selection of methods was based on performance in previous studies and application within Florida. Table 2.1 lists the methods that were reviewed. The list includes methods that are currently in use by Florida WMDs as well as methods that have significant support from the national and international irrigation community. The following sections document each of the methods.

Table 2.1. Reference evapotranspiration equations evaluated

Abbreviation	Approach	Source and Description
McCloud	Temperature	IFAS golf course and turf publications
Thornthwaite	Temperature	Thornthwaite and Mather (1955)
MBC	Temperature	Modified Blaney-Criddle
SFWMD	Temperature	Modified Blaney-Criddle with SFWMD crop coefficients
MMBC	Radiation	SWFWMD Modified-Modified Blaney-Criddle (Shih, 1981)
Harg	Radiation	1985, Hargreaves (Hargreaves et al., 1985)
Turc	Radiation	1961, (Turc, 1961)
Pen48	Combination	1948 Original Version of Penman (Penman, 1948)
Pen63	Combination	1963 Version of Penman (Penman, 1963)
Pen77	Combination	FAO24 Modified Penman (Doorenbos and Pruitt, 1977)
IFAS Pen	Combination	IFAS Florida Modified Penman (Jones et al, 1984)
ASCE PM-90	Combination	ASCE-Penman Monteith, Jensen et al. (1990) w/Rn56, G56, r_a & r_s = F(ht), λ =F(T)
Pen, FAO	Combination	ASCE-PM w/ ht = 0.12 m, r_s = 70 s/m and albedo = 0.23, R_n 56, G = 0, λ = 2.45 MJ kg^{-1} (Allen et al., 1998)
ASCE00	Combination	ASCE-PM, r_a = f(ht), albedo=0.23, daily ET_o r_s = 70 s/m, hourly ET_o r_s = 50 & 200 s m^{-1}; daily ET_r r_s = 45 s m^{-1}, hourly ET_r r_s = 30s/m & 200 s m^{-1} (Walter et al., 2000)

2.2.1. Temperature Methods

The temperature methods are empirical equations that rely on air temperature as a surrogate for the amount of energy that is available to the reference crop for evapotranspiration. However, there is no direct, unique relationship between temperature and energy. This limits the generality of the following temperature methods. Local calibration of the methods may provide some measure of accuracy, particularly for averaging periods on a monthly or seasonal basis. The Florida climate may require multiple calibrations to account for the differences between coastal and inland climates.

McCloud Equation

The McCloud method was developed to predict potential evapotranspiration from turf and golf courses (McCloud, 1955). The McCloud Equation is still used in IFAS golf course and turf publications. The equation, based on daily temperature values, may be calculated as follows:

$$ET_p = KW^{(T-32)}$$

where: ET_p = Potential evapotranspiration, *in*,

K = 0.01,
W = 1.07, and
T = Mean temperature, ^oF.

Thornthwaite Method

Thornthwaite and Mather's (1955) method of estimating potential evapotranspiration (PET) is solely based on air temperature. PET estimates are based upon a 12-hour day (amount of daylight) and a 30-day month. The Thornthwaite method was developed for the east-central U.S. The method requires a constant ratio of reflected radiation to incident radiation (albedo), no advection of wet or dry air, and a constant ratio of the energy used in evaporation to the energy used to heat the air. The formulae are based on the catchment-area data and controlled experiments.

$$PET = 1.6 \ x \ \frac{(10\,T_a)^a}{I}$$

where: PET = Potential evapotranspiration, *cm/mon*,
x = Adjustment factor related to hours of daylight and latitude,
T_a = Mean monthly air temperature, ^oC,
I = Heat Index where $I = \sum_{i=1}^{12} \left(\frac{T_{ai}}{5} \right)^{1.5}$, and
a = A function of the Heat Index given by
= $0.49 + 0.0179\ I - 0.0000771\ I^2 + 0.000000675\ I^3$.

Soil Conservation Service (SCS) Modified Blaney-Criddle Method

The Blaney-Criddle equation was developed to estimate ET losses in the western United States by the SCS (SCS, 1967). This is the method adopted by SFWMD to estimate evapotranspiration necessary to determine supplemental irrigation. The Blaney-Criddle method is simple, using measured data on temperature only. It should be noted, however, that this method is not very accurate; it provides a rough estimate or "order of magnitude" only. Jensen et al. (1990) found this method and the Thornthwaite to be among the poorest temperature methods. Under "extreme" climatic conditions the Blaney-Criddle method is particularly inaccurate. In windy, dry, sunny areas, the reference ET is underestimated. In calm, humid, clouded areas, the reference ET is overestimated.

According to Blaney-Criddle Method, the mathematical expression for the consumptive use of a crop for the growing season is given by

$$U = k \times f$$

where: U = Monthly consumptive water use of the crop, *inches*,
k = Empirical consumptive-use crop coefficient, and

f = Monthly consumptive-use factor. The consumptive use factor is a product of mean monthly temperature and monthly percentage of daylight hours.

$$f = \frac{t \times p}{100}$$

where: t = Mean monthly air temperature, ^{o}F, and
p = Monthly percentage of annual daylight hours (values are provided in SCS Technical Release No. 21 for different latitudes).

Some modifications were made to the original formula. The modifications were

$$k = k_t \times k_c$$

where: k = Empirical consumptive-use crop coefficient which is related to mean air temperature (t),
k_t = 0.0173t - 0.314 (values of k_t for various mean temperature values are provided in TR- 21), and
k_c = Growth stage component of the crop coefficient (values of k_c are obtained from crop growth stage coefficient curves provided in TR-21).

Note: A later and significantly modified FAO-24 Blaney-Criddle method was presented by Doorenbos and Pruitt (1977). The FAO-24 Blaney-Criddle Method is considered to be a much more accurate temperature based method than the SCS Blaney-Criddle Method (Jensen et al., 1990).

SFWMD Model

The SFWMD Model is based on the Modified Blaney-Criddle Equation (SFWMD, 1997). The original Blaney-Criddle method estimated evapotranspiration by correlating average monthly temperature and percentage of daylight, to a crop's ET. SFWMD's calculation of crop ET is identical to that calculated with the Modified Blaney-Criddle method. The difference between the two methods is the crop coefficients used by the models.

The above formula, which describes the method used to determine a crop's monthly potential ET, does not provide a separate estimate of reference ET. To determine the reference ET, it is necessary to have an adjusted crop growth stage coefficient for the reference grass crop. SFWMD does not have such a coefficient. For the purpose of this analysis, the coefficients for pasture were applied.

2.2.2. Radiation Methods

The ET process is controlled by available energy and the ability of evaporated water to be transferred from the surface. The transfer process is a function of the wind speed and the amount of water vapor in the air closest to the surface. Priestley and Taylor (1972) demonstrated that for a well-water surface that extends over a large surface area, the ET process is well described by net radiation, air temperature and pressure. However, Jensen et al. (1990) found the radiation methods considerably underestimated ET for rates greater than 4 mm/day. Florida ET is typically greater than 4 mm/day from April through August. Radiation methods use a measure of solar radiation coupled with air temperature to predict ET. The solar radiation may be used directly to estimate ET or indirectly to provide a measure of the net available radiation.

AGMOD Blaney-Criddle Model

The SWFWMD Agricultural Water Use Model v2.0 (AGMOD) uses a Blaney-Criddle model to estimate crop ET (Cohen, 1989). The AGMOD Blaney-Criddle model, also referred to as the modified-modified Blaney Criddle method, is based on the Modified Blaney-Criddle method. The modified Blaney-Criddle equation estimated evapotranspiration by correlating average monthly temperature and percentage of daylight to a crop's ET. Shih (1977) showed that the Modified Blaney-Criddle method gave more accurate results in Florida using solar radiation and modified crop coefficients. The SWFWMD method replaces *p*, the monthly percent of daytime hours, with the monthly percent of annual incoming solar radiation. The change from percent daytime hours to percent incoming solar radiation adjusts for Florida's humid climate and summer convective systems. These systems reduce the energy available for evapotranspiration. The SWFWMD crop coefficients are approximately 85% of the original Blaney-Criddle coefficients. The reduced crop coefficients are in keeping with Doorenbos and Pruitts' (1977) recommendations for wind and humidity adjustments. The crop's monthly potential ET is given by

$$U_m = \frac{Kc\left[0.0173 * t_m - 0.314\right] * t_m * R_m}{100}$$

where: U_m = Crop's monthly potential ET, *inches*,
Kc = Adjusted crop growth stage coefficient,
t_m = Mean month temperature, ^oF, and
R_m = Monthly percentage of annual incoming solar radiation.

The above formula, which describes the method used to determine a crop's monthly potential ET, does not provide a separate estimate of reference ET. To determine the reference ET, it is necessary to have an adjusted crop growth stage coefficient for the reference grass crop. AGMOD does not have such a coefficient. For the purpose of this analysis, the estimates were made using the approach for pasture and golf course. AGMOD uses the identical ET values for pasture and golf course regardless of location.

Hargreaves

The Hargreaves method (Hargreaves and Samani, 1985) of computing daily grass reference ET is another empirical approach that has been used in cases where the availability of weather data is limited. The method was developed in Davis, California from a lysimeter study on Alta fescue grass. The original Hargreaves formula calculates reference ET from solar radiation and temperature

$$ET_o = 0.0135 \frac{R_s}{\lambda} (T + 17.8)$$

where: ET_o = Reference evapotranspiration, *mm/day*,
λ = Latent heat of vaporization, *MJ/kg* (2.45 *MJ/kg)*,
R_s = Solar radiation, $MJ/m^2\ d^{-1}$, and
T = Mean air temperature, ^oC.

Often, solar radiation data are not available. Therefore, an alternate approach is available that requires only measurements of maximum and minimum temperature, with extraterrestrial radiation (R_a). R_a is determined from the latitude and the day of the year. The relationship between R_s and R_a is given by

$$R_s = k_{Rs} R_a \left(T_{max} - T_{min}\right)^{0.5}$$

where: k_{rs} = Adjustment coefficient based on mean monthly relative humidity
= 0.16 for interior regions not influenced by a large water body
= 0.19 for coastal locations
T_{max} = Mean monthly maximum temperature, ^oC, and
T_{min} = Mean monthly minimum temperature, ^oC.

With this estimate, the method becomes a temperature-based method. The working Hargreaves equation for an interior region is given by

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

where R_a is the extraterrestrial radiation [mm/day].

Here the conversion of radiation units from MJ/m^2 day to mm/day is accomplished using the relationship

$$\text{Radiation [depth of water]} = \frac{\text{Radiation [energy/surface]}}{\lambda \rho_w}$$

where ρ_w is the density of water. By using λ = 2.45 MJ/kg and ρ_w = 1000 kg/m^3,

$$\text{Radiation [mm/day]} = 0.408 \ \text{Radiation [MJ/m}^2 \text{ day]}.$$

Turc Method

The Turc method (Turc, 1961) was developed in Western Europe for regions where the relative humidity is greater than 50%. The potential ET is expressed as

$$ET_o = 0.013 \frac{T_a}{T_a + 15} (0.0239 R_s + 50)$$

where: ET_o = Mean daily grass reference potential evapotranspiration, *mm/day*,
R_s = daily global solar radiation, $KJ/\,m^2\,d^{-1}$, and
T_a = mean daily air temperature, ^oC.

2.2.3. Combination Methods

The combination methods are based on the original Penman (1948) combination equation that consists of two terms: the *radiation* term and the *aerodynamic* term. The combination methods require more data than the previous methods including net radiation, air temperature, wind speed and relative humidity. The combination type of equations give the best results for a variety of vegetated surfaces and climates; and their application is suitable for those locations where measured data on temperature, wind and sunshine duration or radiation are available. The original Penman equation predicted evaporation losses from an open water surface.

Penman 1948 Method

The classical Penman equation (Penman, 1948) is a combination equation that considers both the energy and aerodynamic aspects of the ET process. However, instead of the resistances (r_a and r_s) found in Penman-Monteith, the Penman equation has an empirical wind function (the original coefficients were used in this study). The original Penman derived equation for the above conditions is

$$\lambda ET_o = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} f(u)(e_s - e_d)$$

where: ET_o = Reference evapotranspiration $mm\ d^{-1}$,
λ = Latent heat of vaporization, (MJ kg^{-1}),
R_n = Net radiation, $MJ\ m^{-2}\ d^{-1}$,
G = Soil heat flux $MJ\ m^{-2}\ d^{-1}$,
$(e_s - e_d)$ = Vapor pressure deficit of the air, *mm Hg*,
e_s = Saturation vapor pressure of the air, *mm Hg*,
e_d = Actual vapor pressure of the air, *mm Hg*,
Δ = Slope of the saturation vapor pressure temperature relationship, $kPa\ ^oC^{-1}$,

γ = Psychrometric constant $kPa\ ^{\circ}C^{-1}$,
f(u) = Wind function, and
u = Wind speed.

The 1948 wind function is given as

$$f(u) = 0.40\,(1 + 0.17\,u_2)$$

where u_2 = wind velocity at height of 2m, *mph.*

The equation for the net radiant energy, R_n, taking into account the incoming short-wave radiation from sun and sky is given by

$$R_n = R_s\,(1 - \alpha - \mu) - \sigma T_\alpha^4 \left(0.56 - 0.092\sqrt{e_d}\right)(1 - 0.09m)$$

where: R_s = Measured short-wave radiation, *mm/day*,
α = Surface albedo,
μ = Fraction of R_s used in photosynthesis (typically negligible as compared with r),
σ = Stephan-Boltzmann constant,
T = Air temperature, *K*, and
m/10 = Fraction of sky covered with cloud.

The measured short-wave radiation can be calculated by using the Angot Value of R_s for a completely transparent atmosphere having radiation R_a and the ratio of the possible hours of sunshine. It is given by

$$R_s = R_a\left(0.18 + 0.55\frac{n}{N}\right)$$

where n/N = Ratio of possible sunshine hours.

The combination of the above equations gives the Penman 1948 working equation as

$$ET_p = \frac{\Delta}{\Delta + \gamma}\left[(1 - \alpha)R_s - \sigma T^4\left(0.56 - 0.092\sqrt{e_d}\right)\left(0.1 + 0.9\frac{n}{N}\right)\right] + \frac{\gamma}{\Delta + \gamma}\left[0.4\,(1 + 0.17u_2)\,(e_a - e_d)\right]$$

Penman 1963 Method

This Penman equation (Penman, 1963) is essentially the same as the Penman 1948. The only difference is the wind function, $0.35(1+0.01u_2)$. Here, the wind is measured in miles per day. Upon substitution of the new wind function, the working Penman 1963 equation is given by

$$ET_p = \frac{\Delta}{\Delta + \gamma}\left[(1-\alpha)R_s - \sigma T^4 \left(0.56 - 0.092\sqrt{e_d}\right)\left(0.1 + 0.9\frac{n}{N}\right)\right] + \frac{\gamma}{\Delta + \gamma}\left[0.35\left(1 + 0.01\,u_2\right)\left(e_a - e_d\right)\right]$$

where: ET_p = Evapotranspiration, *mm/day*,
Δ = Slope of the saturation vapor pressure temperature relationship, *kPa* $^{\circ}C^{-1}$,
γ = Latent heat of vaporization, *kPa* $^{\circ}C^{-1}$,
α = Surface albedo,
R_s = Solar radiation in *mm/day*,
e_a = Saturation vapor pressure at the evaporation surface, *mm Hg*,
e_d = Mean vapor pressure in the atmosphere above, *mm Hg*,
u_2 = Wind velocity at height of 2m, *miles/day*,
σ = Stephan-Boltzmann constant,
T = Air temperature, *K*, and
n/N = Ratio of actual to possible hours of possible sunshine.

Penman FAO-24 Method (1977)

Food and Agricultural Organization (FAO) modified the original Penman equation in 1977. The modifications included a revised wind function, an adjustment factor to account for local conditions and the assumption that the daily average ground heat flux is zero. This method uses mean daily climatic data, with an adjustment for day and night time weather conditions. The modified equation used in this method is:

$$ET_o = c\left[WR_n' + (1-W)\,f(u)\,(e_a - e_d)\right]$$

where: ET_o = Reference evapotranspiration, *mm/day*,
W = Temperature related weighting factor,
R_n' = Net radiation in equivalent evaporation, *mm/day*,
f(u) = Wind related function,
e_a = Saturation vapor pressure(e_a) at mean air temperature, *mbar*,
e_d = Mean actual vapor pressure(e_d) of the air, *mbar*, and
c = Adjustment factor to account for day and night weather conditions.

Humidity is expressed as the difference between the mean saturation water vapor pressure (e_a) and the mean actual vapor pressure (e_d). Air humidity data is reported as relative humidity, as psychrometric readings from either ventilated or non-ventilated wet and dry bulb thermometers, or as dewpoint temperature (^{o}C). The vapor pressure is calculated using appropriate tables and equations depending on the available humidity data or by using the equations provided by Bosen (1960). From Bosen (1960), saturated air vapor pressure as a function of temperature, e(T), and the slope of the saturated vapor pressure-temperature function, Δ, can be computed as follows

$$e(T) = 33.8639 \left[(0.00738\,T + 0.8072)^8 - 0.000019\,(1.8T + 48) + 0.001316 \right]$$

$$\Delta = 33.8639 \left[0.05904\,(0.00738T + 0.8072)^7 - 0.0000342 \right]$$

Depending on the available humidity data, one of three methods may be used to determine e_d .

Case I: Given T_{max}, T_{min}, Rh_{max}, Rh_{min}

The saturation vapor pressure is calculated from the average between the minimum and maximum temperature. The actual vapor pressure is calculated using saturation vapor pressure and the mean relative humidity ($e_d = e_a * Rh_{mean}/100$).

Case II: Given T_{max}, T_{min}, $T_{dewpoint}$

From the FAO-24 tables, the vapor pressure at the dewpoint temperature gives e_d. The saturation vapor pressure is calculated from the average between the minimum and maximum temperature.

Case III: Given T_{max}, T_{min}, $T_{drybulb}$ $T_{wetbulb,}$

FAO-24 tables provide e_d based upon the drybulb temperature and the depression i.e., difference between drybulb and wetbulb temperatures.

Wind Factor

The effect of wind on ET using the modified Penman method is given by

$$f(u) = 0.27 \left(1 + \frac{U}{100} \right)$$

where U = 24 hr wind run at 2 m height, *km/day*.

The values of the wind function are provided in the FAO-24 tables. In addition, a correction has to be applied to the above values when the height of observation of the wind data is not at 2 m height. The correction values are provided in the FAO-24 tables for different heights.

Weighting Factor (W)

W is a weighting factor for the effect of wind and humidity on ET. It is given by the equation

$$W = \frac{\Delta}{\Delta + \gamma}$$

where: Δ = Rate of change of saturation vapor pressure with temperature, and
γ = Psychrometric constant.

Values of (1-W) as related to temperature and altitude are provided in FAO-24 tables.

Net Radiation (R_n)

Net radiation (R_n) is the difference between incoming and outgoing radiation. It can be measured, but such data are seldom available. Instead, it is calculated from solar radiation or sunshine hours, temperature, and humidity data. The FAO Penman approach calculates R_n as follows:

- If measured R_s is not available, then it is calculated using the amount of radiation received at the top of the atmosphere (R_a). This value is selected from an FAO-24 table depending on the month and latitude.

- Solar radiation (R_s) is obtained with the Angstrom formulation. The formulation corrects the R_a value for ratio of actual (n) to maximum possible (N) sunshine hours.

$$R_s = \left(0.25 + 0.50\frac{n}{N}\right) R_a$$

where n and N are expressed in hours as mean daily values for the period considered. N values are available for a given month and latitude from tables.

- Net shortwave radiation (R_{ns}) can be calculated by correcting the solar radiation for surface albedo (α) of the crop surface.

$$R_{ns} = (1 - \alpha) R_s$$

For most crops $\alpha = 0.25$.

- Net longwave radiation (R_{nl}) can be determined from available temperature, vapor pressure and n/N ratio data. These values for different conditions are provided in tables.

$$R_{nl} = f(T)\, f(e_d)\, f\left(\frac{n}{N}\right)$$

$$R_{nl} = \left[\sigma T^4\right] * \left[0.34 - 0.044\sqrt{e_d}\right] * \left[0.1 + 0.9\frac{n}{N}\right]$$

where: σ = Stefan-Boltzmann constant,
T = Temperature, *K*,
e_d = Mean actual water vapor pressure, and

n/N = Ratio of actual and maximum bright sunshine hours.

- The net radiation (R_n) is the algebraic sum of the net shortwave radiation (R_{ns}) and net longwave radiation (R_{nl}). As R_{nl} constitutes a loss, this relationship is

$$R_n = R_{ns} - R_{nl} .$$

Adjustment Factor (c)

The Penman equation assumes that the most common conditions occur when radiation is medium to high, maximum relative humidity is medium to high and moderate daytime wind about double the nighttime wind. These conditions are not always met. The Penman equation has to be corrected in such situations using an adjustment factor. FAO 24 provides tables for the adjustment factor based on different conditions of relative humidity, solar radiation, daytime wind speed (U_d), and nighttime wind speeds (U_n). The adjustment factor as developed by Allen and Pruitt (1989) and obtained from Jensen et al. (1990) is given by

$$c = 0.892 - 0.0781 U_d + 0.00219\, U_d R_s + 0.000402\, R_{Hmax} R_s + 0.000196 \frac{U_d}{U_n} U_d R_{Hmax}$$

$$+ 0.0000198 \frac{U_d}{U_n} U_d R_{Hmax} R_s + 0.00000236\, U_d^2 R_{Hmax} R_s - 0.0000086 \left(\frac{U_d}{U_n}\right)^2 U_d R_{Hmax}$$

$$- 0.0000000292 \left(\frac{U_d}{U_n}\right) U_d^2 R_{Hmax}^2 R_s - 0.0000161\, R_{Hmax} R_s^2$$

Working FAO Penman Equation

After combining the above equations into a single equation, the working Penman equation is given by

$$\frac{ET_p}{c} = \frac{\Delta}{\Delta + \gamma}\left[(1-\alpha) R_s - \sigma T^4 \left(0.34 - 0.044\sqrt{e_d}\right)\left(0.1 + 0.9\frac{n}{N}\right)\right]$$

$$+ \frac{\gamma}{\Delta + \gamma}\left[0.27\left(1 + \frac{U}{100}\right)(e_a - e_d)\right]$$

Note: The Penman 1977 method requires day and night wind speed. For the following analysis, wind data to evaluate the correction factor were not available to make daily corrections. Instead, available data were adequate to estimate that the U_d/U_n value is 1.5 during the convective season and 1.85 during the frontal season.

UF IFAS Penman 1984 Method (Bulletin 205)

The Penman formula for potential evapotranspiration is based on four major climatic factors: net radiation, air temperature, and wind speed and vapor pressure deficit. The potential ET after taking into account the above factors can be expressed as

$$ET_p = \frac{\Delta}{\Delta + \gamma}\frac{R_n}{\lambda} + \frac{\gamma}{\Delta + \gamma}E_a$$

where: ET_p = Daily potential evapotranspiration, *mm/day*,
R_n = Net radiation, $cal.cm^{-2}.day^{-1}$,
E_a = $0.263\,(e_a - e_d)(0.5 + 0.006u_2)$,
e_a = vapor pressure of air = $(e_{max} + e_{min})/2$, *mb*,
e_{max} = maximum vapor pressure of air during a day, *mb*,
e_{min} = minimum vapor pressure of air during a day, *mb*,
e_d = vapor pressure at dewpoint temperature (T_d), *mb*,
u_2 = wind speed at a height of 2 m, *km/day*,
Δ = Slope of saturated vapor pressure curve of air, $mb/^oC$, and
γ = Psychrometric constant = 0.66 $mb/^oC$.

Calculation of Δ

From Bosen (1960), saturated air vapor pressure (in kPa) as a function of temperature (in K), e(T), and the slope of the saturated vapor pressure-temperature function, Δ, can be computed as follows

$$e(T) = 33.8639\left[(0.00738\,T + 0.8072)^8 - 0.000019\,(1.8\,T + 48) + 0.001316\right]$$

$$D = 33.8639\left[0.05904\,(0.00738\,T + 0.8072)^7 - 0.0000342\right]$$

Calculation of R_n

Penman proposed a relationship of the form

$$R_n = (1 - \alpha)\,R_s - R_b$$

where: R_n = Net radiation, $cal.cm^{-2}.day^{-1}$,
R_s = Total incoming solar radiation, $cal.cm^{-2}.day^{-1}$,
R_b = Net outgoing thermal or long wave radiation, and
α = Albedo or reflectivity of surface for R_s.
α = 0.05 for water surfaces
= 0.15 for bare soil surfaces
= 0.23 for green vegetated surfaces.

Calculation of R_b

Penman also uses a relationship for R_b of the form

$$R_b = \sigma T^4 \left(0.56 - 0.08\sqrt{e_d}\right)\left(1.42\frac{R_s}{R_{so}} - 0.42\right)$$

where: σ = Stefan-Boltzmann constant, 11.71 x 10^{-8} $cal.cm^{-2}.day^{-1}.K^{-1}$,
T = Average air temperature, *K*,
R_{so} = Total daily cloudless sky radiation,
R_s = Total incoming solar radiation, (0.35 + 0.61 S) R_{so}, and
S = Percent sunshine hours.

Calculation of u_2

Wind speed is measured at many different heights above the ground surface. The Penman equation requires wind speed at a height of 2m. Wind speed can be adjusted to a height of 2 m by

$$u_2 = u_z \left(\frac{2}{z}\right)^{0.2}$$

where: u_2 = wind speed at height of 2 m, *km/day*,
u_z = wind speed at height z, *km/day*, and
z = height of wind measurement, *m.*

Latent Heat of Vaporization (λ)

The latent heat of vaporization is used to convert evapotranspiration from units of energy to units of length as follows

$$\lambda = 59.59 - 0.055\,T_{avg}$$

where: λ = Latent heat of vaporation, $MJ\ kg^{-1}$, and
T_{avg} = Average temperature, ^oC,
T_{max} = maximum daily temperature, ^oC, and
T_{min} = minimum daily temperature, ^oC.

Working IFAS Penman Equation

After merging all the above equations into a single equation, the working IFAS Penman equation is given by

$$ET_p = \frac{\frac{\Delta}{\Delta + \gamma}\left[(1-\alpha)R_s - \sigma T^4\left(0.56 - 0.08\sqrt{e_d}\right)\left(1.42\frac{R_s}{R_{so}} - 0.42\right)\right]}{\lambda}$$

$$+ \frac{\gamma}{\Delta + \gamma}\left[0.263\left(0.5 + 0.0062\,u_2\right)\left(e_a - e_d\right)\right].$$

ASCE Penman Monteith (grass w/ h=0.12 m)

The original Penman-Monteith method has been modified by many researchers and extended to crop surfaces by introducing resistance factors. The "full" version of the Penman-Monteith (PM) equation is described in ASCE Manual 70 (Jensen et al., 1990). The ASCE 1990 Penman-Monteith (ASCE PM-90) method is valid for neutral atmospheric stability. This equation can be applied to either a grass or alfalfa reference surface, with the aerodynamic (r_a) and surface (r_s) resistances treated as functions of vegetation height. The ASCE PM-90 equation can be used for hourly or daily time steps. ASCE PM-90 reference ET values are often used as the measure against which to evaluate the proposed equations. The ASCE PM-90 form of the combination equation is:

$$c \bullet ET = \frac{\Delta\left(R_n - G\right) + k_1 \frac{0.622\,\lambda\rho}{P}\frac{1}{r_a}\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where: $c \bullet ET_o$ = Reference evapotranspiration, *mm day*$^{-1}$,
R_n = Net radiation, *MJ m*$^{-2}$ *day*$^{-1}$,
G = Soil heat flux, *MJ m*$^{-2}$ *day*$^{-1}$,
(e_s-e_a) = Vapor pressure deficit of the air, *KPa*,
ρ = Mean air density at constant pressure, *Kg m*$^{-3}$,
c_p = Specific heat of air, *MJ kg*$^{-1}$ $^oC^{-1}$,
Δ = Slope of the saturation vapor pressure temperature relationship, *KPa* $^oC^{-1}$,
γ = Psychrometric constant, *KPa* $^oC^{-1}$,
λ = Latent heat of vaporization, 0.0583 KPa $^oC^{-1}$,
r_s, r_a = Bulk surface and aerodynamic resistances, *s m*$^{-1}$, and
c = Conversion factor used for conversion of *MJ m*$^{-2}$ *day*$^{-1}$ *to mm/day*.

When using mean daily wind speed in ms^{-1} $$k_1\frac{0.622\,\lambda\rho}{P} = \left(1710 - 6.85T\right).$$

Aerodynamic Resistance (r_a)

The aerodynamic resistance determines the transfer of heat and water vapor from the evaporating surface into the air above the canopy.

$$r_a = \frac{\ln\left[\frac{z_m - d}{z_{om}}\right] \ln\left[\frac{z_h - d}{z_{oh}}\right]}{k^2 u_z}$$

where: r_a = Aerodynamic resistance, *s m*$^{-1}$,
z_m = Height of wind measurements, *m*,
z_h = Height of humidity measurements, *m*,
d = Zero plane displacement height, *m*,
z_{om} = Roughness length governing momentum transfer, *m*,
z_{oh} = Roughness length governing transfer of heat and vapor, *m*,
k = von Karman's constant, 0.41, and
u_z = Wind speed at height z_m, *ms*$^{-1}$.

For a wide range of crops the zero plane displacement height, d, and the roughness length governing momentum transfer, z_{om}, can be estimated from the crop height, h by the following equations:

$$d = 2/3\ h \qquad z_{om} = 0.123\ h$$

The roughness governing transfer of heat and vapor, z_{oh}, can be approximated by

$$z_{oh} = 0.1\ z_{om}$$

Bulk surface resistance (r_s)

The bulk vapor resistance describes the resistance of vapor flow through the transpiring crop and evaporating soil surface. An acceptable approximation to the complex relation of the surface resistance for dense full cover vegetation is:

$$r_s = \frac{r_l}{LAI_{active}}$$

where: r_s = Bulk surface resistance, *s m*$^{-1}$,
r_l = Bulk stomatal resistance of the well illuminated leaf, *s m*$^{-1}$, and
LAI_{active} = Active leaf area index, *m*^{2} *(leaf area) m*$^{-2}$ *(soil surface).*

Only the upper half of the canopy is considered to actively control the transfer of water vapor and sensible heat. Thus, a general equation for LAI_{active} is given as

$$LAI_{active} = 0.5\ LAI$$

and $$LAI = 0.24(h)$$

where LAI = Total leaf area index, and
h = Crop height, *cm.*

The following example shows the derivation of the surface resistance for a grass reference surface. By assuming a crop height of 0.12 m, the surface resistance for the grass reference surface becomes

$$LAI = 0.24 * 12 = 2.88\ sm^{-1}$$

and $$r_s = \frac{100}{0.5 * 2.88} = 69.44\ sm^{-1}$$

The stomatal resistance, of a single leaf has a value of about 69.44 s m^{-1} under well-watered conditions.

Conversion Factor (c)

The conversion factor is equivalent to the latent heat of vaporization. It is used to convert evapotranspiration from units of energy to units of length. The Harrison (1963) method gives the conversion factor is a function of temperature as follows

$$c = 2.501 - 2.361 \times 10^{-3}\ T$$

where: c = Conversion factor, *MJ kg*$^{-1}$, and
T = Air temperature, ^{o}C.

Working ASCE Penman-Monteith 90 Equation

From the original ASCE PM-90 equation and the equations of aerodynamic and surface resistances discussed above, the ASCE Penman-Monteith 90 method for estimating ET_o is given by

$$c\ ET_o = \frac{\Delta (R_n - G) + \gamma \left(1710 - 6.85\ T\right) \frac{1}{r_a} (e_s - e_a)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} .$$

FAO Penman-Monteith Method

The FAO56-PM method (Allen et al., 1998) is an hourly or daily grass reference ET equation derived from the ASCE PM-90 by assigning certain parameter values based on a specific reference surface. This surface has an assumed height of 0.12 m, a fixed surface resistance r_s of 70 s m^{-1}, and an albedo of 0.23. The zero plane displacement height and roughness lengths are estimated as a function of the assumed crop height, so that r_a becomes a function of only the measured wind speed. The height for the temperature, humidity, and wind measurements is assumed to be 2 m. The latent heat of vaporization (λ) is assigned a constant value of 2.45 MJ kg^{-1}.

The Penman-Monteith form of the combination equation is:

$$\lambda \bullet ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where:
- ET = Reference evapotranspiration, *mm day^{-1}*,
- R_n = Net radiation, *MJ m^{-2} day^{-1}*,
- G = Soil heat flux, *MJ m^{-2} day^{-1}*, (Generally very small and assumed to be zero),
- ρ = Mean air density at constant pressure, *Kg m^{-3}*,
- c_p = Specific heat of air, *MJ kg^{-1} $^oC^{-1}$*,
- e_s = Saturation vapor pressure, *KPa*,
- e_a = Actual vapor pressure, *KPa*,
- e_s-e_a = Saturation vapor pressure deficit, *KPa*,
- Δ = Slope of the saturation vapor pressure temperature relationship, *KPa $^oC^{-1}$*,
- γ = Psychrometric constant, *KPa $^oC^{-1}$*, and
- r_s, r_a = Bulk surface and aerodynamic resistances, *s m^{-1}*.

Aerodynamic Resistance (r_a)

The FAO56-PM aerodynamic resistance equation is identical to the ASCE PM-90 formulation. The FAO56-PM aerodynamic resistance equation for a grass reference surface is calculated for reference conditions. Assuming a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m, the aerodynamic resistance for the grass reference surface is only a function of wind speed at 2 m. The aerodynamic resistance is given as

$$r_a = \frac{\ln\left[\frac{2 - 2/3\,(0.12)}{0.123\,(0.12)}\right] \ln\left[\frac{2 - 2/3\,(0.12)}{(0.1)\,0.123\,(0.12)}\right]}{(0.41)^2\, u_2} = \frac{208}{u_2}$$

Bulk surface resistance (r_s)

The bulk vapor resistance which describes the resistance of vapor flow through the transpiring crop and evaporating soil surface also follows the ASCE PM-90 formulation. Again, an acceptable approximation to a much more complex relation of the surface resistance of dense full cover vegetation is:

$$r_s = \frac{r_l}{LAI_{active}}$$

where: r_s = Bulk surface resistance, *s m*$^{-1}$,
r_l = Bulk stomatal resistance of the well illuminated leaf, *s m*$^{-1}$, and
LAI_{active} = Active leaf area index, *m*^{2} *(leaf area) m*$^{-2}$ *(soil surface).*

A general equation for LAI_{active} is:

$$LAI_{active} = 0.5\ LAI$$

Moreover, for clipped grass a general equation for LAI is:

$$LAI = 24\ h$$

where h = Crop height, *m*.

