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Water shortage is one of the biggest problems facing agricultural development in the United Arab Emirates, because of the extremely arid climate and the large amount of irrigation water that is used for crops. Prediction of crop water requirements is essential to solve water management problems in this country.

Two versions of the Penman equation, FAO and Wright, were used to estimate reference crop evapotranspiration from meteorological data for three regions in the U. A. E.; Northern, Central, and Eastern.

Lysimeter measurements at the Northern region were provided for five crops; tomato for one season; cabbage, cucumber, and squash each for two seasons; and watermelon for three seasons.

Crop evapotranspiration was estimated for these crops and related to measured crop evapotranspiration. It was found that there is great variation in measured crop evapotranspiration between seasons for individual crops, due to technical problems

with the lysimeter. Combined seasons were used to calibrate the Penman equation, and the results indicated that the calibration improved the estimated crop evapotranspiration. Calibration coefficients for individual crops and for individual methods were calculated.

Reference crop evapotranspiration (E_{tr}) value for the three regions were correlated. A high correlation of estimated E_{tr} among the three regions was found. Coefficients were developed to predict E_{tr} at the Central and Eastern regions from the E_{tr} at the Northern region.

CALIBRATION OF CROP WATER USE WITH
THE PENMAN EQUATION UNDER
UNITED ARAB EMIRATES CONDITIONS

by

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1. INTRODUCTION

1.1 INTRODUCTION

The United Arab Emirates is located in the Arid Zone with low rainfall and high evaporation. This country in its agricultural development faces many problems. The most important problem, and one which the government has tried to solve, is the great deficit in available water.

A study by the Soil and Water Department in the Ministry of Agriculture and Fisheries shows that there is a 355 million M^3/year water deficit in agriculture, industrial and municipal uses.

In his report on soil and water surveys in the Trucial States (U.A.E.) Sir William Halcrow (1969), indicated that using the same amount of irrigation water would increase the agriculture lands up to 67% if there was better water management and water conservation.

The estimation of reference evapotranspiration, which is the key to estimating crop water requirements, is essential in the solution to develop irrigation management in this country, Therefore this study will focus on determination of reference evapotranspiration in three important agricultural regions in the U.A.E., Northern, Eastern and Central .

1.2 THE OBJECTIVES OF THE STUDY

1. Estimate reference crop evapotranspiration by the Penman equation in the northern, eastern and central regions of the U.A.E.
2. Calibrate the Penman model with actual data from the lysimeter measurements to estimate crop evapotranspiration in the Northern region of the U.A.E.
3. Relate the estimated reference crop evapotranspiration at the Northern region to that of the Eastern and Central region.
4. Use the calibrated model (Penman) to estimate crop water requirements in the northern, eastern and central regions of the U.A.E. .

Meteorological data have been collected daily from three stations for five years. Each station represents an agricultural region, Digdaga station represents the Northern region, Dibba station represents the Eastern region and Falaj Almualla station represents the Central region. The data include minimum and maximum air temperature, minimum and maximum relative humidity, wind speed and sunshine duration. In addition, data of actual crop water requirements from lysimeters have been collected at the Digdaga station .

The Penman method will be used to estimate evapotranspiration. Then the result will be compared with the actual data from the lysimeter. This will show how the empirical method chosen varies from the actual data. Finally the model will be calibrated and the final form of the model will be tested using the meteorological and actual data. Then the final model will be ready to be used in the future to estimate crop water requirements in this country.

2. REVIEW OF LITERATURE

2.1 METHOD SELECTION

Numerous methods have been developed to estimate evapotranspiration from meteorological data. Among all these methods, the combination equations which are derived from energy balance and aerodynamic terms are the most accurate for a very wide range of climatic conditions. Estimates of evapotranspiration obtained from combination equations are reliable for short periods, e.g. daily estimates, Hourly estimates are also possible with slight modifications (Jensen, 1981) .

The Technical Committee on Irrigation Water Requirements, American Society of Civil Engineers, conducted a comprehensive evaluation of prominent methods to estimate evapotranspiration (Jensen, 1974). Sixteen methods were selected and grouped according to their classification into combination, humidity, miscellaneous, radiation and temperature. The results of the evaluation indicate that the best four methods for inland-semiarid to arid regimes were combination methods. The committee said about combination methods :

> " From these comparisons it appears that the combination methods should be the most accurate with improved calibration of the wind function and the vapor deficit term even though the combination methods displayed the best over all fit of all methods without calibration. The combination methods can be calibrated if accurate measured local or regional ET data and meteorological data are available. With such calibration the combination equations probably cannot be excelled. " .

Abdin and Sendil (1984), referred to work done by Sendil et al (1983), in testing the Van Bavel-Businger ($z = 0.25$) method under an extremely arid climate in central Saudi Arabia. The result shows that this method greatly underestimated evapotranspiration .

Saeed (1986) evaluated four methods for estimation of evapotranspiration under hot and arid climates; the methods were modified Blaney-Criddle, Jensen-Haise, Turc and Hargreaves. He found that all of these methods underestimated evapotranspiration in the summer where high evapotranspiration demand.

Doorenbos and Pruitt (1977) presented guidelines to calculate crop water requirements by four methods, Blaney-Criddle, radiation, Penman and pan evaporation. They suggested using the Penman method for areas where measured temperature, humidity, wind and sunshine duration or radiation are available. When they compared the results of all methods, they found that the Penman method provided the most accurate results .

In 1987 Allen conducted a comprehensive study of nineteen methods of estimating evapotranspiration . According to the results the best four methods for arid locations for the full season were four versions of the Penman equation, the first was the Penman-Monteith variable crop height, the second was the Penman-Wright, the third was the Penman-Monteith fixed crop height and the fourth was Penman, 1963. The Penman-FAO method was ranked number nine and the corrected Penman-FAO was ranked number fifteen.

Allen's work has not been published yet, this information was gathered from personal communication with Richard Cuenca[1].
Even though the Penman-Monteith was the first ranked, it will not be used to estimate evapotranspiration in the U.A.E. because it requires data such as canopy resistance which is not available.

Based on these studies and others in the literature, and in view of the available meteorological data, the Penman method seams to be suitable to estimate evapotranspiration in the U.A.E. .

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[1] Dep. of Agricultural Engrg., Oregon State Univ., Corvallis, Oregon.
Chairman of the Review Committee (Jensen, 1974, Consumptive use of water and irrigation water requirements, A.S.C.E.).

2.2 THE PENMAN EQUATION

Based on the Dalton assumption , Penman (1948) combined two theoretical approaches, aerodynamic and energy balance, to come up with a new expression to estimate evaporation from meteorological data. Penman's equation was developed to estimate evaporation from an open water surface. This equation has been successful and has been widely used around the world. While the equation has a theoretical base it becomes more empirical when the parameters have to be estimated.

The Penman equation may take the following form :

$$E_{tr} = \{(\Phi/\Phi+\tau)(R_n - G)\} + \{(\tau/\Phi+\tau)E_a\} \qquad (2.1)$$

Where :

E_{tr} = reference evapotranspiration in mm day^{-1} .

Φ = the slope of the saturation vapor pressure-temperature curve in mbar°C^{-1} .

τ = the psychrometric constant in mbar °C^{-1} .

R_n = net solar radiation equivalent to evapotranspiration in mm day^{-1} .

G = soil heat flux equivalent to evapotranspiration in mm day^{-1} .

E_a = aerodynamic component in mm day^{-1} .

$$E_a = f(u)(e_a - e_d) \qquad (2.2)$$

where :

$f(u)$= wind function equivalent to evapotranspiration in mm day^{-1}. $f(u)$ is calculated as :

$$f(u) = m\ (\ \beta_0 + \beta_1\ U) \qquad (2.3)$$

where m is constant depending on the units used to calculate Etr, β_0 and β_1 are regression coefficients and U is wind movement measured at 2 m height .

e_a = saturation vapor pressure in mbar.

e_d = saturation vapor pressure at dew point temperature in mbar.

2.3 DEVELOPMENT OF THE PENMAN EQUATION

The Penman equation has been subjected to many evaluations and modifications since it was introduced in 1948; some of these modifications concerned the energy balance component while others the aerodynamic component. In both cases the modifications succeeded, and led to increased accuracy of estimated E_{tr}. Sometimes the modified equation over or under estimates E_{tr} if applied in locations different from the original location. Modifications must be made unless there are nearly similar climate conditions. In most cases the equation needs to be calibrated in order to apply it in locations different from the original .

2.3.1 NET RADIATION COMPONENT

Net radiation was defined in the original Penman equation as

$$R_n = (1-\alpha)R_s - \{\sigma T_k^4(0.56-0.092\sqrt{e_d})(0.1+0.9n/N)\} \qquad (2.4)$$

where :

R_n = net radiation

R_s = short wave radiation

α = surface reflection coefficient (albedo)

σ = Stefan-Boltzmann constant (2×10^{-9})

T_k = mean air temperature in °K

n/N= ratio of actual to possible hours of sunshine

e_d = saturation vapor pressure at dewpoint temperature

Albedo values vary with season and type of surface. Penman used albedo values of 0.06 for water, 0.1 for bare soil and 0.2 for turf (Penman, 1948). Later Penman suggested using a value for albedo for short green grass of 0.25 (Penman, 1963) .
The short wave radiation R_s in Eq.2.4 was defined as :

$$R_s = R_a (a + b \ n/N) \qquad (2.5)$$

where :

R_a = the Angot value of R_s for a completely transporting atmosphere, with value based on time of year and latitude. R_a values can be obtained from standard tables. a and b are empirical coefficients. Penman found that the monthly mean values for a and b for Rothamsted over the period 1931-1940 are 0.18 and 0.55 respectively.

Wright and Jensen (1972) conducted an experiment to determine peak water requirements for crops in southern Idaho. In their study they revised the procedure for estimating the net solar radiation . The following equations were used :

$$R_n = (1-\alpha)R_s - R_b \tag{2.6}$$

$$R_b = (a\ R_s/R_{so} + b)\ R_{bo} \tag{2.7}$$

$$R_{bo} = (a_1 - 0.044\sqrt{e_d})(11.71*10^{-8})(T_h{}^4 + T_l{}^4)/2 \tag{2.8}$$

where :

R_b = the long wave radiation

R_{bo}= net outgoing long wave radiation on a clear day

R_{so}= solar radiation on a cloudless day

T_h and T_l are maximum and minimum daily air temperature respectively, in °K. The coefficients a and b in Eq.2.7 were found to be 1.22 and -0.18 respectively in Southern Idaho.

Jensen (1974) presented a table containing values of a and b for various locations and suggested using values of a = 1.2 and b = -0.2 for arid areas .

The parameter a_1 in Eq.2.8 is used to estimate the effective emittance of the atmosphere. a_1 is seasonally dependant, and the following relation is suggested to determine its value (Wright and Jensen, 1972) :

$$a_1 = 0.325+0.045 \sin \{30[(M+N/30)-1.5\ ]\} \qquad (2.9)$$

where :

M = the number of the month (1-12)

N = the day of the month

Equation 2.9 was evaluated in Southern Idaho for the period from March to October only . The results of net radiation predicted by this procedure were considered satisfactory; most of the values fall within ± 10% of the measured values (Fig.2.1a).

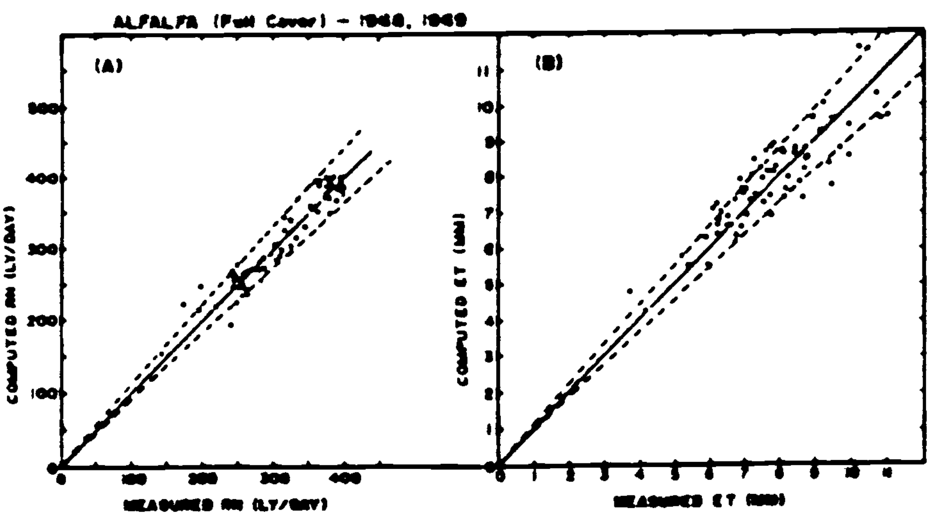

Figure 2.1. (a) Comparison of estimated vs. measured R_n
(b) Comparison of estimated vs. measured E_{tr} for Alfalfa at Kimberly , Idaho.
(Dashed lines indicate ± 10%)
(Adapted from Wright and Jensen, 1972)

Doorenbos and Pruitt (1977) suggested estimating the net radiation as:

$$R_n = (1-\alpha)R_s-(\sigma T_k^4)(0.34-0.044\sqrt{e_d})(0.1+0.9n/N) \qquad (2.10)$$

where R_s is calculated as in Eq.2.5. They recommended using values of 0.25 for the albedo and 0.25 and 0.5 for coefficients a and b respectively in Eq.2.5.

Wright (1982) improved the procedure developed by Wright and Jensen (1972) for estimating R_n. He developed an equation to calculate the value of the albedo which would vary with the date to account for the effect of sun angle. He suggested, for mostly clear days, using the following equation when the ratio (R_s/R_{so}) in Eq.2.7 is grater than 0.7 :

$$\alpha = 0.29+0.06 \sin \{30[M+(0.0333N)+2.25]\} \qquad (2.11)$$

where sine function is in degrees. This equation cannot be applied for the period from October to April in a location different from Kimberly, Idaho, where the equation was developed, because Kimberly is located at a latitude where low sun angles occur during much of the winter which would increase the albedo. It would be better to use a value of 0.25 during this period rather than using Eq.2.11 (Cuenca, 1988).

Wright suggested using values of 1.126 and -0.07 respectively for the coefficients a and b in Eq.2.7 when the ratio

$(R_s/R_{so}) > 0.7$ or 1.017 and -0.06 when $(R_s/R_{so}) \leq 0.7$. Wright also modified Eq.2.9 as:

$$a_1 = 0.26+0.1 \text{ EXP } \{-[0.0154(30M+N-207)]^2\} \qquad (2.12)$$

The effect of soil heat flux on E_{tr}, which was neglected in the original Penman equation, has been given by Wright as :

$$G = (T - T_p) C_s \qquad (2.13)$$

where :

T = mean daily air temperature in °C

T_p = mean air temperature of preceding three days in °C

C_s = empirical soil specific heat coefficient

The magnitude of soil heat flux is usually small from day to day; it's value is very small compared to net radiation. Therefore it is normally neglected for most practical estimates (Jensen,1974).

2.3.2 AERODYNAMIC COMPONENT

The aerodynamic component (E_a)in the Penman equation has two terms; the wind function f(u) which is empirically derived and the saturation vapor pressure deficit (e_a-e_d). It may take the following form :

$$E_a = m\ (\beta_0 + \beta_1\ U)(e_a - e_d) \tag{2.14}$$

where m (β_0 + β_1 U) represents the wind function f(u) as in Eq.2.3 . It is recommended that the regression coefficients β_0 and β_1 be determined locally (Jensen, 1981).

2.3.2.1 WIND FUNCTION

In the original Penman equation the wind function was derived for an open water surface. It was defined as :

$$f(u) = 0.35\ (0.5 + 0.01\ U^*) \tag{2.15}$$

where U^* is the wind run at 2 m height in mile day^{-1}.

Later Penman modified Eq.2.15 to calculate evapotranspiration for a short green crop, completely shading the ground, of uniform height and never short of water. Penman changed the coefficient β_0 from 0.5 to 1 to account for extra roughness of the crop compared with an open water surface (Penman, 1963).

Thus Eq.2.15 became :

$$f(u) = 0.35\ (1 + 0.01\ U^{*}) \tag{2.16}$$

Wright and Jensen (1972) had to modify the wind function in Southern Idaho because it was found that a high proportion of the energy used in evapotranspiration was moved by the wind from surrounding desert lands to the irrigated area, therefore E_{tr} was under-estimated. Local wind function was derived for well-watered alfalfa as the reference corp, actively growing with a rough surface and with at least 300 mm of top growth. The wind function was :

$$f(u) = 15.36\ (0.75 + 0.0185\ U^{*}) \tag{2.17}$$

The climatic situation that led Wright and Jensen to modify the wind function is the same as that in the U.A.E. where most of the cropped lands are surrounded by either desert lands or exposed mountains which release high amounts of energy which would be moved to the crop lands. The wind plays that role in this case, it arrives extremely dry and at the same time carries considerable energy which would increase E_{tr}. Thus such modifications would be suitable to be applied in the U.A.E. .

Doorenbos and Pruitt (1977) recommended using the following wind function :

$$f(u) = 0.27(1 + 0.01\ U) \tag{2.18}$$

where U is wind run at 2 m height in km day^{-1}

Doorenbos and Pruitt found out that the application of the Penman equation to a wide range of climatic conditions is very limited, they said " From wind considerations alone, locally calibrated wind functions must be applied or additional corrections are necessary when using a single f(u) function". Thus to avoid local calibration and to simplify the use of the Penman equation Eq.2.18 was derived to allow for applications under a wide range of climatic conditions. However, the use of Eq.2.18 over wide range would not give reliable estimates unless additional corrections are applied (Doorenbos and Pruitt, 1977).

Doorenbos and Pruitt combined the effect of wind run, relative humidity ,solar radiation and day time period in order to derive a correction factor that enabled the use of Eq.2.18 for wide range of climatic conditions. They came up with the following function :

$$C = f(U_{day}, RH_{max}, R_s, U_{day}/U_{night}) \qquad (2.19)$$

where:

U_{day} = wind run at 2 m height during day time in m s^{-1}

RH_{max} = maximum relative humidity

R_s = short wave solar radiation equivalent to evapotranspiration in mm day^{-1}

U_{day}/U_{night} = the ratio of wind run at day time to wind run at night.

Values for C for various climatic conditions were tabulated in the F.A.O publication NO. 24,"Crop Water Requirements", United Nations. The function derived by Revert et al to estimate C value is accurate within ± 5% error (Burman et al, 1983, Cuenca, 1988) :

$$\begin{aligned} C = {} & 0.6817006 + 0.0027864\ RH_{max} + 0.0181768\ R_s \\ & - 0.0682501\ U_{day} + 0.0126514\ (U_{day}/U_{night}) \\ & + 0.0097297\ U_{day}\ (U_{day}/U_{night}) \\ & + 0.43205 \times 10^{-4}\ RH_{max}\ R_s\ U_{day} \\ & - 0.92118 \times 10^{-7}\ RH_{max}\ R_s\ (U_{day}/U_{night}) \end{aligned} \tag{2.20}$$

Wright (1982) improved the accuracy of the Penman equation at Kimberly, Idaho by developing variable values for the coefficients β_0 and β_1 in Eq. 2.3 to account for seasonal changes in sensible heat advection. Wright presented two equations to estimate β_0 and β_1 :

$$\begin{aligned} \beta_0 = {} & 23.8 - 0.7865\ D + 9.7182 \times 10^{-3}\ D^2 - 5.4589 \times 10^{-5}\ D^3 \\ & + 1.42529 \times 10^{-7}\ D^4 - 1.41018 \times 10^{-10}\ D^5 \end{aligned} \tag{2.21}$$

$$\begin{aligned} \beta_1 = {} & - 0.0122 + 5.2956 \times 10^{-4}\ D - 5.9923 \times 10^{-6}\ D^2 \\ & + 3.4002 \times 10^{-8}\ D^3 - 9.00872 \times 10^{-11}\ D^4 \\ & + 8.79179 \times 10^{-14}\ D^5 \end{aligned} \tag{2.22}$$

where D is the day number in the year.

Allen (1986) said about the variation of the coefficients β_0 and β_1 that " This variation appears to help to account for early and late season effects on canopy roughness and resistances, and on boundary layer stability." .

Wright developed Eq.2.21 and Eq.2.22 in order to estimate evapotranspiration of alfalfa at full cover in Kimberly, Idaho. Therefore, the use of these equations is limited by two factors, first it is limited to the period from April 1^{st} to October 31^{st} where D values range between 91 - 304. Secondly it is limited to conditions at Kimberly, Idaho. Thus Eq.2.21 and Eq.2.22 must be calibrated locally in order to be used in locations different from Kimberly, Idaho.

Since Eq.2.21 and Eq.2.22 are very complex, not easy to calibrate to local conditions and subject to errors. Wright in 1987 simplified these equations and developed the following relations :

$$\beta_0 = 0.4 + 1.4 \text{ EXP } \{-[(D-173)/58)]^2\} \tag{2.23}$$

$$\beta_1 = 0.007 + 0.004 \text{ EXP } \{-[(D-243)/80)]^2\} \tag{2.24}$$

Eq.2.23 and Eq.2.24 are applicable for the entire year. These equations have not been published yet, they were collected by personal communication with R.Cuenca.

However, in order to increase the accuracy of estimated E_{tr} it is imperative that the wind function coefficients β_0 and β_1 be determined locally; most of the researchers recommended doing so. The wind function coefficients could be accurately determined if accurate measured data for E_{tr} such as from sensitive weighing lysimeter are available, and the parameters in the Penman equation such as solar radiation were accurately measured.

To determine wind function coefficients locally the following procedure may followed :

The aerodynamic component E_a in Eq.2.1 is determined from the measured E_{tr} (E_{trm}) as:

$$E_a = E_{trm} - \{(\Phi / \Phi + \tau)(R_n - G)\} \qquad (2.25)$$

then the wind function is determined by using Eq.2.2 as :

$$f(u) = E_a / (e_a - e_d) \qquad (2.26)$$

From the value of f(u) in Eq.2.26 and the wind run a linear regression analysis would be made to determine the coefficients β_0 and β_1.

The previous procedure will not be used in this study, because the measured ET data that are available belong to crop ET not reference ET. Thus, a different procedure will be used in this study to calibrate the Penman equation. More detail about this procedure will be given in the next chapter.

2.3.2.2 SATURATION VAPOR PRESSURE DEFICIT

The second term in the aerodynamic component is the saturation vapor pressure deficit, Penman (1948) defined this term as :

$$e_{def} = e_a - e_d \tag{2.27}$$

where :

e_{def} = saturation vapor pressure deficit in mbar

e_a = mean saturation vapor pressure in mbar

e_d = mean saturation vapor pressure at dew point temperature in mbar.

Calculation of saturation vapor pressure deficit is strongly related to the wind function which is used to estimate E_{tr}. Therefore, the same method which was used to calculate saturation vapor pressure deficit in the derivation of the wind function should be used when estimating E_{tr} with the same wind function (Cuenca and Nicholson, 1982; Doorenbos and Pruitt, 1977).

Several methods have been used to compute saturation vapor pressure deficit. These methods could be categorized as temperature averaging methods and saturation vapor pressure deficit averaging methods. Under the first category, saturation vapor pressure deficit is calculated at mean daily temperature, while under the second category it is calculated at various times during the day and averaged to represent the saturation vapor pressure deficit.

Saturation vapor pressure deficit calculated using the temperature averaging method may not be representative of the average daily deficit (Jensen, 1974). The saturation vapor pressure deficit averaging method is more applicable in arid areas and high elevations where large daily temperature changes occur (Jensen, 1981).

Cuenca and Nicholson (1982) reviewed six methods of computing the vapor pressure deficit, two of them will be chosen to be used in this study :

1. saturation vapor pressure at mean air temperature (e_a) minus the mean relative humidity (RH_{mean}) times the saturation vapor pressure at mean air temperature (e_a)

$$e_{dif} = e_a - [\ e_a\ (RH_{mean}\ /\ 100)] \qquad (2.28)$$

Eq.2.28 is consistent with the Doorenbos and Pruitt wind function.

2. mean saturation vapor pressure at maximum and minimum air temperature minus saturation vapor pressure at mean dew point temperature (e_d).

$$e_{dif} = [(e_{amax} + e_{amin})\ /\ 2] - e_d \qquad (2.29)$$

Eq.2.29 is consistent with the Wright (1982) wind function and is recommended for arid locations.

3. THE PROCEDURE

3.1 THE DATA

All of the data for this study were collected from the Ministry of Agriculture and Fisheries in the U.A.E.. The data are divided into three parts, meteorological data, measured crop evapotranspiration data and crop coefficient data. Meteorological data were used to calculate reference ET; then from crop coefficient data a crop ET was determined. Finally crop ET was compared with measured crop ET.

3.1.1 METEOROLOGICAL DATA

Meteorological data have been collected daily from three stations, Digdaga, Falaj almualla and Dibba for the period from July 1982 to June 1986. Each station represents an agricultural region in the U.A.E., Northern, Central and Eastern respectively.

The data include minimum and maximum air temperature in °C, minimum and maximum relative humidity, wind run at 2 m height in km day^{-1} and sunshine duration in hr. In addition mean annual atmospheric pressure in mbar and latitude for each station were taken.

Days that have some missing data have been omitted from the calculation, only days with a complete data set were used.

3.1.2 MEASURED CROP ET DATA

Experiments have been conducted by the staff of the Ministry of Agriculture and Fisheries at the Humrania experimental farm in the Northern region of the U.A.E. to measure crop water requirements for various vegetable crops. Crops were grown individually in a drainage-type lysimeter for more the one season, and daily crop ET was measured by subtracting the amount of output water from the amount of input water. Table 3.1 shows the period of growing season and the number of seasons for each crop.