The derivation of the surface resistance for the 0.12 m grass reference surface is as follows. The stomatal resistance, of a single leaf has a value of about 100 s m^{-1} under well-watered conditions. By assuming a crop height of 0.12 m, the surface resistance for the grass reference surface becomes

$$r_s = \frac{100}{0.5\,(24)\,(0.12)} \approx 70\ sm^{-1}$$

Working FAO 1998 Penman-Monteith Equation

From the original Penman-Monteith equation and the equation of aerodynamic and surface resistances discussed above, the FAO 1998 Penman-Monteith method to estimate ETo is given by

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

where ET_o = Reference evapotranspiration, *mm day*$^{-1}$.

ASCE-Penman Monteith 2000

The ASCE Evapotranspiration in Irrigation and Hydrology Committee (ASCE-ET) recommends, for the intended purpose of establishing uniform evapotranspiration (ET) estimates and transferable crop coefficients, two standardized reference evapotranspiration surfaces: (1) a short crop (similar to grass) and (2) a tall crop (similar to alfalfa), and one standardized reference evapotranspiration equation based on the Penman-Monteith equation (Allen et al, 2000; Itenfisu et al., 2000; Walters et al., 2000, Wright et al., 2000). Two reference surfaces that are similar to known crops were recommended by the committee due to the widespread use of grass and alfalfa across the United States and due to their individual advantages for specific applications and times of the year. As a part of the standardization, the "full" form of the Penman-Monteith equation and associated equations for calculating aerodynamic and bulk surface resistance were combined and reduced to a single equation having two constants. The constants vary as a function of the reference surface and time step (hourly or daily). This summary of the ASCE PM-2000 approach only uses the grass crop reference that is relevant to the Florida irrigation environment.

$$ET_o = \frac{0.408\ \Delta\ (R_n - G) + \gamma \frac{C_n}{T + 273} u_2\ (e_s - e_a)}{\Delta + \gamma\ (1 + C_d\ u_2)}$$

where:
- ET_o = Reference evapotranspiration, *mm day*$^{-1}$,
- R_n = Net radiation at the crop surface, *MJ m*$^{-2}$ *day*$^{-1}$,
- G = Soil heat flux density, *MJ m*$^{-2}$ *day*$^{-1}$, (Generally very small and assumed to be zero),
- T = Mean daily air temperature at 1.5 to 2.5m height, ^oC,
- u_2 = Wind speed at 2m height, *m s*$^{-1}$,
- e_s = Saturation vapor pressure at 1.5 to 2.5-m height, *KPa*,
- e_a = Actual vapor pressure at 1.5 to 2.5-m height, *KPa*,
- e_s-e_a = Saturation vapor pressure deficit, *KPa*,
- Δ = Slope vapor pressure curve, *KPa* $^oC^{-1}$,
- γ = Psychrometric constant, *KPa* $^oC^{-1}$,
- C_n = A numerator constant for reference type and calculation time step, and
- C_d = A denominator constant for reference type and calculation time step.

The constant in the right-hand side of the numerator (C_n) is a function of the time step and aerodynamic resistance (i.e., reference type). The constant in the denominator (C_d) is a function of the time step, bulk surface resistance, and aerodynamic resistance (the latter two terms vary with reference type, time step and daytime/nighttime). The ASCE Penman-Monteith equation gives the form of the standardized reference evapotranspiration equation for all hourly and daily calculation time steps. Table 2.2 provides values for the constants C_n and C_d.

C_n and C_d are based upon simplifying several terms within the ASCE-PM and limited rounding. The simplified terms are summarized in Table 2.2. The standardized terms used in the ASCE PM-2000 equation appear in Table 2.3.

Table 2.2. Values for C_n and C_d

Calculation Time Step	Short Reference, ET_{OS}		Units for ET_{OS}	Units for R_n G
	C_n	C_d		
Daily	900	0.34	mm d^{-1}	MJ m^{-2} d^{-1}
Hourly – daytime	37	0.24	mm h^{-1}	MJ m^{-2} h^{-1}
Hourly – nighttime	37	0.96	mm h^{-1}	MJ m^{-2} h^{-1}

Table 2.3. ASCE Penman-Monteith 2000 terms standardized for the standardized reference evapotranspiration equation

Term	Value
Reference vegetation height, h	0.12 m
Height of air temperature and humidity measurements, z_h	1.5 - 2.5 m
Height of wind measurements, z_w	2.0 m
Zero plane displacement height	0.08 m
Lambda	2.45 MJ kg^{-1}
Surface resistance, r_s, daily	70 s m^{-1}
Surface resistance, r_s, daytime	50 s m^{-1}
Surface resistance, r_s, nighttime	200 s m^{-1}
R_n to predict daytime	> 0
R_n to predict nighttime	≤ 0

The ASCE PM-2000 method standardizes values for short and tall reference crops on a daily and hourly basis. The standardized method used in this project is the short crop reference on a daily basis. For a grass reference on a daily basis, this method is identical to that used in the FAO 1998 Penman-Monteith equation. These methods differ from the ASCE PM-90 in that the latent heat of vaporization is a constant in the FAO PM-98 and the ASCE PM-2000 and a function of temperature for the ASCE PM-90. In addition, the surface resistance, rs, calculation differs between that used for the ASCE PM-90 and the approach used for the FAO PM-98 and the ASCE PM-2000 methods. Thus, the ASCE PM-90 is a more general method, while the FAO PM-98 and the ASCE PM-2000 methods allow reference ET to be transferred between sites with an implicit understanding of canopy and measurement heights.

Note: In all the Penman Methods except the IFAS Penman method, the ratio n/N has been used in the calculation of longwave radiation. However, sufficient data were not available to determine *n*. The relationship between incoming solar radiation and cloudless sky radiation is used to estimate the n/N ratio.

The IFAS Penman method gives a relationship between the *n/N* ratio and R_s/R_{so} ratio as follows

$$R_s = \left(0.35 + 0.61\left(\frac{n}{N}\right)\right) \cdot R_{so}$$

on rearranging,

$$\frac{n}{N} = 1.64\left(\frac{R_s}{R_{so}} - 0.35\right)$$

This equation has been used in the evaluation of ET in all the Penman and Penman-Monteith methods.

2.3. METEOROLOGICAL DATABASE

A concerted effort was made to obtain high-quality agricultural weather data sets from a range of stations in Florida. Data sets were developed by IFAS/Agricultural Engineering Department (Mr. Suat Irmak) from the NOAA network of weather stations. Weather station sites were sought with adequate fetch and with a surface of grass or other short vegetation. Although a few of the sites may approach the ideal for a reference ET station (irrigated, clipped grass, etc.), it should be recognized that most of the sites are non-irrigated and, in some cases, vegetation maintenance may occur relatively infrequently.

Weather data sets were obtained for three different sites within the SJRWMD. Daily data were provided for all of these sites. Six years of data were furnished per station (1985-1990); the data covered the entire calendar year. Attention was paid to the integrity of the weather data. The first site is in Jacksonville, Florida with latitude N 30^o 30', longitude 81^o 42' W and a site elevation of 9 ft. The second site is in Gainesville, Florida with latitude 29^{o}38' N, longitude 82^{o}22' W and a site elevation of 96 ft. The final site is in Daytona Beach, Florida with latitude 29^{o}11' N, longitude 81^o 3' W and a site elevation of 2 ft. Mean annual rainfall from 1985-1990 was 48.2, 51.1, and 43.5 inches in Jacksonville, Gainesville, and Daytona Beach, respectively.

2.4. REFERENCE EVAPOTRANSPIRATION RESULTS

Daily and monthly grass reference ET values were calculated using a series of FORTRAN software programs written by UF to perform reference ET calculations for the equations described in section 2.2. A separate program was developed for each of the equations. The program results were validated by comparison to a series of hand calculations. Weather data from the three stations were used in each model to obtain consistency in the calculations. For each site, the daily reference ET calculations required a run of each individual ET program. Individuals who processed weather data for the study were encouraged and instructed to apply quality assurance and integrity assessment criteria to the weather data sets. All of the output files were further reviewed and validated by a second reviewer at UF.

Monthly values were calculated using two methods. The first method averages the daily climatic data on a monthly basis, then calculates the monthly reference ET. The second method sums daily ET outputs to provide monthly sums. Given the nonlinearity of the reference equations, the second method is the preferred method. However, as the method use both monthly average and daily climate values, the former method is applied. Appendix A lists the monthly values for each site, year and method. Simple statistics were calculated to describe both the daily and monthly outputs for each site, year and ET equation. These summary statistics included the maximum, minimum, mean, and standard deviation. These values are presented in Appendix B.

The only exception to the above calculation method is for the SWFWMD Modified Modified Blaney Criddle reference ET value calculations. As mentioned earlier, the Modified Modified Blaney Criddle method does not provide a separate estimate of reference ET. To determine the reference ET, it is necessary to have an adjusted crop growth stage coefficient for the reference grass crop. AGMOD does not have such a coefficient. A preliminary analysis was conducted for each of the three sites using the AGMOD grass coefficients, the monthly percentage of annual incoming solar radiation from Gainesville, and the average monthly temperature from the six years of climatic data by site. These grass ET results differed significantly from the other reference methods (see Appendix C for the AGMOD grass ET results). More reasonable estimates were made using the AGMOD pasture values. AGMOD uses the identical values for pasture regardless of location. For the purpose of this analysis, these pasture ET values are in the remainder of this section.

The analyses and results presented here can be divided into the following two sections:

1) For each class of methods, comparisons are provided on a monthly basis among the methods from each of the three method classes and two combination methods; the IFAS 1984 Penman method and the ASCE 1990 Penman-Monteith method. The IFAS Penman and the ASCE PM-90 results are included with each class of methods to provide a basis for comparison. The former is included because it is the method used in the existing AFSIRS consumptive use software. The latter is included as the standard for reference ET. The six years of data were used to determine an average monthly value.
2) For each method, comparisons are provided between the daily and monthly reference ET values and the daily and monthly values calculated using the ASCE PM-90 method. The ASCE PM-90 is used for comparison because it is the international standard adopted by FAO and ASCE. The method's accuracy and robustness is well documented by Jensen et al. (1990). Most importantly, the ASCE PM-90 equation has been shown, at most locations, to accurately track ET measurements made under reference conditions. The ASCE PM-90 was also used as a basis of comparison by the ASCE Evapotranspiration in Irrigation and Hydrology Committee in cooperation with the Water Management Committee of the Irrigation Association to define and establish their standardized reference ET equation. Thus, the comparison provides a measure which has been experimentally validated and which the national and international scientific community has sanctioned.

2.4.1. <u>Comparison By Method</u>

The average monthly reference ET values by method and location are given in Tables 2.4 to 2.6. The total annual reference ET estimates range from 45.6 to 59.2 inches in Daytona

Beach, from 43.7 to 56.0 inches in Gainesville, and from 43.2 to 55.1 inches in Jacksonville. Excluding the temperature-based methods, the annual values typically differ from the ASCE PM-90 method by 5% or less.

Temperature Method Results

The average monthly temperature reference ET values for the three climate stations are shown in Figures 2.1 to 2.3. The figures show that the temperature methods consistently underestimate ET during the winter months and overestimate ET during the summer months. The Thornthwaite method appears to provide comparatively reasonable values during the summer for Daytona Beach, but dramatically underestimates ET during the remainder of the year. Overall, the McCloud method performs the worst. The SFWMD's Blaney-Criddle method is nearly identical to the modified Blaney-Criddle method except in January and February. The SFWMD adjustment does not appear to improve ET estimates during these months.

Radiation Method Results

The average monthly radiation reference ET values for the three climate stations are shown in Figures 2.4 to 2.6. The figures show that the radiation methods provide a much more consistent estimate of ET than the temperature methods. However, ET is still underestimated during the winter months as compared to the ASCE PM-90 method. Note that the Hargreaves method is applied here as a temperature method. While the Hargreaves method underestimates ET during much of the year, it is quite good during the summer months. This method's overall performance far exceeds the other temperature methods. The Turc method underestimates the ASCE PM-90 method ET during the summer, but captures the summer patterns quite well. The SWFWMD's modified-modified Blaney-Criddle has reasonable agreement, except during June. The June value deviates from the ASCE PM-90 method's value by up to 1.0 mm/day. A comparison of the three figures reveals that the relationship among methods differs by location.

Combination Method Results

The average monthly radiation reference ET values for the three climate stations are shown in Figures 2.7 to 2.9. The combination methods are fairly consistent throughout the year.

The FAO Penman-Monteith is nearly identical to the ASCE PM-90 for all locations. The predicted reference ET values for the Jacksonville and Daytona Beach locations can be divided into two groupings that differ in their seasonal patterns of reference ET. The first group includes results from the ASCE PM-90, the FAO Penman-Monteith and the Penman 1977 methods. The second group includes the remaining Penman methods, Penman 1948, Penman 1963 and IFAS

Table 2.4. Average reference ET from 1985-1990 by method for Daytona Beach (mm/day)

Month	Reference ET Method (mm/day)												
	McCloud	Thornthwaite	Bla-Criddle	SFWMD	AGMOD	Hargreaves	Turc	Pen48	Pen63	Pen77	IFAS Pen	PenFAO	ASCE90
January	1.53	0.94	1.43	1.22	2.02	2.05	2.10	1.84	1.73	2.55	2.19	2.63	2.68
February	1.89	1.19	1.85	1.56	2.51	2.59	2.61	2.16	2.05	2.79	2.47	3.04	3.11
March	2.36	1.84	2.79	2.71	3.35	3.61	3.52	3.53	3.42	3.59	3.62	3.76	3.85
April	2.91	2.42	3.73	3.67	4.21	4.76	4.51	4.42	4.31	4.49	4.52	4.78	4.90
May	4.59	4.05	5.36	5.31	5.21	5.56	5.11	5.57	5.47	4.99	5.49	5.28	5.40
June	6.50	5.32	6.29	6.31	4.25	5.47	4.94	5.63	5.52	4.89	5.48	5.21	5.31
July	7.08	5.82	6.65	6.66	4.81	5.60	5.02	5.87	5.76	5.03	5.69	5.28	5.38
August	7.16	5.57	6.31	6.31	4.79	5.07	4.59	5.34	5.22	4.63	5.16	4.81	4.89
September	6.38	4.62	5.18	5.20	3.85	4.37	4.04	4.67	4.57	3.99	4.52	4.13	4.20
October	4.26	3.15	3.71	3.76	3.42	3.39	3.28	3.87	3.78	3.44	3.89	3.50	3.55
November	3.01	2.06	2.48	2.43	2.50	2.51	2.56	2.95	2.84	2.97	3.04	2.84	2.88
December	1.77	1.11	1.43	1.47	1.92	1.93	2.01	2.32	2.20	2.65	2.49	2.48	2.52
Annual Total (m)	1.50	1.16	1.44	1.42	1.30	1.43	1.35	1.47	1.43	1.40	1.48	1.45	1.48
Annual Total (in)	59.20	45.61	56.53	55.82	51.41	56.18	53.04	57.85	56.13	55.10	58.15	57.17	58.26
% of ASCE PM-90	1.07	0.78	0.97	0.96	0.93	0.96	0.91	0.99	0.96	0.95	1.00	0.98	1.00

Table 2.5. Average reference ET from 1985-1990 by method for Gainesville (mm/day)

Month	Reference ET Method (mm/day)												
	McCloud	Thornthwaite	Bla-Criddle	SFWMD	AGMOD	Hargreaves	Turc	Pen48	Pen63	Pen77	IFAS Pen	PenFAO	ASCE90
January	1.27	0.79	1.28	1.09	2.02	1.73	1.79	1.70	1.51	2.43	1.81	2.24	2.34
February	1.63	1.06	1.70	1.43	2.51	2.30	2.34	2.01	1.83	2.86	2.20	2.88	3.00
March	2.20	1.79	2.69	2.61	3.35	3.31	3.25	3.30	3.10	3.76	3.27	3.65	3.78
April	2.75	2.35	3.62	3.56	4.21	4.38	4.18	4.07	3.85	4.60	4.03	4.62	4.78
May	4.57	4.07	5.34	5.29	5.21	5.02	4.65	5.08	4.87	5.09	4.86	5.01	5.16
June	6.54	5.31	6.29	6.30	4.25	5.05	4.59	5.22	5.02	4.95	4.94	4.89	5.02
July	7.06	5.75	6.62	6.64	4.81	5.02	4.55	5.31	5.11	4.89	4.93	4.70	4.82
August	6.99	5.42	6.24	6.24	4.79	4.44	4.07	4.76	4.56	4.39	4.39	4.14	4.25
September	6.02	4.42	5.05	5.07	3.85	3.86	3.63	4.25	4.06	4.02	3.97	3.73	3.82
October	3.62	2.76	3.42	3.47	3.42	3.07	3.03	3.61	3.40	3.63	3.38	3.12	3.22
November	2.68	1.89	2.32	2.28	2.50	2.47	2.52	2.77	2.57	3.00	2.60	2.41	2.50
December	1.40	0.88	1.24	1.27	1.92	1.60	1.69	2.09	1.90	2.36	1.93	1.85	1.93
Annual Total (m)	1.42	1.11	1.39	1.38	1.30	1.29	1.23	1.34	1.27	1.40	1.29	1.32	1.36
Annual Total (in)	55.96	43.70	54.86	54.19	51.30	50.59	48.25	52.89	50.03	55.06	50.67	51.78	53.42
% of ASCE PM-90	1.05	0.82	1.03	1.01	0.96	0.95	0.90	0.99	0.94	1.03	0.95	0.97	1.00

Table 2.6. Average reference ET from 1985-1990 by method for Jacksonville (mm/day)

Month	Reference ET Method (mm/day)												
	McCloud	Thornthwaite	Bla-Criddle	SFWMD	AGMOD	Hargreaves	Turc	Pen48	Pen63	Pen77	IFAS Pen	PenFAO	ASCE90
January	1.13	0.67	1.15	0.99	2.02	1.76	1.78	1.58	1.44	2.34	1.81	2.27	2.34
February	1.43	0.93	1.56	1.31	2.51	2.26	2.28	1.87	1.73	2.63	2.10	2.75	2.83
March	1.99	1.65	2.54	2.46	3.35	3.24	3.19	3.23	3.09	3.54	3.27	3.57	3.67
April	2.61	2.30	3.53	3.48	4.21	4.39	4.20	4.07	3.90	4.44	4.06	4.55	4.67
May	4.22	3.86	5.17	5.12	5.21	5.09	4.73	5.16	4.99	4.97	4.99	5.05	5.17
June	6.59	5.36	6.35	6.37	4.25	5.25	4.76	5.43	5.28	4.98	5.26	5.15	5.26
July	7.55	6.04	6.85	6.86	4.81	5.36	4.81	5.65	5.51	5.03	5.43	5.14	5.24
August	7.45	5.67	6.42	6.42	4.79	4.84	4.39	5.14	4.99	4.59	4.91	4.63	4.72
September	6.00	4.41	5.06	5.07	3.85	4.05	3.79	4.42	4.29	4.00	4.25	3.96	4.04
October	3.42	2.66	3.32	3.36	3.42	3.05	3.01	3.61	3.48	3.49	3.56	3.28	3.36
November	2.41	1.73	2.19	2.15	2.50	2.21	2.29	2.74	2.59	2.92	2.74	2.58	2.64
December	1.24	0.77	1.14	1.17	1.92	1.62	1.69	2.14	1.99	2.46	2.15	2.09	2.15
Annual Total (m)	1.40	1.10	1.38	1.36	1.30	1.31	1.24	1.37	1.32	1.38	1.35	1.37	1.40
Annual Total (in)	55.13	43.17	54.22	53.60	51.30	51.64	49.00	53.94	51.83	54.35	53.32	53.91	55.19
% of ASCE PM-90	1.00	0.78	0.98	0.97	0.93	0.94	0.89	0.98	0.94	0.98	0.97	0.98	1.00

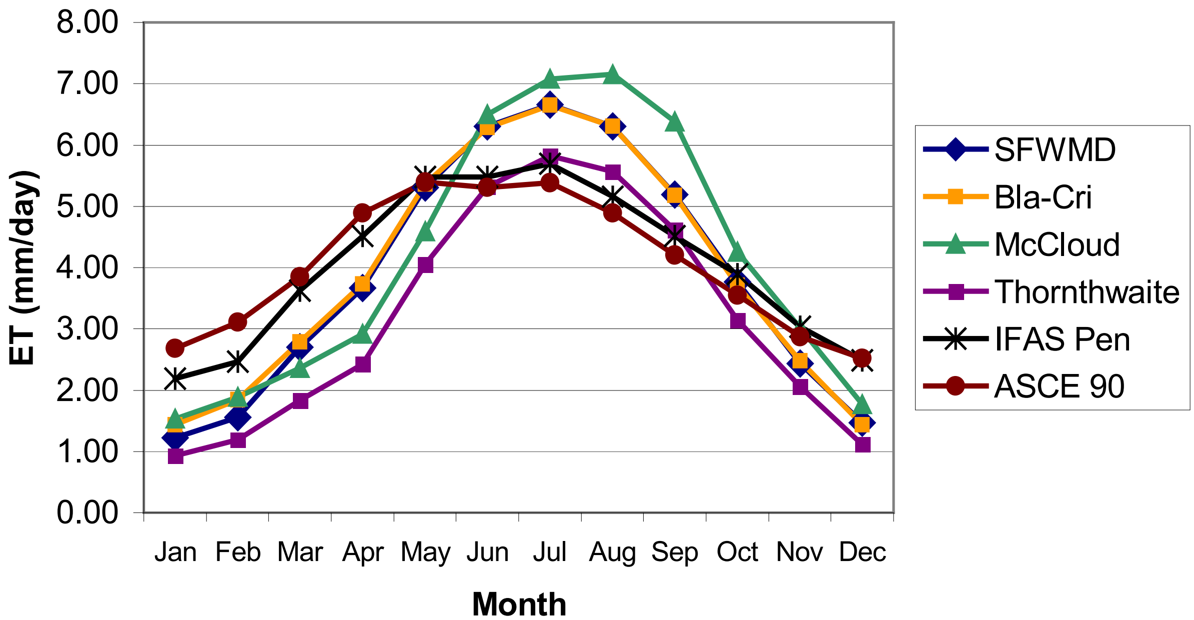

Figure 2.1. Monthly average of the temperature reference evapotranspiration methods for Daytona Beach

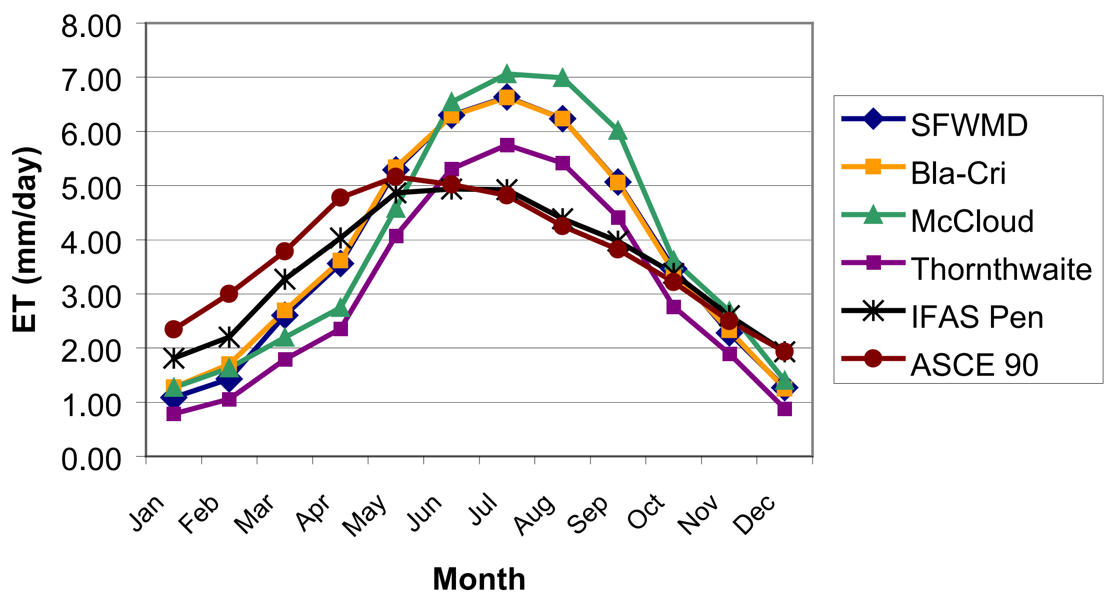

Figure 2.2. Monthly average of the temperature reference evapotranspiration methods for Gainesville

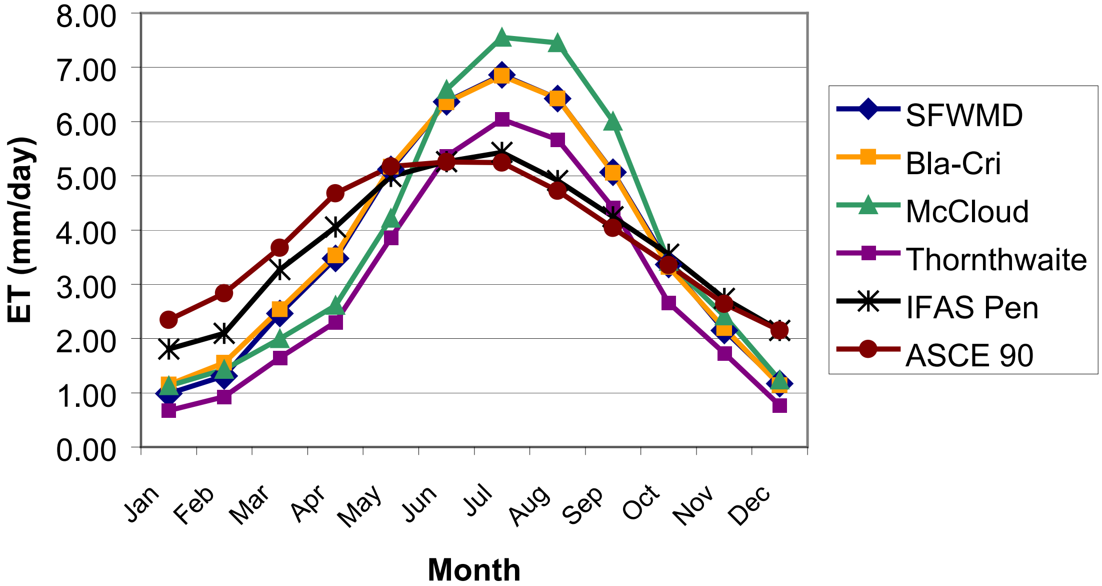

Figure 2.3. Monthly average of the temperature reference evapotranspiration methods for Jacksonville

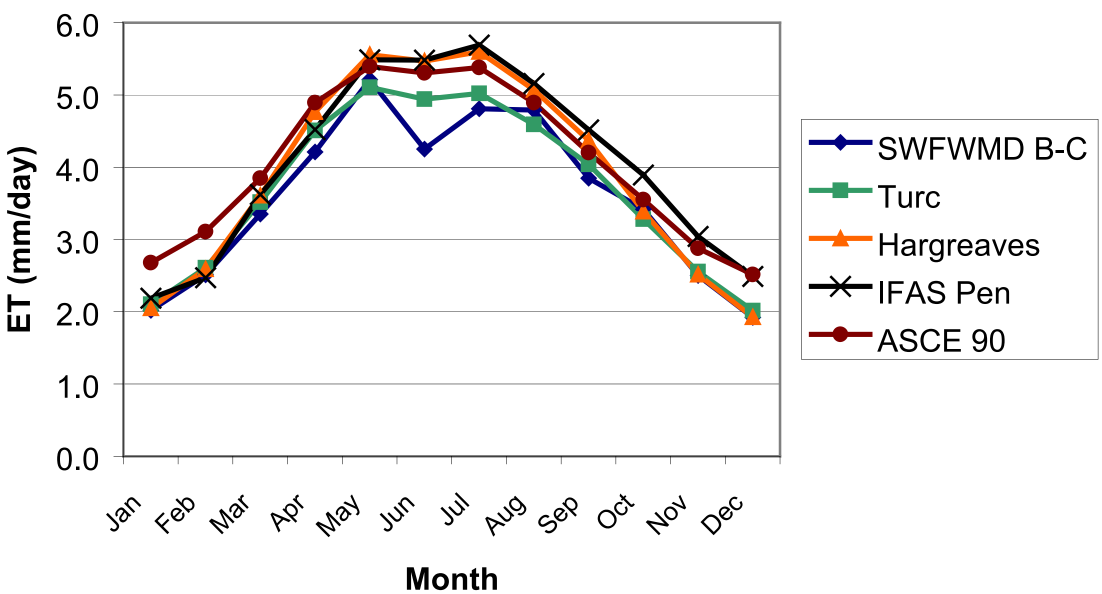

Figure 2.4. Monthly average of the radiation reference evapotranspiration methods for Daytona Beach

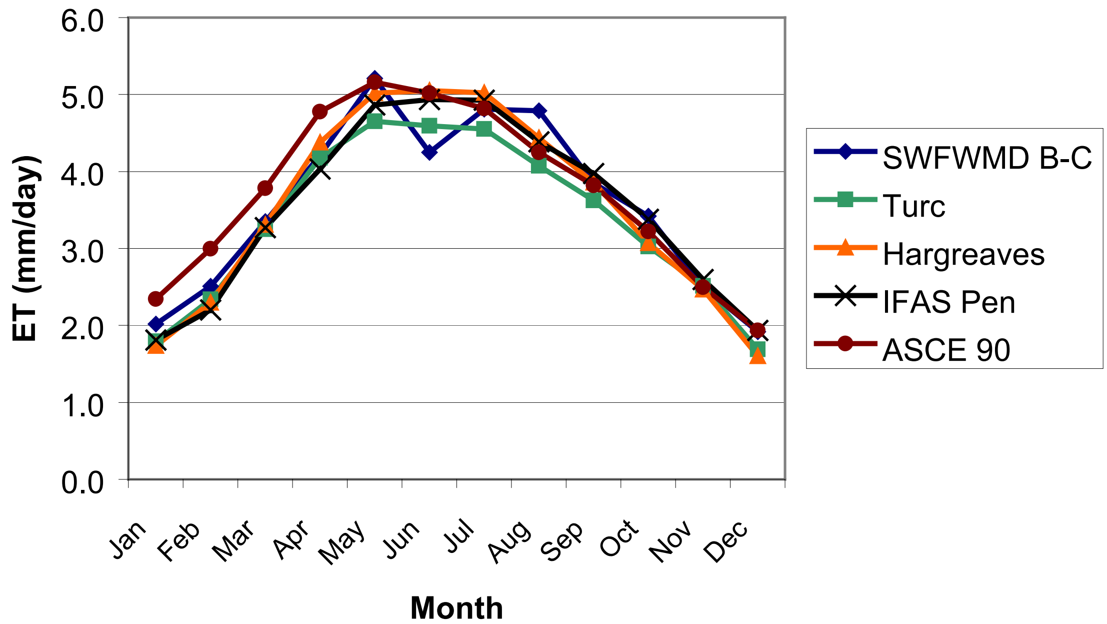

Figure 2.5. Monthly average of the radiation reference evapotranspiration methods for Gainesville

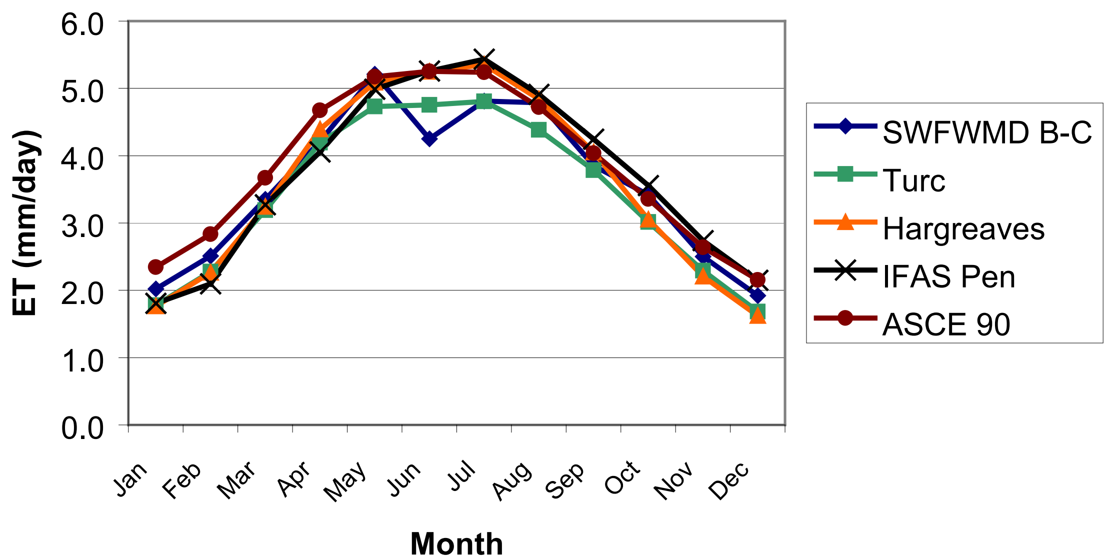

Figure 2.6. Monthly average of the radiation reference evapotranspiration methods for Jacksonville

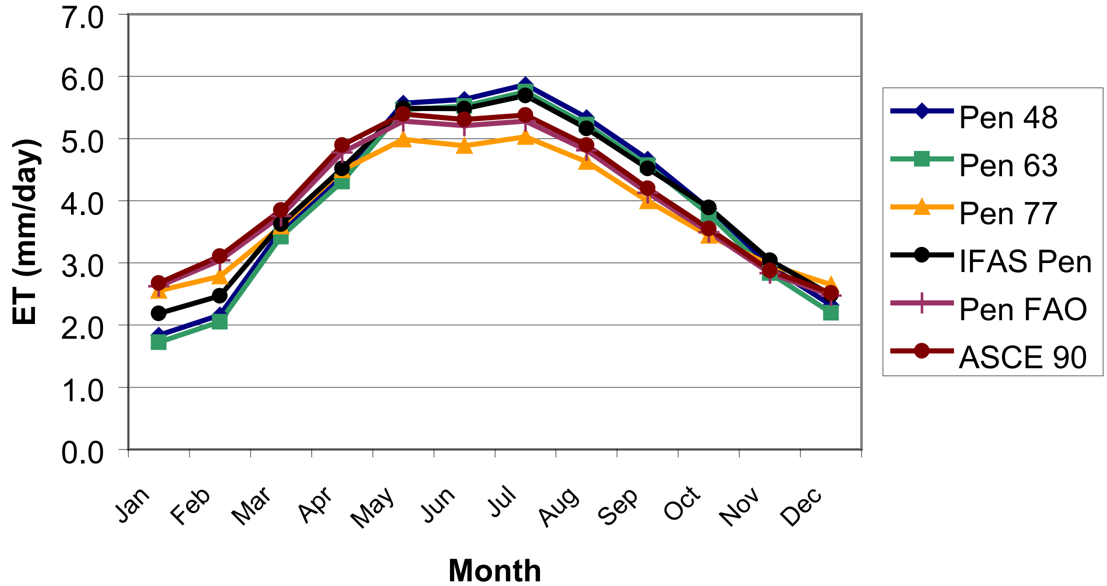

Figure 2.7. Monthly average of the combination reference evapotranspiration methods for Daytona Beach

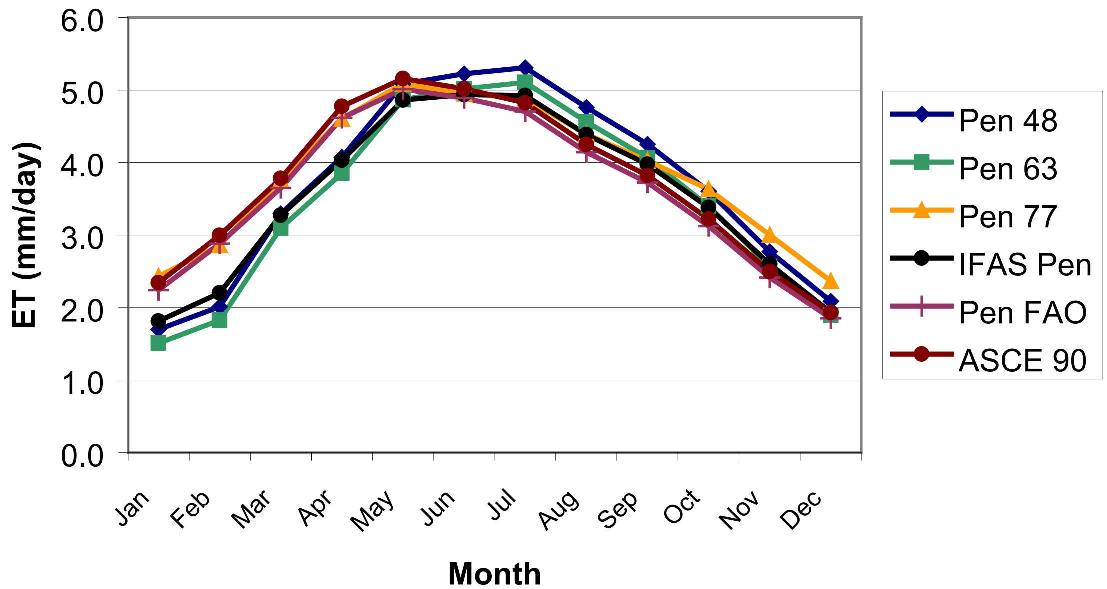

Figure 2.8. Monthly average of the combination reference evapotranspiration methods for Gainesville

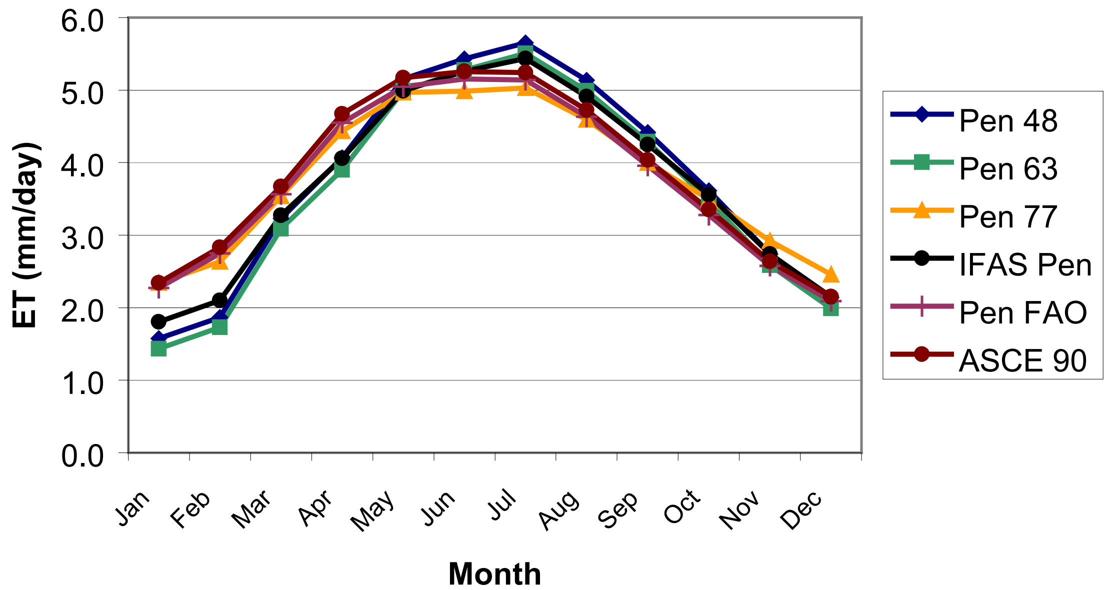

Figure 2.9. Monthly average of the combination reference evapotranspiration methods for Jacksonville

Penman 1984. The second group underestimates ET during the winter months and overestimates it during the summer months. The first group's reference ET rate is fairly constant in May, June and July. The second group's reference ET rate peaks in July. A similar pattern is seen for Gainesville. However, the IFAS Penman method agrees better with the ASCE PM-90 for the Gainesville climate.