3.1.3 CROP COEFFICIENT

The Penman equation and the other methods that estimate evapotranspiration are estimating reference evapotranspiration; the reference could be water, grass, alfalfa or any crop. To determine evapotranspiration for a crop other than the reference crop, a crop coefficient is required. The function of the crop coefficient is to relate crop ET to reference ET as described below:

$$E_{tc} = K_c \, E_{tr} \tag{3.1}$$

where:

E_{tc} = crop evapotranspiration

K_c = crop coefficient

E_{tr} = reference crop evapotranspiration

The crop coefficient should be consistent with the method that estimates reference evapotranspiration, in other word when using the Penman-FAO method in Eq.3.1, crop coefficient values should be determined using the FAO method, and when using the Penman-Wright method, the crop coefficient should be determined using the Wright method (Cuenca ,1987; Doorenbos and Pruitt, 1977).

Table 3.1 Season periods and number of seasons for various vegetable crops in the lysimeter.

Crop	No. of Seasons	Beginning of the season	End of the season
Cabbage	2	10-21-1982 10-24-1983	2-11-1983 2-13-1984
Cucumber	2	8-29-1982 8-31-1983	12-09-1982 12-09-1983
Squash	2	9-17-1984 9-17-1985	1-04-1985 1-19-1986
Tomato	1	10-20-1983	4-30-1984
Water melon	3	3-25-1983 3-18-1984 3-15-1985	7-18-1983 6-15-1984 6-22-1985

3.1.3.1 GRASS REFERENCE CROP COEFFICIENT

Grass reference crop coefficient is referred to as the crop coefficient determined by the FAO method. The FAO procedure for developing crop coefficients is described well by Doorenbos and Pruitt (1977) in the F.A.O publication NO. 24,"Crop water Requirements", United Nations. Crop coefficients for crops under study have been developed by the staff of the Ministry of Agriculture and Fisheries in the U.A.E. using the FAO method. Fig. 3.1 to 3.5 show the curves of crop coefficient for the crops under study .

3.1.3.2 ALFALFA REFERENCE CROP COEFFICIENT

Alfalfa reference crop coefficient refers to the crop coefficient developed by the Wright method. The Wright procedure is unique and different from the FAO procedure. Crop coefficients have not been developed for wide range of crops by this method, also all of the crop coefficients are based on lysimeter measurements made at Kimberly, Idaho (Wright ,1982; Cuenca, 1987).

A procedure presented by Cuenca (1988) was followed to relate grass crop coefficients to alfalfa crop coefficients :

$$K_{c\text{-}alf} = K_{c\text{-}grass} \,/\, (K_{c\text{-}alf/grass}) \tag{3.2}$$

where :

$K_{c\text{-}alf}$ = crop coefficient based on alfalfa reference crop

$K_{c\text{-}grass}$ = crop coefficient based on grass reference crop

$K_{c\text{-}alf/grass}$ = coefficient for alfalfa determined on basis of grass reference crop for peak condition.

Coefficients for alfalfa for full year on grass reference crop bases were provided by the staff of Ministry of Agriculture and Fisheries in the U.A.E. (Fig. 3.6).

Crop coefficients generated on the basis of alfalfa crop reference are presented in Fig. 3.7 to 3.11. (Note that Eq.3.2 was used).

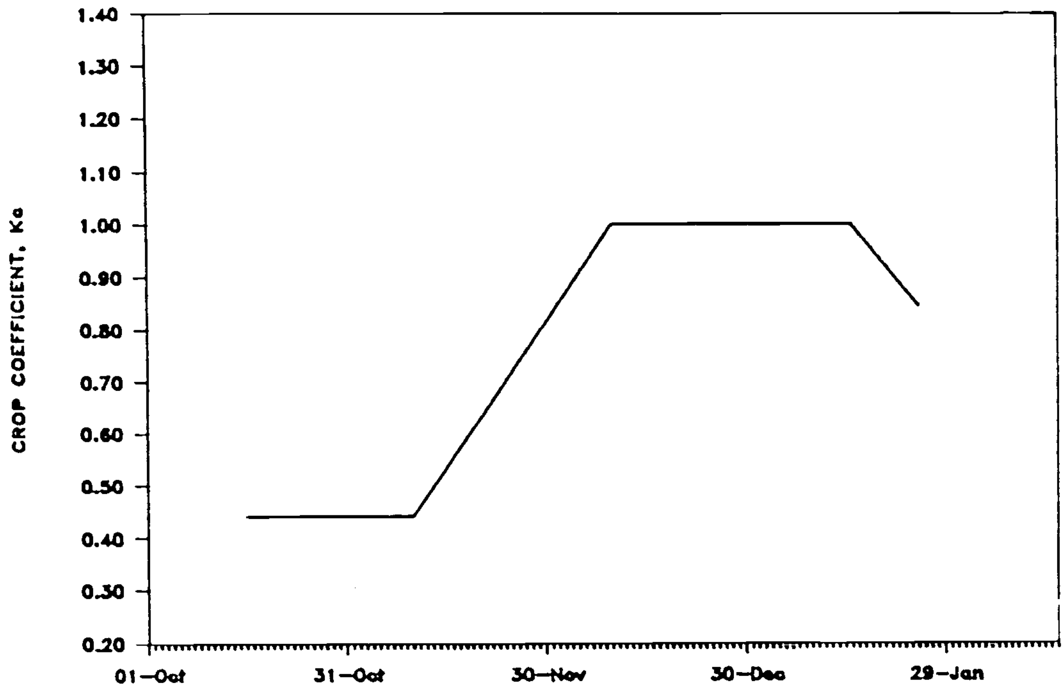

Figure 3.1 Crop coefficient curve for winter cabbage in the Northern region,U.A.E..(grass reference) (adapted from Savva et al, (1984))

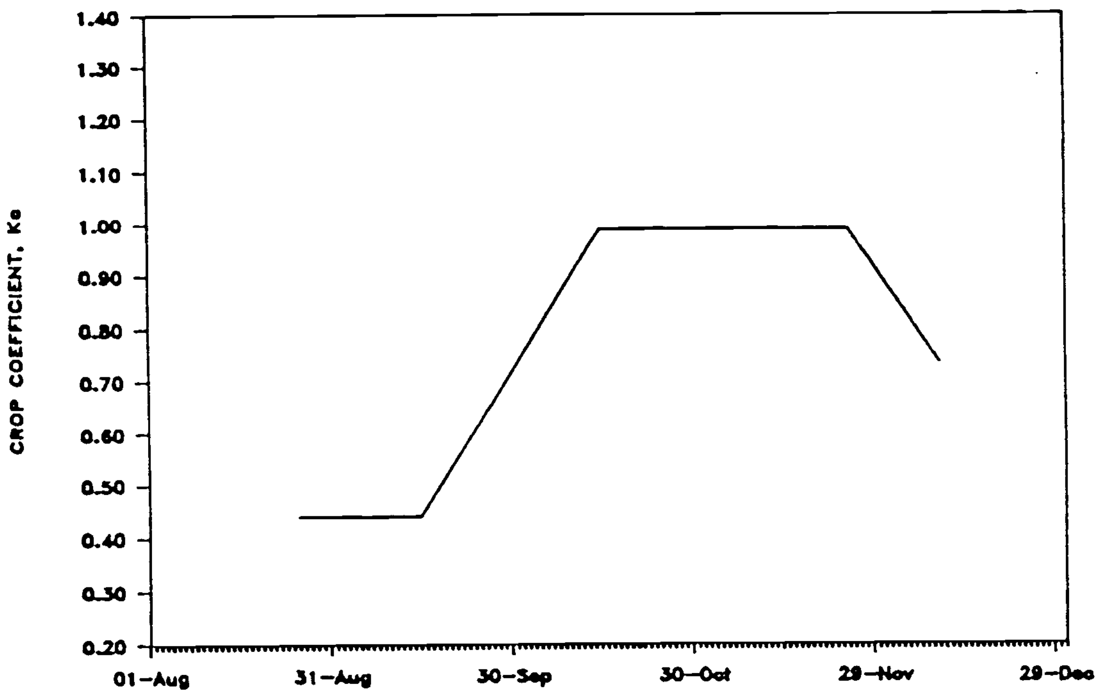

Figure 3.2 Crop coefficient curve for winter cucumber in the Northern region, U.A.E.. (grass reference) (adapted from Savva et al, (1984))

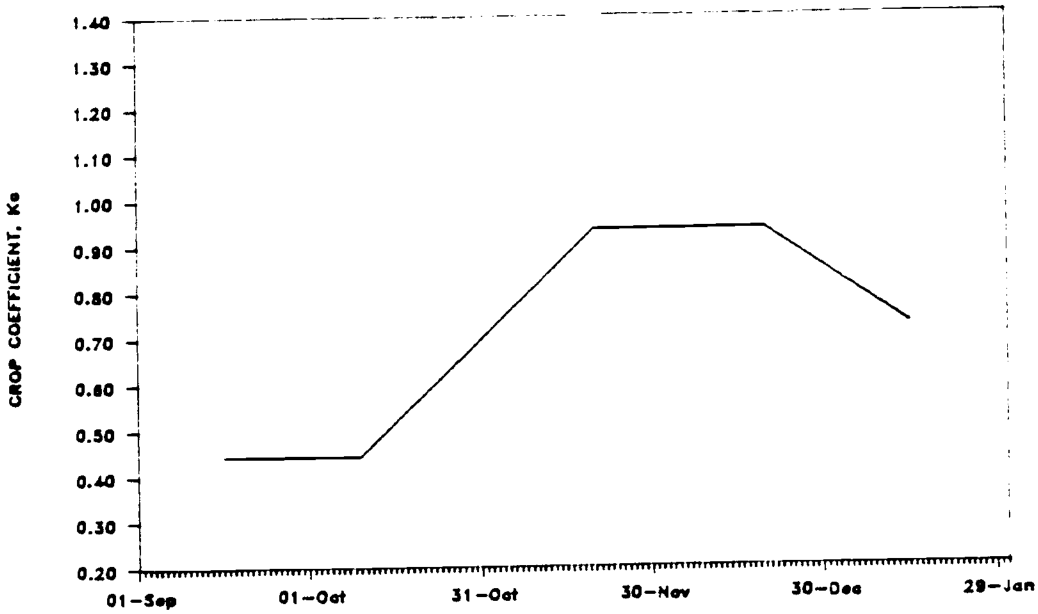

Figure 3.3 Crop coefficient curve for squash in the Northern region, U.A.E.. (grass reference) (adapted from Savva et al, (1984))

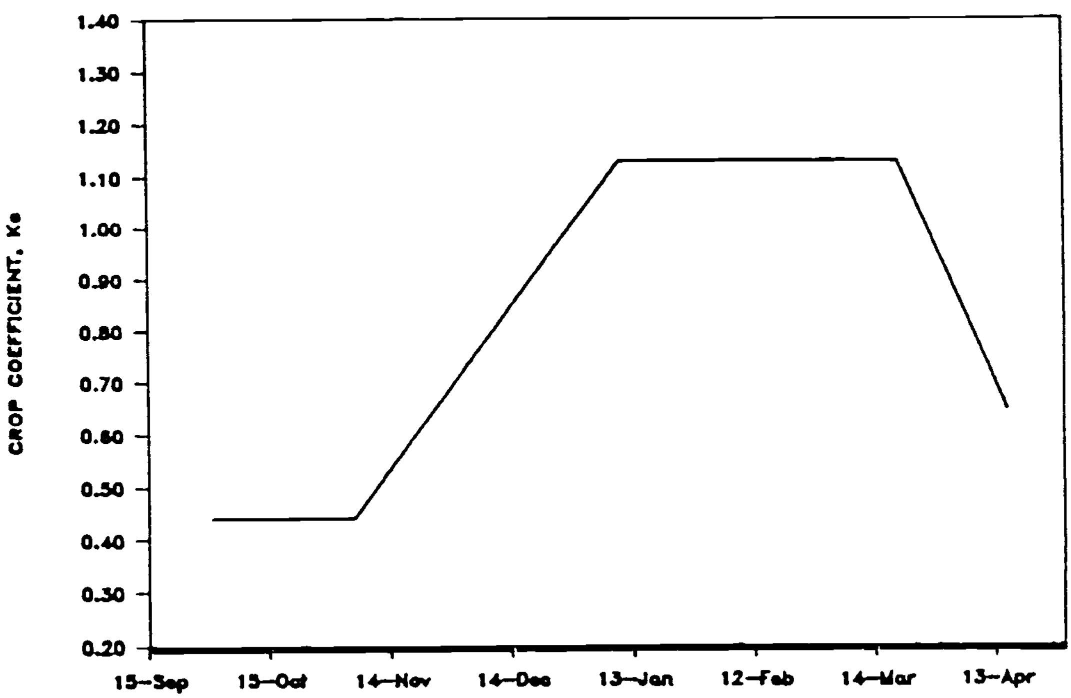

Figure 3.4 Crop coefficient curve for winter tomato in the Northern region, U.A.E.. (grass reference) (adapted from Savva et al, (1984))

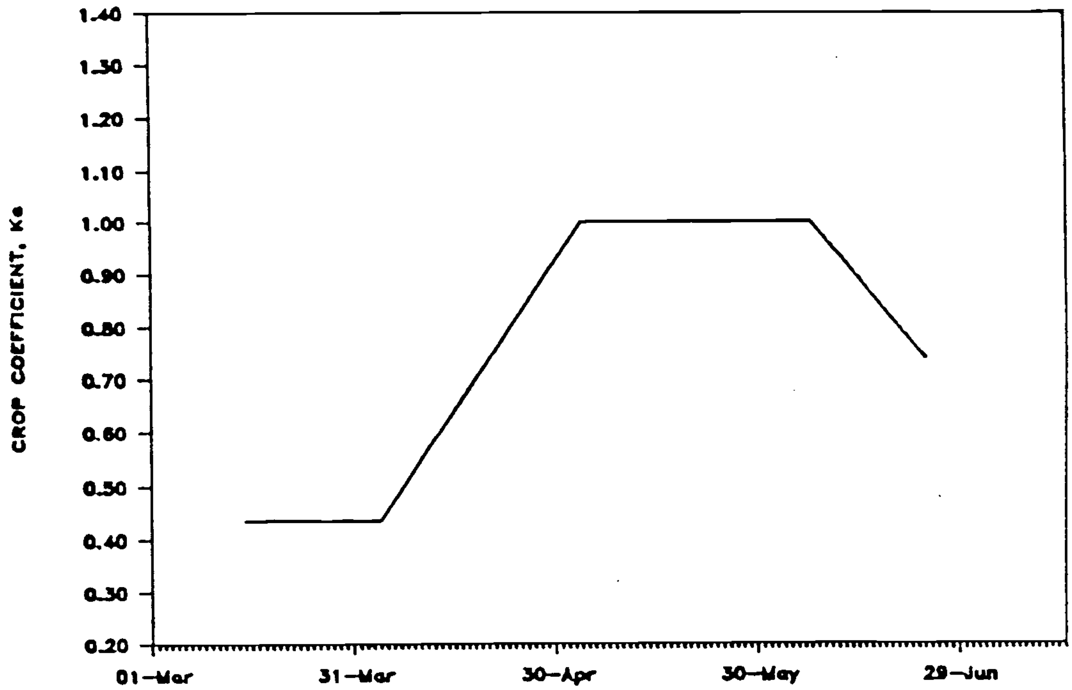

Figure 3.5 Crop coefficient curve for spring water melon in the Northern region, U.A.E.. (grass reference) (adapted from Savva et al, (1984))

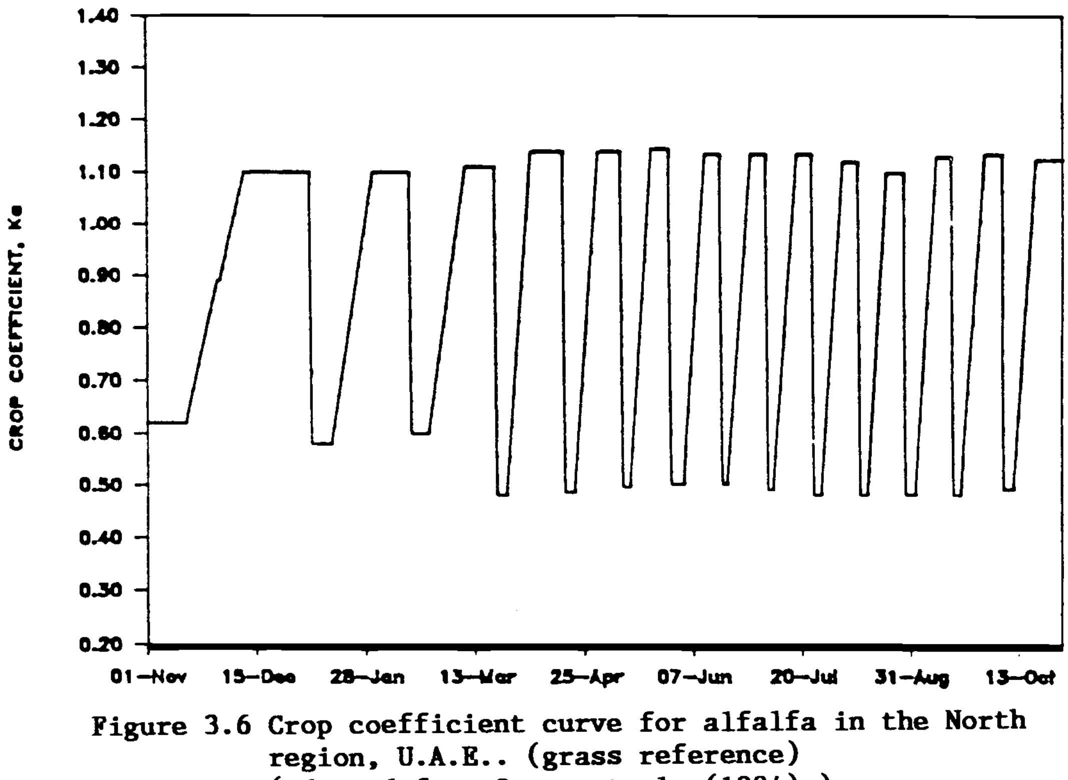

Figure 3.6 Crop coefficient curve for alfalfa in the North region, U.A.E.. (grass reference) (adapted from Savva et al, (1984))

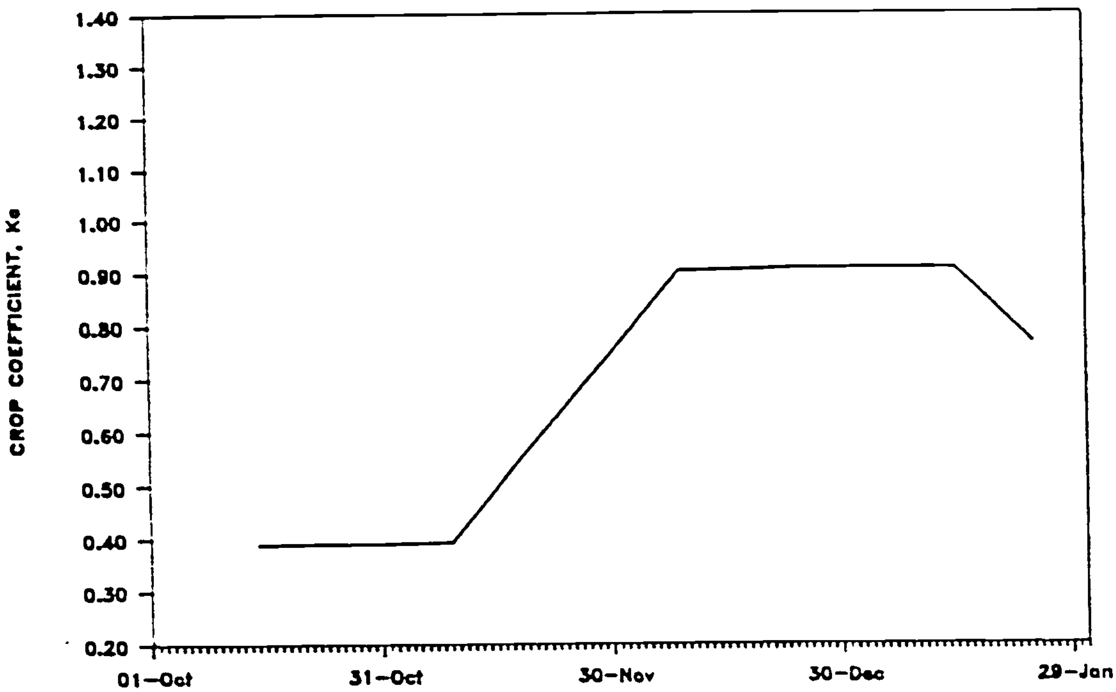

Figure 3.7 Crop coefficient curve for winter cabbage in the Northern region,U.A.E..(alfalfa reference) (generated by Eq.3.2)

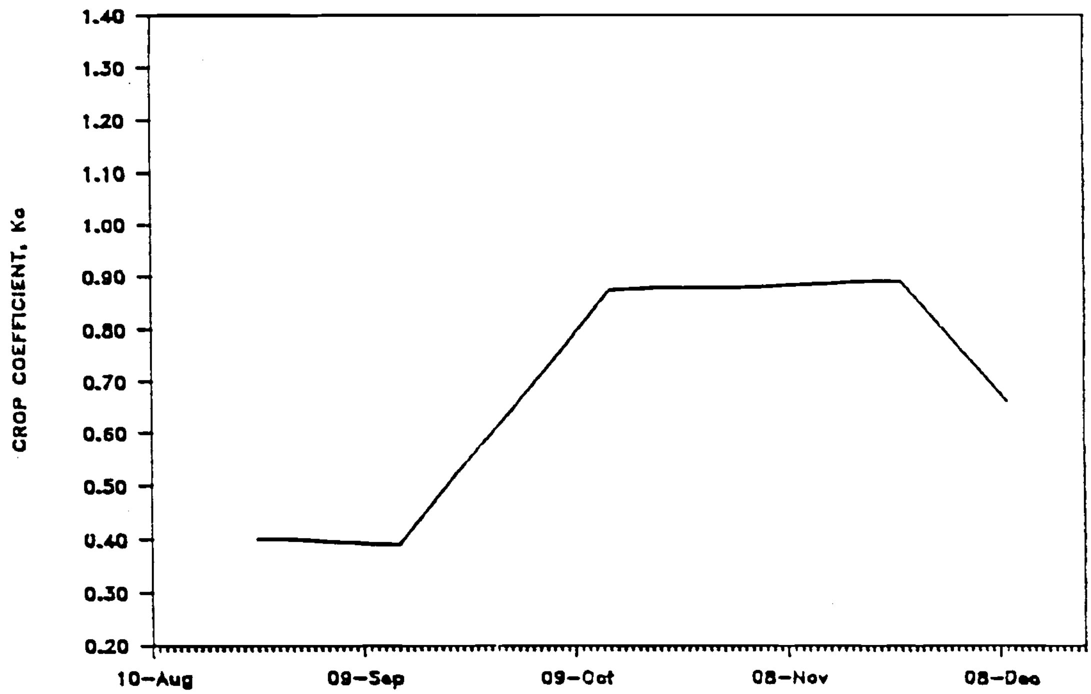

Figure 3.8 Crop coefficient curve for winter cucumber in the Northern region, U.A.E.. (alfalfa reference) (generated by Eq.3.2)

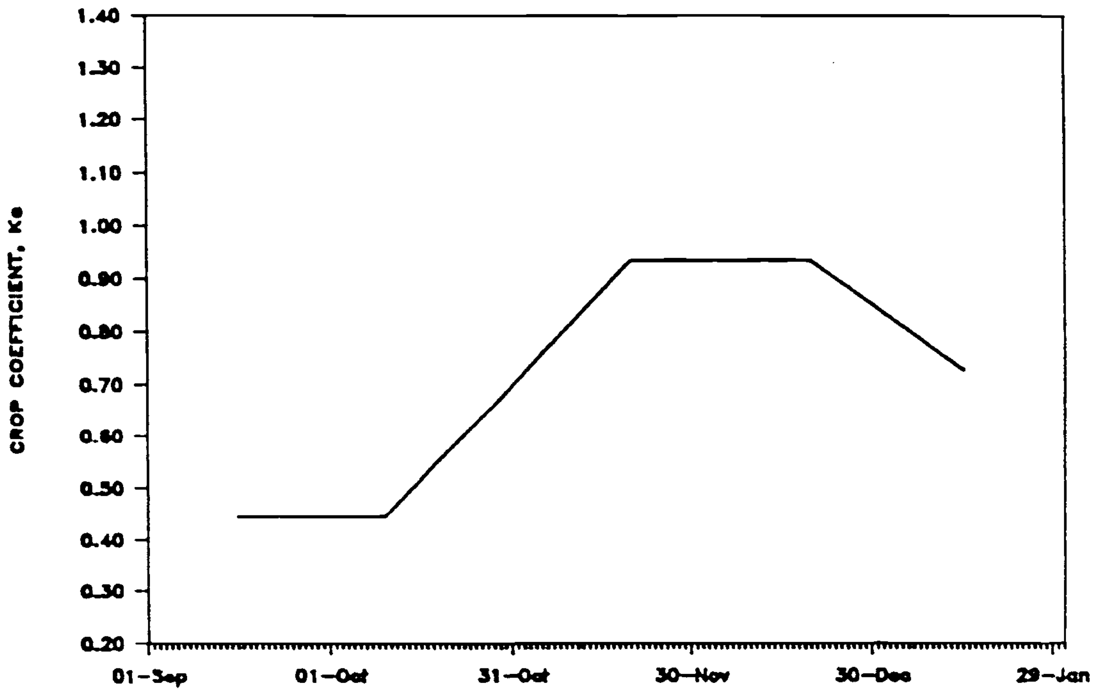

Figure 3.9 Crop coefficient curve for squash in the Northern region, U.A.E.. (alfalfa reference) (generated by Eq. 3.2)