Florida evapotranspiration rates peak in May and either decline or level off in June and July. This pattern appears for pan evaporation rates observed for Gainesville from 1995 to 1998 (Figure 2.10). The 1998 data were from an anomalously hot and dry summer.

2.4.2. Reference ET Methods Compared to ASCE 1990 Penman-Monteith

This section examines the relative difference between the reference ET methods and the nationally and internationally recognized standard, the ASCE PM-90 method. Of particular interest is the relationship between the IFAS Penman and the ASCE PM-90 results. Four comparisons were used. Both the daily and monthly differences between each method and the ASCE PM-90 method were calculated. A positive difference indicates that the method overestimates the ASCE PM-90 method. The daily and monthly ratios of each method to the ASCE PM-90 method were also calculated. The ratio indicates the percent of the ASCE PM-90 method that is predicted by the reference ET method. The analysis of differences indicates the magnitude of error while the ratio indicates its relative importance.

Tables 2.7 and 2.8 list the summary statistics for each method calculated on a monthly basis and a daily basis, respectively. The maximum, minimum, mean and standard deviation are

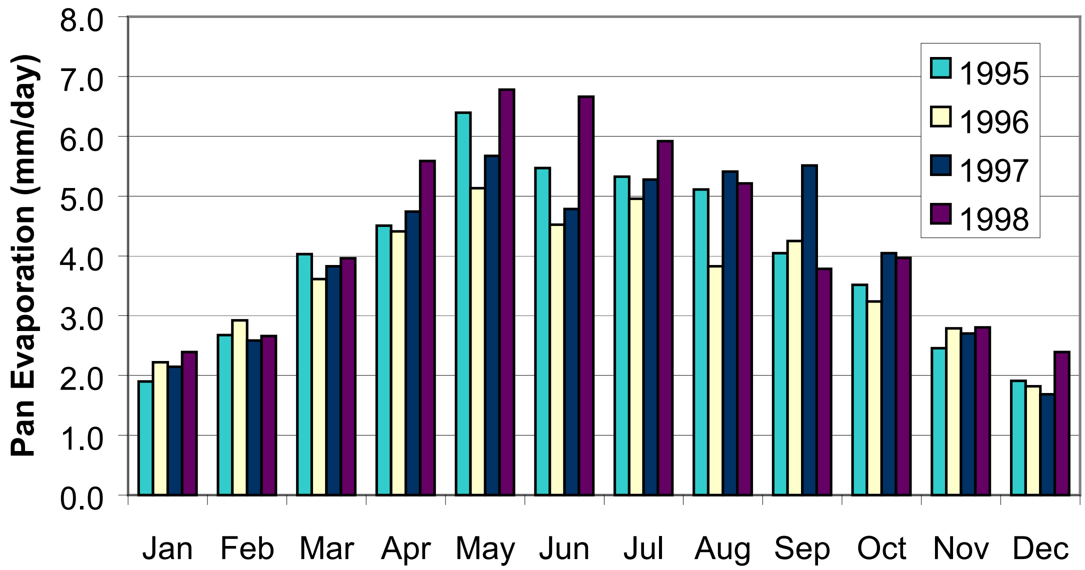

Figure 2.10. Monthly average of daily pan evaporation in Gainesville from 1995-1998

used to provide a summary of the range of differences, the annual difference and the extent to which the methods replicate the ASCE PM-90 method. The best methods should be accurate (low standard deviation) and unbiased (identical mean values). Table 2.7 shows that while the temperature based methods are not accurate, they can be nearly unbiased on an annual basis. The methods that exhibit the least bias and best accuracy for all locations are the Penman 48, the Penman 77, the IFAS Penman and FAO-PM methods are nearly unbiased. Of these methods, the FAO-PM method has by far the best accuracy. Interestingly, the Turc method has the second best accuracy, but is a biased estimator. This suggests that an adjusted Turc method may be able to replicate the ASCE PM-90 method.

The Blaney-Criddle based methods and the Hargreaves method were applied using monthly average climate data. They are excluded from the analysis of daily values calculated using the daily climate data. Table 2.8 summarizes the results for the remaining methods. The daily mean and standard deviation results are also shown in Figures 2.11 and 2.12. Most of the combination approaches are in very good agreement with ASCE PM-90 when comparing the average differences. Based on both the mean and standard deviation, the FAO-PM gives the best agreement. Interestingly, the Turc method is considerably less accurate when applied on a daily basis rather than a monthly basis. The Penman 1963 and 1977 results consistently differ from the ASCE PM-90 results. The Penman 1963 is biased by 7% or more at each site.

Table 2.7. Statistical summary of the comparisons between various reference ET methods using results from 6 years of monthly data. Climate data is averaged to determine monthly value then used to calculate reference ET

Location		Reference ET Methods											
		McCloud	Thornthwaite	Blaney-Criddle	SFWMD	AGMOD	Hargreaves	Turc	Pen48	Pen63	Pen77	IFASPen	PenFAO
Difference between Reference Method and ASCE PM-90 (mm/day)													
Daytona Beach	Max	2.77	1.27	2.05	2.05	0.60	0.44	0.02	0.57	0.50	0.25	0.43	-0.03
	Min	-2.65	-3.11	-1.84	-2.01	-1.31	-0.92	-0.93	-1.19	-1.31	-0.56	-0.83	-0.13
	Mean	0.06	-0.88	-0.12	-0.17	-0.48	-0.15	-0.37	-0.04	-0.15	-0.22	-0.01	-0.08
	St. Dev.	1.51	1.10	1.06	1.12	0.36	0.34	0.17	0.51	0.51	0.19	0.34	0.03
Gainesville	Max	3.36	1.34	2.09	2.09	0.69	0.77	0.66	0.61	0.41	0.80	0.23	-0.06
	Min	-2.73	-3.23	-1.92	-2.17	-1.29	-1.24	-1.29	-1.37	-1.54	-0.35	-1.13	-0.18
	Mean	0.18	-0.68	0.10	0.05	-0.15	-0.20	-0.36	-0.04	-0.24	0.11	-0.19	-0.11
	St. Dev.	1.68	1.23	1.22	1.27	0.44	0.41	0.32	0.53	0.53	0.24	0.36	0.03
Jacksonville	Max	3.16	1.23	2.09	2.09	0.73	0.31	-0.08	0.56	0.42	0.44	0.28	-0.05
	Min	-2.75	-3.09	-1.80	-1.86	-1.34	-0.84	-0.91	-1.14	-1.30	-0.38	-0.88	-0.14
	Mean	0.00	-0.84	-0.07	-0.11	-0.27	-0.25	-0.43	-0.09	-0.24	-0.06	-0.13	-0.09
	St. Dev.	1.67	1.16	1.15	1.20	0.38	0.28	0.16	0.48	0.49	0.20	0.35	0.02
Ratio of Reference Method to ASCE PM-90													
Daytona Beach	Max	1.70	1.30	1.49	1.49	1.14	1.09	1.06	1.14	1.13	1.10	1.11	0.99
	Min	0.36	0.19	0.39	0.33	0.66	0.68	0.75	0.60	0.56	0.84	0.74	0.97
	Mean	0.98	0.74	0.92	0.91	0.87	0.94	0.95	0.97	0.94	0.95	0.99	0.98
	St. Dev	0.37	0.30	0.28	0.30	0.09	0.11	0.06	0.15	0.15	0.05	0.10	0.00
Gainesville	Max	1.74	1.31	1.51	1.51	1.17	1.27	1.27	1.20	1.13	1.28	1.10	0.98
	Min	0.40	0.18	0.44	0.38	0.69	0.64	0.70	0.61	0.56	0.92	0.66	0.95
	Mean	1.01	0.77	0.98	0.96	0.96	0.93	0.93	0.98	0.93	1.05	0.94	0.97
	St. Dev	0.44	0.35	0.33	0.35	0.11	0.13	0.09	0.16	0.16	0.09	0.11	0.01
Jacksonville	Max	1.66	1.30	1.51	1.51	1.18	1.06	1.01	1.13	1.10	1.21	1.09	0.98
	Min	0.31	0.14	0.35	0.30	0.76	0.67	0.69	0.61	0.55	0.90	0.71	0.96
	Mean	0.93	0.72	0.92	0.90	0.93	0.91	0.92	0.96	0.92	1.00	0.96	0.98
	St. Dev	0.43	0.34	0.32	0.34	0.09	0.10	0.06	0.15	0.16	0.07	0.11	0.01

Table 2.8. Statistical summary of the comparisons between various reference ET methods, using results from 6 years of daily data. Daily climate data are used to calculate daily reference ET values and then are averaged to determine a monthly value. Max, min, mean, and standard deviations are calculated from monthly values.

Location		Reference ET Method						
		McCloud	Turc	Pen48	Pen63	Pen77	IFAS Pen	PenFAO
Difference between Reference Method and ASCE PM-90 (mm/day)								
Daytona Beach	Max	5.51	1.14	1.74	1.72	0.61	1.35	0.01
	Min	-4.36	-3.64	-2.05	-2.18	-1.95	-1.04	-0.23
	Mean	0.30	-0.33	0.05	-0.07	-0.20	0.05	-0.07
	St. Dev.	1.79	0.54	0.55	0.57	0.28	0.34	0.03
Gainesville	Max	6.04	2.88	0.98	0.89	1.17	0.57	0.02
	Min	-5.13	-4.39	-2.62	-2.85	-1.26	-1.41	-0.37
	Mean	0.43	-0.35	0.04	-0.17	0.13	-0.13	-0.11
	St. Dev.	1.95	0.60	0.50	0.52	0.28	0.30	0.05
Jacksonville	Max	5.29	0.73	1.02	0.98	1.12	0.77	0.02
	Min	-4.24	-2.74	-1.79	-1.99	-1.15	-1.02	-0.22
	Mean	0.30	-0.40	0.01	-0.15	-0.03	-0.07	-0.09
	St. Dev.	1.94	0.44	0.47	0.49	0.28	0.29	0.04
Ratio of Reference Method to ASCE PM-90								
Daytona Beach	Max	1.42	4.07	1.90	1.87	1.27	1.55	1.01
	Min	0.00	0.12	0.51	0.44	0.53	0.69	0.96
	Mean	0.91	1.08	1.01	0.98	0.96	1.01	0.98
	St. Dev	0.15	0.52	0.16	0.17	0.08	0.11	0.01
Gainesville	Max	5.36	4.54	2.20	2.14	1.64	1.56	1.01
	Min	-0.05	0.09	0.49	0.40	0.69	0.60	0.93
	Mean	0.90	1.13	1.02	0.96	1.06	0.97	0.97
	St. Dev	0.22	0.62	0.17	0.17	0.11	0.11	0.01
Jacksonville	Max	1.51	3.00	2.19	2.17	1.73	1.47	1.02
	Min	0.00	0.09	0.50	0.41	0.74	0.62	0.95
	Mean	0.89	1.05	1.01	0.96	1.01	0.98	0.98
	St. Dev	1.42	0.55	0.17	0.18	0.10	0.11	0.01

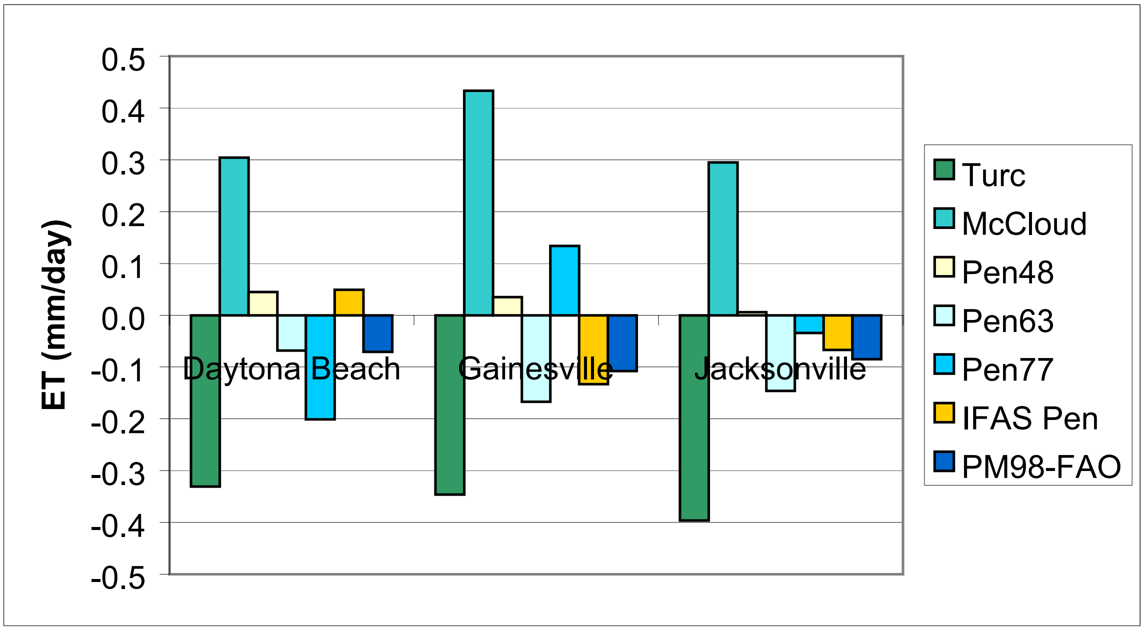

Figure 2.11. Mean of daily differences between reference methods and ASCE PM-90 (mm/day)

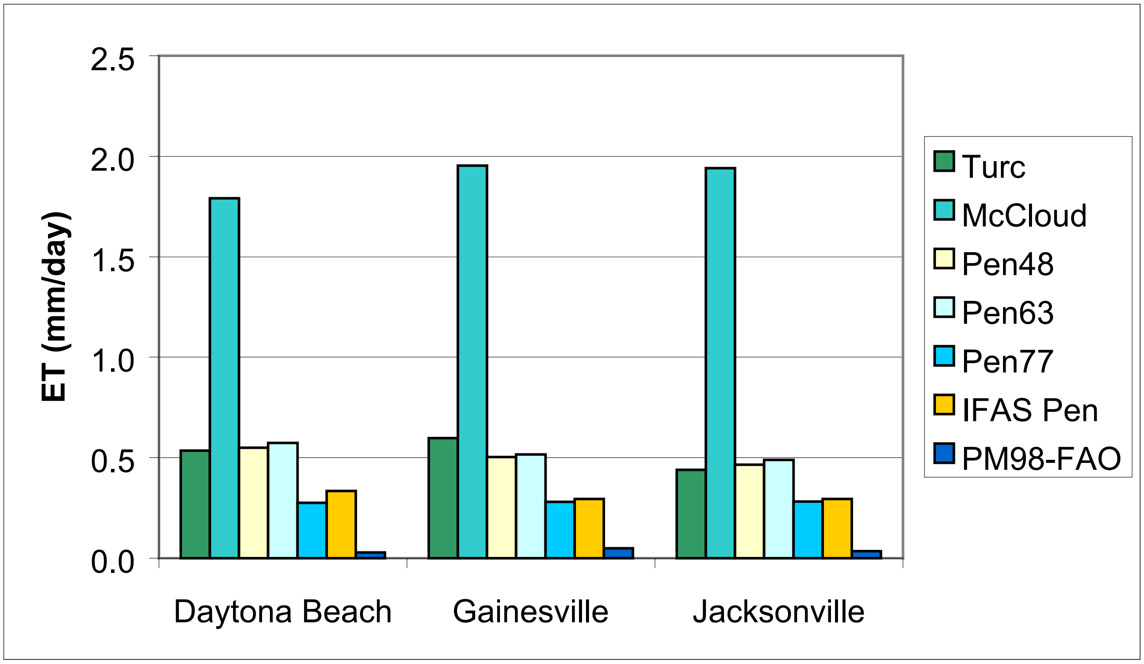

Figure 2.12. Standard deviation of daily differences between reference methods and ASCE PM-90 (mm/day)

Table 2.9. Statistical summary of the comparisons between various reference ET methods using results from 6 years of monthly data for peak months (May, June and July). Climate data is averaged to determine monthly value then used to calculate reference ET

Location		Reference ET Methods											
		McCloud	Thornthwaite	Blaney-Criddle	SFWMD	AGMOD	Hargreaves	Turc	Pen48	Pen63	Pen77	IFASPen	PenFAO
Difference between Reference Method and ASCE PM-90 (mm/day)													
Daytona Beach	Max	1.88	0.60	1.45	1.47	0.20	0.44	0.02	0.57	0.45	-0.27	0.37	-0.09
	Min	-1.29	-1.61	-0.23	-0.27	-1.31	-0.15	-0.54	0.02	-0.10	-0.56	-0.03	-0.12
	Mean	0.70	-0.30	0.74	0.73	-0.60	0.18	-0.34	0.33	0.22	-0.39	0.19	-0.10
	St. Dev.	1.15	0.81	0.60	0.63	0.43	0.15	0.15	0.17	0.18	0.08	0.12	0.01
Gainesville	Max	2.82	1.22	2.02	2.04	0.51	0.47	-0.06	0.61	0.41	0.18	0.14	-0.11
	Min	-1.42	-1.60	-0.27	-0.31	-1.08	-0.57	-0.87	-0.31	-0.54	-0.23	-0.39	-0.15
	Mean	1.06	0.05	1.08	1.08	-0.24	0.03	-0.40	0.21	0.00	-0.02	-0.09	-0.13
	St. Dev.	1.34	0.93	0.76	0.78	0.46	0.31	0.23	0.28	0.28	0.10	0.17	0.01
Jacksonville	Max	2.79	1.05	1.85	1.86	0.31	0.28	-0.18	0.56	0.42	-0.08	0.25	-0.09
	Min	-1.51	-1.64	-0.31	-0.36	-1.34	-0.38	-0.78	-0.20	-0.35	-0.38	-0.29	-0.13
	Mean	0.90	-0.14	0.90	0.89	-0.47	0.01	-0.46	0.19	0.03	-0.23	0.00	-0.11
	St. Dev.	1.46	0.94	0.73	0.75	0.49	0.17	0.16	0.21	0.21	0.09	0.17	0.01
Ratio of Reference Method to ASCE PM-90													
Daytona Beach	Max	1.35	1.12	1.28	1.29	1.04	1.09	1.00	1.11	1.09	0.95	1.07	0.98
	Min	0.75	0.69	0.96	0.95	0.76	0.97	0.90	1.00	0.98	0.90	0.99	0.98
	Mean	1.13	0.95	1.14	1.14	0.89	1.03	0.94	1.06	1.04	0.93	1.04	0.98
	St. Dev	0.22	0.15	0.11	0.12	0.08	0.03	0.03	0.03	0.03	0.01	0.02	0.00
Gainesville	Max	1.58	1.25	1.46	1.46	1.11	1.10	0.99	1.12	1.08	1.04	1.03	0.98
	Min	0.72	0.69	0.95	0.94	0.80	0.89	0.84	0.94	0.90	0.96	0.93	0.97
	Mean	1.22	1.01	1.22	1.22	0.95	1.01	0.92	1.04	1.00	1.00	0.98	0.97
	St. Dev	0.27	0.18	0.16	0.16	0.09	0.06	0.04	0.06	0.06	0.02	0.03	0.00
Jacksonville	Max	1.51	1.21	1.37	1.37	1.06	1.06	0.96	1.12	1.09	0.98	1.04	0.98
	Min	0.71	0.68	0.94	0.93	0.76	0.93	0.86	0.96	0.94	0.93	0.94	0.97
	Mean	1.17	0.97	1.17	1.17	0.91	1.00	0.91	1.04	1.01	0.96	1.00	0.98
	St. Dev	0.28	0.18	0.14	0.15	0.09	0.03	0.03	0.04	0.04	0.02	0.03	0.00

Table 2.10. Statistical summary of the comparisons between various reference ET methods for peak months (May, June and July), using results from 6 years of daily data averaged to determine the monthly rate. Daily climate data are used to calculate daily reference ET values and then are averaged to determine a monthly value. Max, min, mean, and standard deviations are calculated from monthly values.

Location		Reference ET Method						
		McCloud	Turc	Pen48	Pen63	Pen77	IFAS Pen	PenFAO
Difference between Reference Method and ASCE PM-90 (mm/day)								
Daytona Beach	Max	5.51	1.14	1.74	1.72	0.61	1.35	0.01
	Min	-4.36	-3.64	-2.05	-2.18	-1.95	-1.04	-0.23
	Mean	0.30	-0.33	0.05	-0.07	-0.20	0.05	-0.07
	St. Dev.	1.79	0.54	0.55	0.57	0.28	0.34	0.03
Gainesville	Max	5.47	0.52	0.88	0.79	0.48	0.46	-0.01
	Min	-3.85	-2.72	-1.11	-1.28	-0.84	-0.72	-0.28
	Mean	1.21	-0.37	0.26	0.05	0.01	-0.04	-0.12
	St. Dev.	1.75	0.45	0.36	0.38	0.21	0.20	0.04
Jacksonville	Max	5.29	0.62	1.00	0.98	0.36	0.65	-0.01
	Min	-3.61	-1.92	-0.69	-0.93	-1.03	-0.53	-0.22
	Mean	1.11	-0.42	0.25	0.09	-0.21	0.05	-0.10
	St. Dev.	1.84	0.36	0.29	0.30	0.22	0.19	0.03
Ratio of Reference Method to ASCE PM-90								
Daytona Beach	Max	2.57	1.22	1.39	1.38	1.03	1.30	1.00
	Min	0.44	0.59	0.80	0.80	0.75	0.93	0.97
	Mean	1.19	0.95	1.08	1.06	0.93	1.05	0.99
	St. Dev	0.33	0.10	0.09	0.09	0.04	0.05	0.00
Gainesville	Max	3.55	1.10	1.41	1.34	1.19	1.21	1.00
	Min	0.37	0.40	0.76	0.73	0.85	0.89	0.94
	Mean	1.30	0.92	1.06	1.02	1.01	1.00	0.98
	St. Dev	0.43	0.09	0.08	0.08	0.04	0.04	0.01
Jacksonville	Max	2.55	1.16	1.43	1.42	1.09	1.28	1.00
	Min	0.39	0.63	0.89	0.86	0.85	0.91	0.97
	Mean	1.24	0.92	1.06	1.03	0.96	1.01	0.98
	St. Dev	0.38	0.07	0.07	0.07	0.04	0.04	0.00

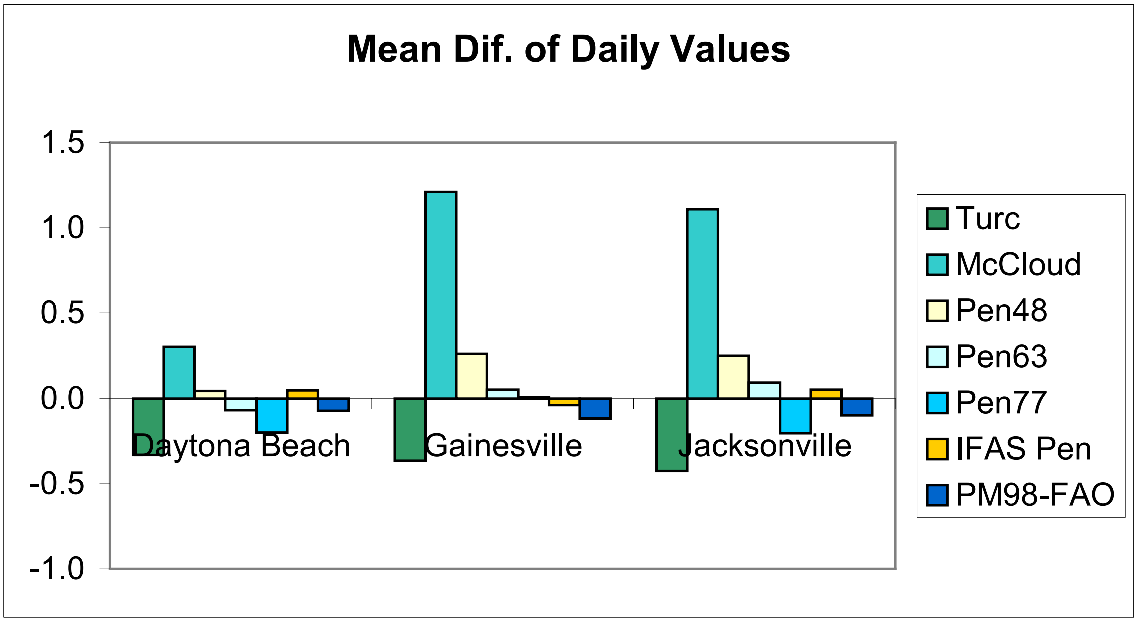

Figure 2.13. Mean of daily differences between reference methods and ASCE PM-90 (mm/day) for peak months

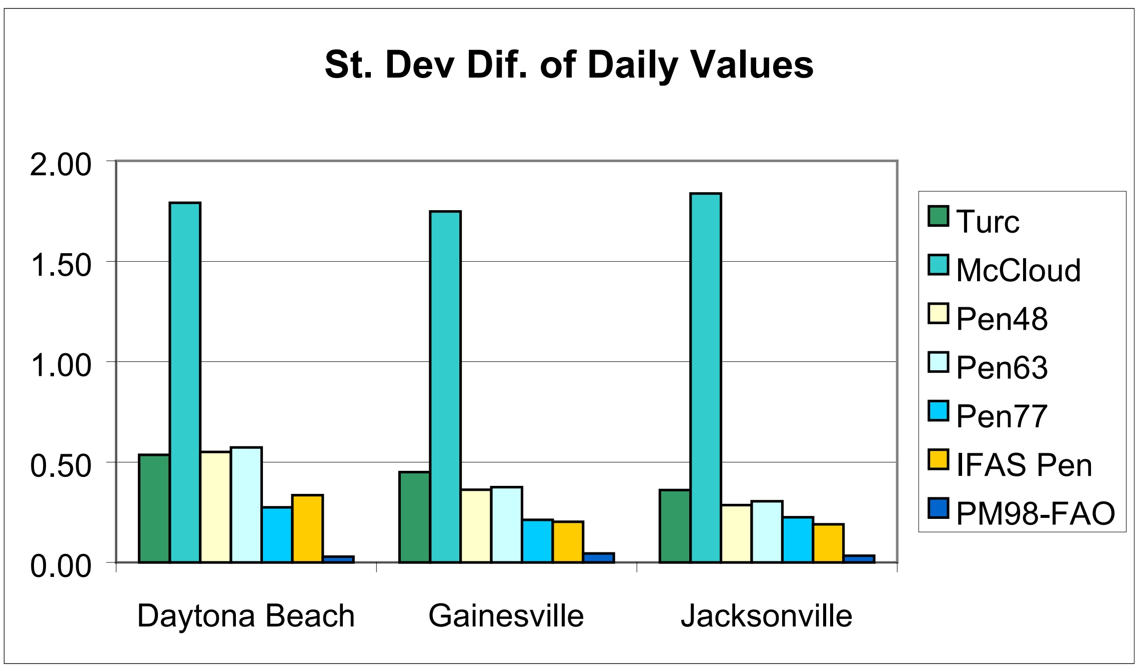

Figure 2.14. Standard deviation of daily differences between reference methods and ASCE PM-90 (mm/day) for peak months

The next set of comparisons focuses on the peak ET values observed during June, July and August. Tables 2.9 and 2.10 list the peak month summary statistics for each method calculated on a monthly basis and a daily basis, respectively. The Hargreaves, the Penman 63, the IFAS Penman and FAO P-M methods all give very good results. The Penman 77 does not do as well over this peak period as it did for the annual period. On a daily basis, most of the combinations give very good results. The IFAS Penman and the FAO-PM give the best agreement with respect to accuracy and bias. The peak season's daily mean and standard deviation results are shown in Figures 2.13 and 2.14. These figures clearly illustrate that the combination methods on average are excellent with biases that are typically less than 0.1 mm/day. The standard deviation figure helps to discern the day-to-day differences that the methods make. The 95% confidence interval (approximately plus or minus two standard deviations) is on the order of 0.5 mm/day for the IFAS Penman and the Penman 77 methods.

2.5. CONSUMPTIVE USE PERMIT COMPARISON

The crop irrigation requirement may be modeled using the AFSIRS numerical simulation model. The AFSIRS model couples historical daily reference ET and rainfall values with crop information. This section compares differences in crop irrigation requirement that results from using the IFAS 1984 Penman method and the ASCE PM-90 method to estimate daily reference ET. The comparison was conducted for citrus and pasture using an eight year climate database (1985-1992) for Gainesville. Aside from the difference in daily reference ET, all other input values were identical including crop coefficients.

Figures 2.15 and 2.16 show the permit differences that result from using IFAS Penman versus the ASCE PM-90 ET values for citrus and pasture. For citrus, the crop ET difference is positive during the summer and negative during the spring. The crop and reference ET differences are identical for February, March, July, September, October, November and December.

The annual crop ET is identical for both methods. The timing of the differences results in a negligible annual difference in net irrigation of -0.1 inches and gross irrigation of -0.13 inches. The major difference between the two methods occurs in July. The pasture differences are similar for crop ET and effective rainfall. The overall pasture difference for net irrigation is -0.2 inches and for gross irrigation is -0.29 inches.

2.6. CROP COEFFICIENTS

The goal of establishing a reference ET methodology is to provide a standard against which to compare ET rates across seasons and regions and to relate crop ET to a reference standard. The method should provide a simple means to represent the physical processes of evapotranspiration. Consistent application of a single standard is critical to the transferability of crop coefficients. The crop coefficient multiplied by the reference ET value yields the crop ET. Thus, the crop ET is determined using the reference ET as an index of the climate demand and the crop coefficient as a measure of the particular crop characteristics that differentiate it from

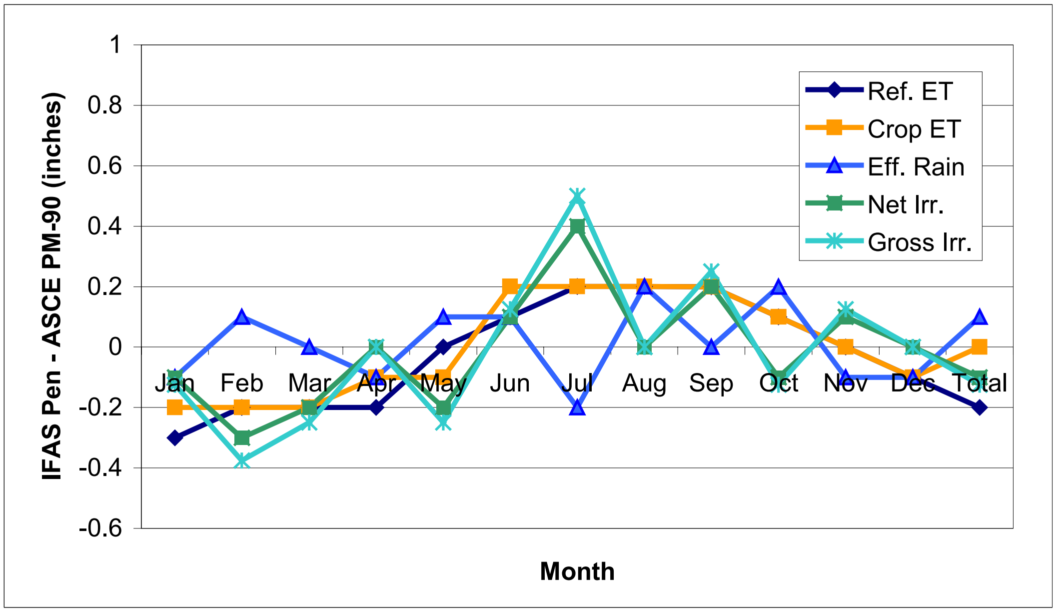

Figure 2.15. The difference in reference evapotranspiration, crop evapotranspiration, effective rainfall, net irrigation and gross irrigation values for citrus calculated using the IFAS Penman and ASCE PM-90 ET values.

the reference crop. Correct estimation of crop ET therefore requires coupling the crop coefficient with an appropriate reference crop ET method.

The establishment of crop coefficients requires considerable time and investment. For this reason, AFSIRS uses some locally determined crop coefficients, but relies on the FAO publications for a large number of crop coefficients. The crop coefficients were likely determined outside the Southeastern United States. Table 2.11 lists all the crops available through the AFSIRS system and the source of their crop coefficients (Smajstrala, 1990). Crop coefficients are available for many crops and are continuously being updated. The development of future crop coefficients will likely use the FAO PM and the ASCE 2000 PM as the standard reference ET method.

2.7. CONCLUSIONS

The ASCE 1990 Penman-Monteith method is well established as the most accurate and robust method to estimate reference ET (Jensen et al., 1990). The past decade of research has solidified its status as the international standard by which to judge other reference ET methodologies and the preferred method by which to estimate crop coefficients. The ASCE PM-90 ET method provides the least bias and the most accurate estimates of reference ET for a range of climates.

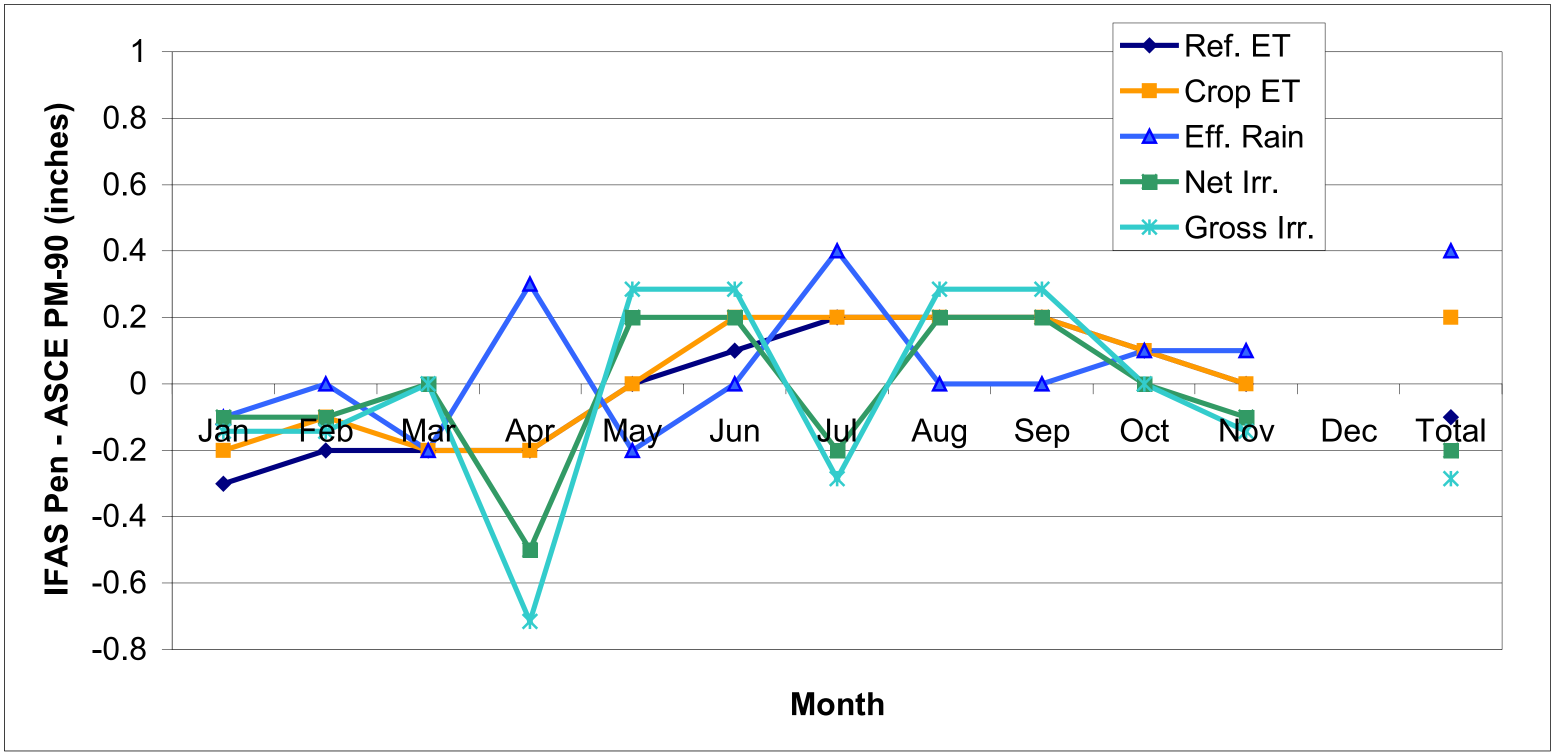

Figure 2.16. The difference in reference evapotranspiration, crop evapotranspiration, effective rainfall, net irrigation and gross irrigation values for pasture calculated using the Penman and the ASCE PM-90 ET values.

Table 2.11. Source of AFSIRS crop coefficients

Crop	Crop Coefficient Source	Notes
PERENNIAL CROPS		
Alfalfa	Jensen	Design and operation of farm irrigation systems
Avocado, Blueberries	FL	Kc coefficients not available for FL
Citrus	FL Rogers	ET from a humid-region developing citrus grove with grass cover, ASAE 26:1778-1783, 1792
Ferns, Nursery	FL	Kc coefficients not available for FL
Pasture	FL Doorenbos & Pruit Stewart and Millis	Crop water requirements, FAO 24. Effect of depth to water table and plant density on ET rate in Southern Florida
Peaches	FL Doorenbos & Pruit Phung and Bartholic	Crop water requirements, FAO 24. Water balance in a peach orchard. Water Research Resource Center, Publication No. 33, UF
Grapes, Pecans	Doorenbos & Pruit	Crop water requirements, FAO 24
Sugarcane	FL Doorenbos and Pruit Campbell	Crop water requirements, FAO 24. Sugar, oil and fiber crops, Ch. 33, Irrigation of Agricultural Lands, Monograph No. 11. Amer. Soc. Agro. Lawns, Turf, Sod – all Kc = 1
ANNUAL CROPS		
Barley, Oats, Beans, Clover, Cotton, Millet, Potatoes, Rice, Sorghum, Sunflowers, Tobacco, Wheat	Doorenbos and Pruit	Crop water requirements, FAO 24
Corn	Doss	Moisture used by various plant species and its relation to pan evaporation and net radiation. ARS-41-112. USDA
Peanuts	Elliot	Crop coefficients for peanut ET. Agricultural Water Mgmt. 15:155-164
Soybeans	FL Smajstrala and Clark	Water stress effects on water use and yield of soybeans. Soil & Crop Sci. Fla. Proc. 41:178-181
Strawberries	FL Locascio	Trickle irrigation and fertilization methods for strawberries. Proc. Fla. State Hort. Soc. 88:185-189
VEGETABLE CROPS		
Beans, Beets, Broccoli, Cucumber, Brussels Sprouts, Cabbage, Carrots, Peppers, Cauliflower, Peas, Melons, Celery, Onion, Eggplant, Greens (Potherbs), Lettuce, Radish	Doorenbos and Pruit	Crop water requirements, FAO 24
Small Vegetables		
Squash, Sweet Corn	Doorenbos & Pruit	Crop water requirements, FAO 24
Sweet Potatoes		No crop coefficients are available
Tomatoes	Locascio and Myers	Tomato response to plug-mix, mulch and irrigation method. Proc. Fla. State Hrt. Soc. 87:126-130
	Stall and Bryan	Effect of production area and irrigation methods on tomato yields in South Dade County. Proc. Fla. State. Hrt. Soc. 88:225-227
	Saxena	Effect of an asphalt barrier on soil water and on yields and water use by tomato and cabbage. Journal of Amer. Soc. Hort. Sci. 96:218-222

Fourteen methods for calculating reference ET were analyzed using six years of data from three Florida locations. The results show considerable variability between methods. In addition, the relationship among methods depends on location. Overall, the FAO Penman-Monteith, the IFAS Penman, and the Hargreaves methods all correlated well with the ASCE PM-90 method. The other Penman methods were quite good in one or more of the comparisons. The remaining methods are not recommended for daily ET estimates. Of those methods that provide reasonable correlation, the FAO Penman-Monteith provided the best overall agreement with the ASCE PM-90 method. The IFAS Penman method also provided good agreement with the ASCE PM-90 method. However, there are seasonal differences in which the IFAS Penman and the Penman 1977 methods underestimates ASCE PM-90 ET during the winter months and overestimates it during the summer months. The Hargreaves method provided good agreement with the ASCE PM-90 method on an annual basis, but on a shorter time scale it was not accurate. The Turc method had good accuracy, but was a biased estimator of ASCE PM-90 method. Unfortunately, no reliable measured data sets of reference ET in Florida were available to provide another means of comparison.

Recent national and international reviews have upheld the ASCE PM-90 ET method as the standard reference ET, but have simplified the method for a standard grass reference with a fixed height, albedo and surface resistance (Allen et al., 1998; Walter et al., 2000). The results shown here and the results of previous researchers indicate that the grass reference simplications have resulted in modest differences between the FAO Penman-Monteith and the ASCE PM-90 method. In addition, work by the Restrepo et al. (1995) for the South Florida Water Management District (SFWMD) found the Penman-Monteith approach to be reliable and accurate in the South Florida region. They recommended this method for the SFWMD staff.

Investigators throughout the United States and in many countries have demonstrated that the Penman-Monteith combination method are preferable to radiation or temperature based methods for estimating reference ET. The climate data requirements for this physically based method are greater than the empirical radiation and temperature methods, but yield much better agreement with measured data on daily time scales. The results here show that modifying the

AFSIRS reference ET to use the FAO Penman-Monteith method in place of the IFAS Penman method will provide consistency with the larger agricultural community without requiring additional climate data. The estimates of crop irrigation requirements for citrus and pasture suggest that only limited permit modifications should result from changing reference ET from the IFAS 1984 Penman method to the FAO Penman-Monteith method. It is recommended that the current AFSIRS climate database be updated from the existing 1950s to 1970 data to include more recent climate data and to use the FAO Penman-Monteith method.

As a whole, these results demonstrated that the differences among the Penman and Penman-Monteith methods are quite small. Typically, the average differences are less than 0.2 mm per day with a maximum standard deviation of 0.5 mm. Given the small variations among the methods, there is considerable confidence in the ability to provide a reasonable reference ET estimate given appropriate model inputs. As the goal is to be able to accurately simulate reference ET, the overall computational process is important. In particular, the validity of the reference ET estimates is a function of both the method as well as the climate data used in the estimates. The available climate data is from NOAA weather stations that may or may not be properly maintained as reference ET sites. Considerable effort to ensure that appropriate climate data input are available and utilized is comparable importance to the method selection.

In addition, it is suggested that one or more lysimeter data sets be developed for coastal and inland Florida to validate the accuracy of the Penman-Monteith method for the Florida climate under true reference conditions. The choice of grass used for such a lysimeter study should be carefully considered as the canopy structure, density and leaf orientation all influence the reference ET rate. Beard (1985) provides a comparison between grass types that may be used to identify one or more appropriate grasses for a Florida study. Finally, if a new reference ET methodology is adopted, all crop coefficients should be appropriately adjusted.

3. IRRIGATION REQUIREMENTS IN FLORIDA CONSUMPTIVE USE PERMITTING

3.1 INTRODUCTION

The irrigation water or supplemental crop water requirement is traditionally determined using a multi-step process in which one aggregates the effect of the crop, climate, and soil on crop water use. The allocated crop water requirement is adjusted to account for the efficiency of the irrigation method. Additional water may be allocated for other tasks such as frost and freeze protection, crop establishment, etc.

This report section identifies and quantifies the differences among three Water Management Districts' supplemental crop water requirements as calculated in consumptive use permitting process. While there are five Water Management Districts in Florida, the primary focus of this study is on the comparison between St. Johns River WMD, South Florida WMD (SFWMD) and South West Florida WMD (SWFWMD). The following sections detail and analyze the irrigation water requirement models currently used by SJRWMD, SFWMD, and SWFWMD. A quantitative comparison is conducted for citrus and pasture crops in Polk County.

An overview of the steps that the three WMDs' models follow is shown in Figure 3.1. The climate, crop and soils data are used to determine the crop evapotranspiration and the effective rainfall. The effective rainfall is that part of the measured rainfall that is available to the plant. The net irrigation requirement is the difference between the amount of water needed by the crop and that supplied by the effective rainfall. Here, the term net irrigation refers to the additional amount of water that must be supplied to the plant. The gross irrigation includes the net irrigation plus the water that is lost during its delivery.

The following sections describe in detail the data and methods used by each WMD for each step. The methods are then used to quantify the differences among values. A complete analysis of consumptive use permit amounts for the three WMDs is conducted for citrus and pasture in Polk County.

3.2. CROP WATER DEMAND/EVAPOTRANSPIRATION

The WMDs use either the Blaney-Criddle Method or a Penman-based method coupled with crop coefficients to estimate the crop water demand. Here, the crop's water demand is the crop evapotranspiration irrigated to prevent yield reducing stress. Each of the three WMDs uses a Blaney-Criddle Method. Only SJRWMD uses a Penman based approach in its AFSIRS model.

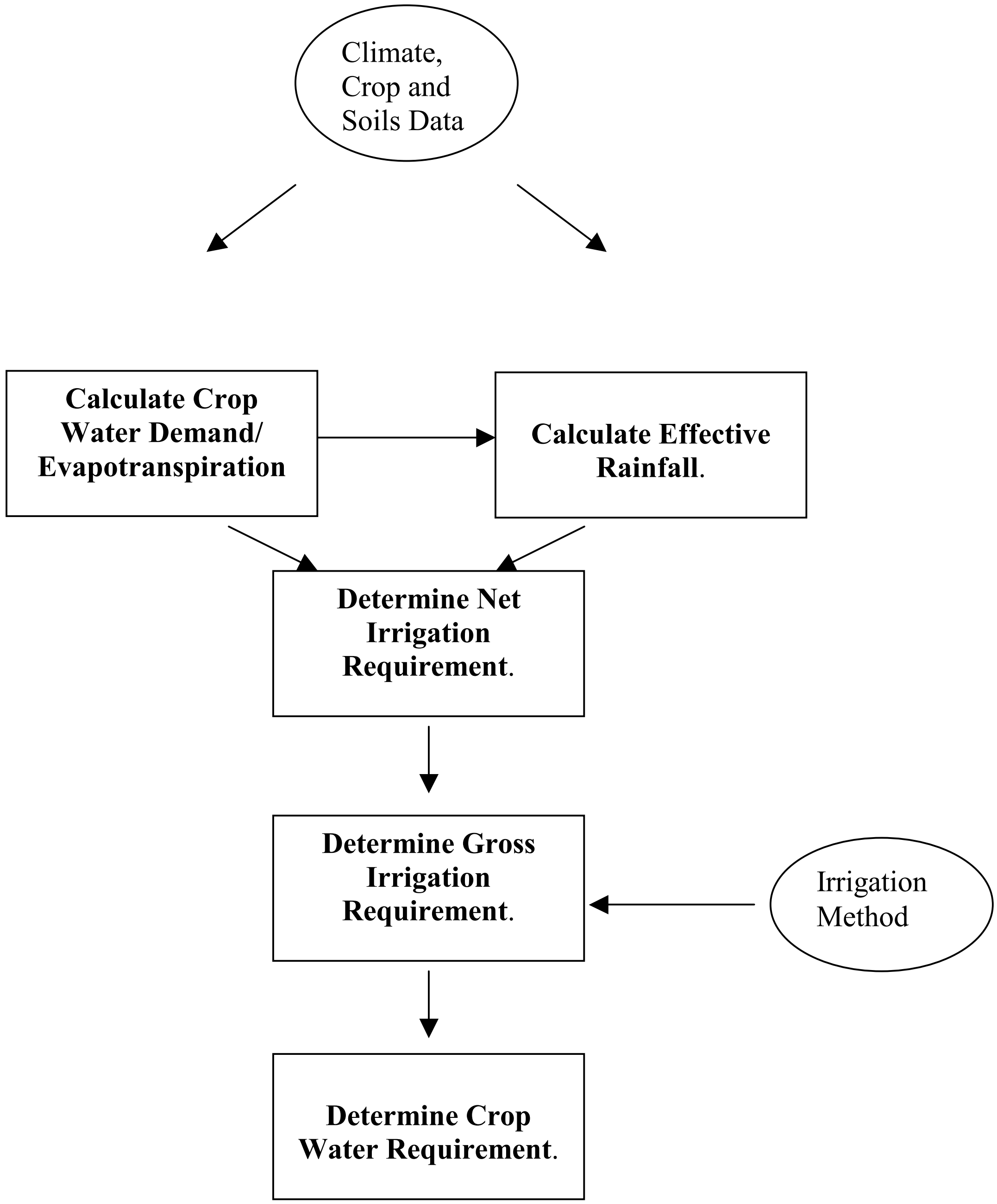

Figure 3.1. Outline of the process used to calculate crop water requirement

3.2.1. The Penman Method

SJRWMD's AFSIRS model determines crop evapotranspiration using the potential evapotranspiration of a reference crop coupled with crop coefficients. The potential evapotranspiration is obtained from a database of daily reference crop ET values for approximately 20 years. There is a database of daily reference crop ET values for a series of NOAA weather stations located throughout Florida and Alabama. These daily values were calculated using the IFAS Penman method (Jones et al., 1984). The working Penman equation is given by

$$ET_p = \frac{\frac{\Delta}{\Delta+\gamma}\left[(1-\alpha)R_s - \sigma T^4\left(0.56-0.08\sqrt{e_d}\right)\left(1.42\frac{R_s}{R_{so}}-0.42\right)\right]}{\lambda}$$

$$+\frac{\gamma}{\Delta+\gamma}\left[0.263\left(0.5+0.0062u_2\right)\left(e_a-e_d\right)\right]$$

where:
- ET_p = daily potential evapotranspiration, *mm day*$^{-1}$,
- R_s = total incoming solar radiation, *cal cm*$^{-2}$ *day*$^{-1}$,
- R_{so} = total daily cloudless sky radiation, *cal cm*$^{-2}$ *day*$^{-1}$,
- T = average air temperature in *K*,
- e_a = vapor pressure of air = $(e_{max} + e_{min})/2$, *mb*,
- e_{max} = maximum vapor pressure of air during a day, *mb*,
- e_{min} = minimum vapor pressure of air during a day, *mb*,
- e_d = vapor pressure at dewpoint temperature (T_d) , *mb*,
- u_2 = wind speed at a height of 2 m, *km/day*,
- Δ = slope of saturated vapor pressure curve of air, *mb/*^oC,
- γ = psychrometric constant = 0.66 *mb/*^oC,
- λ = latent heat of vaporization of water,
  = $(59.59 - 0.055\, T_{avg})$ *cal.cm*$^{-2}$*.mm*$^{-1}$,
- T_{avg} = $(T_{max} + T_{min})/2$, ^oC,
- T_{max} = maximum daily temperature, ^oC, and
- T_{min} = minimum daily temperature, ^oC.

The daily ET values can be obtained from the appropriate AFSIRS climate file, clim.XXX, where XXX is a three letter abbreviation for the site.

The reference crop ET values are adjusted for application to the crop of interest using the crop coefficients in the AFSIRS crop.dat file.

3.2.2. The Blaney-Criddle Method

The Blaney-Criddle method was developed to estimate crop evapotranspiration in the western United States. The method uses temperature, location, and crop type to estimate crop water use. Each of the three WMDs studied has adopted a version of Blaney-Criddle equation. SFWMD use the modified Blaney-Criddle method as described by the Soil Conservation Service's Technical Release-21 (TR-21)(SCS, 1967). SJRWMD uses a slightly different version of this modified Blaney-Criddle method. SWFWMD uses a modified-modified Blaney-Criddle Method that accounts for incoming solar radiation. Here, the general approach is outlined, modifications applied by the individual WMDs are detailed, and the data used to calculate crop ET are specified.

An overview of the steps in the Blaney-Criddle method is shown in Figure 3.2. The Blaney-Criddle method uses the monthly mean temperature and percentage of daylight hours to calculate an evapotranspiration factor F. The mean monthly temperature is used to calculate the climate factor K_t. The ET factor and climate factor are independent of crop type. The crop growth stage coefficient K_c is an adjustment to account for monthly crop ET rate differences. The WMDs calculate F, K_t, K and U on a monthly basis. The sum of the monthly crop potential ET values is the crop's annual ET under well irrigated conditions. For perennial crops, the crop coefficients are given on a monthly basis. For annual crops, the coefficients are given at certain percentages of the growing season. The coefficients are averaged to determine a monthly coefficient.

St. Johns River Water Management District

SJRWMD uses the special publication SJ87-SP4 to determine supplemental crop water requirement. This publication is a technical memorandum that consists of an extensive series of tables detailing the model inputs and outputs by county and crop type. There is also a very brief explanation of its modified Blaney-Criddle model and supplemental irrigation calculations.

Modifications: SJRWMD adjusts UMON (the calculated U value) using a correction factor to determine UMONA. However, no documentation exists on how this correction factor was developed or how it is applied. The correction factor changes by crop type and month. Depending on the crop, the factor may increase, decrease, or not change UMON.

Required Data: The temperature and percent of daytime hours data required for the SJRWMD Blaney-Criddle method are available by county where the measurement station is identified. The temperature and precipitation data are 30 year mean values. The monthly data appear in a tabular form. The monthly crop coefficient is also listed.

Outstanding Issues: The special publication SJ87-SP4 suggests that the crop evapotranspiration is calculated using the modified Blaney-Criddle method, with the exception of the correction factor, that is described above. However, calculations made using the modified Blaney-Criddle method with the publication's temperature, percent daylight and crop coefficient values do not always agree with the publication's reported values.

Table 3.1 shows an example of the discrepancy between the modified Blaney-Criddle calculated and reported values for citrus in Polk County. Here the reported mean monthly temperature, percent daylight, and crop coefficient were used in the modified Blaney-Criddle

$$U(m) = K(m) * F(m)$$

$$K(m) = K_c(m) * K_t(m)$$

$$F(m) = \frac{p(m) * t(m)}{100}$$

$$K_t(m) = 0.01734 * t(m) - 0.$$ [illegible]

Variables

U: Crop's potential ET (inches)
K: Empirical seasonal crop water use coefficient
F: ET Factor
K_c: Crop growth stage coefficient
K_t: Climate Factor
t: Mean Temperature ^{o}F
p: Percentage of daylight hours
m: Month

Required Data

t: Monthly Mean Temperature (^{o}F)
p: Monthly percent of daytime hours of the year during the period
Kc: Crop coefficient

Figure 3.2. Blaney-Criddle method

Table 3.1. SJRWMD Modified Blaney-Criddle model

Month	SJ87-SP4 Reported Values					Blaney-Criddle Values		
	Mean Temp (^oF)	% Daylight	Kc (Citrus)	U_{MON} (in)	U_{MONA} (in)	F	Kt	U (in)
January	59.80	7.39	0.64	1.96	1.63	4.42	0.721	2.04
February	56.70	7.07	0.65	1.75	1.45	4.01	0.667	1.74
March	68.50	8.37	0.67	3.37	2.79	5.73	0.871	3.35
April	70.10	8.67	0.70	3.81	3.16	6.08	0.899	3.82
May	76.50	9.46	0.70	5.12	4.25	7.24	1.009	5.11
June	80.00	9.39	0.71	5.70	4.73	7.51	1.070	5.71
July	83.20	9.58	0.71	6.37	5.29	7.97	1.125	6.37
August	83.60	9.17	0.71	6.12	5.08	7.67	1.132	6.16
September	81.20	8.32	0.70	5.14	4.26	6.76	1.091	5.16
October	75.10	8.02	0.68	4.04	3.36	6.02	0.985	4.04
November	66.90	7.28	0.66	2.73	2.26	4.87	0.843	2.71
December	58.10	7.26	0.64	1.87	1.55	4.22	0.691	1.87
Annual Total				47.98	39.81			48.07

method to calculate crop evapotranspiration (U). The annual total SJ87-SP4 UMON values differ by 0.16 in and the maximum monthly difference (0.04 in) occurs in August. In addition, the adjusted U value (UMONA), 39.81 in, is 8 inches less than that calculated using the modified Blaney-Criddle method.

South West Florida Water Management District

Modifications: Shih (1981) showed that the Blaney-Criddle method gave more accurate results in Florida using solar radiation and the modified crop coefficients. SWFWMD replaces *p*, the monthly percent of daytime hours, with the monthly percent of annual incoming solar radiation. The change from percent daytime hours to percent incoming solar radiation adjusts for Florida's humid climate and summer convective systems that reduce the energy available for evapotranspiration. The SWFWMD crop coefficients are approximately 85% of the original Blaney-Criddle coefficients. The reduced crop coefficients are in keeping with Doorenbos and Pruitt's (1977) recommendations for wind and humidity adjustments.

Required Data: The temperature and percent of annual incoming solar radiation data required for the SWFWMD Blaney-Criddle method are available by county in AGMOD's climate.dat file. Three lines make up a county's record. The first twelve variables of line 1 are average long-term monthly rainfall, of line 2 are long-term average monthly temperatures, and of line 3 is monthly percentage solar radiation.

The crop coefficients are available in AGMOD's cropcv.dat file. This file contains crop factors and typical root zone depths. The first variable is the crop ID followed by the crop name. The crop name is followed by the crop factors and the last variable is the typical root zone depth, which is used in the effective rainfall equation. Special attention is to be given to the crop type as the crop factors are given separately depending upon the crop being a perennial crop or an annual crop. The crop factors are provided on monthly basis for Perennial crops (e.g., Sugarcane). The factors are given for every 5% growth of the crop for Annual crops (e.g., Beans/Dry).

Outstanding Issues: None.

South Florida Water Management District

Modifications: None. SFWMD calculates supplemental crop water requirement using the modified Blaney-Criddle equation as described in Chapter 2 and in the beginning of Section 3.2.2 of this Chapter.

Required Data: The temperature and percent of daytime hours data required for the SFWMD Blaney-Criddle method are available by station. The monthly data appears in a tabular form in their Table C-3 and is also available on an internal SFWMD spreadsheet. The crop coefficients are listed for a series of annual and perennial crops in SFWMD's Tables C-1 and C-2, respectively.

Outstanding Issues: None.

3.3. COMPARISON OF CROP EVAPOTRANSPIRATION

This section compares the calculation of crop evapotranspiration for citrus and pasture in Polk County where data is available for all the WMDs. The analysis includes both a comparison of the input data and the methodologies.

3.3.1. Climate Component

The Blaney-Criddle models require mean monthly temperature and percent daylight hours or incoming solar radiation. Table 3.2 shows the monthly values by WMD and climate station. SFWMD uses data recorded in Kissimmee (62 years) and Avon Park (71 years) for northern and southern Polk County, respectively, for mean monthly temperature. SJRWMD uses 30 years of Lake Alfred data for mean monthly temperature. SWFWMD uses 64 years of Lake Alfred data for mean monthly temperature. The SWFWMD estimates vary by almost 2^{o}F (annual average). Each month has some variability. The sampling period at Lake Alfred results in differences of up to 1^{o}F and a seasonal pattern of differences between the SJRWMD and the SWFWMD mean monthly temperature values. The largest variability occurs in the winter months (December, January and February) with Avon Park having the warmest temperatures and SJRWMD's Lake Alfred values being the lowest. The SJRWMD's February temperature, 56.70°F, is considerably cooler than the other average temperatures. This value may be incorrect. The SJRWMD's December temperature should also be examined.

SFWMD and SJRWMD both use percent daylight hours, while SWFWMD uses percent incoming solar radiation. The maximum difference in percent daylight hours, 0.04%, is quite small. A direct comparison between percent daylight hours and percent incoming solar radiation is not particularly revealing, as the overall crop evapotranspiration calculation will also depend on the crop coefficients.

Table 3.2. Polk County climate data for Blaney-Criddle model

Month	Mean Monthly Temperature (°F)				Percent Daylight Hours or Incoming Solar Radiation			
	SJR	SWF	SF		SJR[1]	SWF[2]	SF[1]	
	Lake Alfred	Lake Alfred	Kissimmee	Avon Park	Lake Alfred	Lake Alfred	Kissimmee	Avon Park
January	59.80	59.83	61.07	63.46	7.39	5.51	7.39	7.42
February	56.70	61.82	62.42	64.71	7.07	7.08	7.07	6.81
March	66.71	68.50	66.43	68.12	8.37	8.48	8.37	8.37
April	70.10	71.84	71.47	72.82	8.67	10.79	8.68	8.67
May	76.50	76.96	76.43	77.45	9.46	11.13	9.47	9.44
June	80.00	80.7	80.22	80.76	9.39	10.24	9.40	9.37
July	83.20	82.06	81.54	81.93	9.58	8.67	9.59	9.56
August	83.60	82.05	81.87	82.37	9.17	9.65	9.18	9.16
September	81.20	80.43	80.06	80.81	8.32	8.50	8.32	8.32
October	75.10	74.66	74.28	75.64	8.02	7.35	8.01	8.03
November	66.90	67.67	66.69	68.67	7.28	7.21	7.27	7.30
December	58.10	62.25	61.87	64.25	7.26	5.67	7.26	7.29
Average	71.64	72.25	72.03	73.42				

[1] Percent Daylight
[2] Percent Incoming Solar Radiation

Table 3.3 shows the calculated climate coefficient Kt and ET factor F by WMD and station. Kt is related to the mean air temperature. F is related to temperature and percent daylight hours or percent incoming solar radiation. These values vary due to the variation of input data listed in Table 3.2. The method of calculation is identical for all WMDs.

3.3.2. <u>Crop Coefficients</u>

The empirical crop growth stage coefficient K_c is used to scale the Blaney-Criddle equation to a specific crop. Similarly, the reference ET developed using the AFSIRS Penman equation also must be scaled by a crop coefficient. This coefficient is the only means by which

Table 3.3. Polk County climate coefficient and ET factor for Blaney-Criddle model

Month	Climate Coefficient Kt				ET Factor F			
	SJR	SWF	SF		SJR	SWF	SF	
	Lake Alfred	Lake Alfred	Kissimmee	Avon Park	Lake Alfred	Lake Alfred	Kissimmee	Avon Park
January	0.72	0.72	0.74	0.78	4.42	3.30	4.51	4.71
February	0.67	0.76	0.77	0.81	4.01	4.21	4.41	4.58
March	0.87	0.84	0.84	0.86	5.73	5.66	5.56	5.70
April	0.90	0.93	0.92	0.95	6.08	7.75	6.20	6.31
May	1.01	1.02	1.01	1.03	7.24	8.57	7.24	7.31
June	1.07	1.08	1.07	1.08	7.51	8.26	7.54	7.57
July	1.13	1.11	1.10	1.10	7.97	7.11	7.82	7.83
August	1.13	1.11	1.10	1.11	7.67	7.92	7.52	7.55
September	1.09	1.08	1.07	1.08	6.76	6.84	6.66	6.72
October	0.99	0.98	0.97	0.99	6.02	5.49	5.95	6.07
November	0.84	0.86	0.84	0.87	4.87	4.88	4.85	5.01
December	0.69	0.76	0.76	0.80	4.22	3.53	4.49	4.68

the crop ET is adjusted to reflect the specific crop's water use. Table 3.4 lists the monthly values of K_c for citrus and pasture for each of the WMDs. Also included are the crop coefficients used in the SJRWMD's AFSIRS model. The SWFWMD does not use a crop coefficient for pasture. Instead the crop ET is directly obtained from the AGMOD cropcv.dat file.