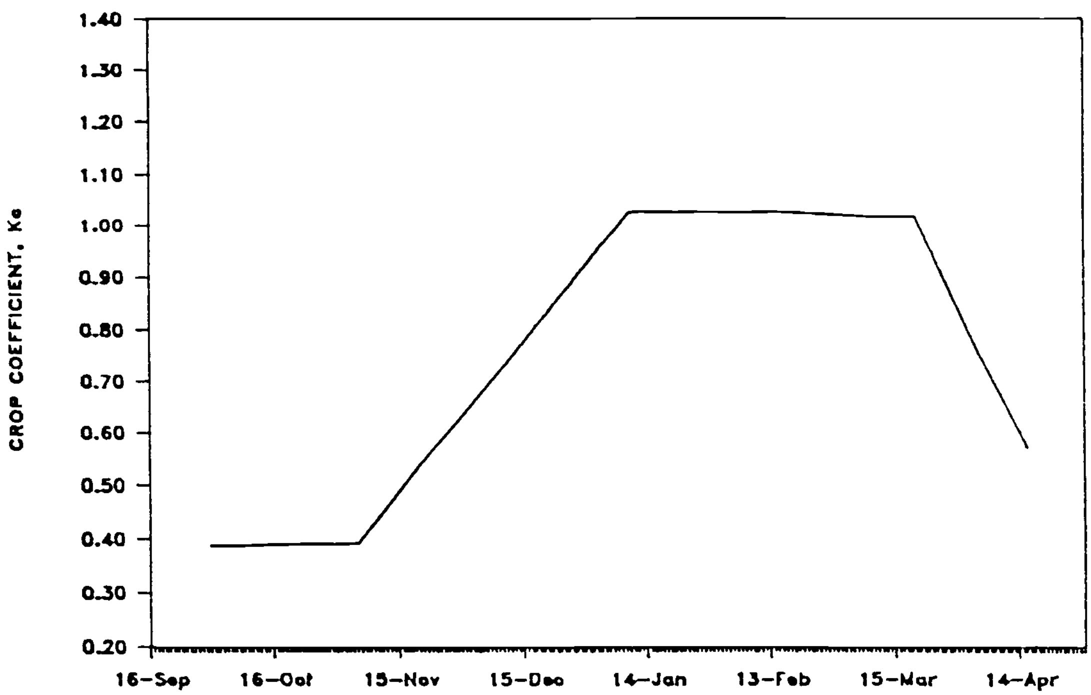

Figure 3.10 Crop coefficient curve for winter tomato in the Northern region, U.A.E.. (alfalfa reference) (generated by Eq. 3.2)

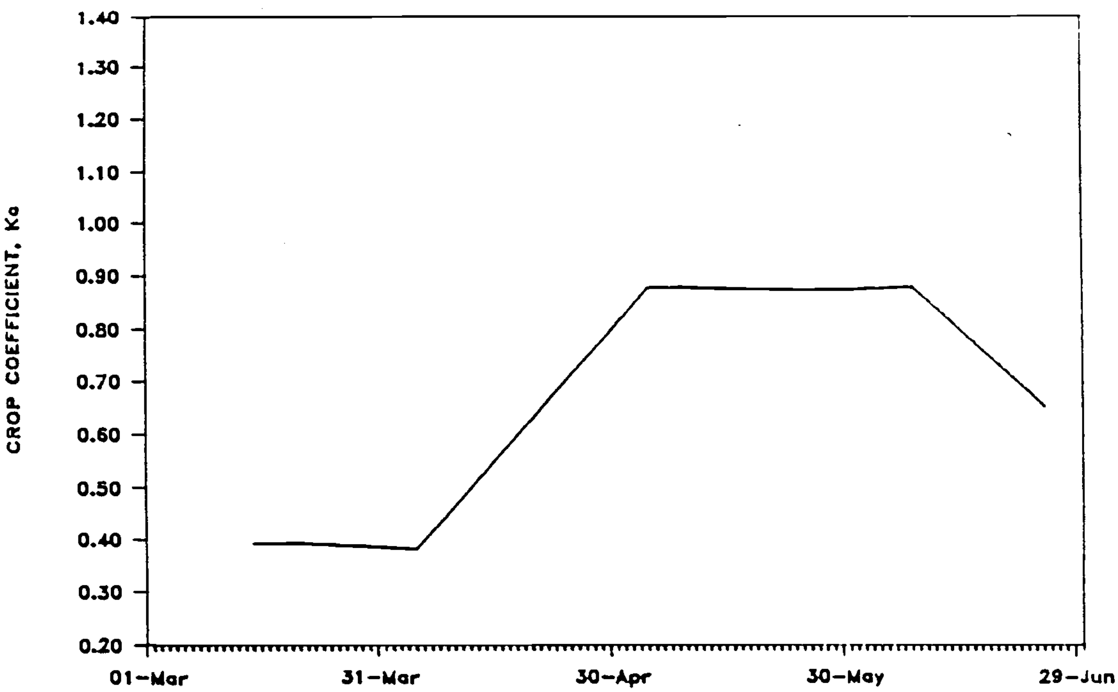

Figure 3.11 Crop coefficient curve for spring water melon in the Northern region, U.A.E.. (alfalfa reference) (generated by Eq. 3.2)

3.2 CALCULATION OF E_{tr}

Based on studies of the literature, and according to the conditions in the U.A.E., it seems that the Penman-Wright method is the appropriate method to be applied in the U.A.E. since it was developed for a dry location. So in this study two methods of the Penman equation were used, the Penman-Wright method and the Penman-FAO method which was modified and corrected by Doorenbos and Pruitt in (1977) to be applied for wide range of locations.

3.2.1 THE PENMAN-FAO VERSION

The expressions that were used to calculate E_{tr} in this method have been chosen from Doorenbos and Pruitt (1977), Burman et al (1983) and others. The form of the Penman equation used in this method is :

$$E_{tr} = C \{(\Phi/\Phi+\tau) R_n + (\tau/\Phi+\tau) f(u) (e_a-e_d)\} \qquad (3.3)$$

where :

C = the correction factor to account for the effect of day and night wind run, relative humidity and solar radiation.

Φ = the slope of saturation vapor pressure-temperature curve in mbar °C^{-1}

τ = the psychrometric constant in mbar °C^{-1}

R_n = net radiation equivalent to evapotranspiration in mm day^{-1}

f(u) = the wind function equivalent to evapotranspiration in mm day^{-1}

e_a = saturation vapor pressure at mean air temperature in mbar °C

e_d = saturation vapor pressure at dewpoint temperature in mbar °C

The slope of the saturation vapor pressure-temperature curve was calculated from the following relation:

$$\Phi = 33.8639[0.05904(0.00738\ T+0.8072)-3.42 \times 10^{-5}] \quad (3.4)$$

where T is the mean air temperature in °C. This relation is valid for T ≥ 23°C (Wright, 1982).

The psychrometric constant was obtained as:

$$\tau = (\ Cp\ P\ )\ /\ (\ \varepsilon\ L\ ) \quad (3.5)$$

where Cp is the specific heat of the air which is equal to (1.0042 J g^{-1} °C), P is the barometric pressure in mbar, ε is the ratio of water vapor to mass of dry air; it's value is equal to (0.62198) and L is the latent heat of vaporization in J g^{-1}, calculated as :

$$L = 2500.8 - 2.3668\ T \quad (3.6)$$

where T is mean air temperature in °C

The net radiation was determined as the difference between net incoming short wave radiation (R_{ns}) and net outgoing long wave radiation (R_{nl}).

$$R_n = R_{ns} - R_{nl} \tag{3.7}$$

The net incoming short wave radiation is defined as :

$$R_{ns} = (1-\alpha) R_s \tag{3.8}$$

where α is the surface reflection coefficient called Albedo, it's value is equal to 0.25 and remains constant around the year. R_s is the short wave radiation equivalent to evapotranspiration in mm day^{-1}. Since there was no measured R_s data, it was calculated from extra-terrestrial radiation and the ratio of actual to possible sunshine duration as follows :

$$R_s = (0.25 + 0.5\ n/N) R_a \tag{3.9}$$

where n is the observed actual sunshine duration, N is the maximum sunshine duration and R_a is the extra-terrestrial radiation. Values for N and R_a depend on the location and time of the year, they are tabulated in standard tables for different months and latitudes (see Table 3.2). Interpolation between months was made for daily values, assuming that the mean value falls in the middle of the month (Doorenbos and Pruitt ,1977; Burman et al, 1983; Cuenca, personal communication).

Table 3.2 Mean daily extra terrestrial radiation (R_a), sunshine duration (N) and clear day solar radiation (R_{so}) for the three stations in the U.A.E..

Station	Digdaga			Dibba			Falaj Almoualla		
Latitude	25°40' N			25°36' N			25°21' N		
Month	R_a	N	R_{so}	R_a	N	R_{so}	R_a	N	R_{so}
January	9.9	10.7	448	9.9	10.7	449	9.9	10.7	451
February	11.6	11.3	589	11.6	11.3	589	11.6	11.3	592
March	13.7	12.0	625	13.7	12.0	626	13.8	12.0	627
April	15.3	12.7	719	15.3	12.7	719	15.3	12.7	720
May	16.4	13.3	742	16.4	13.3	742	16.4	13.3	742
June	16.7	13.7	782	16.7	13.7	782	16.7	13.7	781
July	16.6	13.6	746	16.6	13.5	746	16.6	13.5	746
August	15.7	13.0	703	15.7	13.0	703	15.7	13.0	703
September	14.3	12.3	657	14.3	12.3	657	14.4	12.3	658
October	12.3	11.6	562	12.4	11.6	563	12.4	11.6	566
November	10.4	10.9	479	10.4	10.9	480	10.4	10.9	483
December	9.4	10.5	416	9.4	10.6	417	9.4	10.6	419

Note: the units for R_a, N and R_{so} are mm day^{-1}, hours, and cal cm^{-2} day^{-1}, respectively.

The net outgoing long wave radiation was obtained as :

$$Rnl = \sigma\, T_k^4\ (0.34-0.044\ \sqrt{e_d})\ (0.1+0.9\ n/N) \tag{3.10}$$

where σ is the Stefan-Boltzmann constant (2.0 X 10^{-9}), T_k is the mean air temperature in °K, e_d is the saturation vapor pressure at dewpoint temperature.

The wind function was computed as follow :

$$f(u) = 0.27\ (1+0.01\ U) \tag{3.11}$$

where U is wind run at 2 m height in km day^{-1}.

The saturation vapor pressure was calculated empirically using Murry's method (Burman, 1983):

$$e_a = 6.1078\ EXP\ [17.2693882\ T/(T+237.3)] \tag{3.12}$$

where T is the mean air temperature in °C.

The saturation vapor pressure at dewpoint temperature was determined as :

$$e_d = e_a\ (RH_{mean}/100) \tag{3.13}$$

where RH_{mean} is the mean relative humidity in percent. This method was used because dewpoint temperature was not available.

The correction factor (C) was obtained from the following relation:

$$\begin{aligned} C = {} & 0.6817006 + 0.0027864\ RH_{max} + 0.0181768\ R_s \\ & - 0.0682501\ U_{day} + 0.0126514\ (U_{day}/U_{night}) \\ & + 0.0097297\ U_{day}\ (U_{day}/U_{night}) \\ & + 0.43205 \times 10^{-4}\ RH_{max}\ R_s\ U_{day} \\ & - 0.92118 \times 10^{-7}\ RH_{max}\ R_s\ (U_{day}/U_{night}) \end{aligned} \tag{3.14}$$

where:

U_{day} = wind run at 2 m height during day time in m s^{-1}

RH_{max} = maximum relative humidity

R_s = short wave solar radiation equivalent to evapotranspiration in mm day^{-1}

U_{day}/U_{night} = the ratio of wind run at day time to wind run at night.

For locations where wind run during day time (12 hr) is not measured, such as in the U.A.E., Doorenbos and Pruitt (1977) suggested considering the wind run during day time is twice as much as that during night time, so the ratio of wind run at day time to wind run at night considered to be 2 in this study. According to this the U_{day} wind run was obtained by the following relation :

$$U_{day} = (U_{ratio} / U_{total}) \, 0.023148 \, U \tag{3.15}$$

where U is wind run in km day^{-1}, the parameter 0.023148 converts the units from km day^{-1} to m sec^{-1}, U_{ratio} is the ratio of day to night wind run and U_{total} is the total units of day and night wind run. In this case it was assumed that U_{ratio} is equal to 2 which means that 2 units of wind occur during the day for every 1 unit that occurs at night. Therefore Eq.3.15 become :

$$U_{day} = (2/3) \, 0.023148 \, U \tag{3.16}$$

3.2.2 THE PENMAN-WRIGHT VERSION

The expressions that were used to calculate E_{tr} in this method have been chosen mainly from Wright (1982) and Jensen (1974). The form of the Penman equation used in this method is :

$$E_{tr} = [\{(\Phi/\Phi+\tau)(R_n-G)\}+\{(\tau/\Phi+\tau)15.36f(u)(e_a-e_d)\}]/(0.1L) \quad (3.17)$$

where L is the latent heat of vaporization in cal cm^{-3}. The definitions of the other parameters in this equation were described earlier. The 15.36 and 0.1 L terms are required to convert the units to mm day^{-1}.

The latent heat of vaporization was obtained as :

$$L = 595 - 0.51\ T \quad (3.18)$$

The soil heat flux (G) was assumed to be zero as described in the previous chapter.

The net radiation was calculated as :

$$R_n = (1-\alpha)\ R_s - R_b \quad (3.19)$$

where R_s is the incoming shortwave radiation in cal, R_b is the outgoing long wave radiation in cal and α is the albedo.

The short wave radiation was obtained as :

$$R_s = (0.35 + 0.61\ n/N)\ R_{so} \tag{3.20}$$

where R_{so} is the cloudless day solar radiation in cal, values of R_{so} depend on the location and time of the year and are tabulated in standard tables for different months and latitudes (see Table 3.2), For a daily basis, interpolation between months was made, assuming that the mean value falls in the middle of the month.

The long wave outgoing radiation was calculated as :

$$R_b = [\ a\ (R_s/R_{so}) + b]\ R_{bo} \tag{3.21}$$

where a and b are coefficients whose values depend on the value of (R_s/R_{so}). For an almost clear sky day when $(R_s/R_{so}) > 0.7$ the coefficients take values of 1.126 and -0.07 respectively, when $(R_s/R_{so}) \leq 0.7$ the coefficients become 1.017 and -0.06 respectively. R_{bo} is the net outgoing long wave radiation on a clear day in cal. It was obtained as :

$$R_{bo} = (a_1 - 0.044\sqrt{e_d})(11.71*10^{-8})(T_h{}^4 + T_l{}^4)/2 \tag{3.22}$$

where T_h and T_l are maximum and minimum air temperature in °K, and a_1 is used to estimate the effective emittance of the atmosphere, determined as:

$$a_1 = 0.26+0.1 \text{ EXP } \{-[0.0154(30M+N-207)]^2\} \qquad (3.23)$$

where M is the number of the month (1-12) and N is the day of the month (1-31).

The albedo in this method was determined using the following equation only for the period from April 15th to October 15th, and only for mostly clear days when $(R_s/R_{so}) > 0.7$. Otherwise it was given a constant value of 0.25 as described earlier in the previous chapter.

$$\alpha = 0.29+0.06 \sin \{30[M+(0.0333N)+2.25]\} \qquad (3.24)$$

The wind function was obtained as :

$$f(U) = \beta_0 + \beta_1 U \qquad (3.25)$$

where U is wind run at 2 m height in km day^{-1}, β_0 and β_1 are empirical coefficients determined from :

$$\beta_0 = 0.4 + 1.4 \text{ EXP } \{-[(D-173)/58)]^2\} \qquad (3.26)$$

$$\beta_1 = 0.007 + 0.004 \text{ EXP } \{-[(D-243)/80)]^2\} \qquad (3.26)$$

where D is the day number in the year (1-365).

The saturation vapor pressure (e_a) was computed as the average of saturation vapor pressure at maximum air temperature (e_{max}) and saturation vapor pressure at minimum air temperature (e_{min}) by using the following empirical polynomial equation:

$$\begin{aligned} e_{max} = {} & 6.105 + 4.44 \times 10^{-1} T_h + 1.434 \times 10^{-2} T_h^2 \\ & + 2.623 \times 10^{-4} T_h^3 + 2.953 \times 10^{-6} T_h^4 \\ & + 2.559 \times 10^{-8} T_h^5 \end{aligned} \tag{3.27}$$

$$\begin{aligned} e_{min} = {} & 6.105 + 4.44 \times 10^{-1} T_l + 1.434 \times 10^{-2} T_l^2 \\ & + 2.623 \times 10^{-4} T_l^3 + 2.953 \times 10^{-6} T_l^4 \\ & + 2.559 \times 10^{-8} T_l^5 \end{aligned} \tag{3.28}$$

$$e_a = (e_{max} + e_{min}) / 2 \tag{3.29}$$

Since measured dewpoint temperature was not available, saturation vapor pressure at dewpoint temperature (e_d) was determined from e_a in Eq.3.29 and mean relative humidity as follows (Cuenca, 1987; Burman, 1983):

$$e_d = e_a (RH_{mean} / 100) \tag{3.30}$$

where RH_{mean} is the mean relative humidity in percent.

3.3 PROCEDURE FOR CALIBRATION OF THE PENMAN EQUATION

Calibration for the Penman equation in both versions, FAO and Wright, was made in order to estimate individual crop evapotranspiration (E_{tc}) instead of reference crop evapotranspiration (E_{tr}) such as short grass or alfalfa. The procedure followed for the calibration is described below:

1. A Fortran program was written to calculate reference crop evapotranspiration from the provided meteorological data by both methods, the Penman-FAO and the Penman-Wright.

2. Crop coefficients were prepared for individual crop to compute E_{tc}. As mentioned earlier, grass reference crops coefficients were available, but alfalfa reference crop coefficients had to be prepared using Eq.3.2.

3. Crop evapotranspiration (E_{tc}) was determined using the following equations for individual crops for the full season.

$$E_{tc\text{-}FAO} = K_{c\text{-}grass} \times E_{tr\text{-}FAO} \tag{3.31}$$

$$E_{tc\text{-}Wright} = K_{c\text{-}alf} \times E_{tr\text{-}Wright} \tag{3.32}$$

where $E_{tc\text{-}FAO}$ is crop ET determined by the Penman-FAO method, $E_{tr\text{-}FAO}$ is reference ET determined by the Penman-FAO method, $E_{tc\text{-}Wright}$ is crop ET determined by the Penman-Wright method and $E_{tr\text{-}Wright}$ is reference ET determined by the Penman-Wright method.

4. Then from the measured crop evapotranspiration ($E_{tc\text{-}m}$) and estimated crop evapotranspiration ($E_{tc\text{-}e}$), which resulted from step 3, a linear regression analysis was made to relate the measured E_{tc} to estimated E_{tc} and to determined the possible coefficients which are required to give good estimates by the model. The suggested model is:

$$E_{tc\text{-}m} = a + b\ E_{tc\text{-}e} \tag{3.33}$$

where a and b are the intercept and the slope of the linear regression line.

4. ANALYSIS AND DISCUSSION

4.1 LYSIMETER ERROR

The lysimeter error results from daily measurement of E_{tc} from the drainage lysimeters. Drainage lysimeters cannot give an accurate measurement of daily E_{tc}, only sensitive weighing lysimeters could give accuracy for such measurements. That is because the difference between the amount of water added and that drained from the drainage lysimeter would not represent the E_{tc} for that day. Soil characteristics would influence the amount of water drained. So, when water is added to the lysimeter, the excess water may not drain completely. Consequently, it may influence readings on the second or third day. Sometimes it may have an influence on the 5th or 6th day of measurements. Such influence must be taken into account in considering the daily E_{tc}. To avoid such error, a moving average procedure was followed.

A moving average was used for periods varying from one to ten days for both measured and estimated E_{tc}. In order to select one averaging period that has a minimum effect of error from the drainage lysimeter, correlation coefficients and mean square error were calculated for each averaging period. Tables 4.1 to 4.5 summarize the results.

The tables show a decrease in the mean square error as the moving average period increases. Also, there is an increase in the correlation coefficient as the averaging period increases. There is a significant decrease in the Mean Square Error (MSE) for the averaging period up to five days, after that the decrease in the MSE is less significant for most of the crops in this study. It is clear that 68-87% of the total decrease in MSE took place during the averaging period from one to five days, while it was only 13-32% during the period from six to ten days.

The correlation coefficient (R) has significant increases during the period from one to five days and less significant increases from six to ten days. Fifty-six to seventy-seven percent of the total increases took place during the first five days, with 23-44% during the second five days.

The relation between the averaging periods versus mean square error or correlation coefficient was plotted in figures 4.1 to 4.10. Most of the plots show that the MSE decreases rapidly as the averaging period increases up to the five day averaging period, after that it decreases gradually. Also, the correlation coefficient increases rapidly up to the averaging period of five days, then it increases gradually.

The minimum MSE was found for the maximum averaging period, and a maximum correlation coefficient was found at the maximum averaging period. However, this cannot be used, because an hourly or daily period for estimating E_{tc} is very important for irrigation projects, specially in extremely arid regions and for soils with a high infiltration rate, such as those in U.A.E., which require a short irrigation cycle.

With these considerations, a five day moving average would be the optimum period to be used for the calibration. So, the analyses and the calibration were based on a five-day averaging period.

Table 4.1 Changes in mean square error and correlation coefficients over the averaging periods for Tomato

Season, 1983								
	FAO				Wright			
Averaging period	MSE	% D	R	% I	MSE	% D	R	% I
1	1.27	0.00	0.43	0.00	1.25	0.00	0.44	0.00
2	1.01	34.59	0.46	27.16	1.00	34.53	0.47	26.78
3	0.83	23.45	0.49	22.98	0.83	23.35	0.50	22.43
4	0.73	13.07	0.51	14.08	0.73	12.99	0.52	13.61
5	0.67	8.13	0.53	10.14	0.67	8.27	0.53	10.90
6	0.63	5.58	0.53	6.75	0.63	5.71	0.54	7.48
7	0.60	4.24	0.54	4.63	0.59	4.29	0.55	4.92
8	0.57	3.72	0.55	4.53	0.57	3.71	0.55	4.50
9	0.54	3.73	0.55	4.92	0.54	3.69	0.56	4.68
10	0.52	3.48	0.56	4.83	0.51	3.46	0.57	4.71

Note:

MSE = Mean square error (mm^2/day)
% D = Percentage decrease in MSE at each averaging period
R = Correlation coefficient
% I = Percentage increase in R at each averaging period

Table 4.2 Changes in mean square error and correlation coefficients over the averaging periods for Cabbage

Averaging period	FAO MSE	FAO % D	FAO R	FAO % I	Wright MSE	Wright % D	Wright R	Wright % I
Season, 1982								
1	0.60	0.00	0.23	0.00	0.59	0.00	0.23	0.00
2	0.48	22.90	0.28	11.50	0.49	22.29	0.27	9.00
3	0.38	20.05	0.33	13.76	0.39	20.33	0.33	14.88
4	0.31	15.31	0.39	12.41	0.31	15.51	0.38	13.16
5	0.25	12.24	0.44	12.36	0.25	12.34	0.44	12.77
6	0.20	9.70	0.49	12.13	0.20	9.72	0.49	12.23
7	0.17	6.60	0.53	10.41	0.17	6.61	0.53	10.48
8	0.15	5.01	0.57	9.14	0.15	5.01	0.57	9.15
9	0.12	4.16	0.60	8.48	0.13	4.14	0.60	8.38
10	0.11	4.02	0.64	9.79	0.11	4.05	0.64	9.95
Season, 1983								
1	1.67	0.00	0.46	0.00	1.67	0.00	0.46	0.00
2	0.98	43.99	0.56	22.92	1.00	43.42	0.55	21.42
3	0.57	26.68	0.67	24.40	0.59	26.30	0.65	23.11
4	0.40	10.99	0.74	15.24	0.42	11.11	0.72	15.47
5	0.32	5.00	0.78	9.11	0.34	5.36	0.76	10.21
6	0.25	4.09	0.81	7.94	0.27	4.27	0.80	8.51
7	0.19	3.82	0.85	7.61	0.21	3.90	0.83	7.82
8	0.16	2.43	0.87	5.17	0.17	2.48	0.86	5.28
9	0.13	1.53	0.89	3.62	0.15	1.59	0.87	3.80
10	0.11	1.47	0.90	3.98	0.12	1.58	0.89	4.39

Note:

MSE = Mean square error (mm^2/day)
% D = Percentage decrease in MSE at each averaging period
R = Correlation coefficient
% I = Percentage increase in R at each averaging period

Table 4.3 Changes in mean square error and correlation coefficients over the averaging periods for Cucumber

Averaging period	FAO MSE	FAO % D	FAO R	FAO % I	Wright MSE	Wright % D	Wright R	Wright % I
Season, 1982								
1	1.97	0.00	0.27	0.00	2.07	0.00	0.17	0.00
2	1.78	14.31	0.31	13.96	1.90	13.17	0.20	11.60
3	1.61	12.91	0.37	17.16	1.75	11.65	0.25	16.36
4	1.46	11.28	0.41	14.04	1.61	10.39	0.29	13.22
5	1.36	7.92	0.40	-2.75	1.48	10.27	0.32	10.17
6	1.18	13.61	0.47	22.98	1.33	11.28	0.35	10.17
7	1.03	11.49	0.50	9.37	1.17	12.06	0.38	9.80
8	0.89	10.46	0.52	8.45	1.02	11.26	0.41	9.17
9	0.76	9.72	0.55	8.20	0.88	10.68	0.43	9.30
10	0.65	8.30	0.57	8.59	0.76	9.24	0.46	10.20
Season, 1983								
1	1.31	0.00	0.44	0.00	1.33	0.00	0.42	0.00
2	1.18	16.49	0.45	18.48	1.20	17.02	0.43	25.41
3	1.10	11.04	0.45	9.40	1.11	11.17	0.44	11.55
4	1.03	9.23	0.46	8.01	1.04	9.20	0.44	8.18
5	0.96	9.06	0.45	-10.75	0.96	10.87	0.44	-5.13
6	0.87	11.99	0.47	29.83	0.88	10.07	0.45	23.85
7	0.78	11.12	0.47	10.62	0.80	11.07	0.46	10.31
8	0.70	10.87	0.48	11.26	0.71	11.40	0.46	12.31
9	0.62	10.46	0.48	12.04	0.64	9.67	0.47	7.01
10	0.55	9.74	0.49	11.10	0.56	9.54	0.47	6.50