Table 3.4. Crop coefficients for citrus and pasture

Month	Citrus Kc				Pasture Kc			
	SJRWMD		SWFWMD	SFWMD	SJRWMD		SWFWMD	SFWMD
	SJ87-SP4	AFSIRS	B-C	B-C	SJ87-SP4	AFSIRS	B-C	B-C
January	0.64	0.90	0.53	0.63	0.50	0.65	N/A	0.46
February	0.65	0.90	0.56	0.66	0.58	0.70	N/A	0.60
March	0.67	0.90	0.57	0.68	0.73	0.75	N/A	0.63
April	0.70	0.90	0.58	0.70	0.85	0.90	N/A	0.68
May	0.70	0.95	0.62	0.71	0.90	0.90	N/A	0.70
June	0.71	1.00	0.60	0.71	0.92	0.95	N/A	0.53
July	0.71	1.00	0.60	0.71	0.92	0.95	N/A	0.56
August	0.71	1.00	0.59	0.71	0.90	0.95	N/A	0.58
September	0.70	1.00	0.58	0.70	0.87	0.90	N/A	0.52
October	0.68	1.00	0.57	0.68	0.79	0.80	N/A	0.53
November	0.66	1.00	0.55	0.67	0.67	0.70	N/A	0.49
December	0.64	1.00	0.53	0.64	0.54	0.65	N/A	0.44

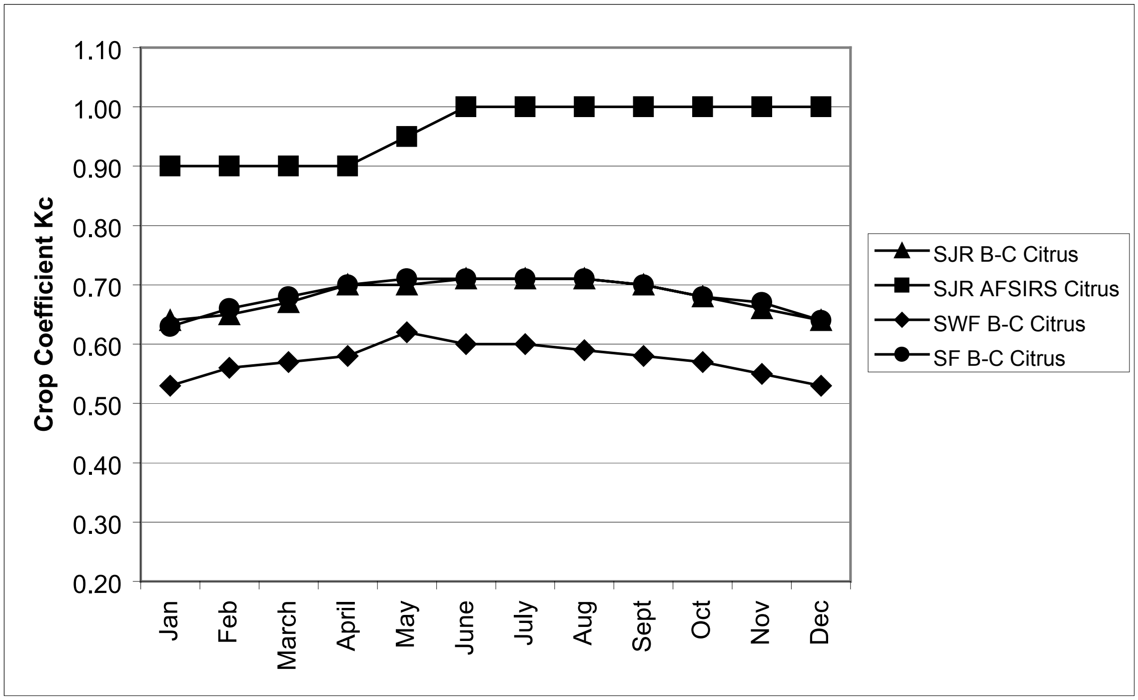

Figure 3.3. Citrus crop coefficients by Water Management District and model where B-C is the Blaney-Criddle Model

The citrus crop coefficient values are plotted on Figure 3.3. For citrus, the SFWMD and the SJRWMD Blaney-Criddle values are nearly identical. The SWFWMD coefficients follow the same trend as the other Blaney-Criddle coefficients, but they are approximately 0.1 smaller. These values are scaled down on the order of 15-20 percent. This scaling is in keeping with Shih's (1981) modified-modified version on the Blaney-Criddle equation. The AFSIRS coefficients are significantly larger than the Blaney-Criddle coefficients. In addition, the AFSIRS coefficients are smallest from January to April and largest from June to December while the Blaney-Criddle coefficients are more cyclical; lowest in December and January and peaking from about May to July. The AFSIRS default coefficients are applied in this analysis. Research in Florida (e.g., the SWAMP project in Ft. Pierce) suggests that improved coefficients are available (personal communication with R. Cohen, SWFWMD). Again, the effect of these differences on crop ET must be considered in conjunction with the other components used to calculate the crop ET.

The pasture crop coefficients are in much better agreement as shown in Figure 3.4. The AFSIRS coefficients are somewhat larger than the Blaney-Criddle during the winter months. Pasture exhibits a stronger seasonal trend and a much greater range of values than citrus.

3.3.3. Crop Potential Evapotranspiration

Crop potential ET is determined by combining the crop coefficients with the climatically based ET. For the Blaney-Criddle methods, $U = K_c * K_t * F$ where Polk County climate values,

K_t and F, are listed in Table 3.3 and K_c values are listed in Table 3.4 for citrus and pasture. For the AFSIRS method, the crop potential ET is the product of the reference crop ET and the crop coefficients listed in Table 3.4 for citrus and pasture. The citrus and pasture ET values are listed in Tables 3.5 and 3.6. The annual cycle of citrus and pasture ET values are shown in Figures 3.5 and 3.6.

The range of citrus annual evapotranspiration values is greater than 10 in. The lowest ET value is the SJRWMD's Blaney-Criddle UMONA value of 39.81 in. The highest ET value is SFWMD's 50.06 in using the Avon Park climate database. The AFSIRS value is included in all tables and figures, but is excluded from comparisons as SJRWMD uses the SJ87-SP4 document to permit citrus.

The WMDs' pasture ET estimates have a 7 in range. The lowest annual ET value is the SFWMD's value of 39.65 in for Kissimmee. The highest ET value is SJRWMD AFSIRS's 46.70 in. The SJ87-SP4 UMONA value is excluded from comparisons as SJRWMD uses the AFSIRS model to permit pasture.

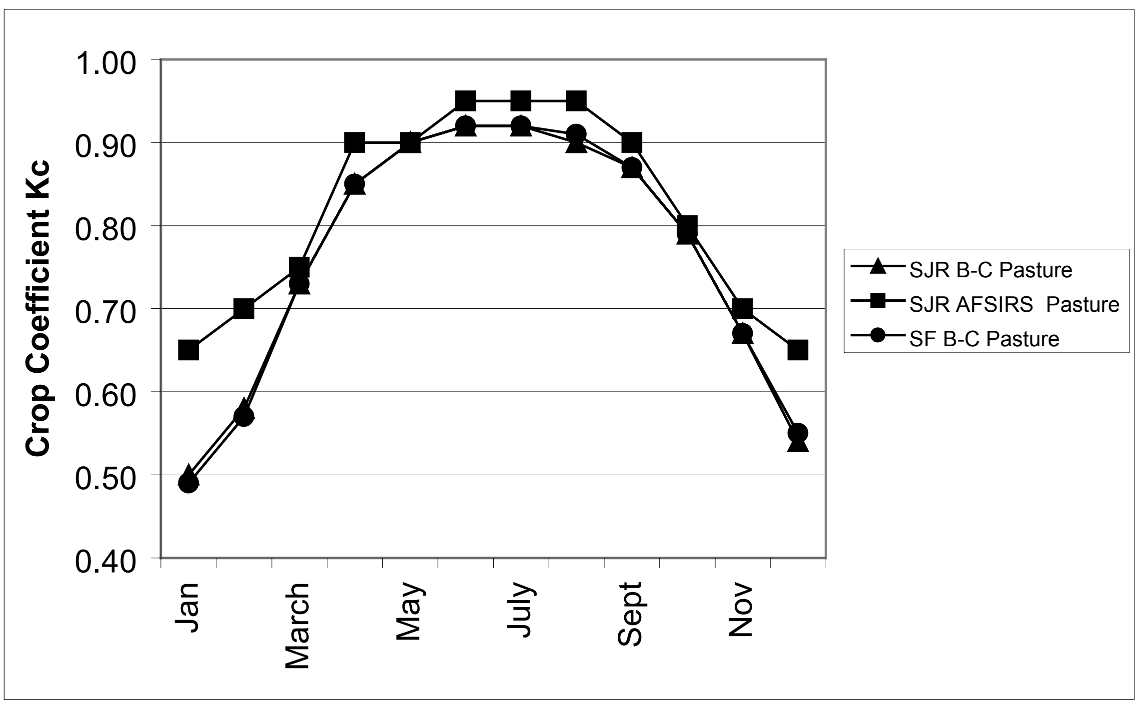

Figure 3.4. Pasture crop coefficients for Water Management District and model where B-C is the Blaney-Criddle model

Table 3.5. Citrus evapotranspiration by WMD, climate station and methodology

Month	Citrus Evapotranspiration (in)					
	SJR			SWF	SF	
	SJ87-SP4 Calc.	SJ87-SP4 U_{MONA}	AFSIRS	AGMOD	Kissimmee	Avon Park
January	2.04	1.63	2.50	1.26	2.11	2.33
February	1.74	1.45	3.10	1.78	2.23	2.44
March	3.35	2.79	4.20	2.71	3.16	3.35
April	3.82	3.16	5.10	4.18	4.01	4.18
May	5.11	4.25	6.00	5.40	5.18	5.33
June	5.71	4.73	5.80	5.37	5.75	5.82
July	6.37	5.29	5.80	4.72	6.09	6.14
August	6.16	5.08	5.30	5.16	5.88	5.95
September	5.16	4.26	4.60	4.27	4.99	5.10
October	4.04	3.36	4.00	3.06	3.93	4.11
November	2.71	2.26	3.00	2.30	2.73	2.94
December	1.87	1.55	2.50	1.43	2.17	2.39
Total	48.07	39.81	51.90	41.63	48.23	50.06

Table 3.6. Pasture evapotranspiration by WMD, climate station and methodology

Month	Pasture Evapotranspiration (in)					
	SJR			SWF	SF	
	SJ87-SP4 Calc.	SJ87-SP4 U_{MONA}	AFSIRS	AGMOD	Kissimmee	Avon Park
January	1.53	1.53	1.90	2.02	1.54	1.70
February	1.54	1.54	2.50	2.51	2.03	2.21
March	3.66	3.66	3.70	3.35	2.93	3.11
April	4.63	4.63	5.00	4.21	3.89	4.06
May	6.57	6.57	5.80	5.21	5.11	5.25
June	7.39	7.39	5.60	4.25	4.29	4.34
July	8.24	8.24	5.60	4.81	4.80	4.84
August	7.85	7.85	5.10	4.79	4.81	4.86
September	6.38	6.38	4.30	3.85	3.71	3.79
October	4.68	4.68	3.30	3.42	3.06	3.20
November	2.75	2.75	2.20	2.50	1.99	2.15
December	1.58	1.58	1.70	1.92	1.49	1.64
Total	56.80	56.80	46.70	42.84	39.65	41.16

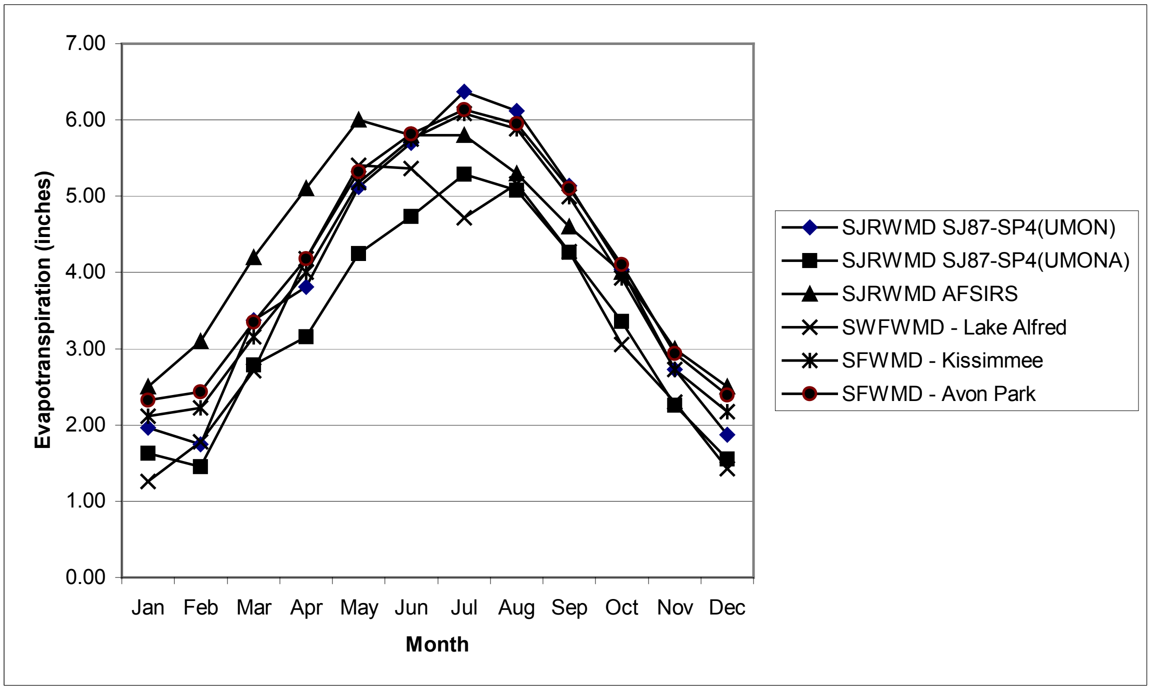

Figure 3.5. Citrus evapotranspiration by WMD and model

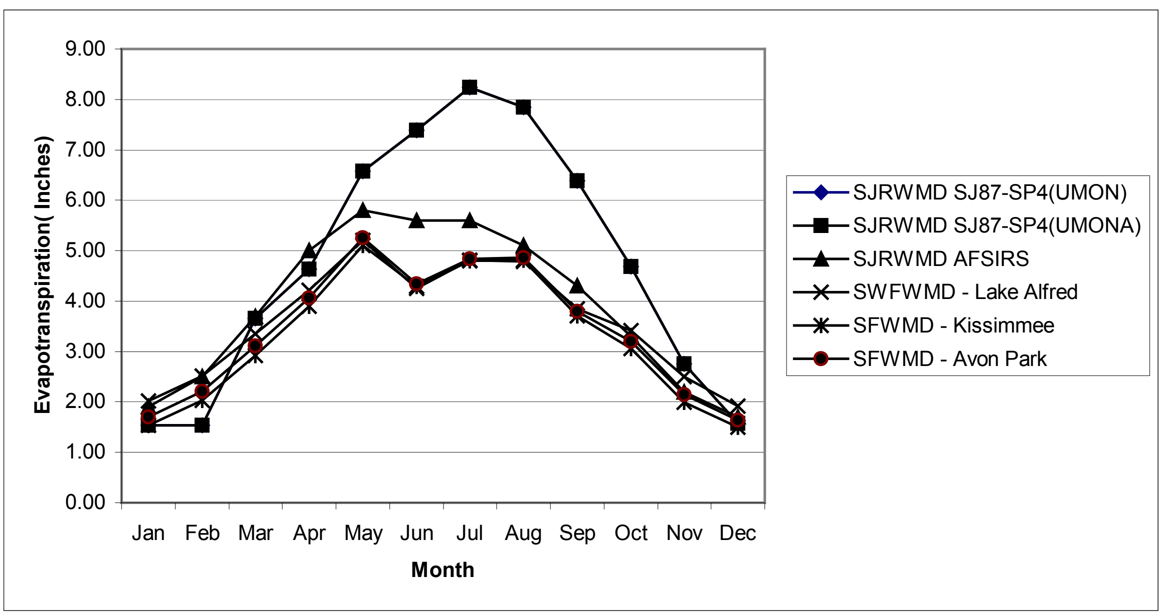

Figure 3.6. Pasture evapotranspiration by WMD and model

3.4. EFFECTIVE RAINFALL

The effective rainfall is that part of the measured rainfall that is available to the plant. The effective rainfall is typically less than the total measured rainfall. There can be several reasons for a difference between the measured rainfall and the effective rainfall. Rainfall that is intercepted by the plants is evaporated. Additional rainfall is directly evaporated from the soil surface. Soils may not be able to infiltrate all the rainfall associated with a long duration or a high intensity storm. The water that is not infiltrated runs off the fields. Significant rainfall events may cause water to infiltrate below the plants' root zone.

The AFSIRS model does not directly calculate the effective rainfall. The model performs a daily water balance using ET, rainfall, and crop and soil information. The irrigation requirement is determined on a daily basis. The sum of the net effective rainfall and the irrigation requirement will equal the crop ET that is required. In this analysis, the net effective rainfall was determined for citrus and pasture by subtracting the monthly irrigation requirements from the monthly crop ET values.

For the Blaney-Criddle models, the effective rainfall is calculated using an empirical equation for the one dimensional irrigation model developed by SCS. This equation considers monthly rainfall, crop water demand, and the crop rooting zone's soil water holding capacity. This capacity is the amount of water that remains in the soil between field capacity and wilting point. It is the water that is available for the crop. The working equation is given by

$$R_e = \left(0.70917 * R_t^{0.82416} - 0.11556\right)\left(10^{(0.024264*U)}\right) F$$

where:
- Re = Monthly effective rainfall depth, inches,
- Rt = Monthly rainfall, inches,
- U = Crop ET predicted by the Blaney-Criddle method,
- F = $\left(0.531747 + 0.295164 * D - 0.057697 * D^2 + 0.003804 * D^3\right)$, and
- D = Net depth of irrigation, inches.

In the above equation D is an indicator of the available storage capacity in the crop's root zone. It is a function of soil, root zone and the water table depth. The effective rainfall depends on the crop ET, the monthly rainfall and the net depth of irrigation. The crop ET was discussed in the previous section. The next sections discuss the monthly rainfall values and the net depth of irrigation by WMD.

3.4.1. <u>Net Depth of Irrigation</u>

St. Johns River Water Management District

SJRWMD provides the R_e values in the tables of the special publication SJ87-SP4.

Outstanding issues: The special publication SJ87-SP4 provides the values of R_e directly. It does not provide an account of the intermediate steps used for calculating the effective rainfall. In particular, the procedure for calculating or evaluating the net depth of irrigation is unknown.

An attempt has been made to establish the D value by trial and error from the equation of effective rainfall discussed above. This has been done to provide a comparison of the three WMDs's D values. Table 3.7 shows the calculations for the evaluation of D values for Polk County. The D value of 2.08 in was found to provide the best agreements between the calculated and the SJ87-SP4 table effective rainfall values. As shown in Figure 3.7, the effective rainfall values were in agreement for all the months except February. February also had an observed temperature discrepancy (see Table 3.2).

Table 3.7. Effective rainfall calculation using SJRWMD data for Polk County (Kissimmee)

	Values from SJ87-SP4 Tables							RE calculations with assumed D				
Month	Temp	Lite	RT	KC	UMON	UMONA	RE	D	RT1(m)	U1(m)	F1	RE
1	59.8	7.39	2.31	0.64	1.96	1.63	1.32	2.08	1.30	1.10	0.93	1.32
2	56.0	7.07	3.09	0.65	1.75	1.45	1.45	2.08	1.68	1.08	0.93	1.70
3	68.5	8.37	3.52	0.67	3.37	2.79	2.05	2.08	1.89	1.17	0.93	2.05
4	70.1	8.67	2.15	0.70	3.81	3.16	1.35	2.08	1.22	1.19	0.93	1.35
5	76.5	9.46	4.62	0.70	5.12	4.25	2.82	2.08	2.39	1.27	0.93	2.82
6	80.0	9.39	6.62	0.71	5.70	4.73	3.94	2.08	3.25	1.30	0.93	3.94
7	83.2	9.58	6.68	0.71	6.37	5.29	4.09	2.08	3.28	1.34	0.93	4.10
8	83.6	9.17	7.12	0.71	6.12	5.08	4.27	2.08	3.46	1.33	0.93	4.27
9	81.2	8.32	6.57	0.70	5.14	4.26	3.81	2.08	3.23	1.27	0.93	3.81
10	75.1	8.02	3.02	0.68	4.04	3.36	1.85	2.08	1.65	1.21	0.93	1.85
11	66.9	7.28	1.84	0.66	2.73	2.26	1.12	2.08	1.06	1.13	0.93	1.12
12	58.1	7.26	1.86	0.64	1.87	1.55	1.08	2.08	1.07	1.09	0.93	1.08
Total	71.58		49.4		47.98	39.81	29.15					29.41

South West Florida Water Management District

Required Data: SWFWMD calculates the net depth of irrigation "D" based on the crop's root depth and the soil's water holding capacity. The individual crop root zone depth is given by the last variable of the corresponding line in AGMOD's cropcv.dat file. The water holding capacities of different soil types are provided in AGMOD's soils.dat file. The soils differ in soil depth and water holding capacities. For example in the area of our study, Polk County, the predominant soil types are Astatula and Candler (Conversation with R. Cohen, SWFWMD). From AGMOD's soils.dat file, these soils' following depths and corresponding water holding capacities (WHC) are given in Table 3.8.

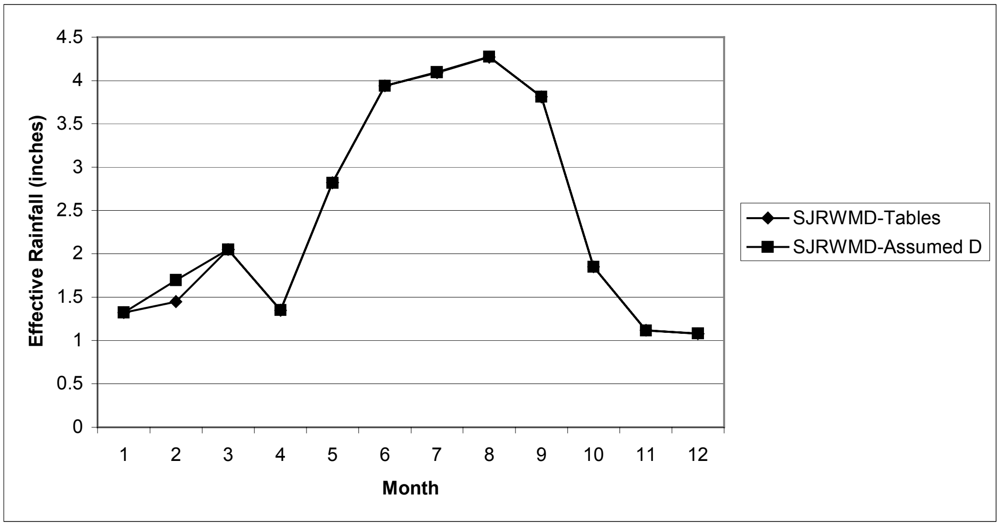

Figure 3.7. Effective rainfall comparison for SJRWMD SJ87-SP4 Tables

Table 3.8. AGMOD soils data for Astatula and Candler

Soil Name	D-1	HWHC	LWHC	AWHC	D-2	HWHC	LWHC	AWHC	D-3	HWHC	LWHC	AWHC
Astatula	3	0.04	0.10	0.07	86	0.02	0.05	0.03				
Candler	5	0.04	0.08	0.06	67	0.02	0.06	0.04	95	0.05	0.08	0.06

For Astatula, the top 3 inches of soil has an Average Water Holding Capacity (AWHC) of 0.07 in/in. and the next 86 inches has an AWHC of 0.03 in/in. This explanation is critical to the calculation of D as the crops root zone depth may fall in different soil layers with different AWHC.

Sample calculation for D

For Citrus in Astatula Soil, the net depth of irrigation is calculated as follows.

From Cropcv.dat file, the typical root zone depth for citrus is 48 inches. Using this root zone and the AWHC by soil layer, the D value is 1.56 (D = 3 * 0.07 + (48-3) * 0.03 = 1.56 inches). This D value is then used in the effective rainfall equation.

Outstanding Issues: None.

South Florida Water Management District

Modifications: None. SFWMD calculates supplemental crop water requirement using the effective rainfall equation as described above.

Required Data: The net depth of application is provided in the Figures C-1 through C-12 for different counties of the SFWMD Basis of Review. For Polk County, the D values vary from 0.4 to 1.5 inches. A 'D' value of 1.5 inches has been used in the calculation of effective rainfall for consistency with SJRWMD and SWFWMD.

Outstanding issues: The source of the above variation in D is not documented. The net depth of application does not account for crop root zone differences with the exception that for small vegetables the net depth of application is to be divided by three.

3.4.2. Monthly Rainfall

The effective rainfall calculations require mean monthly rainfall. Figure 3.8 shows the monthly values by WMD and climate station. SFWMD uses data recorded in Kissimmee (62 years) and Avon Park (71 years) for northern and southern Polk County, respectively for mean monthly rainfall. SJRWMD uses 30 years of Lake Alfred data for mean monthly rainfall in SJ87-SP4. SJRWMD AFSIRS model uses 22 years of daily Orlando station data (1952-1973). SWFWMD uses 64 years of Lake Alfred data for mean monthly rainfall. The annual totals are 49.40" for SJRWMD (Lake Alfred), 54.08" SWFWMD, and 51.18" and 53.89" for SFWMD at Kissimmee and Avon Park, respectively.

3.4.3 Comparison of Effective Rainfall

This section compares the calculations of effective rainfall for citrus and pasture in Polk County. The effective rainfall data for the three WMDs was calculated using climate data from Lake Alfred (SWFWMD and SJRWMD), Kissimmee and Avon Park (SFWMD) and soils data appropriate to Polk County. Note that the modified Blaney-Criddle models only depend on the total rainfall depth during the monthly while the AFSIRS model results will change based on the monthly distribution of rainfall.

Table 3.9 gives the values of the average effective rainfall calculated using all three WMD models for citrus. In the case of SWFWMD, the values have been calculated for the typical two soil types that are permitted in Polk County. For SJRWMD, the values are from SJ87-SP4. For SFWMD, the values are calculated using the climate stations in Kissimmee and Avon Park. The SFWMD selects the climate station for calculating effective rainfall based on the farm's geographic location in the county. The annual average effective rainfall for citrus has less than a 3 inch range. The lowest effective rainfall is 29.19 inches in SFWMD and the highest is 31.87 inches for SWFWMD with Candler soil. Monthly differences are typically less than one inch.

The effective rainfall variation is strongly correlated to the monthly rainfall differences. For example, June and July have large variations in both average monthly rainfall between climate stations and effective rainfall.

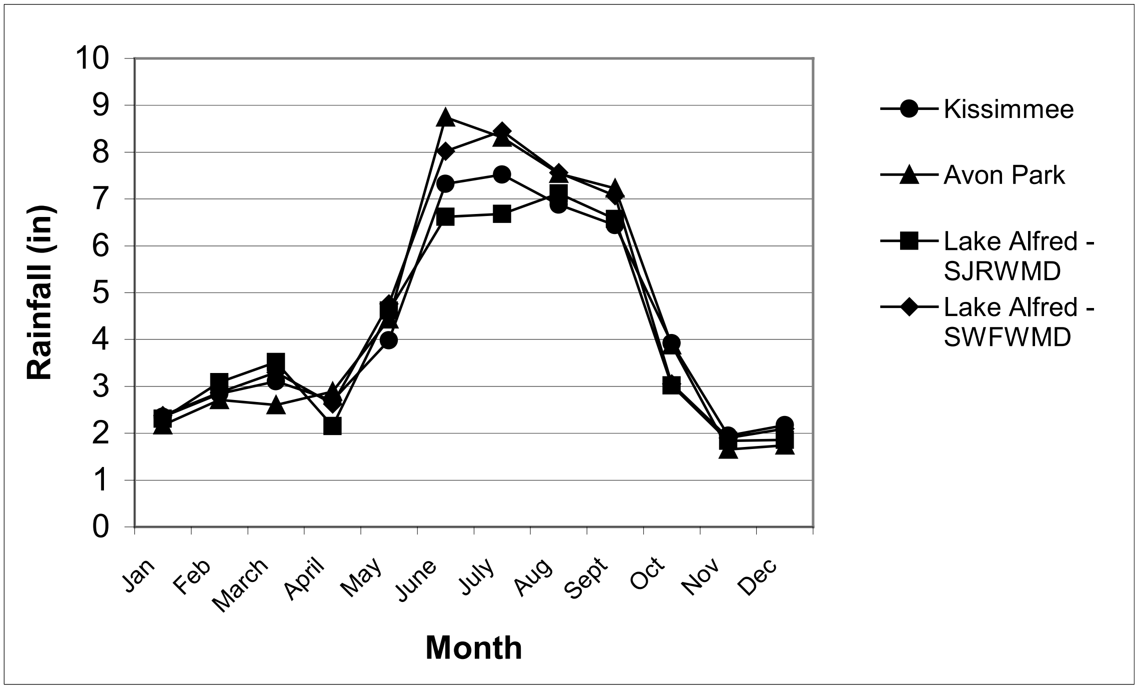

Figure 3.8. Rainfall for effective rainfall calculations by Water Management District and climate station

Table 3.9. Effective rainfall by WMD for citrus (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	1.33	1.60	1.24	1.32	1.27	1.20
2	1.70	2.20	1.51	1.61	1.52	1.47
3	2.05	2.30	1.80	1.91	1.73	1.49
4	1.35	2.30	1.59	1.70	1.60	1.72
5	2.82	2.70	2.87	3.06	2.40	2.66
6	3.95	4.20	4.48	4.77	4.19	4.89
7	4.10	5.10	4.51	4.81	4.37	4.77
8	4.29	4.60	4.21	4.49	4.00	4.34
9	3.82	3.90	3.78	4.03	3.60	4.00
10	1.85	2.80	1.71	1.82	2.21	2.21
11	1.12	1.50	1.07	1.14	1.11	0.97
12	1.08	1.40	1.12	1.19	1.19	0.98
Total	29.45	34.60	29.88	31.87	29.19	30.70

Table 3.10 gives the values of average effective rainfall calculated using all the three WMD models for pasture. The annual average effective rainfall for pasture has approximately a 10 inch range. The AFSIRS model gives an effective rainfall that is over 5 inches larger than the next largest value. Monthly differences greater than 1 inch are frequently observed.

Table 3.10. Effective rainfall by WMD for pasture (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	1.32	1.50	1.05	1.10	1.23	1.16
2	1.46	2.10	1.27	1.34	1.50	1.45
3	2.15	2.60	1.51	1.58	1.71	1.47
4	1.47	2.50	1.29	1.35	1.59	1.71
5	3.21	2.80	2.30	2.42	2.39	2.65
6	4.58	4.40	3.41	3.58	3.86	4.50
7	4.84	4.90	3.68	3.86	4.06	4.43
8	4.99	4.70	3.34	3.51	3.77	4.09
9	4.31	3.70	3.00	3.14	3.35	3.71
10	2.00	2.70	1.41	1.48	2.11	2.10
11	1.15	1.40	0.88	0.92	1.07	0.92
12	1.09	1.20	0.93	0.98	1.14	0.94
Total	32.58	34.50	24.08	25.26	27.79	29.14

The 2-in-10 drought is typically used for permitting purposes. The 2-in-10 drought is characterized by that effective rainfall amount that is equaled, but not exceeded on average twice every ten years. This rainfall amount represents moderate drought conditions. For SFWMD, the 2-in-10 effective rainfall is determined by scaling the average monthly effective rainfall by 0.86 for Avon Park and by 0.85 for Kissimmee. For SWFWMD, the 2-in-10 effective rainfall is determined by scaling the average monthly effective rainfall by 0.86 for Lake Alfred. SWFWMD uses a 6-in-10 effective rainfall rather than the 2-in-10 effective rainfall to permit pasture. For SWFWMD, the 6-in-10 effective rainfall is determined by scaling the average monthly effective rainfall by 1.06 for Lake Alfred.

SJRWMD's irrigation needs under drought conditions are calculated separately from those under average conditions in SJ87-SP4. The AFSIRS model calculates the probability of extreme values by fitting a Weibull distribution using the historical monthly irrigation requirements. The fitted distribution is used to estimate irrigation magnitude for several exceedance probabilities. An exceedance probability of 0.8 corresponds to the 2-in-10 drought condition. Here, the 2-in-10 effective rainfall is estimated by subtracting the irrigation value corresponding to exceedance probability of 0.8 from the crop evapotranspiration. If the Weibull distribution is not well fit, the 2-in-10 drought conditions is estimated directly from the historical data using the Weibull plotting position.

Tables 3.11 and 3.12 list the 2-in-10 effective rainfall values for citrus and pasture, respectively. These values are also illustrated in Figures 3.9 and 3.10. The 2-in-10 effective rainfall results are largely a scaled-down version of the effective rainfall. Two exceptions exist. The SWFWMD pasture values are scaled up. The AFSIRS values are also reduced by 0.79 for citrus and 0.80 for pasture. However, this reduction varies monthly. The combination of the SWFWMD and AFSIRS exceptions effectively reduce the range of effective rainfall values from 10 inches to about 4 inches for permitting pasture and from 5.5 inches to 2.5 inches for citrus.

Table 3.11. 2-in-10 effective rainfall by WMD for citrus (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	1.12	1.10	1.07	1.14	1.08	1.03
2	1.23	1.80	1.30	1.38	1.29	1.27
3	1.74	1.40	1.54	1.65	1.47	1.28
4	1.15	1.10	1.37	1.46	1.36	1.48
5	2.39	1.40	2.47	2.63	2.04	2.29
6	3.34	3.30	3.85	4.10	3.56	4.20
7	3.48	4.70	3.88	4.14	3.71	4.10
8	3.63	4.40	3.62	3.86	3.40	3.74
9	3.24	3.80	3.25	3.47	3.06	3.44
10	1.57	2.30	1.47	1.57	1.88	1.90
11	0.95	0.90	0.92	0.98	0.95	0.83
12	0.92	1.10	0.96	1.03	1.01	0.85
Total	24.76	27.30	25.69	27.40	24.81	26.40

3.5. NET IRRIGATION REQUIREMENT

The average net irrigation is the amount of supplemental water required by the crop. The average supplemental water requirement using the SCS TR-21 method is the difference between the crop evapotranspiration (Tables 3.5 and 3.6) and the effective rainfall (Tables 3.8 and 3.9). Tables 3.13 and 3.14 give the net irrigation values for citrus and pasture, respectively. The comparisons between net irrigation values in this section and gross irrigation values in the next section will focus on the permit values. The results from both SJRWMD methods, the AFSIRS approach and the SJ87-SP4 document, will be presented. However, comparisons among WMDs will be made only using the method with which SJRWMD permits. For citrus, the SJ87-SP4 analysis is the appropriate method. For pasture, the AFSIRS approach is the appropriate method.

Table 3.12. 2-in-10 effective rainfall by WMD for pasture (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)[1]		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	1.29	1.00	1.11	1.17	1.05	1.00
2	1.51	1.55	1.35	1.42	1.27	1.25
3	2.11	2.00	1.60	1.68	1.45	1.27
4	1.44	1.20	1.37	1.44	1.35	1.47
5	3.14	1.40	2.44	2.56	2.03	2.28
6	4.48	3.80	3.61	3.79	3.28	3.87
7	4.73	4.52	3.90	4.09	3.45	3.81
8	4.89	4.50	3.54	3.72	3.20	3.52
9	4.20	3.50	3.18	3.33	2.85	3.19
10	1.95	2.30	1.50	1.57	1.79	1.81
11	1.12	1.00	0.93	0.98	0.91	0.79
12	1.06	0.76	0.99	1.04	0.97	0.81
Total	31.92	27.53	25.52	25.26	23.62	25.06

[1] SWFWMD uses a 6-in-10 effective rainfall for pasture.