Note:

MSE = Mean square error (mm^2/day)
% D = Percentage decrease in MSE at each averaging period
R = Correlation coefficient
% I = Percentage increase in R at each averaging period

Table 4.4 Changes in mean square error and correlation coefficients over the averaging periods for Squash

Averaging period	FAO MSE	FAO % D	FAO R	FAO % I	Wright MSE	Wright % D	Wright R	Wright % I
Season, 1984								
1	0.30	0.00	0.46	0.00	0.30	0.00	0.48	0.00
2	0.24	27.44	0.52	17.65	0.23	25.67	0.53	14.32
3	0.19	17.82	0.57	13.72	0.19	16.96	0.58	11.86
4	0.16	14.48	0.62	14.14	0.15	14.07	0.63	12.90
5	0.13	10.85	0.65	9.85	0.13	8.89	0.66	9.08
6	0.11	7.99	0.69	12.49	0.10	10.76	0.71	14.42
7	0.09	6.60	0.72	9.48	0.08	7.46	0.76	11.16
8	0.08	5.74	0.75	8.47	0.07	6.36	0.79	9.82
9	0.07	5.00	0.78	7.96	0.05	5.44	0.83	9.02
10	0.06	4.06	0.80	6.25	0.04	4.40	0.85	7.42
Season, 1985								
1	1.08	0.00	0.36	0.00	1.11	0.00	0.32	0.00
2	0.72	41.53	0.43	20.86	0.76	41.33	0.37	18.22
3	0.55	19.62	0.49	19.25	0.59	19.82	0.43	21.09
4	0.45	11.54	0.53	13.98	0.48	12.67	0.49	20.42
5	0.38	8.13	0.57	11.32	0.42	7.08	0.50	6.20
6	0.32	6.39	0.61	10.79	0.37	6.32	0.53	10.96
7	0.28	5.08	0.64	9.20	0.32	5.05	0.56	9.26
8	0.25	3.56	0.66	6.53	0.29	3.58	0.58	6.44
9	0.23	2.36	0.67	4.50	0.27	2.36	0.59	4.21
10	0.21	1.80	0.68	3.58	0.26	1.79	0.60	3.20

Note:

MSE = Mean square error (mm^2/day)
% D = Percentage decrease in MSE at each averaging period
R = Correlation coefficient
% I = Percentage increase in R at each averaging period

Table 4.5 Changes in mean square error and correlation coefficients over the averaging periods for Watermelon

Averaging period	FAO MSE	FAO % D	FAO R	FAO % I	Wright MSE	Wright % D	Wright R	Wright % I
Season, 1983								
1	2.69	0.00	0.92	0.00	2.65	0.00	0.92	0.00
2	2.21	33.59	0.93	35.35	2.42	15.74	0.93	16.27
3	2.27	-4.72	0.93	-5.77	2.24	12.61	0.93	12.54
4	2.12	10.75	0.93	10.31	2.08	10.61	0.94	10.12
5	1.98	10.07	0.94	9.53	1.94	9.77	0.94	9.15
6	1.84	9.67	0.94	9.11	1.81	9.62	0.94	9.05
7	1.69	10.15	0.95	9.95	1.65	10.42	0.95	10.30
8	1.54	10.56	0.95	10.73	1.50	11.01	0.95	11.32
9	1.40	10.19	0.95	10.55	1.35	10.46	0.95	10.94
10	1.26	9.75	0.96	10.25	1.20	9.77	0.96	10.32
Season, 1984								
1	2.33	0.00	0.84	0.00	2.31	0.00	0.84	0.00
2	1.68	33.32	0.87	29.52	1.63	33.59	0.88	29.60
3	1.18	25.84	0.91	25.71	1.10	26.55	0.91	26.43
4	0.92	13.30	0.92	14.25	0.83	13.60	0.93	14.60
5	0.80	6.15	0.93	6.54	0.71	6.01	0.94	6.40
6	0.70	5.09	0.94	5.41	0.61	4.71	0.95	4.96
7	0.59	5.56	0.95	6.27	0.51	5.20	0.95	5.84
8	0.50	4.65	0.95	5.36	0.42	4.44	0.96	5.16
9	0.43	3.39	0.96	3.86	0.36	3.25	0.96	3.80
10	0.38	2.69	0.96	3.09	0.30	2.65	0.97	3.20
Season, 1985								
1	0.69	0.00	0.90	0.00	0.66	0.00	0.91	0.00
2	0.54	31.65	0.92	34.12	0.52	30.67	0.92	32.81
3	0.46	15.82	0.93	15.60	0.45	15.44	0.93	15.07
4	0.40	12.60	0.94	12.36	0.39	11.99	0.94	11.52
5	0.35	10.38	0.94	10.21	0.34	10.33	0.95	10.07
6	0.31	7.45	0.95	6.89	0.30	7.86	0.95	7.39
7	0.28	5.91	0.95	5.28	0.27	6.47	0.95	6.03
8	0.26	5.39	0.95	4.80	0.24	6.03	0.96	5.71
9	0.23	5.55	0.96	5.32	0.22	5.85	0.96	5.78
10	0.20	5.26	0.96	5.42	0.19	5.37	0.96	5.61

Note:

MSE = Mean square error (mm^2/day)
% D = Percentage decrease in MSE at each averaging period
R = Correlation coefficient
% I = Percentage increase in R at each averaging period

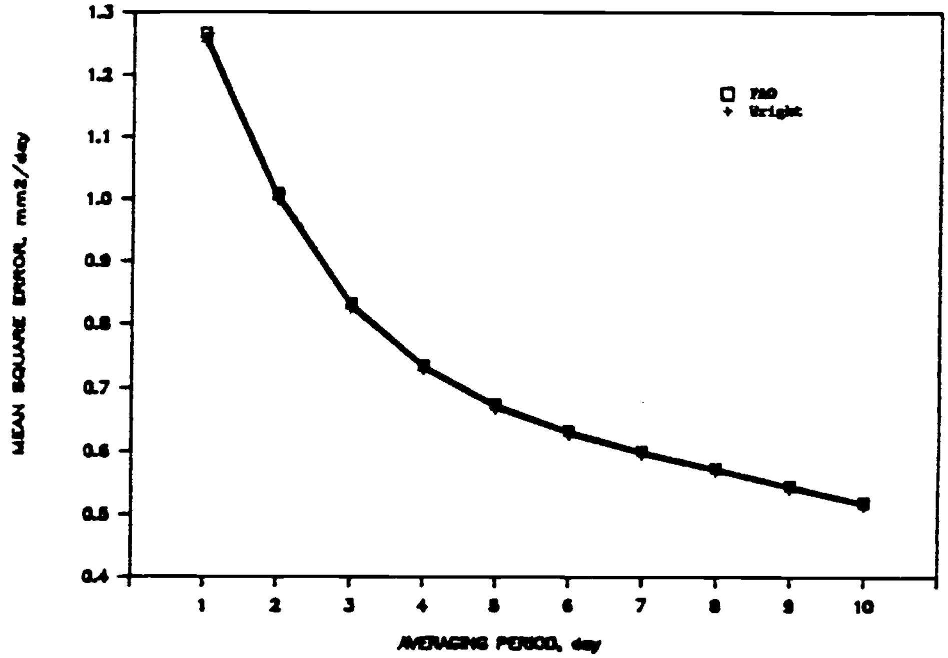

Figure 4.1 Variation of mean square error over the averaging periods for tomato, 1983 season.

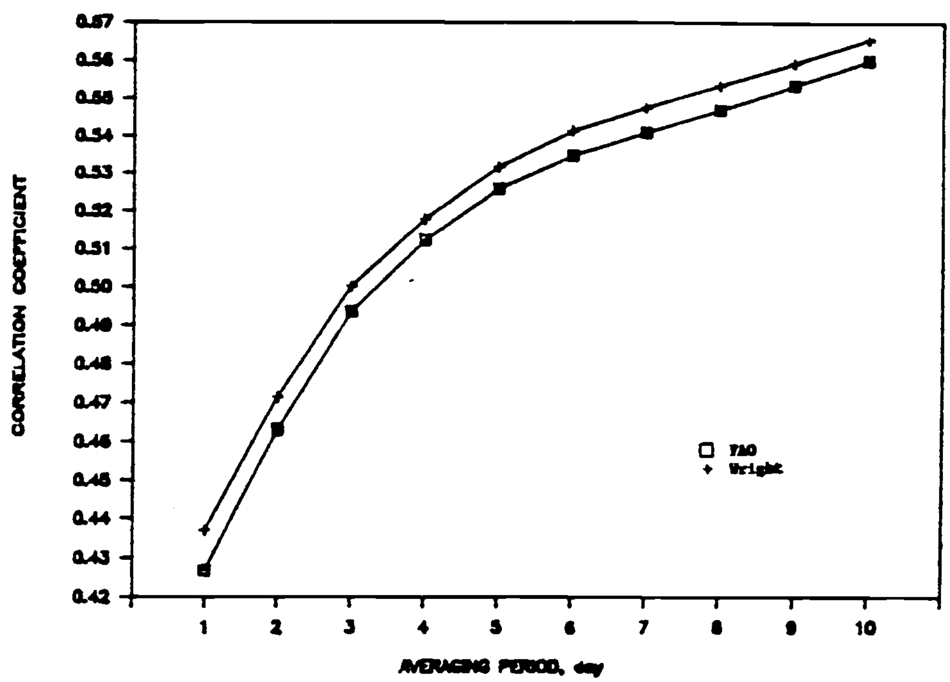

Figure 4.2 Variation of correlation coefficient over the averaging periods for tomato, 1983 season.

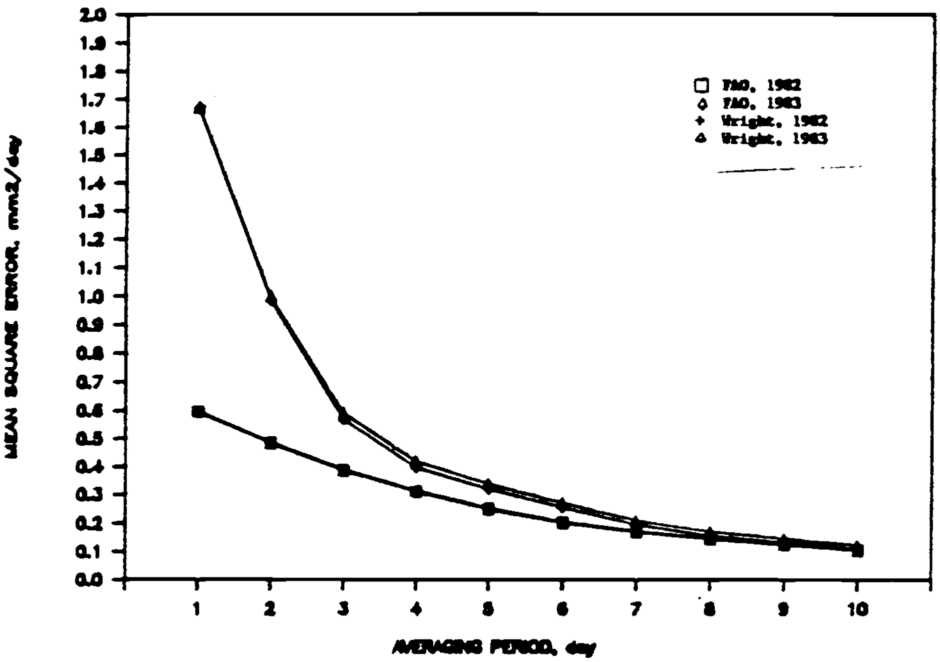

Figure 4.3 Variation of mean square error over the averaging periods for cabbage, 1982 and 1983 seasons.

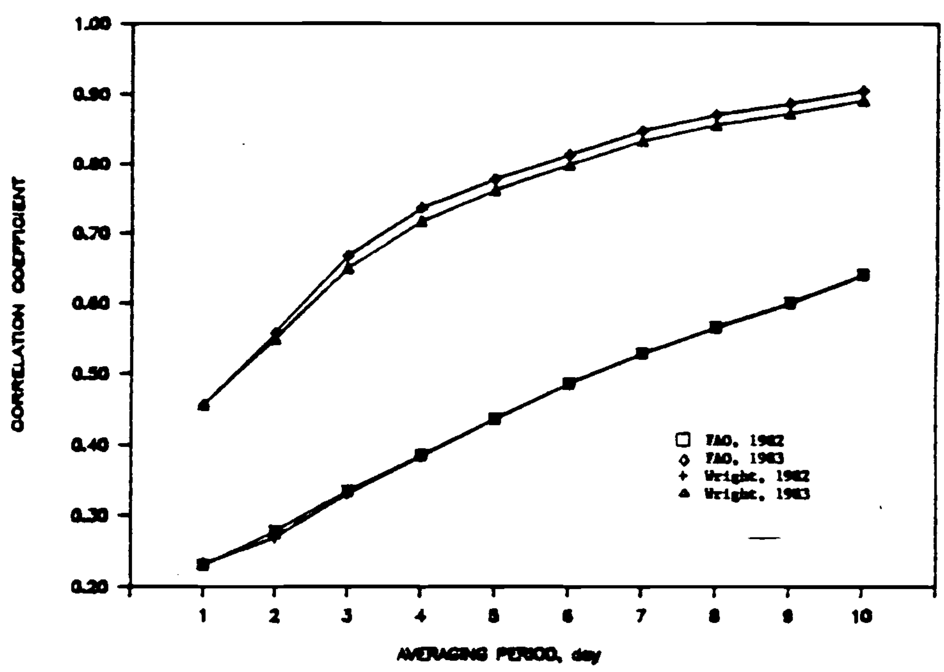

Figure 4.4 Variation of correlation coefficient over the averaging periods for cabbage, 1982 and 1983 seasons.

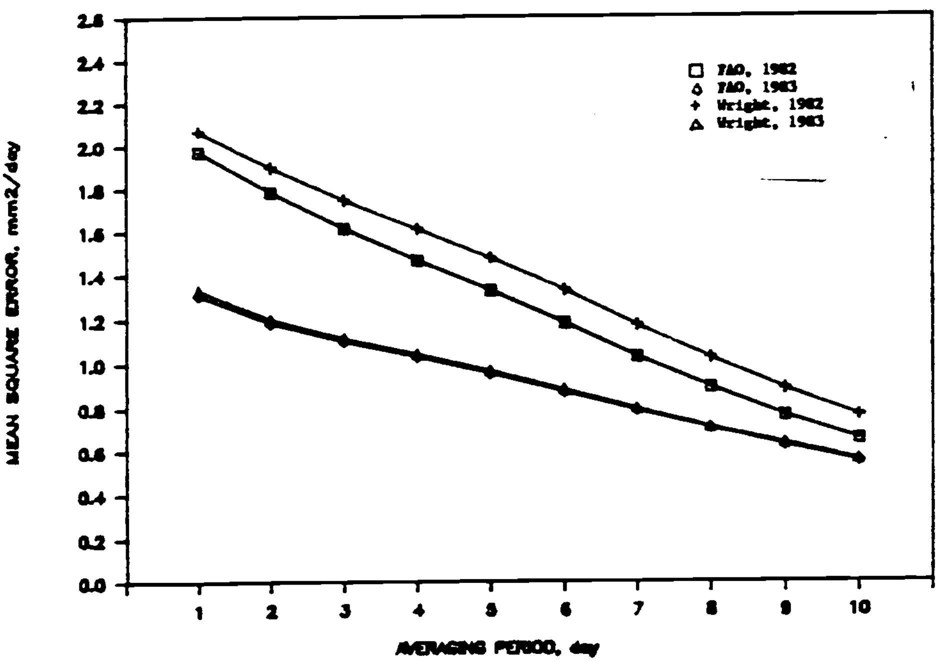

Figure 4.5 Variation of mean square error over the averaging periods for cucumber, 1982 and 1983 seasons.

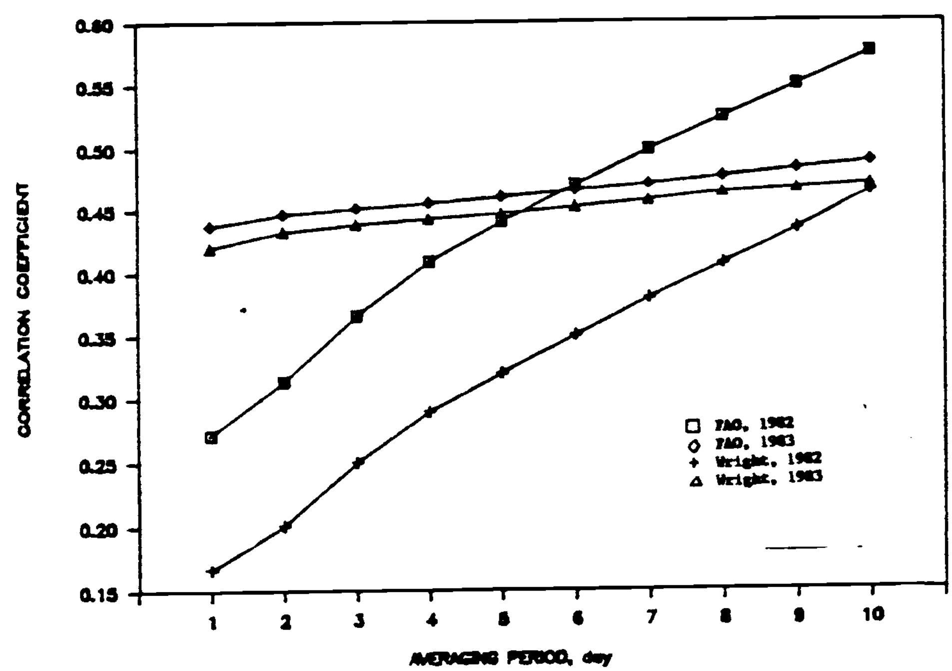

Figure 4.6 Variation of correlation coefficient over the averaging periods for cucumber, 1982 and 1983 seasons.

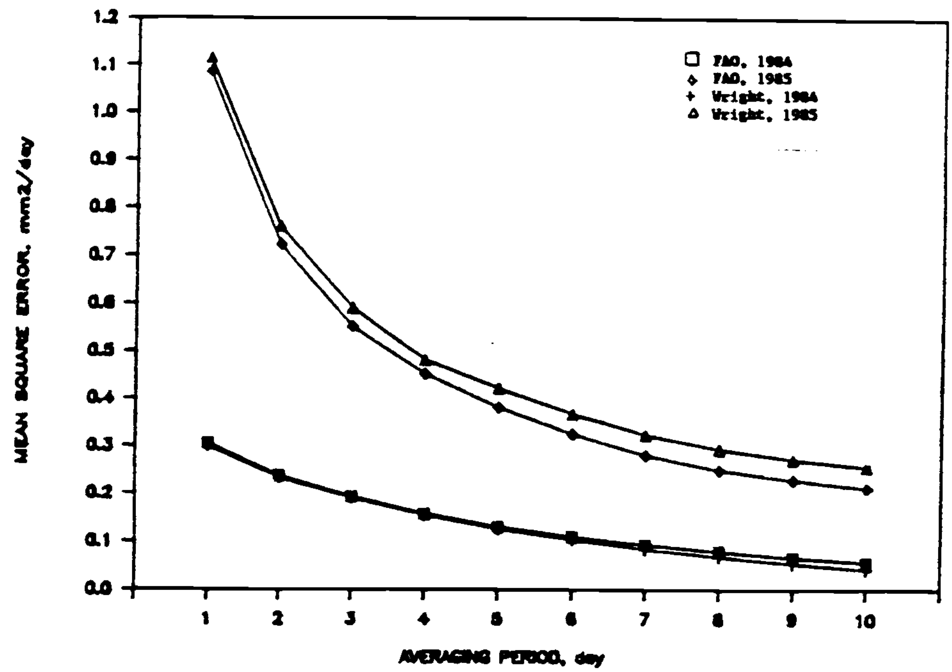

Figure 4.7 Variation of mean square error over the averaging periods for squash, 1984 and 1985 seasons.

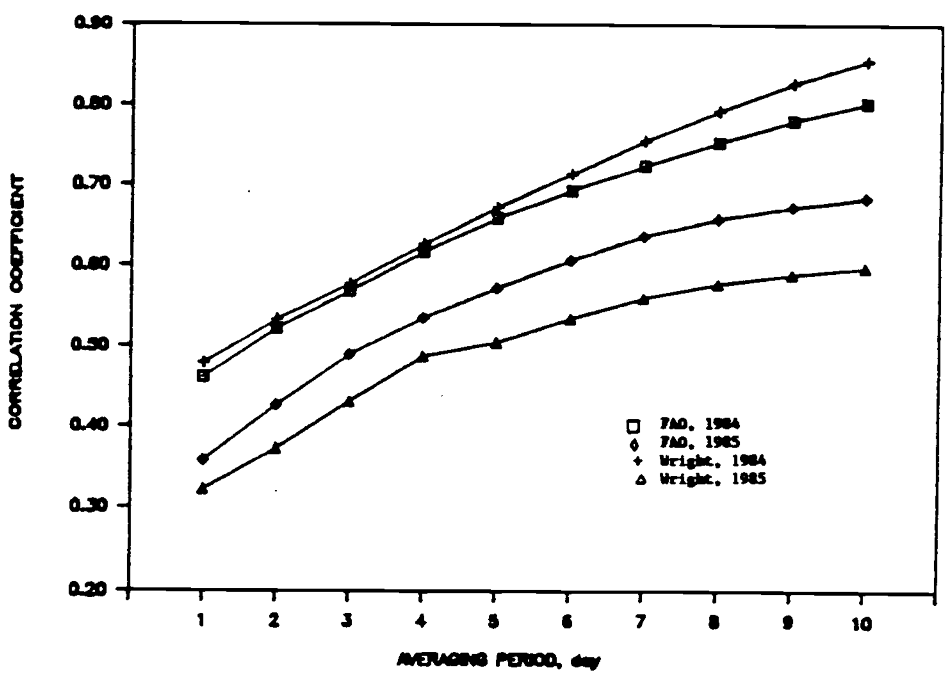

Figure 4.8 Variation of correlation coefficient over the averaging periods for squash, 1984 and 1985 seasons.

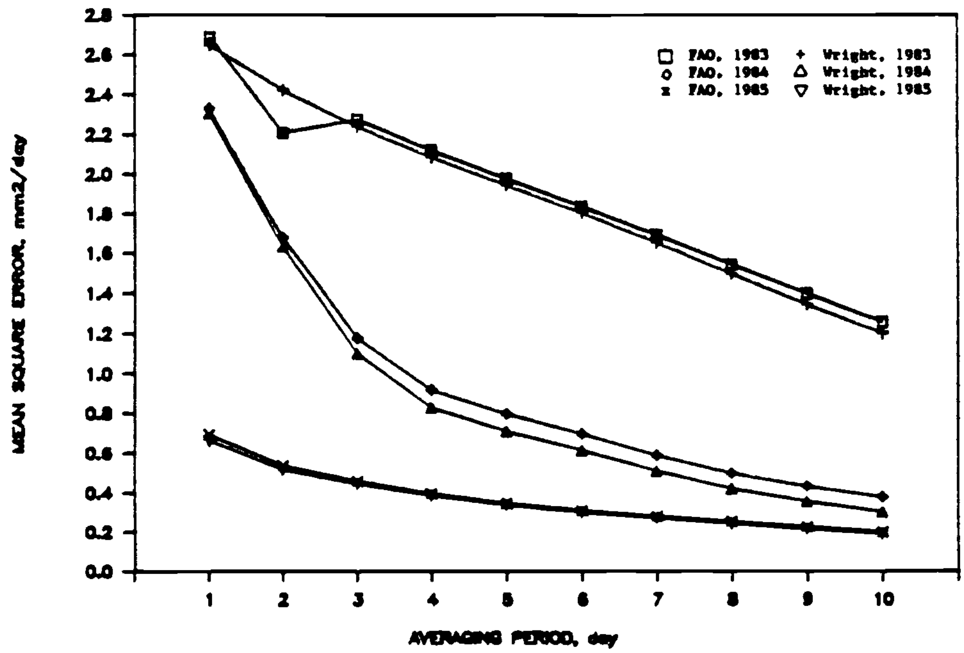

Figure 4.9 Variation of mean square error over the averaging periods for watermelon,1983,1984 and 1985 seasons.

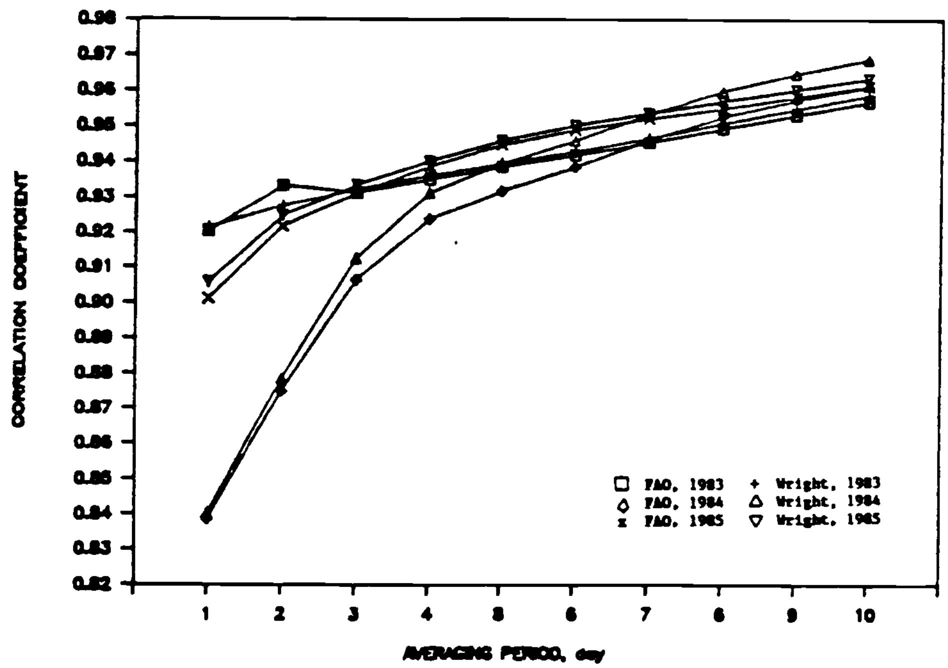

Figure 4.10 Variation of correlation coefficient over the averaging periods for watermelon, 1983, 1984 and 1985 seasons.