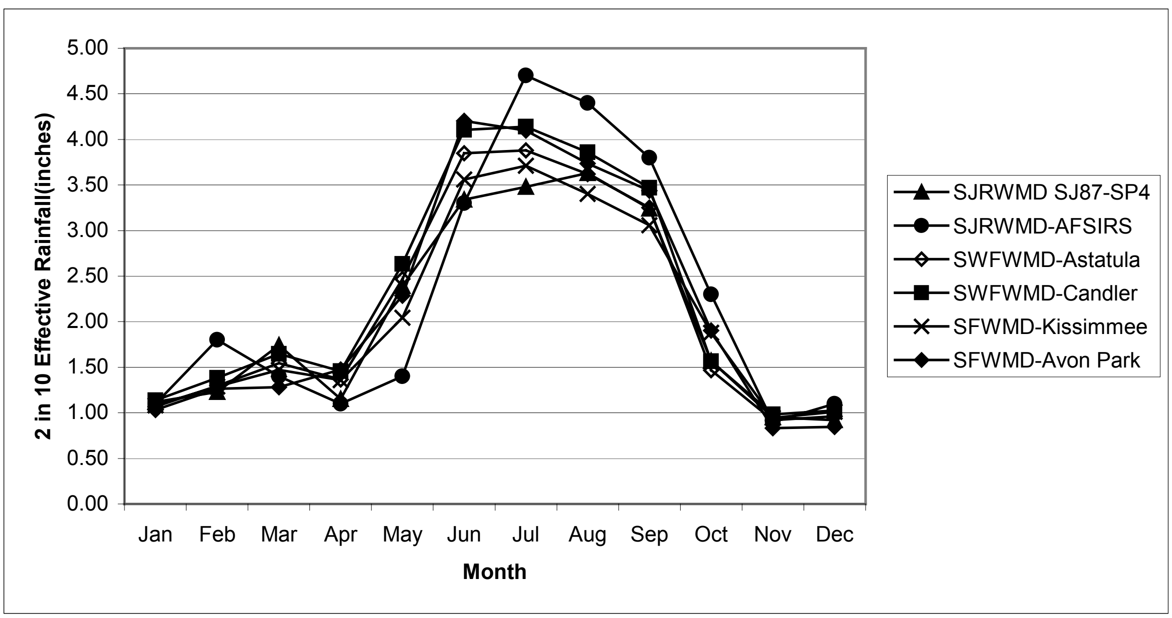

Figure 3.9. Comparison of 2-in-10 effective rainfall by WMD for citrus

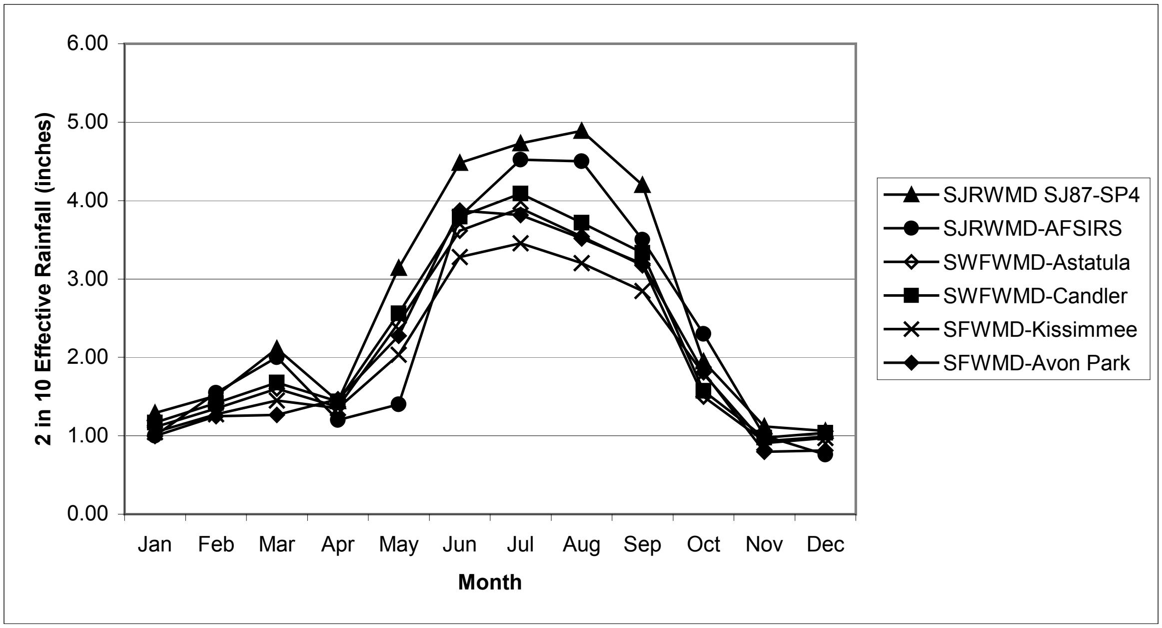

Figure 3.10. Comparison of 2-in-10 effective rainfall by WMD for pasture

The annual net irrigation requirement for citrus ranges from 9.92 inches to 19.37 inches with approximately 9.5 inches of difference between the values for SFWMD and those for SWFWMD and SJRWMD. The relationship among WMD irrigation values differs monthly. During April and May, SWFWMD and SFWMD irrigation values agree well while the July and December values differ by up to 1.5 inches. For citrus, the effective rainfall is quite similar between WMDs. Therefore, the 9.5 inch difference between net irrigation amounts is largely due to the ET estimate differences.

The annual net irrigation requirement for pasture ranges from 11.87 to 18.76 inches with approximately 7 inches of difference among the values for SWFWMD and those for SFWMD and SJRWMD. The relationship between the SFWMD and the SWFWMD irrigation values is similar on a monthly basis. The AFSIRS values are similarly patterned from December through June, but diverge beginning in July. Unlike citrus, the pasture effective rainfall and the ET values differ among WMDs. Therefore, the 7 inch difference between net irrigation amounts is a combination of the ET and the effective rainfall differences.

The 2-in-10 supplemental irrigation is the difference between the crop evapotranspiration (Tables 3.5 and 3.6) and the 2-in-10 effective rainfall (Tables 3.11 and 3.12). Tables 3.15 and 3.16 give the 2-in-10 supplemental irrigation values for citrus and pasture, respectively. The annual 2-in-10 supplemental irrigation requirement for citrus ranges from 14.23 inches to 23.66 inches with approximately 8 inches of difference among the values for SFWMD and those for SWFWMD and SJRWMD. Thus, the 2-in-10 values are somewhat closer than the average values due differences between the 2-in-10 and the average effective rainfall values. The monthly distribution of the citrus 2-in-10 supplemental irrigation is shown in Figure 3.11.

Table 3.13. Net irrigation requirement for citrus under average rainfall conditions by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.37	0.90	0.02	0.00	0.84	1.13
2	0.00	0.90	0.27	0.17	0.71	0.96
3	0.74	1.90	0.91	0.79	1.43	1.86
4	1.83	2.80	2.59	2.48	2.41	2.46
5	1.44	3.30	2.53	2.34	2.78	2.67
6	0.81	1.60	0.89	0.59	1.56	0.93
7	1.21	0.70	0.21	0.00	1.72	1.37
8	0.85	0.70	0.96	0.68	1.88	1.61
9	0.48	0.70	0.49	0.24	1.39	1.10
10	1.51	1.20	1.35	1.24	1.72	1.89
11	1.14	1.50	1.23	1.16	1.62	1.97
12	0.47	0.50	0.31	0.23	0.99	1.41
Total	10.86	16.70	11.76	9.92	19.04	19.37

Table 3.14. Net irrigation requirement for pasture under average rainfall conditions by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.27	0.40	0.97	0.92	0.31	0.54
2	0.00	0.40	1.24	1.17	0.53	0.76
3	1.50	1.10	1.84	1.77	1.22	1.63
4	3.18	2.50	2.92	2.86	2.30	2.36
5	3.37	3.00	2.91	2.79	2.71	2.60
6	2.82	1.20	0.84	0.67	0.43	0.00
7	3.42	0.70	1.13	0.95	0.74	0.41
8	2.83	0.40	1.45	1.28	1.04	0.77
9	2.11	0.60	0.85	0.71	0.36	0.08
10	2.70	0.60	2.01	1.94	0.96	1.10
11	1.61	0.80	1.62	1.58	0.93	1.22
12	0.49	0.50	0.99	0.94	0.35	0.70
Total	24.29	12.20	18.76	17.58	11.87	12.17

The annual 2-in-10 supplemental irrigation requirement for pasture ranges from 16.03 inches to 19.17 inches with a difference of only 3 inches between WMDs. While pasture ET differences among WMDs were up to 7 inches, these differences were mitigated by the effective rainfall differences. For example, the SJRWMD AFSIRS model had both the largest ET values and the largest effective rainfall amounts. The monthly distribution of the pasture 2-in-10 supplemental irrigation is shown in Figure 3.12. Interestingly, the SWFWMD's 6-in-10 pasture values are quite similar to those 2-in-10 values for SFWMD. Also, the SJRWMD AFSIRS monthly distribution of the annual net irrigation requirement differs significantly from the other WMDs.

3.6. GROSS IRRIGATION AND CROP WATER REQUIREMENT

The gross irrigation includes the net irrigation plus the water that is lost during its delivery. The delivery losses are the sum of losses that occur during the application and the conveyance of water. Typically, these losses are aggregated as an irrigation method efficiency. For example, an irrigation system with an 85% efficiency will only deliver 85% of the pumped water to the plant. The gross irrigation requirement is calculated by dividing the net supplemental irrigation values by the irrigation system's efficiency. The WMDs each have different names and categories of irrigation systems and associated efficiencies. SFWMD has different efficiency values for the irrigation system depending on whether or not the permit is a surface water management (SWM). Table 3.17 lists the irrigation systems and their efficiencies by WMD.

Finally, a WMD may adjust the gross irrigation quantity to reflect other factors such as water quality, frost and freeze protection, crop establishment, etc. when granting a permit. SWFWMD provides an additional allocation, "other water uses" in the gross irrigation requirement calculations. This increases the actual permitted water by a certain percentage of the gross irrigation calculated. A 5% increase is applied to pasture and a 10% increase is applied to citrus by SWFWMD.

The gross irrigation requirements for citrus and pasture in Polk County for the three WMDs are calculated using the most commonly permitted irrigation systems by each WMD. For citrus, the most common irrigation system is a micro-spray jet. The corresponding efficiencies are 0.75, 0.80, and 0.85 for SWFWMD, SJRWMD, and SFWMD, respectively. For pasture, the most common irrigation system is a gun except for SFWMD where it is seepage/furrow. The corresponding efficiencies are 0.65, 0.70, and 0.40 for SWFWMD, SJRWMD, and SFWMD, respectively. Tables 3.18 and 3.19 list the gross irrigation requirements for citrus and pasture by WMD respectively. Tables 3.20 and 3.21 show the 2-in-10 gross irrigation requirements for citrus and pasture by WMD. The monthly distribution of the citrus and pasture gross irrigation are shown in Figures 3.13 and 3.14. Figures 3.15 and 3.16 show the monthly distribution of 2-in-10 gross irrigation for citrus and pasture. The irrigation efficiency up-scales the net irrigation requirement. If the irrigation efficiency is equivalent, the gross irrigation requirements differences among WMDs will be greater than the net irrigation differences due to this scaling. This is the case for pasture where the range increases from 7

Table 3.15. Net 2-in-10 supplemental irrigation requirement for citrus by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.50	1.40	0.19	0.12	1.03	1.29
2	0.22	1.30	0.48	0.40	0.94	1.17
3	1.05	2.80	1.16	1.06	1.69	2.07
4	2.01	4.00	2.81	2.72	2.65	2.70
5	1.86	4.60	2.93	2.77	3.14	3.04
6	1.39	2.50	1.52	1.26	2.19	1.62
7	1.81	1.10	0.84	0.58	2.38	2.04
8	1.45	0.90	1.54	1.30	2.48	2.22
9	1.03	0.80	1.02	0.80	1.93	1.66
10	1.79	1.70	1.59	1.49	2.05	2.20
11	1.32	2.10	1.38	1.32	1.78	2.10
12	0.63	1.40	0.47	0.40	1.16	1.54
Total	15.06	24.60	15.94	14.23	23.42	23.66

Table 3.16. Net 2-in-10 supplemental irrigation requirement for pasture by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)[1]		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.25	0.90	0.91	0.85	0.49	0.70
2	0.03	0.95[2]	1.16	1.09	0.75	0.96
3	1.55	1.70	1.75	1.67	1.47	1.84
4	3.19	3.80	2.84	2.77	2.54	2.59
5	3.42	4.40	2.77	2.65	3.07	2.97
6	2.91	1.80	0.64	0.46	1.01	0.47
7	3.51	1.08[2]	0.91	0.72	1.35	1.03
8	2.96	0.60	1.25	1.07	1.60	1.35
9	2.17	0.80	0.67	0.52	0.86	0.60
10	2.73	1.00	1.92	1.85	1.27	1.39
11	1.62	1.20	1.57	1.52	1.09	1.35
12	0.52	0.94[2]	0.93	0.88	0.52	0.83
Total	24.86	19.17	17.32	16.06	16.03	16.09

[1] SWFWMD uses a 6-in-10 effective rainfall for pasture.

[2] Calculated using Weibull plotting position as sufficient number of non-zero elements were not available.

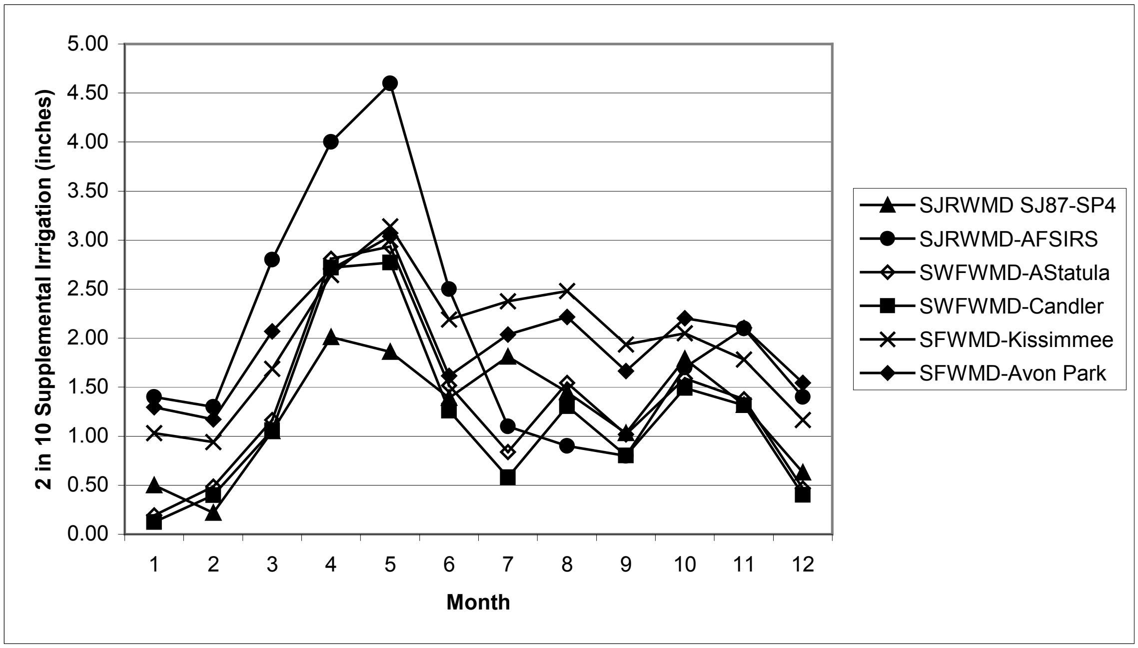

Figure 3.11. Comparison of net 2-in-10 supplemental irrigation by WMD for citrus

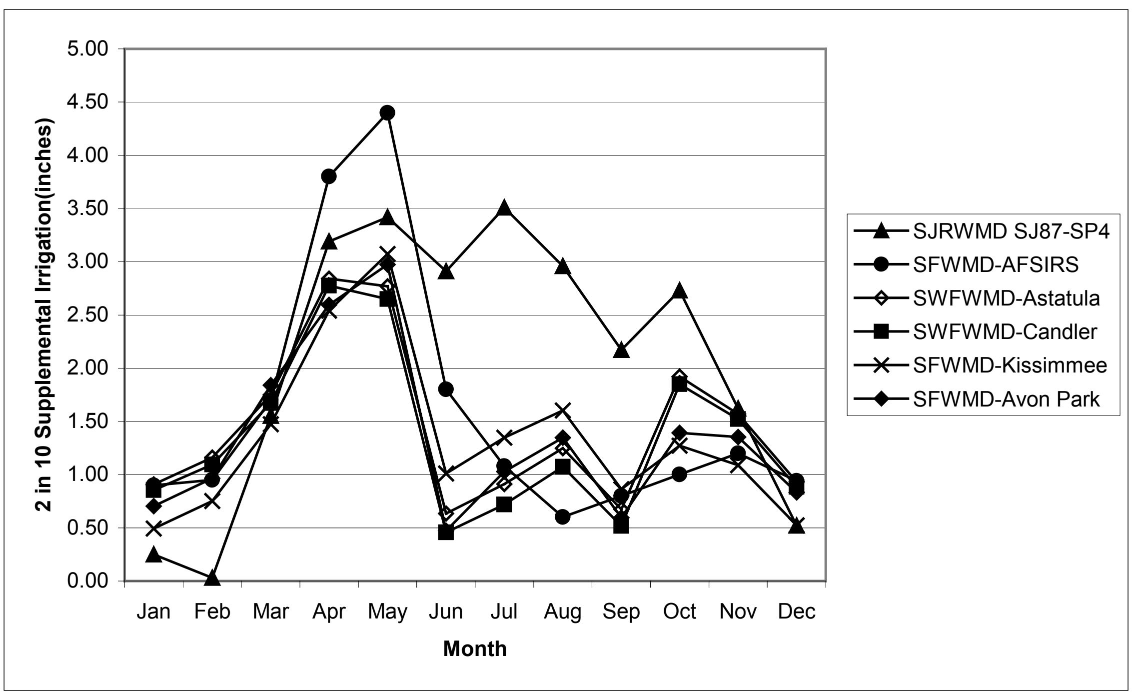

Figure 3.12. Comparison of net 2-in-10 supplemental irrigation by WMD for pasture

Table 3.17. Irrigation application efficiencies by WMD

Irrigation System Type	Efficiency			
	SWF AGMOD	SF Basis of Review	SJR Consumptive Use Handbook	AFSIRS
Trickle			98%	
Drip – Without Mulch	75%	85%	90%	85%
Drip – With Mulch	75%	85%	90%	85%
Fully Enclosed Seepage	75%			
Spray Jet or Spinner –SWF, Jet Irrigation –SJR, Micro, Spray –AFSIRS	75%		80%	80%
Micro-Sprinkler		85%		
Multiple Sprinkler				75%
Sprinkler (Over Plant-SW) (Overhead-SJR)	75%		70%	
Sprinkler (Undertree)	75%			
Sprinkler W/Recovery	75%			
Solid Set Sprinkler		75% or 80%		
Sprinkler, Large Guns				70%
Portable Gun	75%	65% or 70%	70%	
Traveling Gun	75%	70% or 75%	70%	
Center Pivot			80%	
Texas Sidewalker			70%	
Linear Move				
Seepage, Subirrigation		40% or 60%		50%
Seepage –Citrus, Pasture or Sod	65%			
Seepage – With Mulch	50%			
Seepage –Without Mulch	50%			
Pipeline Seepage			60%	
Flood, Rice				50%
Ditch Seepage			50%	
Crown Flood		40% or 60%	50%	50%
Seepage, Furrow		40% or 60%		
Semi-Closed Flow-Through		40% or 60%		
Nursery Container		20% or 35%		
OverHead		75% or 80%		
Low Volume		85%		
Surface Gravity		40% or 60%		
Flood/Seepage		40% or 60%		
Container		20% or 35%		
Volume Gun		70% or 75%		
Walking Gun		70% or 75%		
Sprinkler, Container Nursery				20%

Table 3.18. Gross irrigation requirement for citrus under average rainfall conditions by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.46	1.13	0.03	0.00	0.99	1.33
2	0.00	1.13	0.37	0.23	0.84	1.13
3	0.92	2.38	1.22	1.06	1.68	2.19
4	2.29	3.50	3.45	3.31	2.83	2.90
5	1.80	4.13	3.38	3.12	3.27	3.14
6	1.01	2.00	1.19	0.79	1.84	1.10
7	1.51	0.88	0.28	0.00	2.03	1.61
8	1.06	0.88	1.27	0.90	2.21	1.89
9	0.60	0.88	0.65	0.32	1.64	1.30
10	1.89	1.50	1.80	1.65	2.02	2.23
11	1.43	1.88	1.64	1.54	1.90	2.32
12	0.59	1.25	0.41	0.31	1.16	1.66
Total	13.57	21.50	15.68	13.23	22.40	22.78

Table 3.19. Gross irrigation requirement for pasture under average rainfall conditions by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.39	0.57	1.49	1.41	0.77	1.35
2	0.00	0.57	1.90	1.81	1.32	1.90
3	2.14	1.57	2.83	2.72	3.05	4.08
4	4.54	3.57	4.49	4.39	5.75	5.89
5	4.81	4.29	4.47	4.30	6.79	6.51
6	4.03	1.71	1.29	1.03	1.08	0.00
7	4.88	1.00	1.74	1.46	1.84	1.02
8	4.05	0.57	2.23	1.97	2.59	1.94
9	3.02	0.86	1.31	1.09	0.90	0.19
10	3.85	0.86	3.09	2.98	2.39	2.74
11	2.29	1.14	2.49	2.43	2.32	3.06
12	0.70	0.71	1.52	1.45	0.88	1.75
Total	34.70	17.43	28.87	27.05	29.67	30.42

Table 3.20. 2-in-10 gross irrigation requirement for citrus by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.63	1.75	0.26	0.16	1.21	1.52
2	0.28	1.63	0.65	0.53	1.10	1.38
3	1.31	3.50	1.55	1.42	1.99	2.43
4	2.51	5.00	3.75	3.62	3.11	3.18
5	2.33	5.75	3.91	3.69	3.69	3.58
6	1.74	3.13	2.02	1.68	2.58	1.90
7	2.26	1.38	1.12	0.77	2.80	2.40
8	1.81	1.13	2.06	1.74	2.92	2.61
9	1.29	1.00	1.36	1.07	2.28	1.96
10	2.24	2.13	2.12	1.99	2.41	2.59
11	1.65	2.63	1.84	1.75	2.10	2.48
12	0.79	1.75	0.62	0.54	1.37	1.82
Total	18.83	30.75	21.25	18.97	27.55	27.84

Table 3.21. 2-in-10 gross irrigation requirement for pasture by WMD (inches)

Month	SJR (Lake Alfred)		SWF (Lake Alfred)[1]		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
1	0.36	1.29	1.40	1.31	1.24	1.76
2	0.04	1.36[2]	1.79	1.68	1.88	2.41
3	2.21	2.43	2.69	2.57	3.69	4.60
4	4.56	5.43	4.37	4.27	6.35	6.48
5	4.89	6.29	4.26	4.08	7.68	7.43
6	4.16	2.57	0.98	0.70	2.53	1.18
7	5.01	1.54[2]	1.40	1.11	3.37	2.57
8	4.23	0.86	1.92	1.65	4.00	3.37
9	3.10	1.14	1.04	0.80	2.15	1.49
10	3.90	1.43	2.96	2.84	3.18	3.48
11	2.31	1.71	2.41	2.34	2.72	3.38
12	0.74	1.34[2]	1.43	1.36	1.31	2.08
Total	35.51	27.38	26.65	24.71	40.09	40.23

[1] SWFWMD uses a 6-in-10 effective rainfall for pasture.
[2] Calculated using Weibull plotting position as sufficient number of non-zero elements were not available.

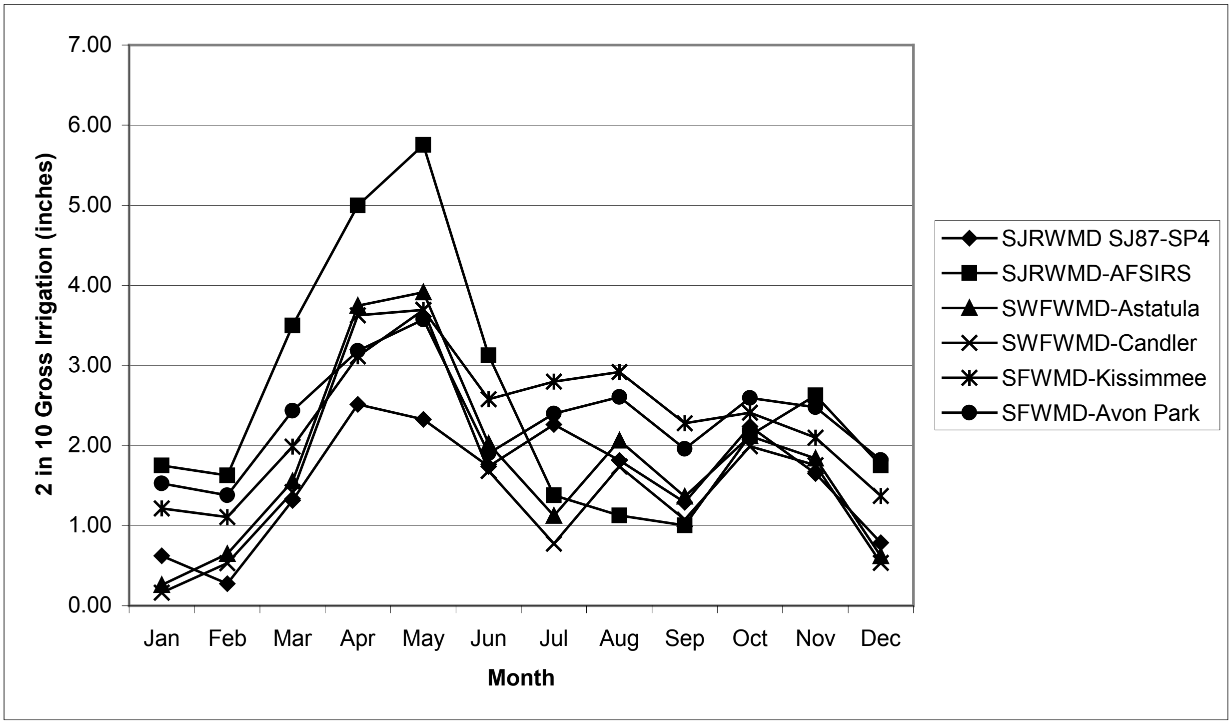

Figure 3.13. Comparison of gross irrigation by WMD for citrus

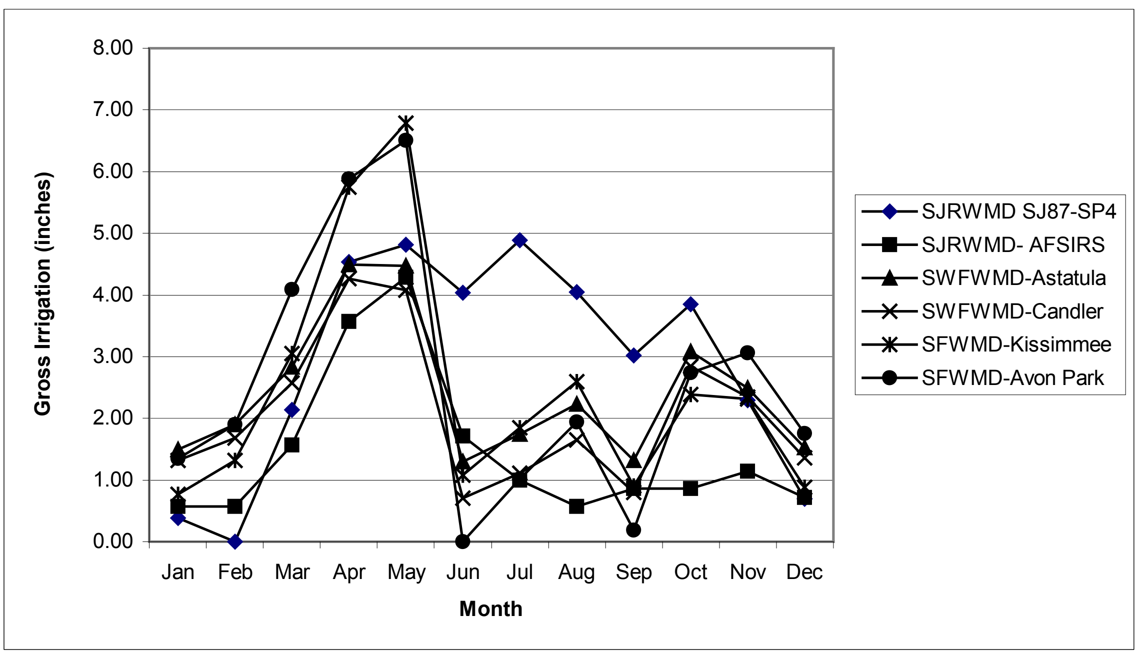

Figure 3.14. Comparison of gross irrigation by WMD for pasture

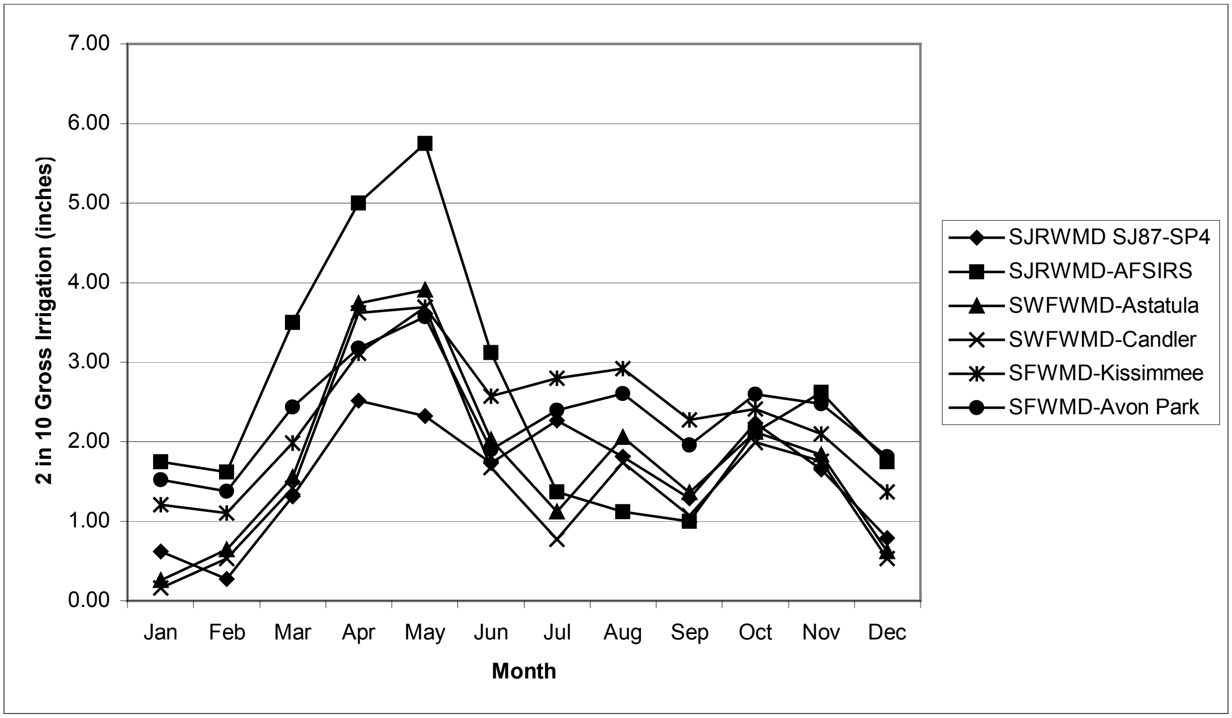

Figure 3.15. Comparison of 2-in-10 gross irrigation by WMD for citrus

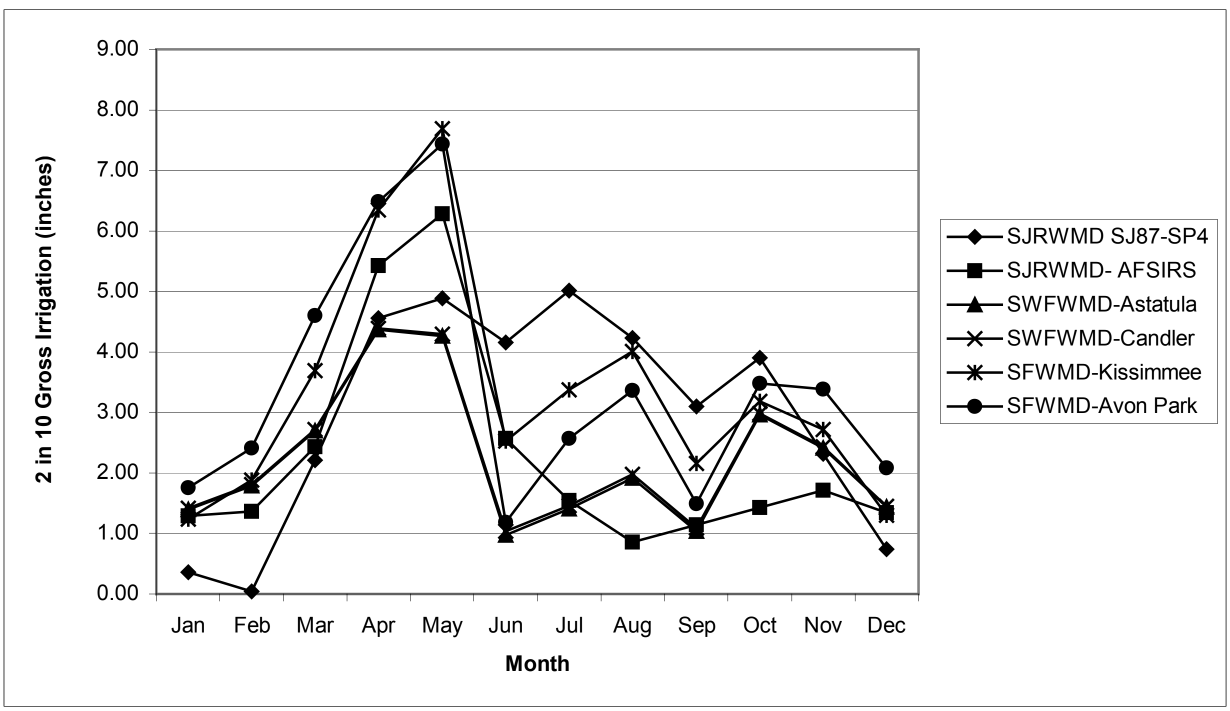

Figure 3.16. Comparison of 2-in-10 gross irrigation by WMD for pasture

inches to 12 inches for the average requirements and from 3 inches to 4.5 inches for the 2-in-10 requirements. For citrus, the allocation differences among WMDs remain similar as the smallest net irrigation requirement is scaled by the smallest efficiency.

Finally, Tables 3.22 through 3.25 list the 2-in-10 gross irrigation requirements and any additional allocations for citrus and pasture by WMD.

3.7. CONCLUSIONS

The previous sections identified significant differences between WMDs in their permitting of two perennial crops and their sources. Tables 3.22 – 3.25 summarize the results from the previous sections. The following list characterizes the major differences and their causes and identifies opportunities for improvement:

- Climate databases differ significantly between WMDs. The climate databases provide air temperature and rainfall that are necessary for both ET and effective rainfall calculations. The differences are due to location differences or sample period differences. In addition, SJRWMD's special publication SJ87-SP4 appears to use erroneous temperature data for at least one month.
- ET losses differ by up to 10 inches for citrus and 7 inches for pasture. The differences result from a combination of the climate database, the crop coefficient and the reference ET calculation method. As discussed in Task 1, the method used to calculate ET appears to be a primary source of the differences. Validation of the magnitude and timing ET is necessary.
- The effective depth of irrigation differs among WMDs. SWFWMD and SJRWMD use a similar approach that combines root zone and soil type. SFWMD uses a county map that does not account for differences in effective depth of irrigation between crops.
- Conversion from average effective rainfall to 2-in-10 rainfall differs between WMDs.