4.2 STATISTICAL ANALYSIS

Regression analysis was used to relate the estimated E_{tc}, by the Penman equation, to the measured E_{tc} from the lysimeter. The regression analysis was done for five crops on individual seasons and the regression model was:

$$E_{tc-m} = a + b\ E_{tc-e} \qquad (4.1)$$

where:

E_{tc-m} = measured crop evapotranspiration as dependant variable

E_{tc-e} = estimated crop evapotranspiration as independent variable

a and b = regression coefficients where a is the intercept and b is the slope of the regression line

The regression results are presented in table 4.6. The scatter plots and residuals plots are presented in Appendix B, fig. B.1 to fig. B.32.

The statistical tests that were used to test regression parameters, were, first the hypothesis test B_0=0, the intercept is not significantly different from zero against B_0 not equal zero, the intercept is significantly different from zero. The second, hypothesis tests B_1=0, no linear relationship exists between estimated E_{tc} and measured E_{tc} against B_1 not equal zero, the linear relationship between estimated E_{tc} and measured E_{tc} exists. The third hypothesis tests P=0, estimated E_{tc} does not explain a significant amount of variation in measured E_{tc} against P not equal zero, estimated E_{tc} explains a significant amount of measured E_{tc}, where P is the population correlation coefficient.

From statistical tests it was found that the intercept was significantly different from zero at the 99% confidence level for all crops and for both versions of the Penman equation. Except for squash and cucumber (season 1982 with FAO and season 1983 with both equations), the intercept was not significantly different from zero at 90-99% confidence level for both versions of the Penman equation.

There is a significant linear relationship between estimated E_{tc} and measured E_{tc} at the 99% confidence level for all crops and for both versions of the Penman equation.

The estimated E_{tc} explains a significant amount of variation in measured E_{tc} at 99% confidence level for all crops and for both versions of the Penman equation.

The plots of the residuals for cabbage and squash show that they are independent, normally distributed, and with constant variance. For the other crops, the constancy of the variance was vague, therefore, a transformation as well as weighted regression was used. This, however, did not improve the constancy of the variance.

Table 4.6 Results of the regression analysis, for individual seasons, for FAO and Wright versions.

Crop and season		FAO				Wright			
		a	b	R	SEE	a	b	R	SEE
Tomato	83	2.24	0.27	0.53	0.82	2.45	0.32	0.53	0.82
Cabbage	82	1.19	0.37	0.44	0.50	1.23	0.41	0.44	0.50
,,	83	1.31	1.05	0.78	0.56	1.49	1.12	0.76	0.58
Cucumber	82	0.00	0.76	0.40	1.17	1.42	0.51	0.32	1.22
,,	83	0.00	0.61	0.45	0.98	0.00	0.72	0.44	0.98
Squash	84	0.00	0.83	0.65	0.36	0.00	0.96	0.66	0.36
,,	85	0.00	1.16	0.57	0.61	0.00	1.37	0.50	0.65
W.melon	83	-1.82	1.47	0.94	1.41	-1.33	1.61	0.94	1.39
,,	84	-0.86	1.07	0.93	0.89	-0.52	1.17	0.94	0.84
''	85	-0.49	0.86	0.94	0.59	-0.36	1.07	0.95	0.58

Note:

a = Intercept of the regression line.
b = Slope of the regression line.
R = Correlation coefficient.
SEE = Standard error of estimates (mm/day).

4.3 DISCUSSION

The Penman-FAO version estimates reference crop evapotranspiration (E_{tr}) slightly higher than that of the Penman-Wright version (see Fig. 4.11). The Wright version is supposed to estimate E_{tr} higher than that of the FAO version because the Wright version is based on alfalfa and the FAO version is based on grass. Alfalfa has a rough surface compared to grass, which would allow more evapotranspiration. Comparison between the two methods cannot be done in this case, because there was no measured data for alfalfa and grass.

Comparison of standard errors of estimate (SEE) in Table 4.6, shows that the SEE for cucumber in 1982 is higher than that for 1983. SEE for cabbage in 1982 is lower than that for the season of 1983. SEE for squash in 1984 is lower than that for the season 1985. SEE for watermelon in 1983 is the highest, and the season of 1985 has the lowest SEE.

Comparison of correlation coefficients (R) among seasons, shows that cucumber in 1982 has relatively lower correlation coefficient compared to 1983. Cabbage in 1983 has higher compared to 1982. Squash in 1984 has a higher correlation coefficient compared to 1985. Watermelon has relatively the same correlation coefficient among all seasons.

There is fluctuation in the SEE and R between the two versions. The FAO version in some seasons has a lower SEE and a higher R than the Wright version, whereas in other seasons it

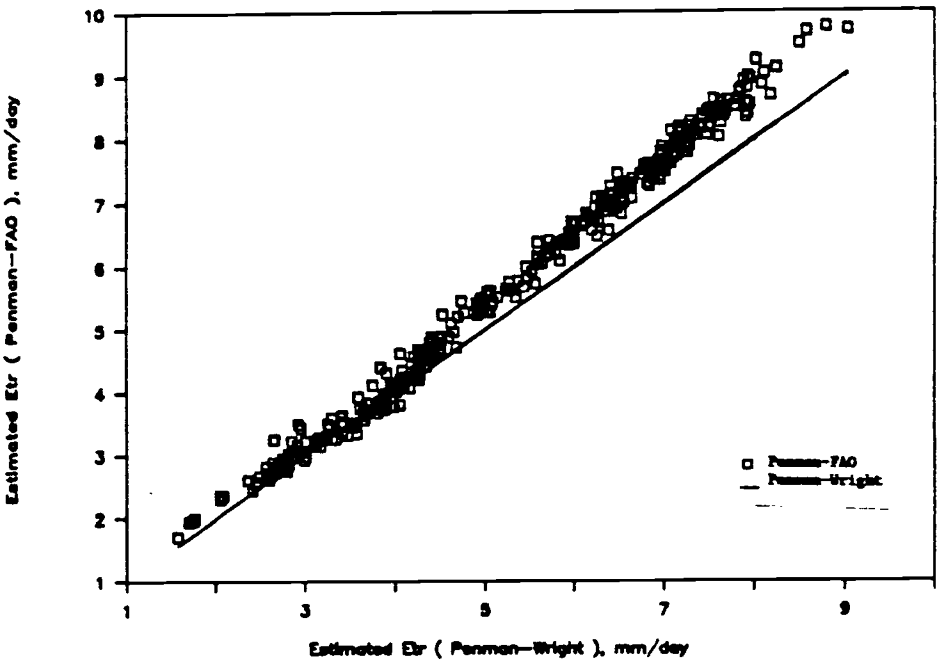

Figure 4.11 Relationship between estimated E_{tr} by FAO version and estimated E_{tr} by Wright version.

has higher SEE and a lower R than the Wright version.

From these comparisons it seems that there is great variation between seasons. This variation could be due to the estimated E_{tc} by the Penman equation, or due to measured E_{tc} in the lysimeter. The Penman equation is affected only by weather parameters, and the variations in the weather parameters between the seasons in this area are small. It was found that the variation is in the measured E_{tc} from the lysimeters. To illustrate this, the seasonal measured Et were plotted in fig.4.12 to 4.15. It is clear from the figures that the variation among seasons was due to measured E_{tc}. There are two possible reasons that created the variation in measured E_{tc} among seasons:

1. Effects on plant growth.

Fertilization, water quality, plant diseases, and existence of grasses, etc., are factors affecting plant growth, and this correspondingly would effect crop Et. For instance, fertilizers would increase plant growth, which will increase E_{tc}. On the other hand, high levels of fertilizers and water with high salinity would build a high concentration of salts in the root zone. This would decrease plant growth and decrease crop Et. Also, existence of weeds in the lysimeter would increase the measured E_{tc} because weeds transpire significant amounts of water.

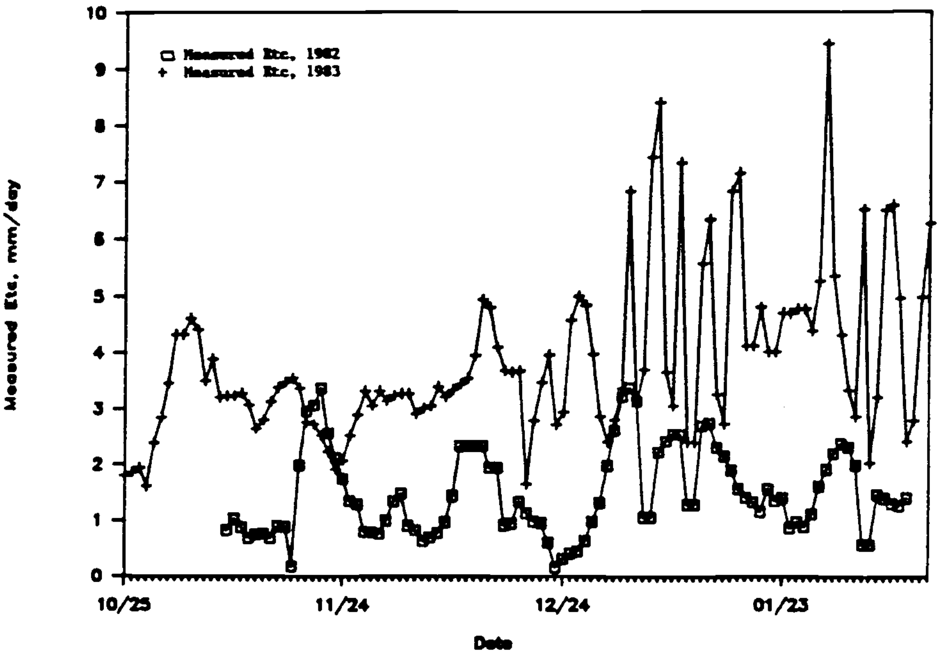

Figure 4.12 Seasonal variation in measured E_{tc} for cabbage, 1982 and 1983.

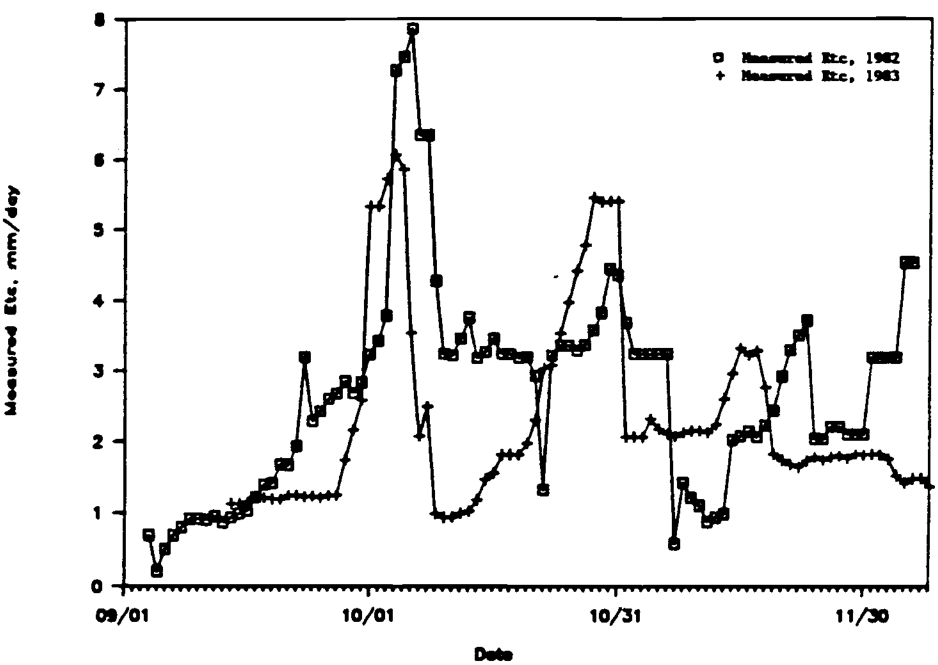

Figure 4.13 Seasonal variation in measured E_{tc} for cucumber, 1982 and 1983.

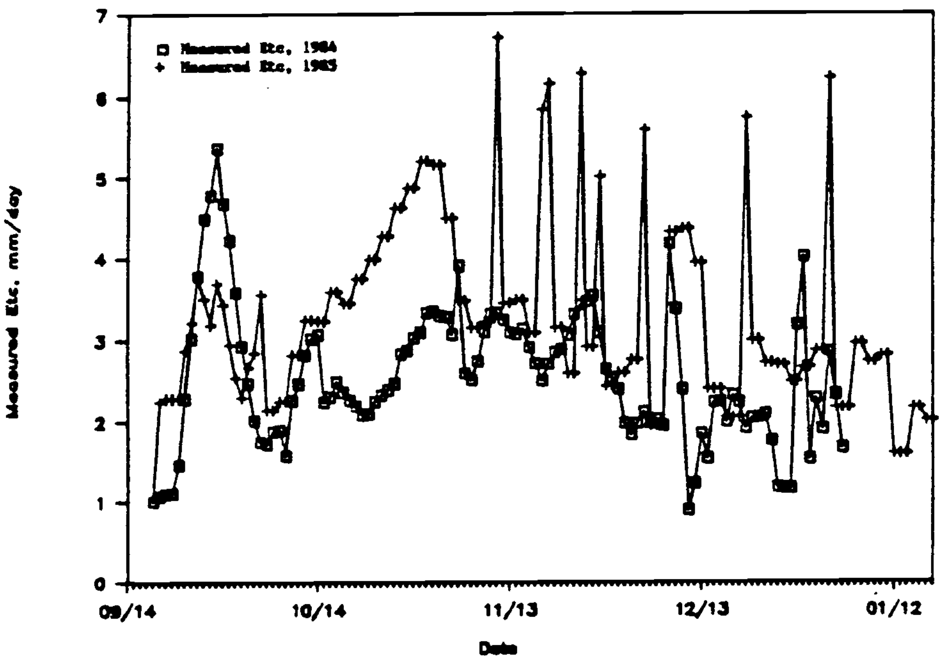

Figure 4.14 Seasonal variation in measured E_{tc} for squash, 1984 and 1985.

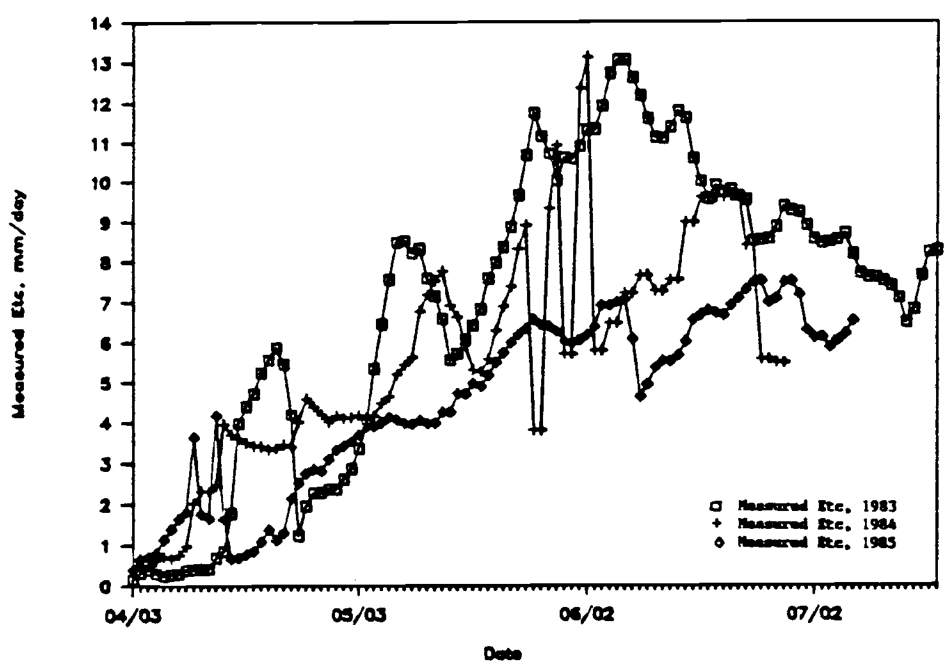

Figure 4.15 Seasonal variation in measured E_{tc} for watermelon, 1983, 19842 and 1985.

Variation in these factors in the lysimeter from one season to the next would affect the crop Et and create variation in the measured Et between seasons.

Unfortunately, information about plant treatments in the lysimeter, such as type and amount of fertilizers, water quality, soil conditions, etc. is not available, so it is hard to tell which season has the best result to be considered for the calibration.

2. Problems in the lysimeter.

The most common problem in the drainage lysimeter is that water can creates channels in the soil as a result of irrigation, especially near the edges of the lysimeter. When water is added to the lysimeter, some of it flows through these channels and leaves the remainder of the soil dry. So, when daily crop Et is measured by subtracting the amount of output water from the amount of input water,the results will show low E_{tc} while the crop has not had the chance to transpire enough water. These channels increase in time in terms of size and quantity, which will lead to an increase in the effects on measured E_{tc} from one season to the other. Since no information is available about the condition of the lysimeter during the experiments, the magnitude of this effect cannot be determined.

These two reasons can explain the fluctuation of SEE and R with season. As mentioned earlier, estimates of Etr by the FAO version are higher than by the Wright version, so when the estimated E_{tc} is less than that of the measured E_{tc}, estimated E_{tc} by the FAO version tends to be closer to the measured E_{tc}, and the SEE for the FAO version is lower than that of the Wright version. On the other hand, when the estimated E_{tc} is higher than the measured E_{tc}, estimated E_{tc} by the Wright version tends to be closer to the measured E_{tc}, therefore, SEE for the Wright version is lower than that of the FAO version. The correlation coefficient takes the same trend, the closer the estimated E_{tc} is to the measured values of E_{tc}, the higher the correlation coefficient.

The errors for the estimated E_{tc} (table 4.7) show the magnitude of the error of direct estimate of E_{tc}, and the error after the regression coefficients have been used. It is clear from the table that there is improvement in the estimated E_{tc} using the regression model, a significant amount of the error was reduced. Cabbage in 1983 and squash in 1984 ranked first with average error of ± 11.47% to ± 11.75%, followed by watermelon in 1985 with average error of ± 13.70%. The rest of the crops, except cucumbers, have average error of ± 15.57% to ± 25-87%.

The cucumber has a relatively high error, over ± 33% on both seasons. Watermelon in 1983 seems to have the highest error for both versions of the Penman equation, ± 45.57% to ± 53.67%.

It was found that 50-70% of the error was due to the value of crop coefficients during the initial crop growth stage. They were not low enough to describe crop Et at this stage.

Table 4.7 Daily average error of estimated E_{tr} from direct estimates (RAW) and regression model estimates (MOD).

CROP		FAO		WRIGHT	
		RAW	MOD	RAW	MOD
CUCUMBER	82	± 57.27 %	± 36.82 %	± 43.73 %	± 36.04 %
,,	83	± 95.63 %	± 34.67 %	± 66.96 %	± 33.46 %
CABBAGE	82	± 33.27 %	± 24.49 %	± 25.82 %	± 24.80 %
,,	83	± 36.75 %	± 11.47 %	± 44.46 %	± 11.65 %
TOMATO	83	± 42.83 %	± 18.94 %	± 37.72 %	± 18.99 %
SQUASH	84	± 23.91 %	± 11.62 %	± 13.27 %	± 11.75 %
,,	85	± 16.28 %	± 15.57 %	± 25.11 %	± 16.42 %
W.MELON	83	± 80.19 %	± 45.57 %	± 71.05 %	± 53.62 %
,,	84	± 27.79 %	± 20.04 %	± 22.48 %	± 20.59 %
,,	85	± 35.81 %	± 13.35 %	± 14.73 %	± 13.70 %

NOTE:

RAW = difference between measured E_{tc} and estimated E_{tc}

$$RAW\ \% = (|E_{tcm} - E_{tce}| \ / \ E_{tcm}) \times 100$$

MOD = difference between measured E_{tc} and predicted E_{tc} by the regression model

$$MOD\ \% = (|E_{tcm} - E_{tcp}| \ / \ E_{tcm}) \times 100$$

where :

E_{tcm} = measured E_{tc}
E_{tce} = estimated E_{tc} by the Penman equation
E_{tcp} = predicted E_{tc} by the regression model

Selection of the crop coefficient at this stage according to the FAO method (Doorenbos and Pruitt, 1977 in F.A.O publication NO. 24 " Crop Water Requirements") depends on the intervals of rainfall and E_{tr} during this stage. Since rainfall is not a factor under U.A.E. conditions, and irrigation water is applied daily, the FAO method of estimating crop coefficient gives relatively high values of crop coefficients. Considering this, crop coefficients that have been used in this study were corrected by the staff of the Ministry of Agriculture and Fisheries in the U.A.E.(Savva, 1984). However, the values that have been chosen were still high and needed to be lowered. Table 4.8 presents the percentage of average error without considering the initial stage, comparing the error with those in the table 4.7 shows that the error is reduced by 50-70% in the watermelon in all seasons, in the cabbage it is reduced by ≈ 20% and there was a slight improvement in the error in squash and tomato.

Error of ± 20% to ± 25% are not surprising when estimating crop water requirements under conditions such as those in the U.A.E., especially since the Penman equation was not calibrated locally. Although the error is relatively high, the estimates are still good considering the conditions (Personal Communication with R. Cuenca).

Considering that ± 20% to ± 25% error would be reasonable under these conditions, E_{tc} for all of the crops, except cucumber, which has relatively high error(more than ± 33%), could be predicted by the suggested model.

Table 4.8 Daily error of estimated E_{tr} from direct estimates (RAW) and regression model estimates (MOD) (E_{tc} at initial stage is not included).

CROP		FAO		WRIGHT	
		RAW	MOD	RAW	MOD
CUCUMBER	82	*	*	*	*
,,	83	± 88.07 %	± 34.27 %	± 62.58 %	± 34.27 %
CABBAGE	82	± 24.60 %	± 17.03 %	± 20.03 %	± 17.08 %
,,	83	*	*	*	*
TOMATO	83	± 43.00 %	± 18.47 %	± 35.28 %	± 18.38 %
SQUASH	84	*	*	*	*
,,	85	± 17.28 %	± 14.94 %	± 26.39 %	± 16.63 %
W.MELON	83	± 24.97 %	± 19.30 %	± 27.78 %	± 18.97 %
,,	84	± 13.32 %	± 11.58 %	± 11.42 %	± 10.60 %
,,	85	± 26.27 %	± 7.97 %	± 7.97 %	± 7.58 %

NOTE:

1. (*) Means that the calculations for E_{tc} were started after initial stage because there were no meteorological data available during that stage.

2. RAW = difference between measured E_{tc} and estimated E_{tc}

   $$RAW\ \% = (|E_{tcm} - E_{tce}| / E_{tcm}) \times 100$$

   MOD = difference between measured E_{tc} and predicted E_{tc} by the regression model

   $$MOD\ \% = (|E_{tcm} - E_{tcp}| / E_{tcm}) \times 100$$

where :

E_{tcm} = measured E_{tc}
E_{tce} = estimated E_{tc} by the Penman equation
E_{tcp} = predicted E_{tc} by the regression model

The regression coefficients for cabbage, squash and watermelon in table 4.6 vary seasonally, so each season suggests different coefficients to relate the estimated E_{tc} to the measured E_{tc}. Since the Penman equation in both versions was not calibrated locally, and there is no information available about crop treatment and lysimeter condition during the experiments, it is unclear which season has the best results to be used as calibration coefficients for the Penman equation.

Under these circumstances, and in order to obtain an unbiased regression coefficient to calibrate the Penman equation, combined seasons were used to obtain the calibration coefficients for cabbage, squash and water melon, Since there was only one season of measured E_{tc} for tomato, the coefficients in table 4.6 will be used.

4.4 CALIBRATION

Combined seasons were used to calibrate the Penman equation to estimate crop evapotranspiration. The combined seasons were two seasons of measured E_{tc} (1982 and 1983) for cabbage, two seasons for squash (1984 and 1985), and three seasons for watermelon (1983, 1984, and 1985).

Combined seasons of measured E_{tc} for each crop was regressed on estimated E_{tc}; the regression model used is the same as that in Eq.4.1. Table 4.9 presents the regression results. The parameters in the table are regression coefficients, a and b, correlation coefficients, R, and Standard Error of Estimate, SEE, which is the mean standard deviation of the regression from measured data.

The regression parameters (a, b and R) were for tested significance. It was found that the intercept, a, is significantly different from zero at the 99% confidence level for squash and watermelon with both versions and for cabbage with the Wright version, and at the 95% confidence level for cabbage with FAO version.

The linear relationship is significant at the 99% confidence level for all crops and for both versions of the Penman equation. The test of the correlation coefficient shows that the estimated E_{tc} by both versions of the Penman equation explains significant amounts of measured E_{tc} for all crops at the 99% confidence level. The correlation coefficient for squash is low, but it is still significant.

Table 4.9 The results of the regression analysis for combined seasons for cabbage, squash and watermelon.

Crop	FAO				Wright			
	a	b	R	SEE	a	b	R	SEE
Cabbage	0.53	1.05	0.53	1.05	0.62	1.16	0.55	1.04
Squash	1.57	0.50	0.29	0.70	1.95	0.44	0.23	0.71
W.melon	-1.13	1.13	0.86	1.50	-0.99	1.32	0.89	1.33

Note:

a = Intercept of the regression line.
b = Slope of the regression line.
R = Correlation coefficient.
SEE = Standard error of estimates (mm/day).

Comparing SEE values indicates that the Penman-Wright version has slightly better estimates than that of the Penman-FAO version for both cabbage and watermelon, while the FAO version has slightly better estimates for the squash. It was previously pointed out that the estimates of E_{tc} by FAO would be closer to the measured E_{tc} when the measured E_{tc} has a high value. The measured E_{tc} for squash in 1984 was lower than that in 1985, and a number of days were omitted from the 1984 season because weather parameters were not available during that period. When the seasons were combined and regressed, the model was biased toward the 1985 season which has high values of measured E_{tc}. This explains why the FAO version gave better estimation for squash only.