Table 3.22. Citrus summary of average irrigation requirements (inches)

Quantity	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
Crop ET	39.8	51.9	41.6	41.6	48.2	50.1
Effective Rainfall	29.2	33.8	29.9	31.9	29.2	30.7
Net Irr.	10.7	16.7	11.8	9.9	19.0	19.4
Gross Irr.	13.3	20.9	15.7	13.2	22.4	22.8

Table 3.23. Citrus summary 2-in-10 of irrigation requirements (inches)

Quantity	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
Crop ET	39.8	51.9	41.6	41.6	48.2	50.1
Effective Rainfall	24.8	27.3	25.7	27.4	24.8	26.4
Net Irr.	15.1	24.6	15.9	14.2	23.4	23.7
Gross Irr.	18.8	30.8	21.3	19.0	27.5	27.8
Gross Irr. +	18.8	30.8	23.4	20.9	27.5	27.8

Table 3.24. Pasture summary of average irrigation requirements (inches)

Quantity	SJR (Lake Alfred)		SWF (Lake Alfred)		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
Crop ET	56.8	46.7	42.8	42.8	39.7	41.2
Effective Rainfall	32.6	34.5	24.1	25.3	27.8	29.1
Net Irr.	24.3	12.2	18.8	17.6	11.9	12.2
Gross Irr.	34.7	17.4	28.9	27.1	29.7	30.4

Table 3.25. Pasture summary 2-in-10 of irrigation requirements (inches)

Quantity	SJR (Lake Alfred)		SWF (Lake Alfred)[1]		SF	
	SJ87-SP4	AFSIRS	Astatula	Candler	Kissimmee	Avon Park
Crop ET	56.8	46.7	42.8	42.8	39.7	41.2
Effective Rainfall	31.9	27.5	25.5	26.8	23.6	25.1
Net Irr.	24.9	19.2	17.3	16.1	16.0	16.1
Gross Irr.	35.5	27.4	26.6	24.7	22.9	23.0
Gross Irr. +	35.5	27.4	28.0	26.0	40.1	40.2

[1] SWFWMD uses a 6-in-10 effective rainfall for pasture.

- Irrigation efficiencies and naming conventions vary between WMDs. Application of the current approaches can lead to significantly differences in gross irrigation requirements. A consistent working document is necessary.
- Additional agricultural water needs are inconsistently identified and quantified. SWFWMD provides additional water to growers for other uses such as water quality, frost and freeze protection, crop establishment. SFWMD permits additional water if the permittee has a surface water management permit. A critical assessment of additional needs is necessary.

4. AFSIRS Software Review

4.1. INTRODUCTION

The Agricultural Field Scale Irrigation Requirements Simulation (AFSIRS) model was developed for the water management districts by Dr. Allen G. Smajstrala, University of Florida. The model estimates irrigation requirements for Florida crops, soils, irrigation systems and climate conditions. The model was last revised in 1990. Over the past decade, two significant advances have affected the viability of the existing AFSIRS model: 1) additional research on crop water requirements has been conducted in Florida and 2) computer technology has significantly changed.

The operational use requirements and computer platforms have changed over the past decade. The current AFSIRS model is an MS-DOS based program written in Fortran that can be run in an interactive mode or a batch mode. The interactive mode prompts the user for input while the batch mode processes an ASCII input file created by the user. An evaluation of the user interface, reporting capabilities and program platform was conducted to identify and prioritize potential improvements.

An evaluation of the operational use of the AFSIRS Software was conducted. The objective of this task was to identify the limitations to the operational use of the AFSIRS software and to develop a list of proposed model modifications. This task included a peer review of the software and meetings with SJRWMD personnel who have an interest in using AFSIRS for consumptive use permitting. This review focused on data entry and reporting limitations as well as user interface and software issues. The evaluation of the user interface status sought to identify opportunities to develop a more user-friendly interface. The following section contains a list of model modifications categorized and presented according to priority. In addition, the Task 1 and 2 recommendations also appear below.

4.2. PROPOSED AFSIRS MODIFICATIONS

4.2.1. <u>Software Interface Issues</u>

Analysis Software Modification: Use a windows based compiler that has or is compatible with a visual interface. Currently the program uses a DOS based interface developed using the Fortran computer language. It is incompatible with newer MS windows-based compilers. The code should be update and improved using an object-oriented language.

User Interface Enhancement: The AFSIRS software interface is an inflexible DOS based tool. Suggested user interface enhancements include online help, ability to modify system inputs, flexible reporting requirements and a choice of return periods. A windows version of AFSIRS was created, but is used by SJRWMD. This version was developed using an early version MS Visual Basic©. The windows AFSIRS version may serve as an interim solution until such time as further software changes can be implemented.

Modular Design: The current software cannot easily be modified to include technical or user interface ranges. A revised system should be developed in an object-oriented framework that will allow components of the model to easily be update or replaced.

GIS Integration: Promote planning, permitting and modeling consistency by coupling the AFSIRS software with the SJRWMD GIS/Oracle databases. The GIS databases should include soil types, long-term climate data, water table data, and irrigation system and land-use data. The land-use and water table data should include present and projected irrigated acreage, irrigation system type and crop type. Many of these databases already exist at SJRWMD in an acceptable format. The GIS integration should have the flexibility to use existing and planned layers.

Reduce Defaults Dependency: The current system allows the user to apply default values throughout the AFSIRS model. Significant differences may exist between the default values and the true values. It is desired that the user provide values or information necessary to aid the selection of an appropriate default. This may be accomplished by a tiered set of questions that guide the user to identify conditions that best reflect reality. Another option is to develop upper and lower boundaries.

Reporting Capabilities: Modification to the AFSIRS model should allow for flexible reporting that captures present needs and is easily adaptable to future requirements. Current needs include a more completely documented output that clearly indicates user inputs. The output must also be able to be understood by non-technical users. In addition, it is desirable to provide consistent presentation of results for any analysis period averaged on a daily, weekly, monthly or annual basis.

Internet-based Implementation: Create a web page implementation of AFSIRS suitable for use by farmers, agencies and consultants.

4.2.2. <u>Software Functionality</u>

Single Tool: SJRWMD determines agricultural consumptive use permits using both AFSIRS and the SJ87-SP4 document. A single tool would reduce confusion, increase confidence and provide a more uniform and defensible approach for permitting.

Planning and Management Application: Access data at scales larger than an individual farm. For example, the Suwannee River WMD and the North West Florida WMD have used AFSIRS to estimate current and future agricultural water requirements by county and region.

Spatial Interpolation of Climate: Water requirements for users located away from a NOAA weather station is estimated by permitters by interpolating results from two or more stations. Florida has significantly different climate regimes for the coastal regions as compared to the inland regions. An appropriate and consistent tool for interpolating climate databases to local farms is essential to implement AFSIRS at a local scale.

Expand Irrigation Options: Currently, the irrigation options are 1. Irrigate to field capacity, 2. Irrigate to fixed depth, and 3. Deficit Irrigation. Landscape and golf courses automatically irrigate to a fixed depth. However, the scheduling of automatic irrigation may not coincide with the AFSIRS irrigation timing. An option for scheduled irrigation would more realistically simulate water needs as well as provide information on water losses for scheduled systems and identify improved scheduling. In addition, a no irrigation option may significantly improve the functionality.

Crop Models Linkage: Provide the ability to include extended models of crop water use where appropriate. Allow the development and integration of specific crop models for important crops with high potential for improvement.

Irrigation Management Tool: Extend AFSIRS to use as a management tool or benchmark. Provide the ability to input actual rainfall and climate data on a shorter time scale for comparison with actual irrigation use.

WMD Comparison: Chapter 3 of the present report compares pasture and citrus irrigation requirements among three WMDs. A consistency check between the permit values is possible if SFWMD and SWFWMD models are also included with the revised AFSIRS model. The software would provide detailed information necessary for comparison of model differences much as appears in Chapter 3.

4.2.3. <u>Model and Data Needs</u>

Update and Expand Historical Climate Databases: The climate databases include approximately 20 years of data ending in the 1970s. The climate databases should be updated to include more recent data. In addition, the spatial distribution of climate databases is quite sparse. The NOAA databases should be complemented with other climate resources to create an expanded climate database. Based on the Chapter 2 results, the updated reference ET databases should use the FAO Penman-Monteith method. These databases should be cooperatively developed by all WMDs and should include methods for determining 1-in-10 rainfall.

Improve Crop Estimates: Add or update crop coefficients and rooting depths for crops. Priority crops include citrus (both ridge and flatwood), turf grass, sod, golf courses, and landscape. Separate tees, greens, and fairways for golf course permits. Review and revise crop coefficients to reflect Florida climate and soils. Validate critical crops using model sites. Compare AFSIRS estimates to actual irrigation use and use this information to continuously improve the model.

Improve Irrigation Efficiencies: Identify irrigation systems and quantify their efficiencies. Each WMD has a set of data and procedures that should be reviewed. A standard set of system definitions and efficiencies is needed. These efficiencies should be based on actual field use on an annual basis. Perhaps develop seasonal coefficients where wind and evaporation strongly affect efficiencies.

Water Table Interaction: Currently, the AFSIRS model does not include water table effects on crop water requirements. The handling of seepage irrigation is a major limitation of the current AFSIRS model. Inclusion of the water table interactions should improve the ability to predict water requirements in regions with near surface water tables.

Additional Water Requirements: Additional water requirements for fertigation, chemigation and freeze protection need to identified and quantified. The requirements should be prescribed by IFAS or developed cooperatively by the WMDs.

Improved Soil Information: Water use estimates are highly sensitive to the range of soil parameters based on the NRCS soil survey. Improved data are necessary for the most widely observed soils and those with the greatest range of parameters.

4.2.4. Additional Requirements

Software Demonstration Example: New users require training in the AFSIRS software. One or more examples of the application of the AFSIRS model should be created to train and guide users.

Software Training: Improve the knowledge of AFSIRS users by developing and routinely providing an AFSIRS course. The course should include training in software use and education on the modeling approach.

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APPENDIX A

MONTHLY REFERENCE EVAPOTRANSPIRATION VALUES

Table A.1. Monthly evapotranspiration values in mm/day for Gainesville by ET method

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Jan	2.02	1.65	1.64	0.90	1.05	0.94	0.44	1.64	1.43	2.44	1.75	2.20	2.31
	Feb	2.51	2.19	2.13	1.42	1.69	1.59	0.97	1.99	1.78	2.77	2.09	2.70	2.81
	Mar	3.35	3.29	3.36	2.92	3.02	2.70	2.15	3.36	3.13	3.86	3.30	3.68	3.81
	Apr	4.21	3.77	3.92	3.81	3.87	3.13	2.60	3.84	3.63	4.08	3.64	4.03	4.17
	May	5.21	4.61	5.00	5.56	5.61	5.07	4.39	5.07	4.85	5.04	4.83	4.95	5.09
	Jun	4.25	5.01	5.60	6.66	6.64	7.44	5.85	5.62	5.43	5.18	5.29	5.20	5.33
	Jul	4.81	4.86	5.39	6.56	6.55	6.87	5.66	5.53	5.33	4.99	5.03	4.80	4.92
	Aug	4.79	4.11	4.48	6.19	6.19	6.86	5.37	4.77	4.60	4.27	4.36	4.10	4.21
	Sep	3.85	3.89	4.17	4.99	4.98	5.79	4.29	4.45	4.29	4.09	4.15	3.90	4.00
	Oct	3.42	3.25	3.38	4.16	4.10	5.24	3.76	3.74	3.57	3.56	3.50	3.19	3.27
	Nov	2.50	2.62	2.60	2.64	2.69	3.51	2.41	2.86	2.69	2.92	2.68	2.45	2.52
	Dec	1.92	1.96	1.92	1.16	1.13	1.17	0.63	2.06	1.84	2.54	1.92	1.93	2.02
1986	Jan	2.02	1.97	1.92	1.07	1.25	1.21	0.66	1.56	1.37	2.31	1.60	2.09	2.18
	Feb	2.51	3.06	3.09	1.59	1.89	1.91	1.21	1.93	1.74	2.94	2.04	2.99	3.11
	Mar	3.35	3.64	3.75	2.47	2.55	1.98	1.49	3.36	3.14	3.94	3.25	3.77	3.91
	Apr	4.21	5.39	5.77	3.58	3.64	2.77	2.27	4.52	4.26	5.36	4.37	5.32	5.50
	May	5.21	5.45	5.99	5.56	5.61	5.07	4.38	5.63	5.39	5.69	5.32	5.56	5.71
	Jun	4.25	4.86	5.39	6.44	6.43	6.88	5.53	5.37	5.15	4.98	4.89	4.81	4.94
	Jul	4.81	4.84	5.41	6.86	6.85	7.66	6.15	5.59	5.39	5.15	5.22	4.99	5.11
	Aug	4.79	3.99	4.33	6.19	6.19	6.86	5.38	4.66	4.46	4.26	4.25	4.00	4.10
	Sep	3.85	4.07	4.41	5.27	5.26	6.60	4.75	4.58	4.38	4.29	4.19	3.91	4.01
	Oct	3.42	2.94	2.99	3.77	3.72	4.22	3.12	3.51	3.31	3.42	3.23	2.92	3.01
	Nov	2.50	2.07	1.96	2.71	2.76	3.69	2.51	2.56	2.40	2.50	2.35	2.06	2.13
	Dec	1.92	1.60	1.43	1.53	1.50	1.83	1.17	2.06	1.91	2.10	1.89	1.73	1.79

Table A.1. Monthly evapotranspiration values in mm/day for Gainesville by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1987	Jan	2.02	1.67	1.59	1.05	1.24	1.18	0.72	1.67	1.48	2.26	1.68	2.02	2.12
	Feb	2.51	2.10	2.02	1.40	1.67	1.56	1.01	1.96	1.78	2.57	2.01	2.54	2.64
	Mar	3.35	2.69	2.67	2.56	2.64	2.11	1.72	3.00	2.84	3.14	2.87	3.04	3.15
	Apr	4.21	4.35	4.57	3.27	3.32	2.34	2.00	4.03	3.78	4.61	3.84	4.52	4.69
	May	5.21	4.47	4.80	5.37	5.41	4.70	4.16	4.88	4.69	4.65	4.51	4.56	4.70
	Jun	4.25	4.68	5.17	6.43	6.42	6.84	5.48	5.27	5.08	4.90	4.91	4.83	4.96
	Jul	4.81	4.71	5.25	6.89	6.87	7.71	6.11	5.45	5.25	4.95	5.03	4.78	4.89
	Aug	4.79	4.47	4.96	6.58	6.58	7.94	5.92	5.14	4.94	4.68	4.73	4.47	4.58
	Sep	3.85	3.52	3.74	5.18	5.17	6.34	4.59	4.14	3.95	3.88	3.82	3.55	3.64
	Oct	3.42	3.32	3.39	3.10	3.05	2.83	2.22	3.70	3.49	3.73	3.37	3.12	3.23
	Nov	2.50	2.33	2.25	2.16	2.20	2.38	1.69	2.67	2.48	2.77	2.43	2.19	2.27
	Dec	1.92	1.84	1.73	1.39	1.36	1.57	1.04	2.17	1.95	2.56	2.04	1.96	2.04
1988	Jan	2.02	1.51	1.50	0.86	1.01	0.89	0.52	1.58	1.44	2.07	1.62	1.93	2.03
	Feb	2.51	2.10	2.09	1.15	1.37	1.15	0.76	1.89	1.72	2.69	2.05	2.69	2.81
	Mar	3.35	3.10	3.15	2.31	2.39	1.77	1.54	3.20	3.02	3.62	3.16	3.51	3.65
	Apr	4.21	3.87	4.03	3.74	3.79	3.00	2.70	4.06	3.87	4.48	4.18	4.63	4.78
	May	5.21	4.49	4.78	4.78	4.82	3.67	3.49	4.96	4.77	4.95	4.80	4.94	5.09
	Jun	4.25	4.41	4.79	5.91	5.90	5.63	4.77	5.15	4.96	5.00	5.09	5.10	5.23
	Jul	4.81	4.40	4.82	6.51	6.50	6.74	5.53	5.21	5.02	4.83	4.92	4.72	4.84
	Aug	4.79	4.02	4.37	6.16	6.16	6.79	5.28	4.70	4.52	4.30	4.33	4.09	4.20
	Sep	3.85	3.48	3.68	5.14	5.13	6.22	4.52	4.15	3.99	3.85	3.95	3.70	3.80
	Oct	3.42	3.06	3.09	2.98	2.94	2.62	2.18	3.71	3.49	3.97	3.62	3.47	3.58
	Nov	2.50	2.21	2.11	2.14	2.18	2.32	1.76	2.80	2.60	3.10	2.78	2.65	2.74
	Dec	1.92	1.69	1.61	1.18	1.15	1.21	0.82	2.10	1.91	2.43	1.98	1.94	2.03

Table A.1. Monthly evapotranspiration values in mm/day for Gainesville by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1989	Jan	2.02	1.97	1.86	1.35	1.58	1.75	1.29	1.95	1.76	2.87	2.29	2.80	2.91
	Feb	2.51	2.30	2.27	1.34	1.59	1.45	0.98	2.14	1.97	3.23	2.62	3.37	3.51
	Mar	3.35	3.48	3.57	2.70	2.79	2.33	1.99	3.57	3.41	4.16	3.85	4.26	4.41
	Apr	4.21	3.79	3.93	3.52	3.57	2.68	2.38	4.10	3.91	4.73	4.41	4.92	5.08
	May	5.21	4.42	4.72	5.02	5.07	4.07	3.76	4.98	4.75	5.20	4.92	5.14	5.29
	Jun	4.25	4.28	4.66	6.23	6.22	6.36	5.19	4.99	4.78	4.86	4.81	4.80	4.92
	Jul	4.81	4.32	4.73	6.53	6.52	6.79	5.57	5.12	4.92	4.79	4.82	4.62	4.74
	Aug	4.79	3.95	4.28	6.20	6.20	6.89	5.34	4.69	4.48	4.44	4.39	4.18	4.29
	Sep	3.85	3.17	3.30	4.94	4.92	5.66	4.23	3.92	3.74	3.77	3.74	3.52	3.61
	Oct	3.42	2.70	2.67	3.26	3.21	3.13	2.51	3.44	3.24	3.50	3.29	3.06	3.15
	Nov	2.50	3.53	3.64	1.90	1.94	1.89	1.38	2.97	2.71	3.67	2.76	2.76	2.87
	Dec	1.92	1.24	1.26	0.80	0.79	0.72	0.32	1.98	1.80	2.18	1.79	1.71	1.80
1990	Jan	2.02	1.99	1.89	1.30	1.52	1.64	1.09	1.79	1.58	2.63	1.93	2.40	2.50
	Feb	2.51	2.27	2.18	1.67	1.99	2.10	1.41	2.16	1.97	2.96	2.39	3.00	3.10
	Mar	3.35	3.29	3.35	2.67	2.76	2.29	1.84	3.29	3.05	3.86	3.20	3.63	3.76
	Apr	4.21	3.90	4.05	3.45	3.50	2.57	2.17	3.89	3.65	4.35	3.75	4.28	4.43
	May	5.21	4.47	4.82	5.45	5.50	4.86	4.25	4.98	4.76	5.00	4.80	4.93	5.07
	Jun	4.25	4.31	4.69	6.12	6.10	6.09	5.03	4.94	4.71	4.77	4.62	4.59	4.72
	Jul	4.81	4.17	4.54	6.46	6.44	6.61	5.49	4.94	4.72	4.60	4.53	4.31	4.42
	Aug	4.79	3.89	4.20	6.09	6.09	6.60	5.21	4.61	4.38	4.39	4.25	4.02	4.12
	Sep	3.85	3.62	3.84	4.87	4.86	5.49	4.12	4.27	4.03	4.25	3.99	3.77	3.87
	Oct	3.42	2.89	2.91	3.52	3.47	3.66	2.79	3.53	3.29	3.60	3.27	2.98	3.08
	Nov	2.50	2.33	2.25	2.13	2.17	2.31	1.61	2.76	2.52	3.04	2.58	2.37	2.46
	Dec	1.92	1.80	1.66	1.57	1.53	1.91	1.29	2.15	1.96	2.37	1.98	1.85	1.92

Table A.2. Monthly evapotranspiration values in mm/day for Jacksonville by ET method

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Jan	2.02	1.63	1.70	0.77	0.90	0.78	0.36	1.55	1.40	2.54	1.91	2.45	2.54
	Feb	2.51	2.30	2.29	1.24	1.48	1.29	0.81	1.82	1.67	2.67	2.04	2.75	2.84
	Mar	3.35	3.43	3.51	2.60	2.69	2.18	1.82	3.36	3.20	3.79	3.43	3.81	3.92
	Apr	4.21	4.03	4.21	3.56	3.62	2.73	2.40	3.96	3.79	4.21	3.85	4.29	4.41
	May	5.21	4.81	5.21	5.39	5.44	4.70	4.20	5.21	5.06	4.84	4.94	4.93	5.05
	Jun	4.25	4.58	5.04	6.40	6.39	6.67	5.40	5.28	5.15	4.71	5.11	4.93	5.03
	Jul	4.81	4.61	5.07	6.55	6.54	6.75	5.59	5.35	5.21	4.69	4.97	4.68	4.79
	Aug	4.79	3.86	4.17	6.15	6.15	6.72	5.29	4.57	4.45	3.93	4.28	3.97	4.06
	Sep	3.85	3.63	3.83	4.83	4.82	5.37	4.06	4.27	4.17	3.75	4.13	3.79	3.87
	Oct	3.42	2.87	2.91	3.94	3.89	4.67	3.48	3.47	3.37	3.13	3.40	3.06	3.12
	Nov	2.50	2.42	2.35	2.50	2.55	3.17	2.26	2.77	2.65	2.76	2.74	2.52	2.58
	Dec	1.92	1.69	1.67	1.00	0.98	0.97	0.53	2.11	1.96	2.51	2.13	2.11	2.18
1986	Jan	2.02	1.72	1.72	0.90	1.05	0.95	0.50	1.51	1.39	2.21	1.73	2.15	2.23
	Feb	2.51	2.42	2.39	1.43	1.69	1.61	1.06	1.92	1.78	2.70	2.16	2.84	2.92
	Mar	3.35	3.24	3.31	2.29	2.36	1.74	1.38	3.23	3.08	3.63	3.29	3.63	3.74
	Apr	4.21	4.77	5.05	3.42	3.48	2.53	2.19	4.33	4.13	5.06	4.40	5.14	5.28
	May	5.21	4.74	5.09	5.04	5.09	4.07	3.71	5.14	4.96	5.05	4.97	5.08	5.21
	Jun	4.25	4.81	5.33	6.53	6.52	7.00	5.60	5.42	5.25	4.94	5.10	4.99	5.10
	Jul	4.81	4.97	5.60	7.14	7.12	8.30	6.46	5.86	5.71	5.28	5.69	5.41	5.51
	Aug	4.79	4.28	4.70	6.28	6.28	7.04	5.48	5.03	4.89	4.51	4.81	4.54	4.63
	Sep	3.85	4.02	4.34	5.15	5.14	6.24	4.54	4.59	4.44	4.17	4.33	4.05	4.13
	Oct	3.42	2.95	2.98	3.55	3.50	3.73	2.86	3.53	3.39	3.35	3.39	3.10	3.17
	Nov	2.50	2.03	1.90	2.43	2.48	3.01	2.13	2.56	2.43	2.53	2.47	2.23	2.28
	Dec	1.92	1.53	1.39	1.29	1.26	1.40	0.89	2.05	1.95	2.06	1.98	1.81	1.86

Table A.2. Monthly evapotranspiration values in mm/day for Jacksonville by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1987	Jan	2.02	1.63	1.60	0.92	1.07	0.98	0.60	1.60	1.46	2.27	1.81	2.20	2.27
	Feb	2.51	1.97	1.94	1.15	1.36	1.15	0.74	1.79	1.67	2.31	1.92	2.39	2.48
	Mar	3.35	2.69	2.69	2.23	2.30	1.67	1.43	2.97	2.87	2.96	2.95	3.02	3.12
	Apr	4.21	4.31	4.52	3.17	3.22	2.19	2.01	4.12	3.95	4.64	4.19	4.74	4.88
	May	5.21	4.45	4.75	5.05	5.09	4.07	3.80	4.94	4.78	4.69	4.77	4.78	4.90
	Jun	4.25	4.81	5.31	6.37	6.35	6.58	5.34	5.45	5.29	5.05	5.25	5.17	5.27
	Jul	4.81	4.96	5.55	6.85	6.84	7.52	5.98	5.78	5.62	5.21	5.53	5.26	5.37
	Aug	4.79	4.89	5.49	6.73	6.73	8.34	6.06	5.63	5.47	5.07	5.37	5.09	5.18
	Sep	3.85	3.83	4.11	5.07	5.05	6.00	4.41	4.40	4.25	4.02	4.10	3.83	3.91
	Oct	3.42	3.08	3.11	2.68	2.65	2.17	1.81	3.70	3.54	3.76	3.68	3.45	3.54
	Nov	2.50	2.14	2.04	1.93	1.96	1.95	1.46	2.68	2.54	2.80	2.69	2.51	2.58
	Dec	1.92	1.86	1.77	1.29	1.26	1.40	0.99	2.23	2.06	2.65	2.29	2.27	2.34
1988	Jan	2.02	1.47	1.51	0.77	0.90	0.78	0.41	1.41	1.29	1.92	1.46	1.80	1.87
	Feb	2.51	2.10	2.15	1.03	1.22	0.98	0.61	1.70	1.56	2.52	1.90	2.57	2.66
	Mar	3.35	3.22	3.29	2.22	2.29	1.65	1.44	3.18	3.03	3.53	3.18	3.50	3.62
	Apr	4.21	3.98	4.15	3.62	3.68	2.82	2.58	3.95	3.79	4.13	3.85	4.24	4.36
	May	5.21	4.88	5.23	4.76	4.81	3.61	3.48	5.15	4.96	5.04	4.83	4.99	5.12
	Jun	4.25	4.82	5.28	6.02	6.00	5.77	4.88	5.45	5.30	5.01	5.27	5.18	5.29
	Jul	4.81	4.81	5.34	6.70	6.68	7.11	5.76	5.62	5.47	5.01	5.37	5.09	5.19
	Aug	4.79	4.39	4.85	6.49	6.49	7.64	5.72	5.14	4.99	4.59	4.90	4.62	4.71
	Sep	3.85	3.63	3.87	5.14	5.13	6.20	4.51	4.29	4.18	3.76	4.14	3.81	3.89
	Oct	3.42	3.06	3.09	2.98	2.93	2.63	2.20	3.64	3.49	3.64	3.56	3.32	3.41
	Nov	2.50	2.32	2.24	2.12	2.16	2.31	1.76	2.80	2.65	3.05	2.88	2.74	2.81
	Dec	1.92	1.81	1.76	1.13	1.10	1.15	0.77	2.12	1.93	2.54	2.06	2.04	2.10

Table A.2. Monthly evapotranspiration values in mm/day for Jacksonville by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1989	Jan	2.02	2.11	2.02	1.34	1.57	1.75	1.23	1.71	1.55	2.49	1.93	2.44	2.50
	Feb	2.51	2.46	2.44	1.38	1.63	1.52	1.00	1.90	1.74	2.83	2.18	2.95	3.04
	Mar	3.35	3.11	3.14	2.73	2.81	2.37	1.98	3.24	3.10	3.49	3.28	3.54	3.63
	Apr	4.21	4.08	4.26	3.58	3.64	2.75	2.41	4.02	3.86	4.26	3.97	4.39	4.51
	May	5.21	4.72	5.07	5.11	5.16	4.19	3.82	5.15	4.98	5.02	5.01	5.09	5.21
	Jun	4.25	4.71	5.20	6.44	6.43	6.76	5.46	5.41	5.25	4.98	5.25	5.15	5.25
	Jul	4.81	4.57	5.06	6.87	6.86	7.57	6.06	5.43	5.29	4.79	5.22	4.92	5.01
	Aug	4.79	4.33	4.76	6.39	6.39	7.36	5.64	5.08	4.94	4.51	4.85	4.56	4.65
	Sep	3.85	3.41	3.60	5.08	5.07	6.03	4.43	4.09	3.98	3.60	3.95	3.64	3.71
	Oct	3.42	2.87	2.89	3.40	3.35	3.41	2.67	3.51	3.39	3.31	3.46	3.16	3.23
	Nov	2.50	2.32	2.24	1.93	1.96	1.95	1.38	2.74	2.56	3.06	2.70	2.58	2.64
	Dec	1.92	1.38	1.43	0.81	0.79	0.73	0.30	2.05	1.91	2.32	2.04	1.97	2.04
1990	Jan	2.02	2.10	2.03	1.22	1.43	1.51	0.94	1.68	1.52	2.63	1.99	2.58	2.65
	Feb	2.51	2.42	2.36	1.64	1.95	2.04	1.33	2.08	1.95	2.76	2.39	2.98	3.06
	Mar	3.35	3.44	3.52	2.71	2.80	2.35	1.85	3.40	3.24	3.84	3.51	3.89	3.99
	Apr	4.21	4.00	4.17	3.51	3.56	2.65	2.21	4.03	3.87	4.31	4.08	4.48	4.60
	May	5.21	4.77	5.16	5.38	5.42	4.67	4.12	5.34	5.19	5.16	5.41	5.42	5.54
	Jun	4.25	4.81	5.32	6.44	6.42	6.75	5.48	5.57	5.42	5.21	5.58	5.49	5.59
	Jul	4.81	4.92	5.51	7.05	7.03	8.05	6.39	5.86	5.73	5.19	5.82	5.48	5.57
	Aug	4.79	4.56	5.06	6.49	6.49	7.62	5.83	5.36	5.20	4.94	5.25	5.02	5.11
	Sep	3.85	4.20	4.56	5.13	5.12	6.18	4.51	4.86	4.70	4.67	4.83	4.63	4.71
	Oct	3.42	3.25	3.34	3.63	3.58	3.91	2.93	3.83	3.69	3.77	3.84	3.59	3.66
	Nov	2.50	2.52	2.47	2.00	2.04	2.09	1.39	2.88	2.69	3.32	2.95	2.88	2.95
	Dec	1.92	1.84	1.71	1.48	1.45	1.77	1.13	2.29	2.13	2.66	2.38	2.34	2.39

Table A.3. Monthly evapotranspiration values in mm/day for Daytona Beach by ET method

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Jan	2.02	2.08	2.09	1.00	1.17	1.09	0.56	1.82	1.70	2.83	2.40	2.94	3.01
	Feb	2.51	2.73	2.72	1.51	1.79	1.76	1.10	2.18	2.07	2.95	2.60	3.26	3.33
	Mar	3.35	3.89	4.04	2.86	2.95	2.59	2.04	3.76	3.65	3.99	3.95	4.19	4.29
	Apr	4.21	4.33	4.57	3.85	3.91	3.18	2.64	4.34	4.24	4.11	4.33	4.44	4.55
	May	5.21	5.26	5.76	5.49	5.53	4.91	4.28	5.73	5.62	5.22	5.70	5.55	5.66
	Jun	4.25	4.93	5.48	6.55	6.53	7.10	5.69	5.67	5.56	4.88	5.55	5.26	5.35
	Jul	4.81	5.03	5.58	6.49	6.47	6.65	5.55	5.81	5.69	4.95	5.53	5.14	5.24
	Aug	4.79	3.94	4.27	6.24	6.24	6.96	5.46	4.69	4.60	3.88	4.51	4.11	4.19
	Sep	3.85	3.90	4.18	4.99	4.98	5.81	4.29	4.53	4.46	3.62	4.39	3.88	3.96
	Oct	3.42	3.42	3.59	4.15	4.09	5.23	3.75	3.95	3.87	3.35	3.89	3.44	3.50
	Nov	2.50	2.77	2.76	2.67	2.72	3.59	2.45	3.06	2.96	2.97	3.13	2.89	2.93
	Dec	1.92	1.93	1.87	1.23	1.20	1.30	0.73	2.30	2.17	2.70	2.50	2.51	2.56
1986	Jan	2.02	1.98	1.92	1.14	1.34	1.34	0.77	1.79	1.68	2.43	2.08	2.48	2.53
	Feb	2.51	2.56	2.53	1.60	1.90	1.94	1.23	2.16	2.04	2.79	2.43	3.01	3.07
	Mar	3.35	3.45	3.54	2.52	2.60	2.06	1.56	3.47	3.37	3.53	3.56	3.68	3.77
	Apr	4.21	4.74	5.02	3.44	3.50	2.56	2.10	4.47	4.32	4.91	4.59	5.09	5.21
	May	5.21	4.76	5.13	5.11	5.16	4.21	3.74	5.30	5.18	4.91	5.30	5.18	5.28
	Jun	4.25	4.58	5.03	6.24	6.22	6.33	5.21	5.28	5.17	4.59	5.11	4.86	4.95
	Jul	4.81	4.72	5.23	6.62	6.60	6.96	5.75	5.58	5.45	4.85	5.42	5.06	5.15
	Aug	4.79	4.45	4.89	6.25	6.25	7.01	5.49	5.21	5.09	4.58	5.05	4.73	4.81
	Sep	3.85	4.06	4.40	5.17	5.16	6.31	4.58	4.66	4.54	4.09	4.44	4.11	4.18
	Oct	3.42	3.28	3.39	3.94	3.89	4.66	3.40	3.83	3.72	3.50	3.78	3.44	3.50
	Nov	2.50	2.46	2.42	2.77	2.82	3.88	2.62	2.85	2.74	2.71	2.82	2.57	2.61
	Dec	1.92	1.85	1.70	1.73	1.69	2.30	1.53	2.22	2.14	2.17	2.27	2.11	2.15

Table A.3. Monthly evapotranspiration values in mm/day for Daytona Beach by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1987	Jan	2.02	1.94	1.88	1.10	1.29	1.26	0.78	1.83	1.72	2.54	2.20	2.61	2.66
	Feb	2.51	2.18	2.11	1.44	1.71	1.63	1.06	2.07	1.97	2.47	2.28	2.66	2.73
	Mar	3.35	2.91	2.91	2.53	2.61	2.07	1.67	3.14	3.06	2.93	3.10	3.06	3.15
	Apr	4.21	4.54	4.78	3.27	3.32	2.33	1.99	4.37	4.24	4.63	4.50	4.84	4.97
	May	5.21	5.03	5.45	5.22	5.26	4.40	3.95	5.45	5.36	4.62	5.22	4.89	5.01
	Jun	4.25	5.12	5.68	6.23	6.22	6.33	5.20	5.75	5.65	4.91	5.51	5.20	5.31
	Jul	4.81	5.25	5.88	6.71	6.69	7.19	5.85	6.04	5.92	5.21	5.76	5.38	5.48
	Aug	4.79	5.07	5.68	6.44	6.44	7.53	5.74	5.80	5.68	5.01	5.55	5.18	5.27
	Sep	3.85	4.02	4.34	5.16	5.15	6.27	4.55	4.62	4.49	4.12	4.40	4.10	4.17
	Oct	3.42	3.16	3.21	3.31	3.27	3.23	2.51	3.78	3.71	3.28	3.84	3.39	3.45
	Nov	2.50	2.34	2.26	2.27	2.31	2.60	1.85	2.81	2.73	2.65	2.89	2.61	2.66
	Dec	1.92	2.11	2.01	1.56	1.52	1.91	1.30	2.35	2.22	2.73	2.51	2.52	2.56
1988	Jan	2.02	1.76	1.69	1.06	1.24	1.20	0.73	1.71	1.62	2.10	1.88	2.13	2.18
	Feb	2.51	2.40	2.40	1.28	1.52	1.35	0.84	2.02	1.91	2.75	2.34	2.93	3.01
	Mar	3.35	3.48	3.57	2.49	2.57	2.02	1.64	3.46	3.35	3.61	3.53	3.71	3.81
	Apr	4.21	4.38	4.62	3.79	3.85	3.08	2.66	4.40	4.28	4.54	4.58	4.86	4.97
	May	5.21	5.01	5.40	4.95	4.99	3.93	3.61	5.38	5.26	4.94	5.19	5.10	5.22
	Jun	4.25	4.98	5.49	6.09	6.07	5.98	4.99	5.62	5.51	4.78	5.40	5.08	5.19
	Jul	4.81	4.90	5.44	6.57	6.55	6.84	5.64	5.74	5.64	4.85	5.55	5.11	5.21
	Aug	4.79	4.66	5.15	6.26	6.26	7.02	5.46	5.37	5.25	4.63	5.12	4.77	4.86
	Sep	3.85	3.79	4.09	5.30	5.28	6.67	4.76	4.43	4.34	3.73	4.25	3.86	3.93
	Oct	3.42	3.27	3.35	3.41	3.36	3.43	2.66	3.86	3.75	3.67	3.90	3.59	3.65
	Nov	2.50	2.50	2.44	2.35	2.39	2.78	1.99	2.95	2.81	3.14	3.05	2.91	2.95
	Dec	1.92	2.11	2.03	1.43	1.40	1.65	1.11	2.28	2.14	2.69	2.37	2.40	2.44

Table A.3. Monthly evapotranspiration values in mm/day for Daytona Beach by ET method (cont.)