Regression results are presented graphically in Fig.4.16 to Fig.4.27. From the plots of actual E_{tc} and the regression lines it appears that the regression models are an unbiased estimate of E_{tc} for all crops for both versions. The plot of the residuals shows that the residuals are normally distributed, independent and with constant variation, except for watermelon where the variance seems not to be constant. The residuals variation increases at low values and at high values of estimated E_{tc}.

In order to improve the residuals variation,and to make them uniform, the following transformations were used:

1. $E_{tcm} = a + b \sqrt{E_{tce}}$ (4.2)
2. $\sqrt{E_{tcm}} = a + b \sqrt{E_{tce}}$ (4.3)
3. $E_{tcm} = a + b \log E_{tce}$ (4.4)
4. $\log E_{tcm} = a + b \log E_{tce}$ (4.5)
5. $E_{tcm} = a + b\ 1/E_{tce}$ (4.6)
6. $1/E_{tcm} = a + b\ 1/E_{tce}$ (4.7)
7. $E_{tcm} = a + (E_{tce})^b$ (4.8)
8. $E_{tcm} = a + b\ E_{tce} + c\ (E_{tce})^2$ (4.9)

where c is the regression coefficient.

Non of these transformations helped to improve the uniformity of the variance. This led to an analysis of the source of variation in the residuals plot. They were categorized into three classes. The first class was the variation at estimated E_{tc} < 3mm/day, the second class was 3mm/day ≤ estimated E_{tc} ≤

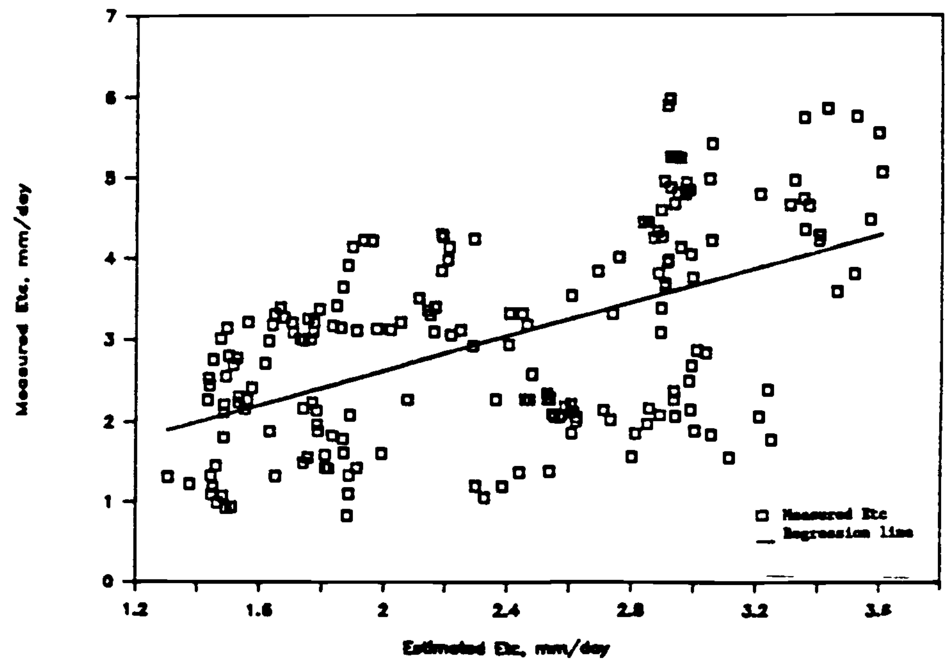

Figure 4.16 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of cabbage, for Penman-FAO.

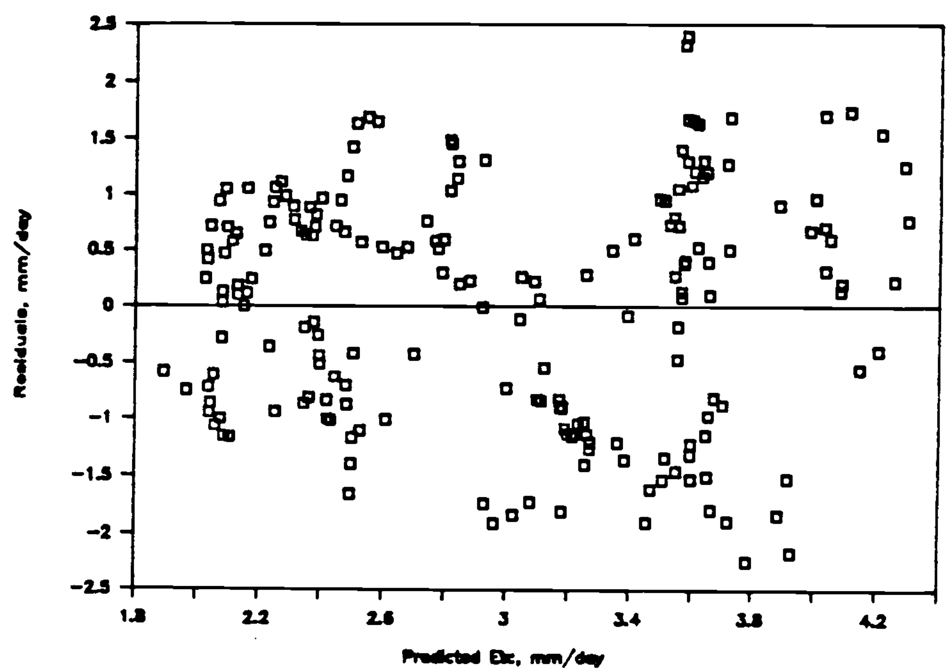

Figure 4.17 Residuals plot for combined seasons of cabbage, for the Penman-FAO.

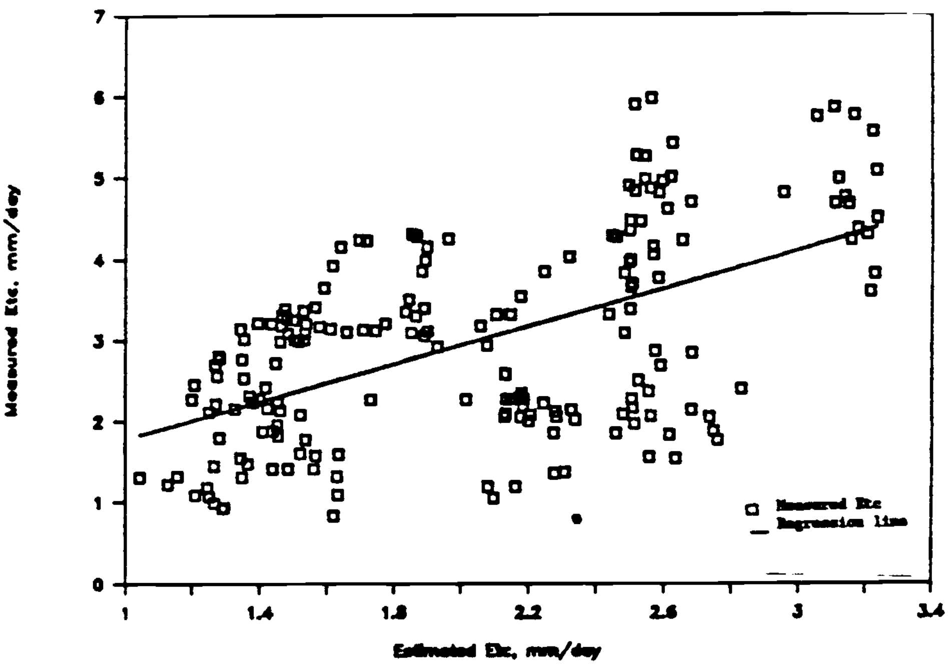

Figure 4.18 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of cabbage, for Penman-Wright.

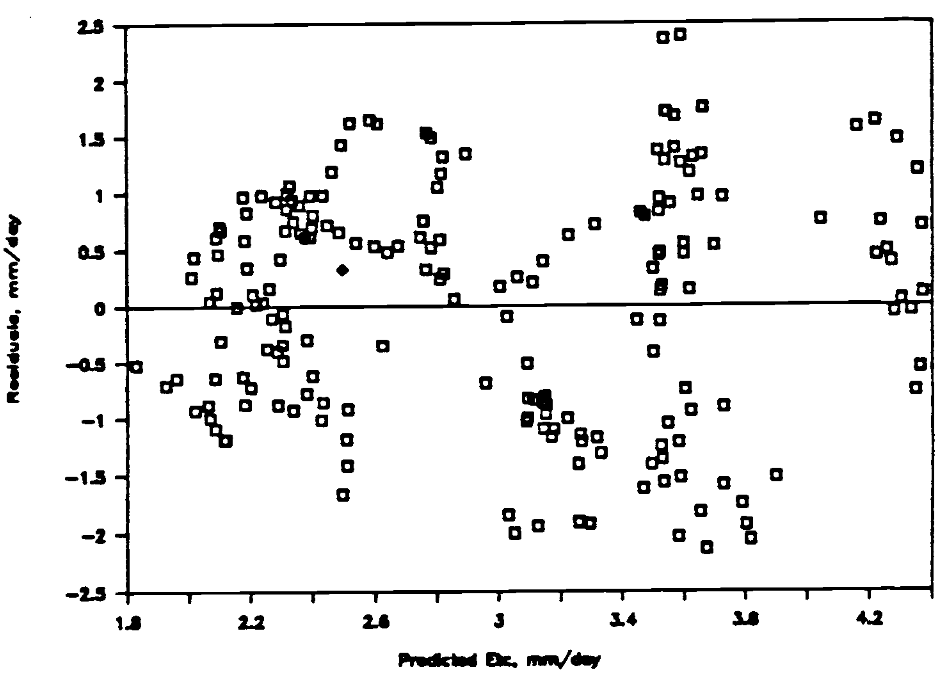

Figure 4.19 Residuals plot for combined seasons of cabbage, for the Penman-Wright.

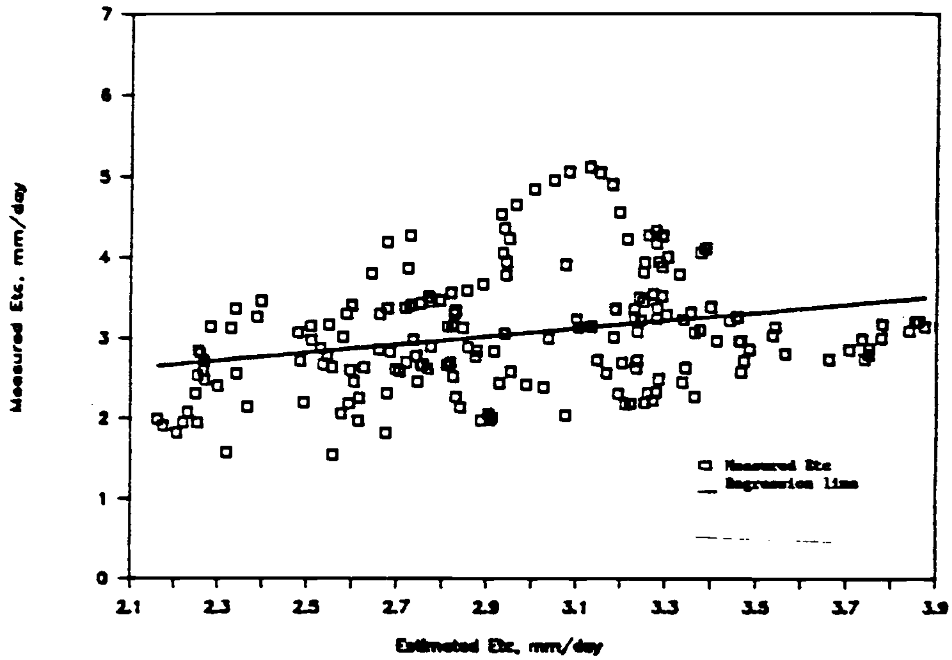

Figure 4.20 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of squash, for Penman-FAO.

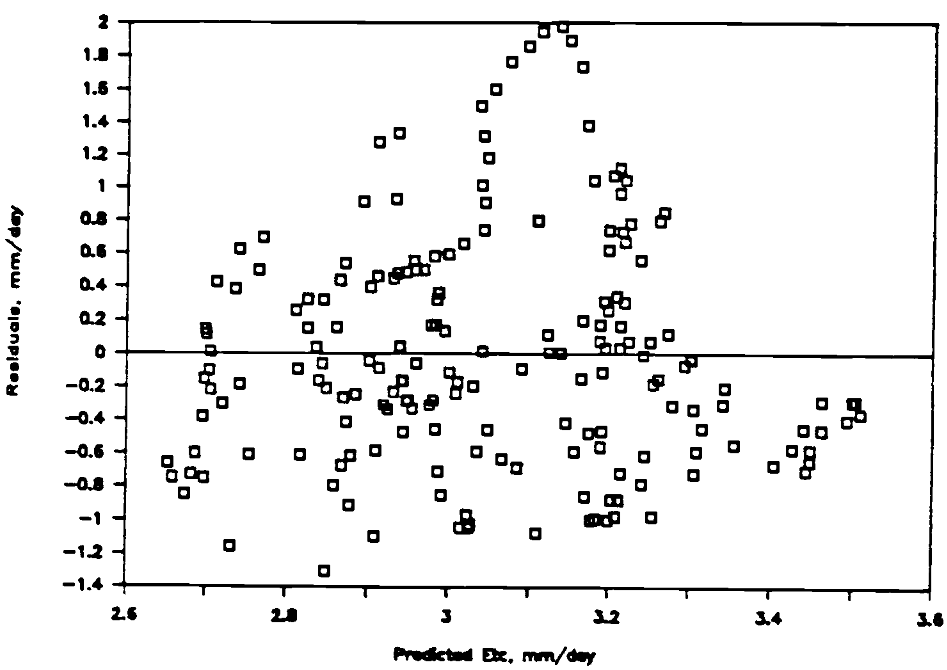

Figure 4.21 Residuals plot for combined seasons of squash, for the Penman-FAO.

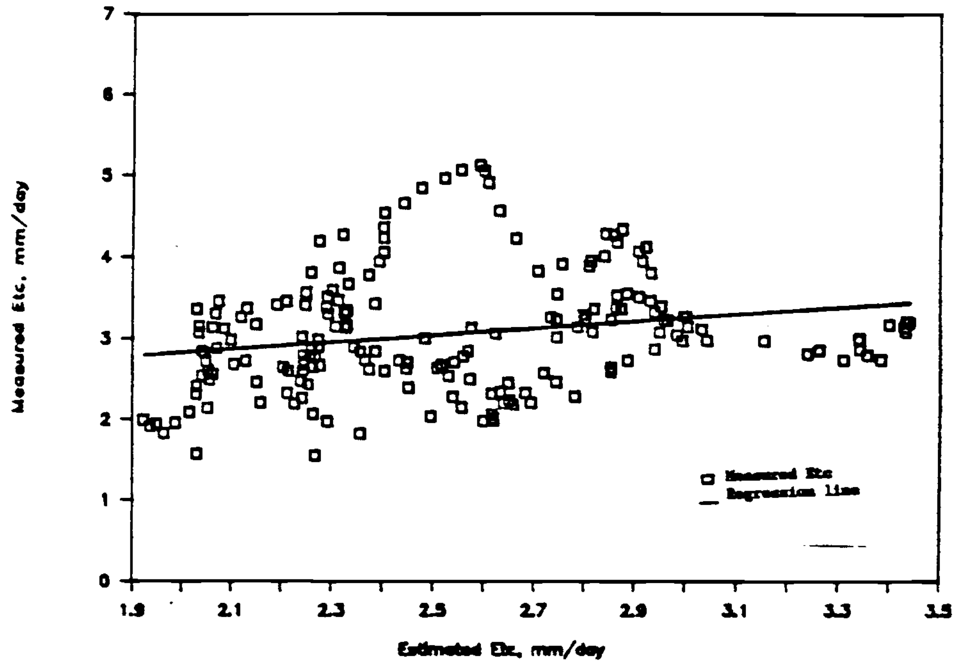

Figure 4.22 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of squash, for Penman-Wright.

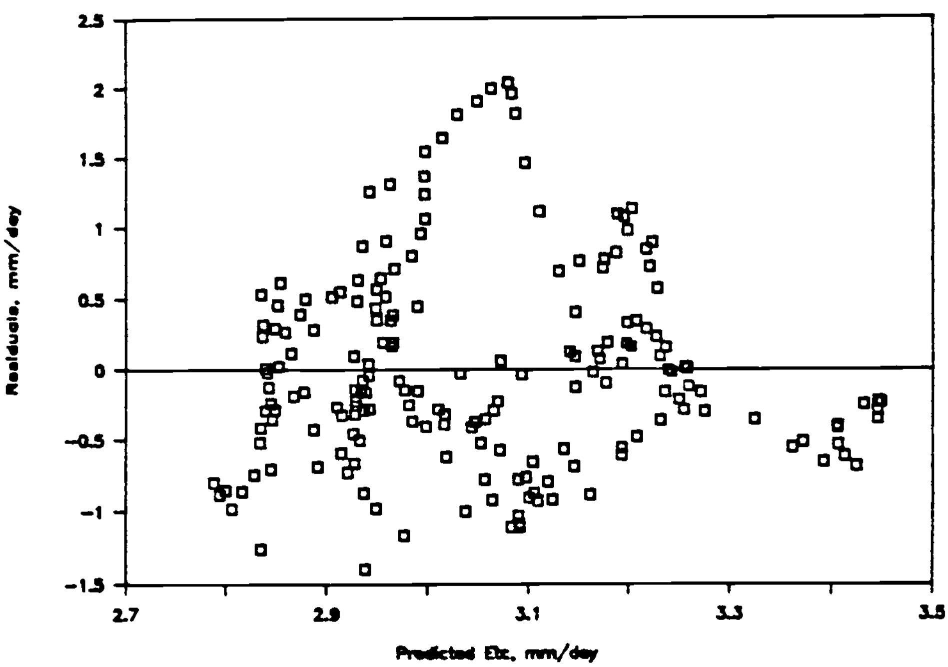

Figure 4.23 Residuals plot for combined seasons of squash, for the Penman-Wright.

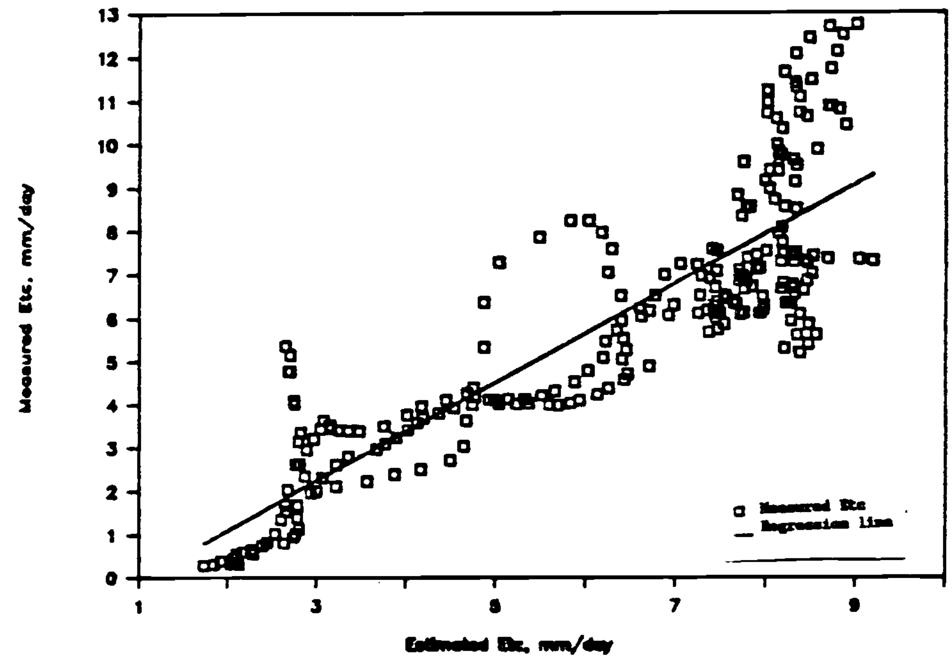

Figure 4.24 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of watermelon, for Penman-FAO.

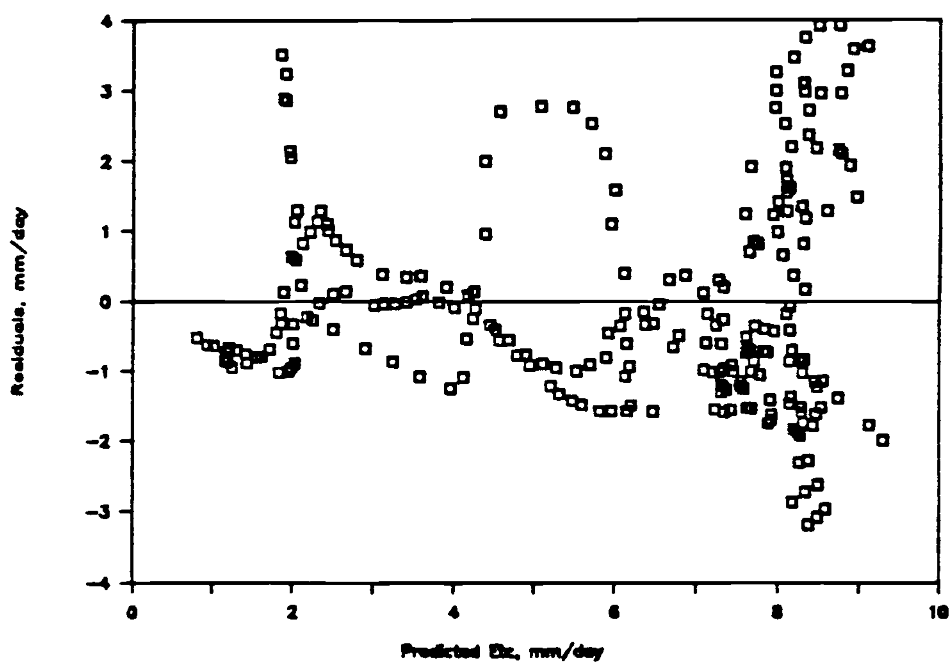

Figure 4.25 Residuals plot for combined seasons of watermelon, for the Penman-FAO.

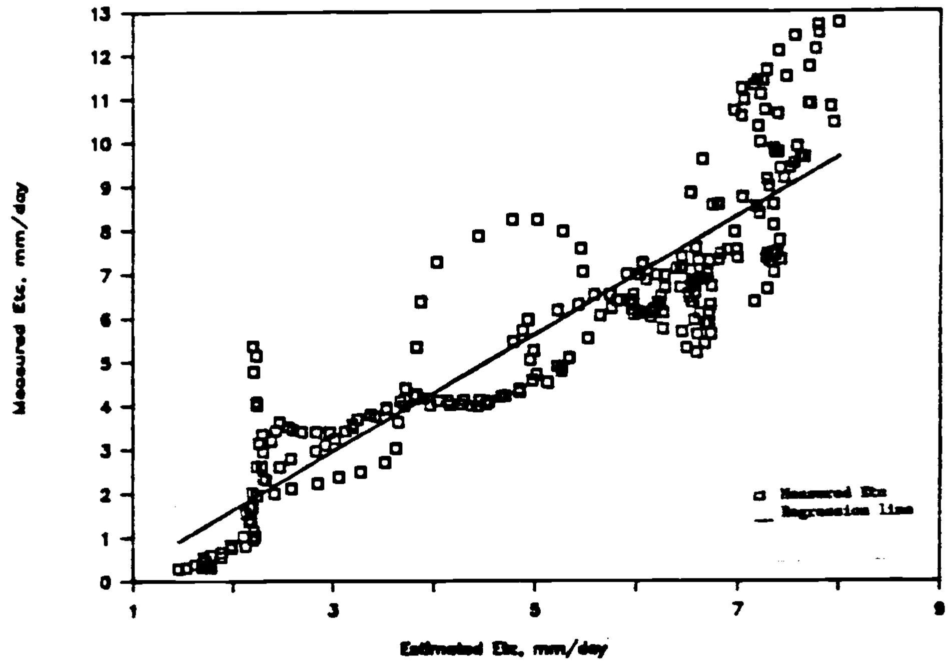

Figure 4.26 Relationship between measured E_{tc} and predicted E_{tc} for combined seasons of watermelon, for Penman-Wright

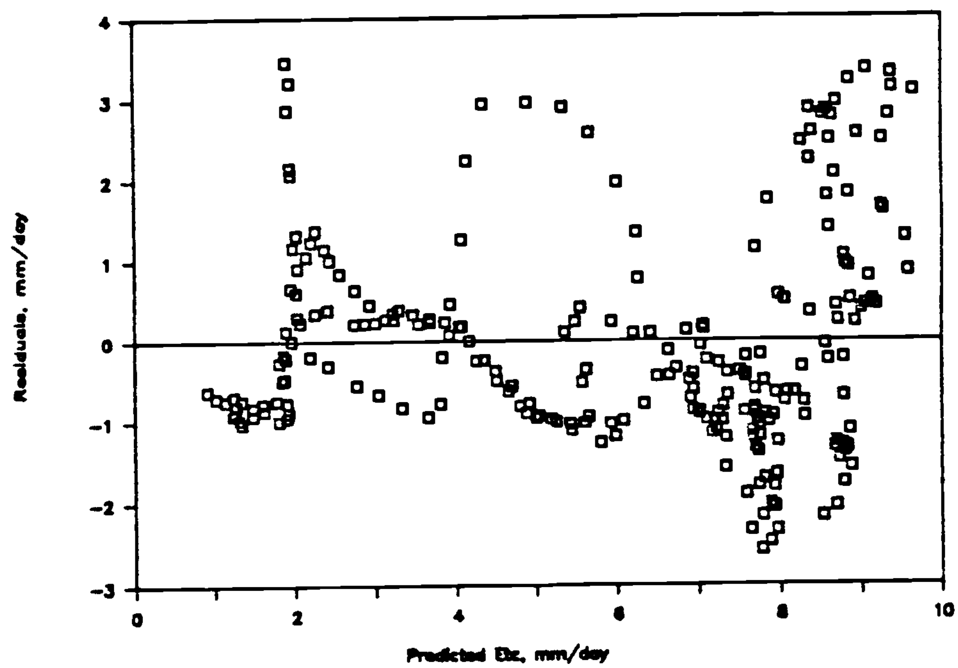

Figure 4.27 Residuals plot for combined seasons of watermelon, for the Penman-Wright.