Year	Month	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1989	Jan	2.02	2.43	2.36	1.58	1.85	2.32	1.57	1.96	1.82	2.68	2.24	2.74	2.79
	Feb	2.51	2.88	2.89	1.58	1.87	1.89	1.19	2.12	1.98	2.97	2.40	3.16	3.23
	Mar	3.35	3.50	3.59	2.99	3.09	2.82	2.22	3.62	3.52	3.59	3.80	3.87	3.95
	Apr	4.21	4.35	4.59	3.83	3.89	3.15	2.60	4.39	4.28	4.35	4.52	4.70	4.81
	May	5.21	5.28	5.77	5.40	5.45	4.74	4.15	5.73	5.61	5.26	5.69	5.55	5.66
	Jun	4.25	5.03	5.58	6.33	6.32	6.56	5.36	5.76	5.64	5.10	5.71	5.47	5.56
	Jul	4.81	5.20	5.84	6.87	6.85	7.62	6.16	6.12	6.01	5.30	6.07	5.65	5.74
	Aug	4.79	4.69	5.20	6.32	6.32	7.18	5.59	5.48	5.36	4.81	5.38	5.04	5.12
	Sep	3.85	4.16	4.52	5.27	5.26	6.60	4.74	4.82	4.73	4.13	4.74	4.33	4.40
	Oct	3.42	3.02	3.07	3.73	3.67	4.12	3.05	3.70	3.62	3.27	3.79	3.40	3.46
	Nov	2.50	2.55	2.51	2.21	2.25	2.49	1.68	2.96	2.82	3.14	3.06	2.92	2.96
	Dec	1.92	1.73	1.69	1.08	1.06	1.07	0.52	2.26	2.14	2.61	2.46	2.43	2.48
1990	Jan	2.02	2.42	2.36	1.45	1.70	1.99	1.21	1.93	1.81	2.73	2.32	2.85	2.90
	Feb	2.51	2.89	2.89	1.93	2.30	2.75	1.74	2.41	2.34	2.78	2.78	3.23	3.29
	Mar	3.35	3.86	4.01	2.85	2.94	2.57	1.90	3.71	3.59	3.89	3.80	4.04	4.13
	Apr	4.21	4.70	5.00	3.85	3.91	3.18	2.52	4.57	4.48	4.41	4.60	4.74	4.86
	May	5.21	5.29	5.83	5.70	5.76	5.36	4.56	5.84	5.76	4.98	5.81	5.43	5.54
	Jun	4.25	5.01	5.56	6.39	6.37	6.70	5.46	5.72	5.60	5.05	5.62	5.38	5.48
	Jul	4.81	5.03	5.61	6.72	6.71	7.23	5.97	5.92	5.82	5.02	5.82	5.36	5.45
	Aug	4.79	4.73	5.24	6.33	6.33	7.23	5.66	5.49	5.36	4.85	5.35	5.03	5.11
	Sep	3.85	4.29	4.69	5.28	5.27	6.61	4.77	4.96	4.86	4.27	4.89	4.48	4.56
	Oct	3.42	3.54	3.72	4.03	3.98	4.89	3.50	4.10	4.02	3.55	4.16	3.71	3.76
	Nov	2.50	2.71	2.69	2.32	2.37	2.73	1.76	3.08	2.97	3.20	3.29	3.12	3.16
	Dec	1.92	2.35	2.27	1.76	1.72	2.36	1.47	2.52	2.38	3.01	2.81	2.88	2.91

APPENDIX B

SUMMARY STATISTICS OF DAILY AND MONTHLY REFERENCE EVAPOTRANSPIRATION VALUES

Table B.1. Statistics of daily evapotranspiration values by ET method for Gainesville

Year	Statistics	Evapotranspiration in mm/day from Different ET Methods							
		Turc	McCloud	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.40	4.39	3.75	3.55	3.78	3.54	3.54	3.64
	SD	1.48	2.44	1.55	1.54	1.31	1.44	1.40	1.43
	Max	6.88	11.61	7.49	7.27	7.71	7.89	8.10	8.38
	Min	0.00	0.14	0.95	0.79	1.15	0.81	1.03	1.05
1986	Mean	3.62	4.41	3.84	3.64	3.90	3.59	3.63	3.72
	SD	1.58	2.45	1.58	1.55	1.45	1.47	1.50	1.52
	Max	6.66	10.49	6.93	6.73	7.29	6.74	7.12	7.38
	Min	0.00	0.24	1.15	0.85	1.03	1.11	0.94	0.97
1987	Mean	3.31	4.13	3.66	3.46	3.69	3.42	3.42	3.51
	SD	1.43	2.61	1.47	1.46	1.27	1.37	1.33	1.35
	Max	6.03	10.86	6.60	6.38	6.36	6.24	6.19	6.36
	Min	0.51	0.41	1.14	0.99	1.00	0.98	0.87	0.88
1988	Mean	3.14	3.69	3.63	3.45	3.72	3.54	3.55	3.67
	SD	1.42	2.37	1.41	1.40	1.27	1.40	1.39	1.42
	Max	5.79	10.49	6.32	6.17	6.74	6.47	6.87	7.17
	Min	0.32	0.38	1.05	0.96	0.86	0.86	0.74	0.75
1989	Mean	3.22	3.89	3.67	3.47	3.90	3.65	3.71	3.85
	SD	1.32	2.36	1.31	1.30	1.20	1.31	1.33	1.37
	Max	5.69	9.17	6.21	6.00	6.47	6.35	6.72	7.01
	Min	0.00	0.11	0.84	0.77	0.80	0.56	0.64	0.64
1990	Mean	3.21	4.06	3.62	3.39	3.79	3.44	3.47	3.59
	SD	1.18	2.13	1.25	1.24	1.07	1.16	1.14	1.16
	Max	5.55	8.86	6.23	5.96	6.00	5.86	5.96	6.17
	Min	0.70	0.47	1.32	1.09	1.05	1.20	1.09	1.11

Table B.2. Statistics of daily evapotranspiration values by ET method for Jacksonville

Year	Statistics	Evapotranspiration in mm/day from Different ET Methods							
		Turc	McCloud	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.27	4.04	3.68	3.54	3.58	3.58	3.54	3.62
	SD	1.41	2.44	1.49	1.48	1.24	1.38	1.32	1.34
	Max	6.53	11.63	7.47	7.34	6.75	7.40	7.17	7.34
	Min	0.00	0.21	0.96	0.83	0.99	0.97	0.95	0.95
1986	Mean	3.42	4.19	3.81	3.66	3.76	3.71	3.69	3.77
	SD	1.48	2.73	1.58	1.56	1.41	1.52	1.49	1.52
	Max	6.41	12.82	7.62	7.47	6.80	7.77	7.35	7.53
	Min	0.00	0.23	1.08	0.85	0.95	1.03	0.89	0.90
1987	Mean	3.34	3.86	3.76	3.61	3.72	3.68	3.65	3.73
	SD	1.46	2.78	1.56	1.55	1.37	1.49	1.45	1.48
	Max	6.15	10.49	7.08	6.90	6.53	7.01	6.76	6.91
	Min	0.64	0.36	1.06	0.91	0.86	1.03	0.82	0.83
1988	Mean	3.33	3.76	3.72	3.56	3.68	3.60	3.58	3.66
	SD	1.48	2.63	1.55	1.54	1.34	1.48	1.42	1.45
	Max	6.42	10.11	7.13	6.97	6.68	7.16	7.01	7.16
	Min	0.30	0.34	1.04	0.91	0.64	0.73	0.52	0.52
1989	Mean	3.31	4.14	3.73	3.58	3.69	3.65	3.63	3.72
	SD	1.44	2.61	1.52	1.51	1.32	1.46	1.42	1.45
	Max	6.14	10.88	6.93	6.75	6.56	6.82	6.68	6.84
	Min	0.00	0.20	0.90	0.86	0.71	0.83	0.59	0.58
1990	Mean	3.54	4.37	3.93	3.78	3.97	3.98	3.99	4.09
	SD	1.31	2.67	1.53	1.53	1.26	1.50	1.40	1.42
	Max	6.25	11.63	7.44	7.31	6.86	7.96	7.62	7.84
	Min	0.89	0.53	1.29	1.12	0.97	1.30	1.01	1.01

Table B.3. Statistics of daily evapotranspiration values by ET method for Daytona Beach

Year	Statistics	Evapotranspiration in mm/day from Different ET Methods							
		Turc	McCloud	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.65	4.37	4.02	3.92	3.76	4.05	3.92	3.99
	SD	1.44	2.30	1.56	1.56	1.25	1.46	1.36	1.38
	Max	6.48	10.17	7.31	7.17	7.23	8.90	8.57	8.80
	Min	0.00	0.18	1.12	1.03	1.06	1.11	1.20	1.21
1986	Mean	3.55	4.29	3.94	3.82	3.72	3.92	3.82	3.88
	SD	1.34	2.18	1.46	1.45	1.25	1.40	1.33	1.35
	Max	6.27	10.11	7.35	7.23	6.52	7.59	7.15	7.29
	Min	0.30	0.28	1.36	1.27	0.87	1.43	1.11	1.13
1987	Mean	3.61	4.05	4.00	3.89	3.71	3.96	3.81	3.88
	SD	1.53	2.36	1.65	1.64	1.35	1.52	1.42	1.44
	Max	6.42	9.46	7.15	7.05	7.13	7.18	7.49	7.68
	Min	0.97	0.48	1.38	1.30	0.93	1.14	0.87	0.87
1988	Mean	3.57	4.00	3.95	3.83	3.73	3.91	3.80	3.87
	SD	1.47	2.32	1.55	1.55	1.25	1.44	1.34	1.35
	Max	6.38	9.46	6.87	6.82	6.82	6.74	6.85	7.01
	Min	0.78	0.51	1.39	1.21	0.79	1.09	0.78	0.77
1989	Mean	3.71	4.42	4.11	3.99	3.91	4.16	4.06	4.14
	SD	1.49	2.36	1.62	1.63	1.34	1.58	1.47	1.49
	Max	6.36	9.81	7.15	7.04	6.77	7.98	7.78	7.97
	Min	0.00	0.21	1.25	1.22	0.80	1.19	0.77	0.78
1990	Mean	3.89	4.65	4.21	4.10	3.93	4.26	4.13	4.21
	SD	1.33	2.25	1.53	1.53	1.14	1.40	1.22	1.24
	Max	6.47	10.17	7.37	7.33	6.59	8.32	7.68	7.85
	Min	0.66	0.59	1.38	1.35	1.10	1.57	1.28	1.30

Table B.4. Statistics of monthly evapotranspiration values by ET method for Gainesville

Year	Statistics	Evapotranspiration in mm/day from Different ET Methods												
		AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.57	3.43	3.63	3.91	3.96	4.19	3.21	3.74	3.55	3.81	3.55	3.59	3.71
	SD	1.13	1.14	1.36	2.11	2.06	2.33	1.95	1.39	1.40	0.98	1.23	1.10	1.12
	Max	5.21	5.01	5.60	6.66	6.64	7.44	5.85	5.62	5.43	5.18	5.29	5.20	5.33
	Min	1.92	1.65	1.64	0.90	1.05	0.94	0.44	1.64	1.43	2.44	1.75	1.93	2.02
1986	Mean	3.57	3.66	3.87	3.92	3.97	4.22	3.22	3.78	3.58	3.91	3.55	3.68	3.79
	SD	1.13	1.34	1.60	2.08	2.02	2.33	1.94	1.48	1.47	1.25	1.34	1.33	1.36
	Max	5.21	5.45	5.99	6.86	6.85	7.66	6.15	5.63	5.39	5.69	5.32	5.56	5.71
	Min	1.92	1.60	1.43	1.07	1.25	1.21	0.66	1.56	1.37	2.10	1.60	1.73	1.79
1987	Mean	3.57	3.35	3.51	3.78	3.83	3.96	3.06	3.67	3.48	3.73	3.44	3.47	3.58
	SD	1.13	1.18	1.42	2.19	2.14	2.58	2.05	1.36	1.36	1.02	1.22	1.13	1.15
	Max	5.21	4.71	5.25	6.89	6.87	7.94	6.11	5.45	5.25	4.95	5.03	4.83	4.96
	Min	1.92	1.67	1.59	1.05	1.24	1.18	0.72	1.67	1.48	2.26	1.68	1.96	2.04
1988	Mean	3.57	3.20	3.34	3.57	3.61	3.50	2.82	3.63	3.44	3.77	3.54	3.61	3.73
	SD	1.13	1.09	1.26	2.08	2.04	2.26	1.84	1.30	1.29	1.01	1.21	1.12	1.14
	Max	5.21	4.49	4.82	6.51	6.50	6.79	5.53	5.21	5.02	5.00	5.09	5.10	5.23
	Min	1.92	1.51	1.50	0.86	1.01	0.89	0.52	1.58	1.44	2.07	1.62	1.93	2.03
1989	Mean	3.57	3.26	3.41	3.65	3.70	3.64	2.91	3.65	3.46	3.95	3.64	3.76	3.88
	SD	1.13	1.02	1.17	2.09	2.03	2.24	1.84	1.19	1.18	0.91	1.08	1.06	1.08
	Max	5.21	4.42	4.73	6.53	6.52	6.89	5.57	5.12	4.92	5.20	4.92	5.14	5.29
	Min	1.92	1.24	1.26	0.80	0.79	0.72	0.32	1.95	1.76	2.18	1.79	1.71	1.80
1990	Mean	3.57	3.24	3.37	3.78	3.83	3.84	3.03	3.61	3.39	3.82	3.44	3.51	3.62
	SD	1.13	0.96	1.15	1.94	1.88	1.96	1.68	1.18	1.17	0.88	1.04	0.98	1.00
	Max	5.21	4.47	4.82	6.46	6.44	6.61	5.49	4.98	4.76	5.00	4.80	4.93	5.07
	Min	1.92	1.80	1.66	1.30	1.52	1.64	1.09	1.79	1.58	2.37	1.93	1.85	1.92

Table B.5. Statistics of monthly evapotranspiration values by ET method for Jacksonville

		Evapotranspiration in mm/day from Different ET Methods												
Year	Statistics	AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.57	3.32	3.50	3.74	3.79	3.83	3.02	3.64	3.51	3.63	3.58	3.61	3.70
	SD	1.13	1.13	1.30	2.14	2.09	2.28	1.92	1.36	1.36	0.88	1.17	1.01	1.02
	Max	5.21	4.81	5.21	6.55	6.54	6.75	5.59	5.35	5.21	4.84	5.11	4.93	5.05
	Min	1.92	1.63	1.67	0.77	0.90	0.78	0.36	1.55	1.40	2.51	1.91	2.11	2.18
1986	Mean	3.57	3.46	3.65	3.79	3.83	3.97	3.07	3.76	3.62	3.79	3.69	3.75	3.84
	SD	1.13	1.30	1.55	2.19	2.14	2.56	2.05	1.50	1.49	1.20	1.37	1.30	1.32
	Max	5.21	4.97	5.60	7.14	7.12	8.30	6.46	5.86	5.71	5.28	5.69	5.41	5.51
	Min	1.92	1.53	1.39	0.90	1.05	0.95	0.50	1.51	1.39	2.06	1.73	1.81	1.86
1987	Mean	3.57	3.39	3.57	3.62	3.66	3.67	2.89	3.77	3.63	3.79	3.71	3.73	3.82
	SD	1.13	1.30	1.55	2.27	2.23	2.71	2.10	1.51	1.50	1.14	1.36	1.23	1.25
	Max	5.21	4.96	5.55	6.85	6.84	8.34	6.06	5.78	5.62	5.21	5.53	5.26	5.37
	Min	1.92	1.63	1.60	0.92	1.07	0.98	0.60	1.60	1.46	2.27	1.81	2.20	2.27
1988	Mean	3.57	3.37	3.56	3.58	3.62	3.55	2.84	3.70	3.55	3.73	3.62	3.66	3.75
	SD	1.13	1.24	1.43	2.19	2.15	2.48	1.98	1.48	1.48	1.07	1.35	1.19	1.21
	Max	5.21	4.88	5.34	6.70	6.68	7.64	5.76	5.62	5.47	5.04	5.37	5.18	5.29
	Min	1.92	1.47	1.51	0.77	0.90	0.78	0.41	1.41	1.29	1.92	1.46	1.80	1.87
1989	Mean	3.57	3.34	3.51	3.76	3.81	3.87	3.03	3.69	3.55	3.72	3.65	3.70	3.79
	SD	1.13	1.14	1.34	2.18	2.13	2.45	1.99	1.39	1.39	0.97	1.25	1.11	1.12
	Max	5.21	4.72	5.20	6.87	6.86	7.57	6.06	5.43	5.29	5.02	5.25	5.15	5.25
	Min	1.92	1.38	1.43	0.81	0.79	0.73	0.30	1.71	1.55	2.32	1.93	1.97	2.04
1990	Mean	3.57	3.57	3.77	3.89	3.94	4.13	3.18	3.93	3.78	4.04	4.00	4.07	4.15
	SD	1.13	1.13	1.38	2.14	2.08	2.44	2.00	1.47	1.48	1.02	1.37	1.18	1.19
	Max	5.21	4.92	5.51	7.05	7.03	8.05	6.39	5.86	5.73	5.21	5.82	5.49	5.59
	Min	1.92	1.84	1.71	1.22	1.43	1.51	0.94	1.68	1.52	2.63	1.99	2.34	2.39

Table B.6. Statistics of monthly evapotranspiration values by ET method for Daytona Beach

Year	Statistics	Evapotranspiration in mm/day from Different ET Methods												
		AGMOD	Turc	Hargreaves	SFWMD	Blaney-Criddle	McCloud	Thornthwaite	Pen48	Pen63	Pen77	Pen84	PenFAO	ASCE90
1985	Mean	3.57	3.68	3.91	3.92	3.97	4.18	3.21	3.99	3.88	3.79	4.04	3.97	4.05
	SD	1.13	1.12	1.34	2.06	2.01	2.22	1.89	1.41	1.41	0.88	1.19	1.00	1.02
	Max	5.21	5.26	5.76	6.55	6.53	7.10	5.69	5.81	5.69	5.22	5.70	5.55	5.66
	Min	1.92	1.93	1.87	1.00	1.17	1.09	0.56	1.82	1.70	2.70	2.40	2.51	2.56
1986	Mean	3.57	3.57	3.77	3.88	3.93	4.13	3.17	3.90	3.79	3.76	3.90	3.86	3.93
	SD	1.13	1.13	1.35	1.97	1.90	2.11	1.78	1.38	1.37	1.03	1.25	1.13	1.15
	Max	5.21	4.76	5.23	6.62	6.60	7.01	5.75	5.58	5.45	4.91	5.42	5.18	5.28
	Min	1.92	1.85	1.70	1.14	1.34	1.34	0.77	1.79	1.68	2.17	2.08	2.11	2.15
1987	Mean	3.57	3.64	3.85	3.77	3.82	3.90	3.04	4.00	3.90	3.76	3.98	3.87	3.95
	SD	1.13	1.33	1.61	2.08	2.03	2.33	1.90	1.55	1.55	1.09	1.35	1.17	1.20
	Max	5.21	5.25	5.88	6.71	6.69	7.53	5.85	6.04	5.92	5.21	5.76	5.38	5.48
	Min	1.92	1.94	1.88	1.10	1.29	1.26	0.78	1.83	1.72	2.47	2.20	2.52	2.56
1988	Mean	3.57	3.60	3.81	3.75	3.79	3.83	3.01	3.94	3.82	3.79	3.93	3.87	3.95
	SD	1.13	1.20	1.42	2.04	1.99	2.23	1.83	1.45	1.46	0.97	1.29	1.10	1.13
	Max	5.21	5.01	5.49	6.57	6.55	7.02	5.64	5.74	5.64	4.94	5.55	5.11	5.22
	Min	1.92	1.76	1.69	1.06	1.24	1.20	0.73	1.71	1.62	2.10	1.88	2.13	2.18
1989	Mean	3.57	3.74	3.97	3.93	3.99	4.21	3.24	4.08	3.96	3.93	4.16	4.11	4.18
	SD	1.13	1.21	1.46	2.07	2.01	2.27	1.91	1.52	1.53	1.02	1.40	1.17	1.19
	Max	5.21	5.28	5.84	6.87	6.85	7.62	6.16	6.12	6.01	5.30	6.07	5.65	5.74
	Min	1.92	1.73	1.69	1.08	1.06	1.07	0.52	1.96	1.82	2.61	2.24	2.43	2.48
1990	Mean	3.57	3.90	4.16	4.05	4.11	4.47	3.38	4.19	4.08	3.98	4.27	4.19	4.26
	SD	1.13	1.09	1.34	1.98	1.91	2.08	1.81	1.45	1.45	0.90	1.27	1.01	1.04
	Max	5.21	5.29	5.83	6.72	6.71	7.23	5.97	5.92	5.82	5.05	5.82	5.43	5.54
	Min	1.92	2.35	2.27	1.45	1.70	1.99	1.21	1.93	1.81	2.73	2.32	2.85	2.90

APPENDIX C

SWFWMD AGMOD GRASS REFERENCE EVAPOTRANSPIRATION

Table C.1. AGMOD reference ET using grass coefficients, the monthly percentage of annual incoming solar radiation from Gainesville, and the average monthly temperature for six years of climatic data by site.

Daytona Beach

Month	Rso	Average T (°F)						Kc	ET (in)						ET Avg
		1985	1986	1987	1988	1989	1990		1985	1986	1987	1988	1989	1990	
Jan	5.30	53.57	56.55	55.71	54.93	64.72	62.40	0.49	0.85	0.98	0.94	0.91	1.35	1.24	1.05
Feb	6.56	61.00	61.73	59.22	57.04	61.73	67.07	0.53	1.57	1.62	1.46	1.33	1.62	1.97	1.60
Mar	8.29	66.31	62.91	63.01	62.62	67.58	66.21	0.55	2.52	2.22	2.23	2.20	2.63	2.51	2.39
Apr	10.32	69.36	66.17	64.73	68.90	69.21	69.34	0.60	3.80	3.40	3.23	3.75	3.79	3.80	3.63
May	10.69	75.77	73.50	74.12	72.47	75.25	77.06	0.63	5.09	4.74	4.83	4.59	5.01	5.29	4.92
Jun	11.02	81.21	79.56	79.48	78.66	80.04	80.26	0.65	6.35	6.05	6.04	5.90	6.14	6.18	6.11
Jul	11.12	80.26	80.94	81.41	80.67	82.26	81.50	0.65	6.23	6.35	6.44	6.31	6.59	6.46	6.40
Aug	9.03	80.93	81.04	82.09	81.07	81.39	81.49	0.63	5.00	5.02	5.17	5.02	5.07	5.08	5.06
Sep	8.54	78.26	79.48	79.38	80.30	80.14	80.18	0.61	4.24	4.39	4.38	4.50	4.48	4.48	4.41
Oct	7.80	76.69	75.01	69.60	70.47	73.20	75.73	0.58	3.51	3.34	2.80	2.89	3.15	3.41	3.18
Nov	6.03	71.13	72.27	66.40	67.38	65.75	67.10	0.54	2.12	2.20	1.80	1.87	1.76	1.85	1.94
Dec	5.28	56.10	64.56	61.80	59.62	53.26	64.95	0.50	0.97	1.37	1.23	1.13	0.85	1.39	1.16

Gainesville

Month	Rso	Average T (°F)						Kc	ET (in)						ET Avg
		1985	1986	1987	1988	1989	1990		1985	1986	1987	1988	1989	1990	
Jan	5.30	51.31	55.03	54.74	50.48	60.56	59.60	0.49	0.76	0.91	0.90	0.73	1.15	1.11	0.93
Feb	6.56	59.41	61.47	58.83	54.72	58.07	63.38	0.53	1.47	1.60	1.44	1.20	1.39	1.72	1.47
Mar	8.29	66.94	62.37	63.27	60.68	64.74	64.48	0.55	2.58	2.18	2.25	2.04	2.38	2.36	2.30
Apr	10.32	69.12	67.30	64.80	68.52	66.80	66.23	0.60	3.77	3.54	3.24	3.70	3.48	3.41	3.52
May	10.69	76.26	76.26	75.11	71.47	73.02	75.61	0.63	5.16	5.16	4.99	4.44	4.67	5.06	4.91
Jun	11.02	81.87	80.84	80.40	77.63	79.63	78.76	0.65	6.46	6.28	6.20	5.72	6.07	5.92	6.11
Jul	11.12	80.74	82.34	82.45	80.45	80.56	80.16	0.65	6.32	6.61	6.63	6.27	6.29	6.22	6.39
Aug	9.03	80.71	80.71	82.87	80.56	80.77	80.15	0.63	4.97	4.97	5.28	4.95	4.98	4.89	5.01
Sep	8.54	78.22	80.15	79.55	79.27	77.87	77.43	0.61	4.23	4.48	4.40	4.37	4.19	4.14	4.30
Oct	7.80	76.73	73.55	67.65	66.52	69.10	71.44	0.58	3.52	3.19	2.62	2.52	2.76	2.98	2.93
Nov	6.03	70.80	71.57	65.07	64.70	61.67	64.65	0.54	2.10	2.15	1.72	1.70	1.51	1.69	1.81
Dec	5.28	54.63	61.23	58.94	55.02	47.40	61.85	0.50	0.91	1.20	1.10	0.93	0.63	1.23	1.00

Jacksonville

Month	Rso	Average T (°F)						Kc	ET (in)						ET Avg
		1985	1986	1987	1988	1989	1990		1985	1986	1987	1988	1989	1990	
Jan	5.30	47.88	51.46	51.91	48.49	60.50	58.32	0.49	0.64	0.77	0.79	0.66	1.15	1.05	0.84
Feb	6.56	55.94	58.95	54.12	52.37	58.56	62.64	0.53	1.27	1.45	1.17	1.08	1.42	1.68	1.34
Mar	8.29	63.59	60.47	59.83	59.67	65.01	64.86	0.55	2.28	2.02	1.97	1.95	2.40	2.39	2.17
Apr	10.32	67.08	65.98	63.87	67.56	67.22	66.65	0.60	3.52	3.38	3.13	3.58	3.53	3.46	3.43
May	10.69	74.78	72.98	72.99	71.23	73.42	75.02	0.63	4.93	4.66	4.66	4.41	4.73	4.97	4.73
Jun	11.02	80.40	81.03	79.93	77.98	80.44	80.20	0.65	6.20	6.31	6.12	5.78	6.21	6.17	6.13
Jul	11.12	80.28	83.53	82.07	81.25	82.17	83.08	0.65	6.24	6.83	6.56	6.41	6.58	6.75	6.56
Aug	9.03	80.63	81.09	83.59	82.31	81.74	82.27	0.63	4.96	5.02	5.38	5.20	5.12	5.19	5.15
Sep	8.54	77.01	79.32	78.72	79.23	78.81	79.18	0.61	4.09	4.37	4.30	4.36	4.31	4.35	4.30
Oct	7.80	75.09	71.71	63.74	66.56	70.40	72.41	0.58	3.35	3.01	2.27	2.52	2.88	3.07	2.85
Nov	6.03	69.38	68.52	62.15	64.65	62.16	63.13	0.54	2.00	1.94	1.54	1.69	1.54	1.60	1.72
Dec	5.28	52.56	57.24	57.23	54.31	47.67	60.68	0.50	0.83	1.02	1.02	0.90	0.64	1.18	0.93

APPENDIX D

LIST OF ALL TECHNICALLY/SCIENTIFICALLY INVOLVED INDIVIDUALS

TECHNICALLY INVOLVED INDIVIDUALS

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APPENDIX E

COMMENTS NOT INCLUDED IN REPORT

A significant effort was made to include SFWMD. A number of the comments and requests were beyond the scope of the project. The complete set of SFWMD comments is included below.

March 1, 2001

Transmitted via E-mail: jjaco@ce.ufl.edu

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Re: Comments to January AFSIRS Report

Dear Ms. Jacobs:

We appreciate your efforts in compiling the technical report reviewing the various evapotranspiration methods and the AFSIRS simulation model. Overall the report appears to be a thorough review of the differing methods of estimating evapotranspiration and a good comparison and contrast of the varying approaches of the districts in determining water use based upon these methods. In review the report we have just a few comments and suggestions.

General Comments:

1. Under section 1.2.4 of the report there are five goals identified that the technical report will try to address. Although goals 1 –3 are straight forward and easy to follow, we found ourselves having difficulty in identifying the recommendations for further work (goal 4) and the prioritization of this work (goal 5). Each section of the report has a set of general conclusions for that section, but these conclusions appear independent and it is difficult to see how these components relate to one another. We would recommend the preparation of a report summary that would pull the specific conclusions and recommendations from each section and thereby identify the interaction of the various conclusions and specify a course of action to reach the identified goal of method consistency and software development.

2. In prioritizing the report recommends we would like to identify the magnitude of the changes necessary for the district's to achieve consistency in water use estimation. To do this, we would hope that the report could briefly describe the type of work necessary to complete each recommendation and an estimate of the time to complete such work. For example, if we wish to improve the identification of irrigation efficiencies, we would like to see; who would typically be involved in completing this work, what are the general steps involved and how much time might this effort take to complete. We are hoping that this report will provide sufficient identification of the issues that need to be resolved to lead to the development of an inter-district work plan to address the consistency goal.

Specific Comments:

Comments on report. "Evaluation of Reference Evapotranspiration Methodologies and AFSIRS Crop Water Use Simulation, by Jennifer M. Jacobs and Sudheer Reddy Satti

- p. 1- The statement is made, "The current AFSIRS model is an MS-DOS based program written in Fortran that can be run in an interactive mode or batch mode." A Windows version of AFSIRS is available. The original version is described in: Moraga, J., H. Uribe, F.S. Zazueta and A.G. Smajstrla. 1995. A graphical user interface for AFSIRS. ASAE Tech. Paper No.FL95-102. ASAE, St. Joseph, MI.. The Windows version is available from IFAS Software for $30.

- p.11- More explanation is needed of "monthly percentage of annual incoming solar radiation." This probably should be changed to "mean monthly percentage of annual incoming solar radiation."

- p. 56- "Crop water demand" needs to be defined. By definition effective rainfall cannot exceed crop ET. In addition, irrigation methods and practices influence effective rainfall. Below is a discussion of "effective rainfall" from the AFSIRS Technical Manual.

- "Effective rainfall is rain that is stored in the crop root zone and available for crop use. From this definition effective rainfall is calculated as the difference between rainfall and drainage."

- Drainage should be explicitly addressed in Figure 3.1. "Crop water demand" should be differentiated from "crop water requirement."

- p. 64 The value in the 7th column of Table 3.2 under SWF Lake Alfred for January probably should be 5.10, not 55.10. The statistical significance of the difference between the 30-year Lake Alfred temperature data used by SJRWMD and the 64-year data used by SWFWMD should be discussed. The visible seasonal pattern of this difference, with SJRWMD being higher in the months July through October and lower in the other months should also be noted. The data sets should be tested to verify that the means are stable. The presence of trends or cycles in the data would raise a number of potential problems.

- pp.68-72- Net depth of application (D) is highly dependent on irrigation scheduling. This point is made clear in the publication "Basic Irrigation Scheduling in Florida," by Smajstrla, Boman, Haman, Izuno, Pitts, and Zazueta. http://coop.co.pinellas.fl.us/fyn/publications/basicirr.html

- A critical concept is "allowable water depletion," which, in conjunction with soil characteristics and crop rooting depth act to determine how much irrigation water is used.

- p. 74, It is stated with regard to SFWMD, "The net depth of application does not account for crop root zone differences." However, Volume III of the Permit Information Manual specifically provides that for small vegetables the default net depth of application is to be divided by three. This function is, admittedly, often turned off in the model and is thereby not recognized.

- p. 75- Because the AFSIRS model operates on a daily time step. Comparisons of monthly effective rainfall depend not only on total rainfall during the month, but also on the distribution of the rainfall within the month.

- p. 76- An implicit assumption of the original AFSIRS model is that one is irrigating so that there is no reduction in crop ET and, by extension, crop yield. Irrigation for maximum ET may not be realistic for pasture; to a certain extent this is a management or economic decision, rather than a technical decision. The entire issue of pasture irrigation needs to be addressed in a coherent manner.

- p. 84- A fundamental difference between AFSIRS and the various versions of Blaney-Criddle is that AFSIRS calculates based on a distribution of simulated irrigation requirements, while Blaney-Criddle uses a distribution of effective rainfall. Because AFSIRS utilizes soil, climate (rainfall and reference ET), and crop information simultaneously, is the interpretation of the "2-in-10 supplemental irrigation requirement."

- p.96- A Windows version of AFSIRS does exist; I suggest that we work with the Windows version for software extensions in the interim until such time as further software changes, as suggested, can be implemented.

- p. 98- It should be fairly straight forward to change irrigation strategies in AFSIRS.
  Because AFSIRS operates at a daily time step and the various Blaney-Criddle models operate on a monthly time step, different AFSIRS results will result depending upon intra-monthly rainfall distribution.

- p. 99- We strongly agree with the recommendation to add water table interactions. The handling of seepage irrigation with the current AFSIRS model is a major limitation of the current version of the model.

We hope that these comments are helpful and timely. If you have questions on any comment, please feel free to contact our office.

Sincerely,

Chris Sweazy, P.G.
South Florida Water Management District

Cc: Dick March
Mariano Guardo
Jeff Scott