8mm/day, and the third class was at estimated E_{tc} > 8mm/day. Weighted regression analysis was applied using the inverse of the variance of the corresponding class as weighing factor. The results of the weighted regression were no improvement; the variation was not only inconsistent, but also the variance of most of the observations was increased.

Adding another variable to the regression model was also tried to improve the calibration for the watermelon. The second variable was the effect of the crop coefficient (Kc), so the model became:

$$E_{tcm} = a + b\ E_{tce} + c\ Kc \tag{4.10}$$

where c is the regression coefficient. Application of this model did not improve the calibration.

Fig.4.28 to 4.33 present the plots of combined measured E_{tc} versus predicted E_{tc} from the combined model and models developed for individual seasons. For all crops and both versions of the Penman equation it is clear that the combined model is an unbiased estimate of E_{tc}. Because of the uncertainty of which season represents the best measurements of E_{tc}, it would be safe to use the combined model even though the error will be slightly higher. It would not be safe to use either model developed for an individual season under these uncertain conditions.

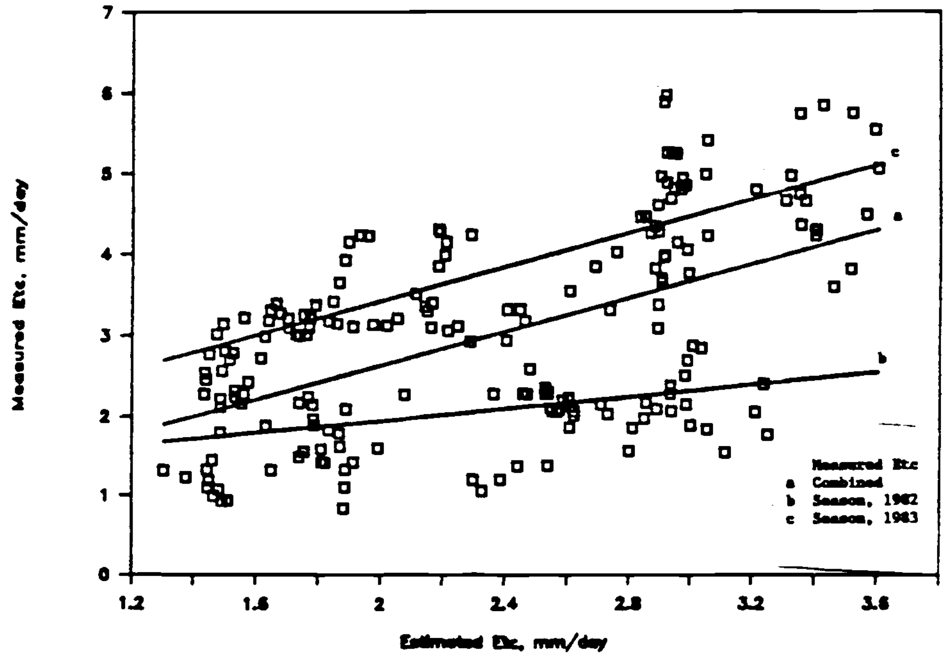

Figure 4.28 Relationship between measured E_{tc} and predicted E_{tc} by: a. using coefficients for combined seasons
b. using coefficients for the 1982 season
c. using coefficients for the 1983 season
For cabbage, for the Penman-FAO.

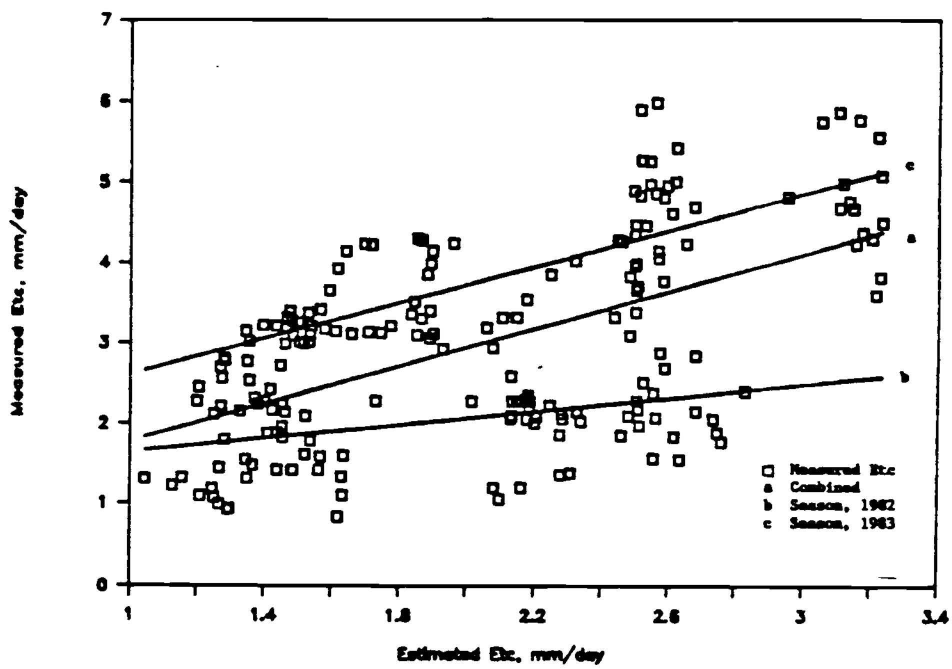

Figure 4.29 Relationship between measured E_{tc} and predicted E_{tc} by: a. using coefficients for combined seasons
b. using coefficients for the 1982 season
c. using coefficients for the 1983 season
For cabbage, for the Penman-Wright.

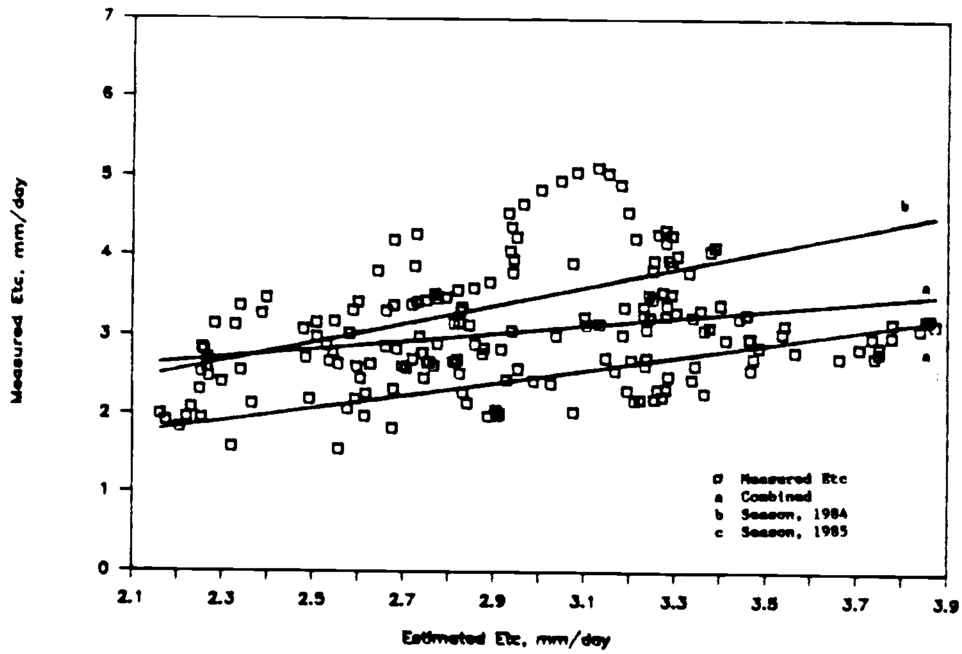

Figure 4.30 Relationship between measured E_{tc} and predicted E_{tc}
by: a. using coefficients for combined seasons
b. using coefficients for the 1984 season
c. using coefficients for the 1985 season
For squash, for the Penman-FAO.

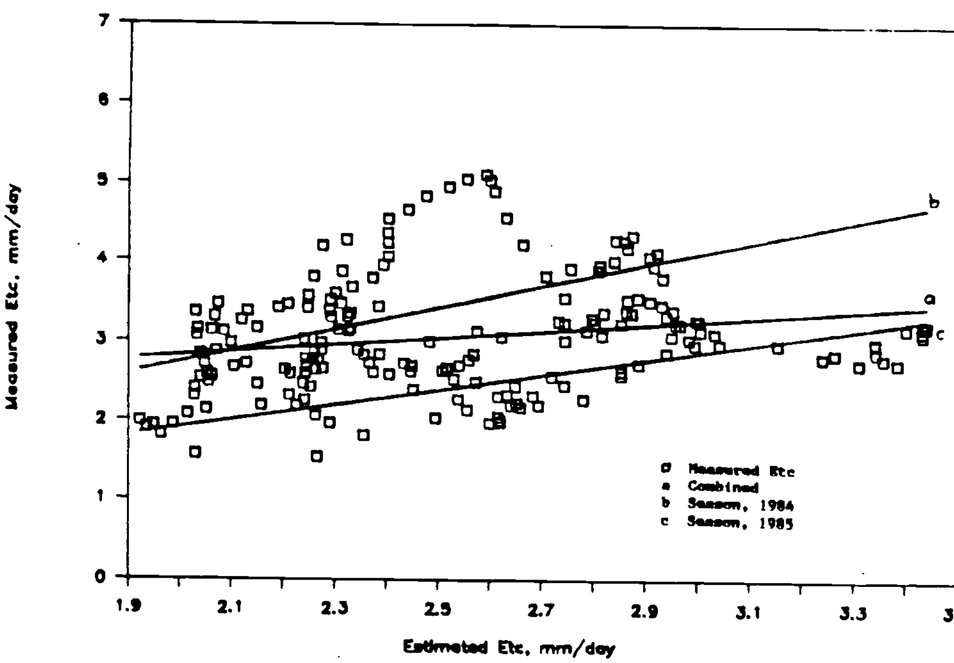

Figure 4.31 Relationship between measured E_{tc} and predicted E_{tc}
by: a. using coefficients for combined seasons
b. using coefficients for the 1984 season
c. using coefficients for the 1985 season
For squash, for the Penman-Wright.

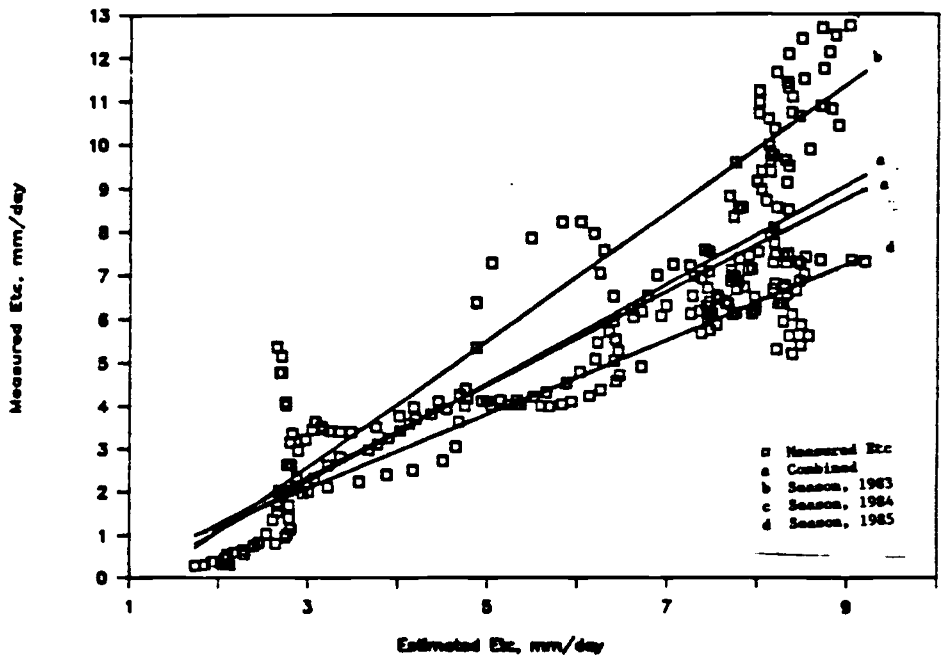

Figure 4.32 Relationship between measured E_{tc} and predicted E_{tc} by:
a. using coefficients for combined seasons
b. using coefficients for the 1983 season
c. using coefficients for the 1984 season
d. using coefficients for the 1985 season
For watermelon, for the Penman-FAO.

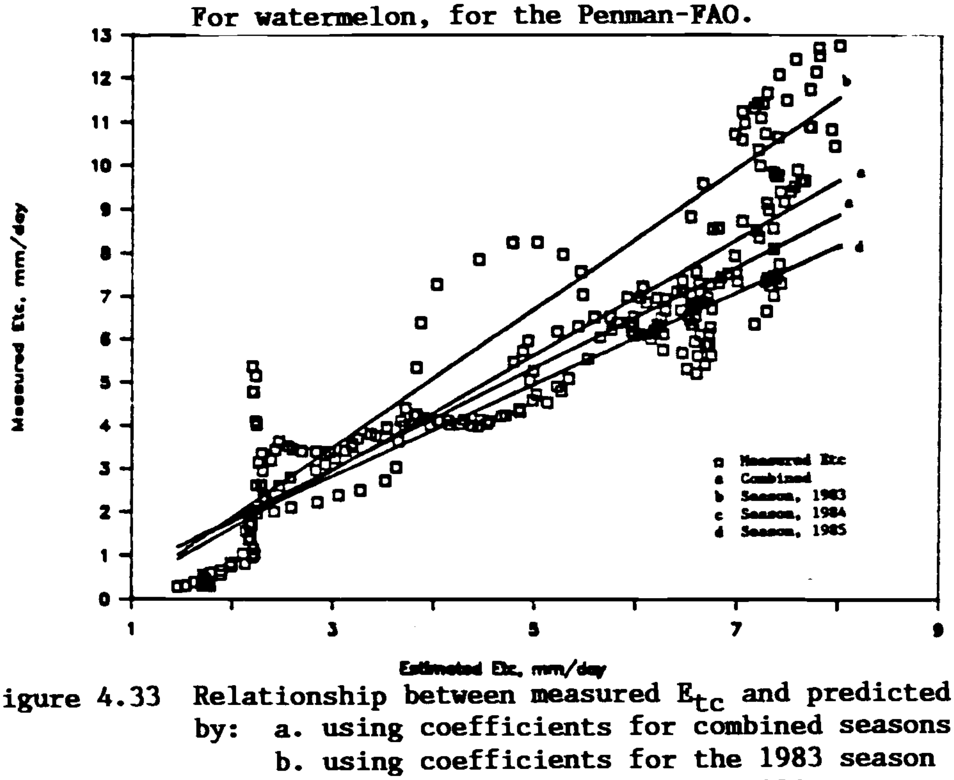

Figure 4.33 Relationship between measured E_{tc} and predicted E_{tc} by:
a. using coefficients for combined seasons
b. using coefficients for the 1983 season
c. using coefficients for the 1984 season
d. using coefficients for the 1984 season
For watermelon, for the Penman-Wright.

Due to variation in the measured E_{tc}, it is difficult to tell whether the Penman equation overestimates or underestimates crop water requirements in this region, especially when no information is available about the conditions of the lysimeter experiment so that one can understand the source of the variations. Under these circumstances, and according to the data provided, it is found that the coefficients a and b in table 4.9 and those for tomato in table 4.1 are suitable to calibrate the Penman equation, FAO and Wright versions, to estimate crop water requirements for cabbage, tomato, squash, and watermelon in the northern region of the U.A.E.

The calibrated models to estimate E_{tc} of cabbage, tomato, squash and watermelon were evaluated over a growing season. The cumulative seasonal estimated E_{tc} was compared to cumulative seasonal measured E_{tc}, and the results are presented in table 4.10. Tomatoes show no difference in the seasonal E_{tc} between measured and estimated in both versions of the Penman equation. In the 1982 season, cabbage E_{tc} was highly overestimated by both Wright (44.87%) and FAO (46.26%) while it was underestimated in the season of 1983 by both versions (≈20%). The error for squash and watermelon for all seasons range between 1.94% and 22.28% for both versions of the Penman equation.

Table 4.10 Error on estimated E_{tc} over seasonal period for tomato, cabbage, squash and watermelon.

Season	Tomato	Cabbage	Squash	Watermelon
FAO				
1982	**	-46.26 %	**	**
1983	0.00 %	+20.52 %	**	+18.74 %
1984	**	**	-19.69 %	- 1.94 %
1985	**	**	+ 9.19 %	-22.28 %
Wright				
1982	**	-44.87 %	**	**
1983	0.00 %	+19.90 %	**	+16.02 %
1984	**	**	-19.06 %	- 6.11 %
1985	**	**	+ 8.89 %	-13.85 %

Note:

1. **(**) = No data available.**
2. **Positive sign indicates under estimates and negative sign indicates over estimates.**
3. **Seasonal Error was calculated from cumulative seasonal E_{tc} as following:**

$$\text{Error} = \frac{\text{Seasonal measured } E_{tc} - \text{Seasonal estimated } E_{tc}}{\text{Seasonal measured } E_{tc}} \times 100$$

4.5 CORRELATION BETWEEN ESTIMATED E_{tr} AT NORTHERN, CENTRAL AND EASTERN REGIONS OF THE U.A.E.

Reference crop evapotranspiration was estimated by the Penman-FAO and the Penman-Wright equations for five years (1982-1986) in the Northern and Central regions, and two years (1982-1983) in the Eastern region of the U.A.E..

Simple linear regression was used to relate estimated E_{tr} at the northern region to estimated E_{tr} at both the central and eastern regions. The regression model was:

$$E_{tr} = a + b\ NE_{tr} \qquad (4.11)$$

where E_{tr} is reference crop evapotranspiration estimated at the Central or Eastern regions as a dependent variable, a and b are regression coefficients and NE_{tr} is reference crop evapotranspiration estimated at the Northern region as independent variable. The regression results are presented in table 4.11, scatter plots and residuals plots are shown in Fig. 4.33 to Fig. 4.40.

The study of the residuals indicates that the variation was not constant for the Wright version at the Central region. Second degree polynomial regressions corrected the erratic variance of the residuals. The corrected model for the Penman-Wright version at the Central region is:

$$E_{tr} = a + b\ NE_{tr} + c\ (NE_{tr})^2 \qquad (4.12)$$

where c is regression coefficient.

Table 4.11 The results of the regression analysis for the Central and eastern regions.

Region	FAO				Wright				
	a	b	R	SEE	a	b	c	R	SEE
Central	0.27	1.02	0.97	0.49	-0.82	1.52	-0.06	0.97	0.45
Eastern	0.23	1.01	0.88	0.28	0.42	0.90	**	0.88	0.24

Note:

(**) = c coefficient is not applicable
a, b and c regression coefficient.
R = Correlation coefficient.
SEE = Standard error of estimates (mm/day).

The residual variance for The Penman-Wright version at the eastern region was increased at high values of E_{tr}. A transformation was used to solve this problem. The regression model becomes :

$$\sqrt{E_{tr}} = a + b \sqrt{NE_{tr}} \qquad (4.13)$$

High correlation of E_{tr} was found between these regions, however, E_{tr} at the northern and E_{tr} at the central region was more highly correlated than that of the northern and eastern regions. The correlation coefficient in table 4.11 shows no difference between the FAO and Wright versions at both central (R=0.97) and eastern(R=0.88) regions. Comparing SEE, the Wright version ranked first at both the central and eastern regions.

However, SEE at the eastern region was found to be less than that of the central region.

The average daily error of estimated E_{tr} from the suggested models is presented in table 4.12. The average daily error at the Central region tends to be lower, and the Wright version tends to estimate E_{tr} with a slightly lower error than that of the FAO version at both the central and eastern regions.

The coefficients in table 4.11 could be used to estimate E_{tr} at the central and eastern regions by using meteorological data from the northern region in cases when no meteorological data are available at the former regions.

Table 4.12 Average daily error on predicted E_{tr} by the suggested models at the Central and Eastern regions.

Region	FAO	Wright
Central	± 6.60 %	± 6.30 %
Eastern	± 8.78 %	± 7.88 %

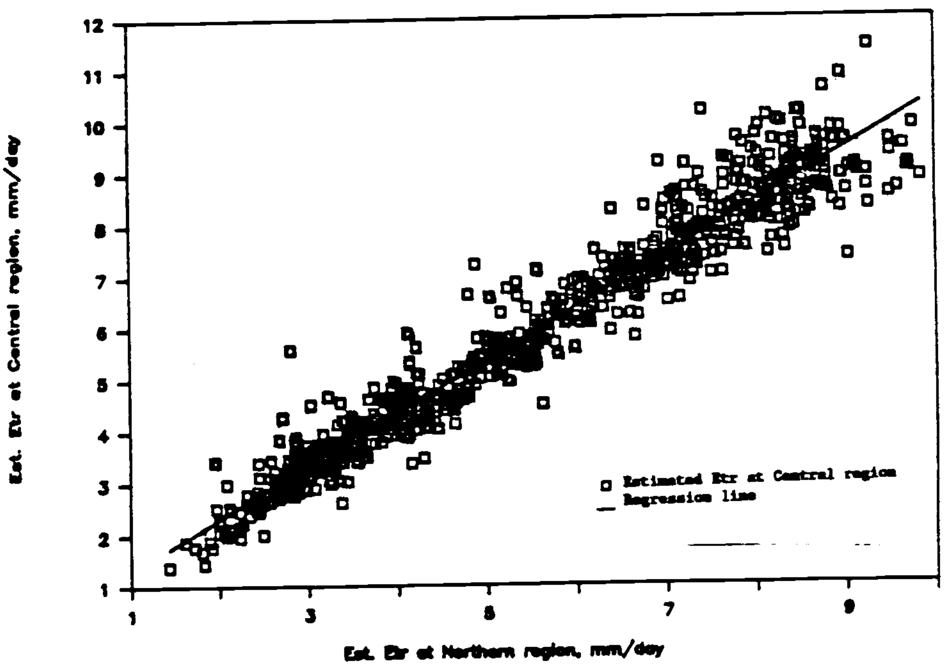

Figure 4.34 Relationship between estimated E_{tr} at the Northern region and predicted E_{tr} at the Central region by Penman-FAO.

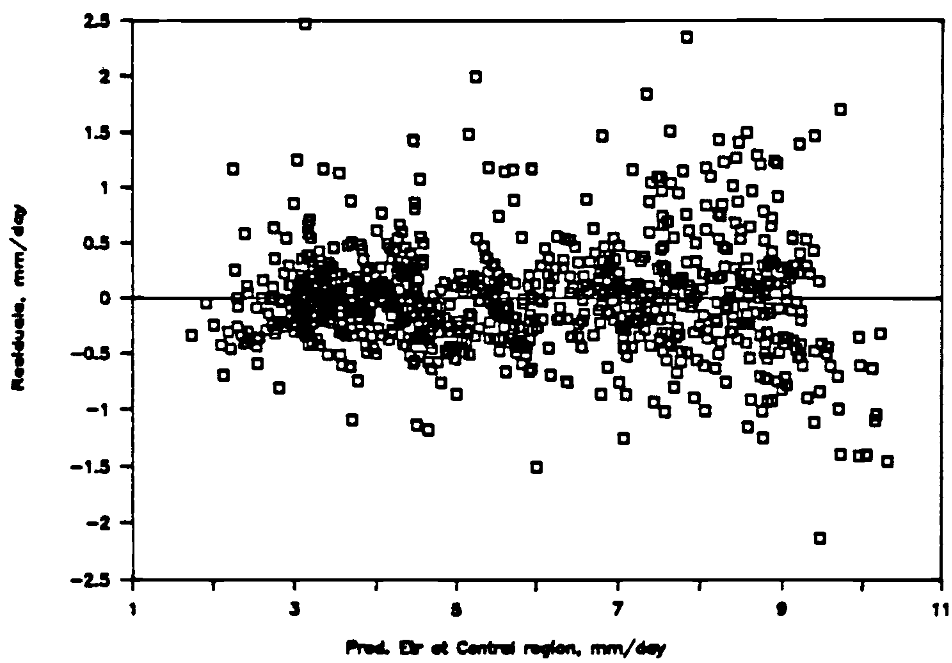

Figure 4.35 Residual plot for predicted E_{tr} by Penman-FAO at the Central region.

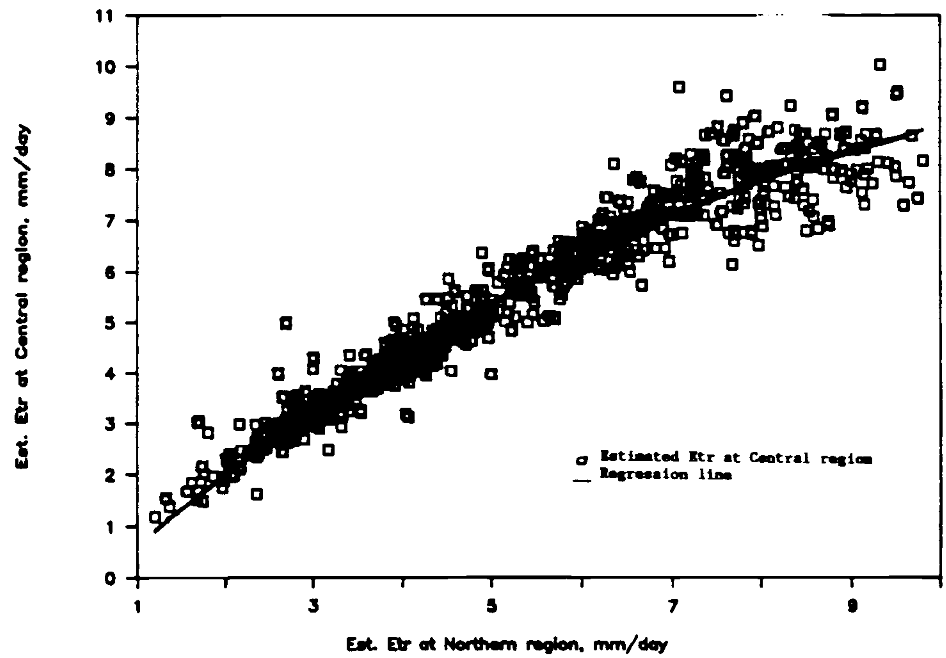

Figure 4.36 Relationship between estimated E_{tr} at the Northern region and predicted E_{tr} at the Central region by Penman-Wright.

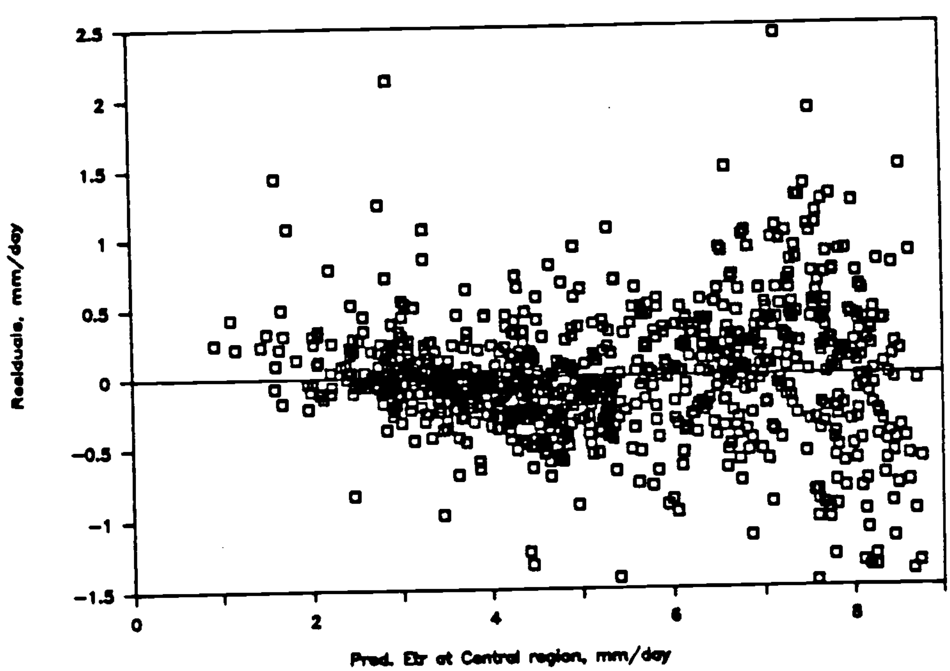

Figure 4.37 Residual plot for predicted E_{tr} by Penman-Wright at the Central region.

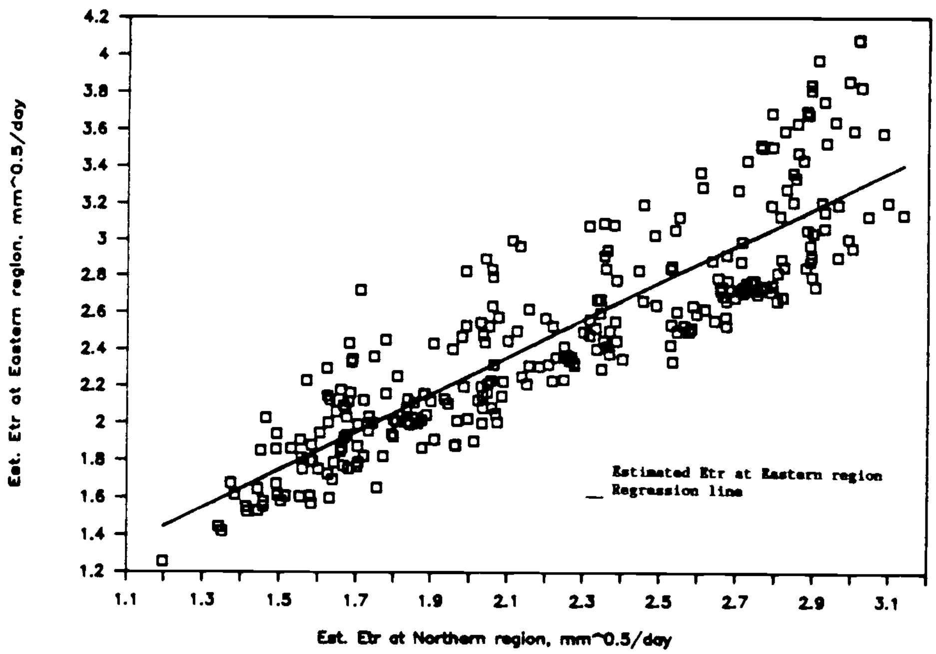

Figure 4.38 Relationship between estimated E_{tr} at the Northern region and predicted E_{tr} at the Eastern region by Penman-FAO.

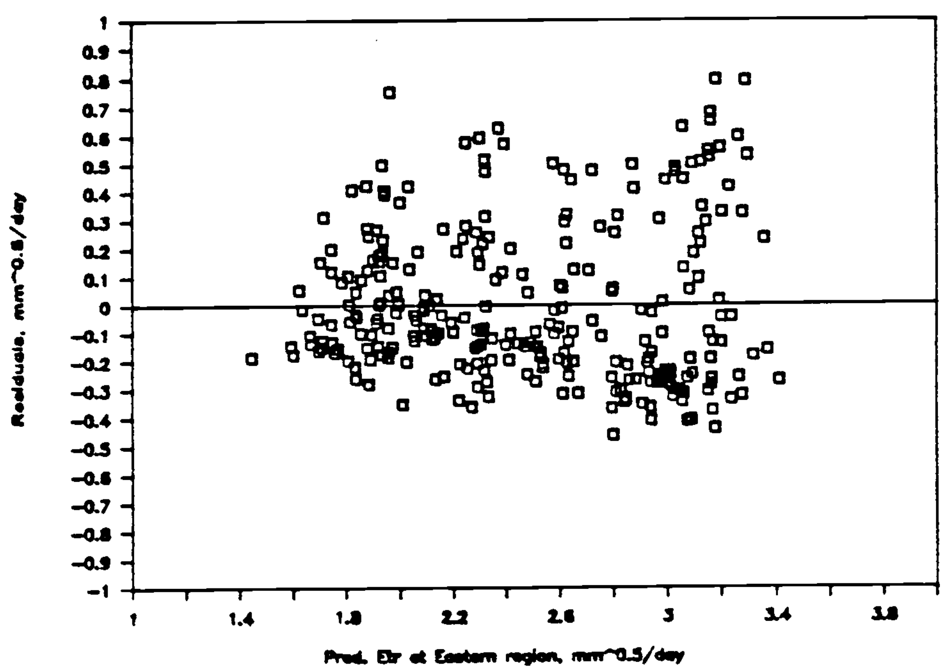

Figure 4.39 Residual plot for predicted E_{tr} by Penman-FAO at the Eastern region.

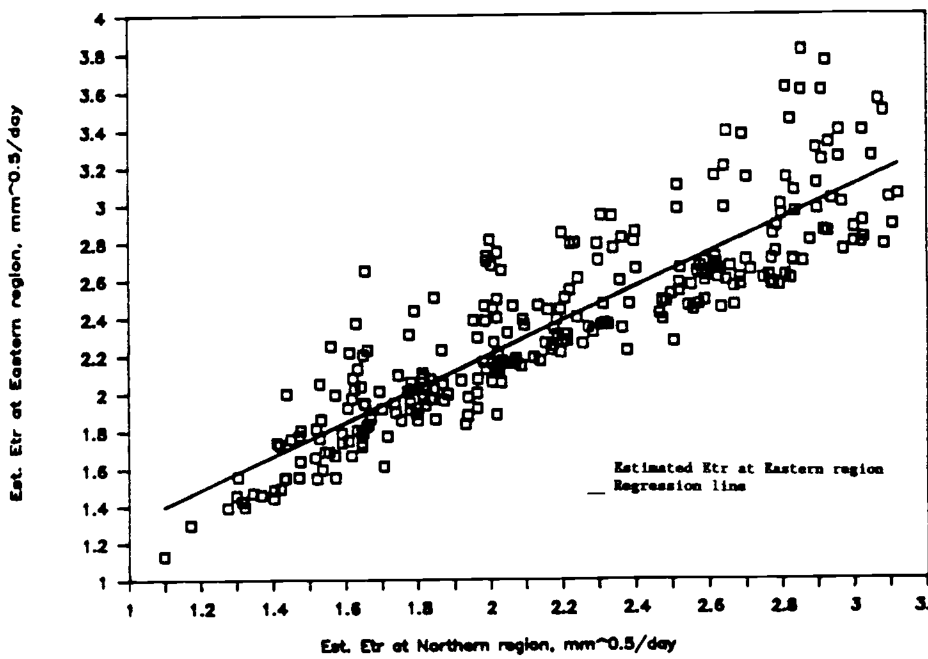

Figure 4.40 Relationship between estimated E_{tr} at the Northern region and predicted E_{tr} at the Eastern region by Penman-Wright.

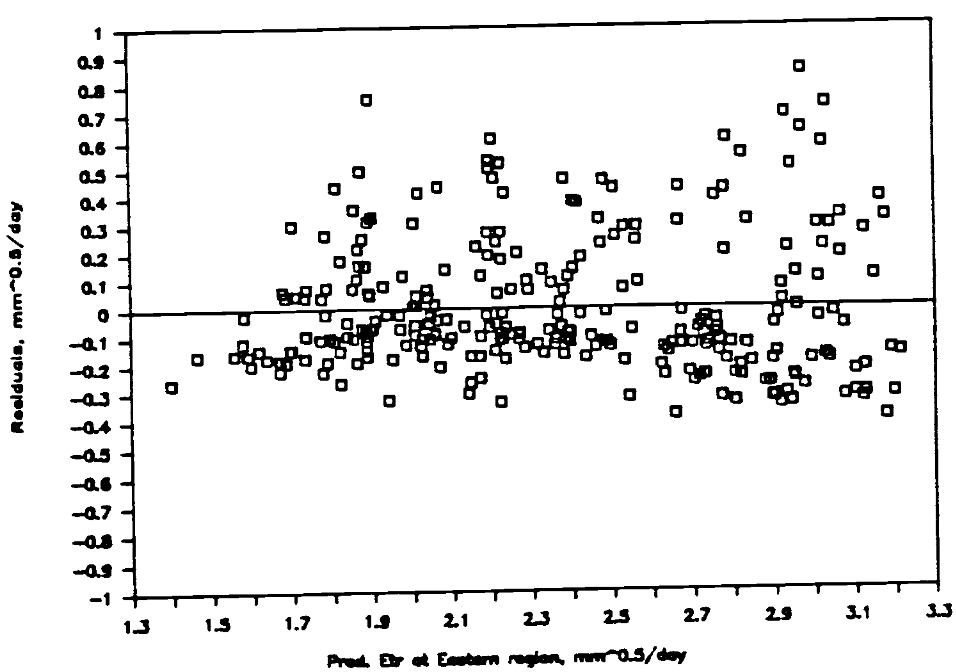

Figure 4.41 Residual plot for predicted E_{tr} by Penman-Wright at the Eastern region.

5. SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

Water shortage is one of the biggest problems facing the agricultural development in the U.A.E. Because of the extremely arid location and the tremendous amount of irrigation water that is used for crops, prediction of crop water requirements is essential to solve water management problems in this country. The Penman method was chosen because it is appeared the best to estimate reference crop water requirements under conditions like that of the U.A.E.

Three important agricultural regions in the U.A.E. were selected for this study; northern, central and eastern. Meteorological data which is required for the Penman equation were collected for five years from representative stations as well as actual crop water use for five crops (cabbage, cucumber, tomato, squash and watermelon) from drainage lysimeters at the northern station. Two forms of the Penman equation were used, the FAO version and the Wright version.

Comparison between the FAO and Wright versions couldn't be made because of the enormous variation of the measured E_{tc} between seasons for each individual crop. This variation made the calibration of the Penman equation difficult. In order to provide unbiased calibration, combined seasons were used. The desired calibration coefficients were furnished for cabbage, tomato, squash and watermelon. It was found that the estimated E_{tc} of the cucumber has a relatively high error; therefore, it was omitted from the calibration.

Estimated E_{tr} at the northern region was related to estimated E_{tr} at the central and eastern regions, and a high correlation was found between the regions.

5.2 RECOMMENDATIONS

This study is an attempt to help improve agricultural water management in the U.A.E., which suffers from water shortage.

A test of the results of this thesis at the Homrania experimental farm (northern region of the U.A.E.) is strongly recommended before any direct applications are made. Great care must be taken for any direct applications.

Even though the results of this study could be applied within the average error found, improvements to this study are highly recommended in order to provide better results. To improve this study the following recommendations are presented:

1. The wind function in the Penman equation has not been calibrated locally, and such calibration would provide better results.

2. The crop coefficients that were provided for this study by the FAO method have a significant error at the initial stage of plant growth. Better crop coefficients at this stage would decrease the error by 50-70%.

3. The crop coefficients that were used for the Wright version have been generated from FAO crop coefficients. Crop coefficients developed by the Wright method would produce better results when used with the Wright version.

4. Replications of the actual crop water use experiments show great variation. In future studies, all of the variables (fertilizers, water quality, etc.) that affect crop water use should be kept constant, except the weather parameters. This will help in judging whether or not the Penman equation over- or underestimates crop evapotranspiration.

BIBLIOGRAPHY

Allen, G. R., 1986, "A Penman for all Seasons", J. Irrig. and Drain. Engrg., ASCE, 112, 348-368.

Burman, R. H., Cuenca, R. H., and Weiss A., 1983,"Techniques For Estimating Irrigation Water Requirements" in Advances in Irrigation, D. Hillel, Ed. 2:335-393

Chatterjee, S., and Price B.; Regression Analysis by Example; John Wiley and Sons, 1977

Cuenca, R. H., and Nicholson, M. T.; "Application of the Penman Equation Wind Function" J. Irrig. and Drain. Div., ASCE, 1982, 108, 13-23.

Cuenca, R., Irrigation System Design: An Engineering Approach, Draft text, Prentice Hall, 1988, in press.

Doorenbos, J., and Pruitt, W. O., 197,7 Crop Water Requirements. Food and Agricultural Organization of the United Nations. Irrigation and Drainage Paper 24, Revised, Rome, Italy, 1977, 144 pp.

Halcrow, Sir William; "Report on soil and water survey in the Trucial States"; Ministry of Agriculture and Fisheries, Dubai U.A.E, 1969.

Jensen, M. E., ed., Consumptive Use of Water and Irrigation Water Requirements, ASCE, New York ,N.Y., 1974, 215 pp.

Jensen, M. E.; Design and Operation of Farm Irrigation Systems; Basselman, 1980

Ministry of Agriculture and Fisheries, Agriculture in the United Arab Emirates, Dubai,U.A.E,1981.

Neter, J., Wasserman, W., Kutner, M. H., 1983, Applied Linear Regression Models, Richard D. Irwin, Inc. pp. 547.

Penman, H. L., 1948, "Natural Evaporation from Open Water, Bare Soil and Grass" Proc. Roy. Soc. London, A193: 120-146.

Penman, H. L., 1963, "Vegetation and Hydrology", Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England.

Saeed, M., 1986, "The Estimation of Evapotranspiration by Some Equations Under Hot and Arid Conditions", ASAE,29, 434-438.

Salih, A. M. A., and Sendil U., 1984, "Evapotranspiration Under Extremely Arid Climates", J. Irrig. and Drain. Engr., ASCE, 110, 289-303.

Savva, A. P., Thanki, S. B., Al Asam, M. Sager, Fathi, M., Awartani, M., Al Rayyis, S. N., and Abbas, S.; Crop Water Requirements (Estimates and Field Measurements); Technical Report #7, Food and Agriculture Organization of the United Nations, Ministry of Agriculture and Fisheries, Dubai U.A.E, March 1984.

Sharma, M. L., 1985, "Estimating Evapotranspiration" in Advances in Irrigation, D. Hillel, Ed. 3:213-281.

Snedecor, G. W., and Cocran W. G., 1980, Statistical Methods,The Iowa State Univ. Press. pp.507.

Steel, R. G. D, and Torrie, J. H.; Principles and Procedures of Statistics; McGraw-Hill Book Co., Inc., 1960

Tanner, C. B., 1967, Measurement of Evapotranspiration, Irrigation of Agricultural Lands, Hagan R. M., Haise, M. R., and Edminster, T. W., Eds. No. 11 of Agronomy Series, Amer. Soc. Agron.,p. 534-74

Weiss, A. 1983, "A Quantitative Approach to the Pruitt and Doorenbos Version of the Penman Equation", Irrig. Sci. 4:267-275.

Wright, J. L., and Jensen, M. E., 1972, "Peak Water Requirements of Crops in Southern Idaho", J. Irrig. and Drain. Div., ASCE, 96(IR1),193-201.

Wright, J. L., 1982, "New Evapotranspiration Crop Coefficients", J. Irrig. and Drain, Div., ASCE, 108(IR2), 57-74.

APPENDICES

APPENDIX A

Computer Program for Estimating Reference Crop Evapotranspiration

1. INTRODUCTION

The computer program calculates reference crop evapotranspiration according to the Penman-FAO version and the Penman-Wright version as presented previously in chapter 3. This program was maintained to estimate E_{tr} within latitudes between 25° N and 30° N, which covers the area of the U.A.E.. This was done to minimize the size of the data of extra terrestrial radiation (R_a), maximum possible sunshine hours (N) and clear day solar radiation (R_{so}) in order to increase the speed of calculation. A slight modification could be made to the program to increase it's ability to calculate E_{tr} over wide locations.

2. VARIABLE DEFINITION

Main Program:

ASUNHR = Possible sunshine duration, hr.

DAY = Number of the day in the month

DNR = The ratio of day to night wind movement

DOFY = Subroutine calculates the number of days in the year

DOY = Number of day in the year

FAO = Result of Etr that is calculated by the Penman-FAO method

FAOPEN = Subroutine calculates Etr according to Penman-FAO method

G = Soil heat flux

INF = The name of the input data file

LAT = Latitude (should be between 25°N and 30°N)

LATHIT = Latent heat of vaporization

METHOD = Name of method that calculates Etr, Penman-FAO, Penman-Wright

MONTH = Number of the month

OUTF = The name of the output file

PRESS = Atmospheric pressure, mbar

PSYCH = Psychrometric constant

RA = Extra-terrestrial radiation

RHa = Average relative humidity during the day, in percent

RHmax = Maximum relative humidity, in percent

RRS = Subroutine provides the value of RSO, RA, and AsunHR

RSO = Clear sky short wave radiation

SLPVP = Slope of saturation vapor pressure-temperature curve

STA = Station name

SUNR = The ratio of actual to possible sunshine duration

SUNHR = Actual sunshine duration, hr.

Ta = Average air temperature during the day in °C

Tmax = Maximum air temperature, °C

Tmin = Minimum air temperature, °C

W = Variable, calculates (Φ /Φ+τ)

WIND = Wind movement at 2m height, Km/day

WRHT = Result of Etr that is calculated by the Penman-Wright method

WRIGHT = Subroutine calculates Etr according to Penman-Wright

<u>Subroutine FAOPEN:</u>

C = Correction factor

DWIND = Daytime wind speed, m/sec.

FU = Wind function

LONRAD = Long wave radiation

NETRAD = Net radiation

SHORAD = Shortwave radiation

SVP = Saturation vapor pressure at average air temperature

SVPOP = Saturation vapor pressure at dew point temperature

<u>Subroutine WRIGHT:</u>

AW and BW = Wind function coefficients

DG = Converts SIN into degrees

RBO = Net outgoing radiation on clear day

RSORAT = The ratio of shortwave radiation to clear sky shortwave radiation

SVPDF = Saturation vapor pressure at deficit air temperature

SVPMAX = Saturation vapor pressure at maximum air temperature

SVPMIN = Saturation vapor pressure at minimum air temperature

WF = Wind function

3. PROGRAM

```
      PROGRAM PENMAN
C
      IMPLICIT REAL (A-Z)
      INTEGER MONTH,DAY,DOY
      COMMON/ONE/Ta,RHa,WIND,SUNR
      COMMON/TWO/SLPVP,PRESS,Tmax,Tmin,G
      COMMON/THREE/DNR,W,RHmax
      COMMON/FOUR/DOY,LAT,RSO,RA,ASUNHR
      COMMON/FIVE/MONTH,DAY
      CHARACTER*20 INF,OUTF
      CHARACTER*80 STA
C
C
      WRITE (*,10)
10    FORMAT(//,'   INPUT THE NAME OF INPUT FILE  ')
      READ (*,20) INF
20    FORMAT(A)
      WRITE (*,30)
30    FORMAT(//,'   INPUT THE NAME OF OUTPUT FILE  ')
      READ (*,40) OUTF
40    FORMAT(A)
C
      WRITE (*,50)
50    FORMAT(//,'   ENTER STATION NAME  ')
      READ (*,60) STA
60    FORMAT(A)
      WRITE (*,70)
70    FORMAT(/,'    ENTER ATMOSPHERIC PRESSURE AND LATITUDE')
      READ (*,*) PRESS,LAT
C
      WRITE(*,80)
80    FORMAT(//,'   THERE ARE TWO METHODS TO ESTIMATE ETR IN THIS
     +       PROGRAM ')
      WRITE(*,90)
90    FORMAT(/,'           1-FAO VERSION')
      WRITE(*,100)
100   FORMAT(/,'           2-WRITE VERSION')
      WRITE(*,110)
110   FORMAT(/,'           3-BOTH ')
      WRITE(*,120)
120   FORMAT(//,'   SELECT METHOD TO ESTIMATE ETR ( 1  2 or 3):')

      READ (*,*)METHOD
C
      OPEN (5,FILE=INF)
      OPEN (6,FILE=OUTF,STATUS='NEW')
C
      WRITE(6,125)STA
```

```
125   FORMAT(//,2X,A)
      WRITE(6,126)
126   FORMAT(/,5X,'DATE',6X,'FAO',5X,'WRIGHT')
C
C     READ THE ENTIRE DATA
C
130   READ (5,*,END=500)MONTH,DAY,Tmax,Tmin,RHmax,RHmin,WIND,
     +        SUNHR,G,DNR
C
C
C     CALCULATION OF AVERAGE TEMPERATURE AND RELATIVE HUMIDITY

C
      Ta   = (Tmax +  Tmin ) / 2
      RHa = (RHmax + RHmin) / 2
C
C     CALCULATION OF LATENT HEAT OF VAPORIZATION, PSYCHROMETRIC
C     CONSTANT AND SLOPE OF SATURATION VAPOR PRESSURE-TEMPERATURE
C     CURVE
C
      LATHIT  = 2500.80 - (2.3668 * Ta)
      PSYCH   = (1.0042 * PRESS) / (0.62198 * LATHIT)
      SLPVP   = 33.8639*(0.05904*((((0.00738*Ta)+0.8072)**7)-
     +            3.43E-5))
C
C
C
C
      W = SLPVP/(SLPVP+PSYCH)
C
C     CALL SUBROUTINE DOFY TO DETERMINE DAY NUMBER
C
      CALL DOFY(DOY)
C
C     CALL SUBROUTINE RRS FOR SOLAR RADIATION DATA
C
      CALL RRS(RSO,RA,ASUNHR)
      SUNR = SUNHR / ASUNHR
C
C
      IF (METHOD .EQ. 2) THEN
            FAO = 0.0
            GOTO 150
      ELSE
C
C     CALL SUBROUTINE FAOPEN TO CALCULATE Etr
C
140   CALL FAOPEN(FAO)
      END IF
C
C
150   IF (METHOD .EQ. 1) THEN
```

```
            WRGHT = 0.0
            GOTO 160
      ELSE
C
C     CALL SUBROUTINE WRIGHT TO CALCULATE Etr
C
      CALL WRIGHT(WRGHT)
        END IF
C
C     WRITE THE RESULTS
C
160   WRITE (6,170)MONTH,DAY,FAO,WRGHT
170   FORMAT(5X,I2,'/',I2,5X,F6.2,5X,F6.2)
C
      GOTO 130
500   STOP
      END
```

```
      SUBROUTINE FAOPEN(FAO)
      IMPLICIT REAL (A-Z)
      COMMON/ONE/Ta,RHa,WIND,SUNR
      COMMON/THREE/DNR,W,RHmax
      COMMON/FOUR/DOY,LAT,RSO,RA,ASUNHR
C
      SVP=6.1078*EXP((17.2693882*Ta)/(Ta+237.3))
      SVPDP = SVP * (RHa / 100)
C
C CALCULATION OF WIND FUNCTION  f(u)
C
      FU = 0.27 * (1.0 + ( WIND/100))
C
C     CALCULATE NET RADIATION
C
      SHORAD = (0.25 + (0.5 * SUNR)) * RA
      LONRAD = 2.0E-9*((Ta+273)**4)*(0.34-(0.044*SQRT(SVPDP)))*
     + (0.1+(0.9*SUNR))
C
      NETRAD = ((1 - 0.25) * SHORAD) - LONRAD
C
C CALCULATION OF WIND SPEED AT DAY TIME m/s
C
      DWIND = (((DNR / (DNR + 1)) * WIND) / 12) * 0.2778
C
C CALCULATION OF CORRECTION FACTOR ( C )
C
      C = 0.6817006+(0.0027864*RHmax)+(0.0181768*SHORAD)
     +   -(0.0682501*DWIND)+(0.0126514*DNR)
     +   +(0.0097297*DWIND*DNR)
     +   +(0.43205E-4*RHmax*SHORAD*DWIND)
     +   -(0.92118E-7*RHmax*SHORAD*DNR)
C
C CALCULATION OF REFERENCE ET
C
      FAO = C * ((W * NETRAD) + ((1 - W) * FU * (SVP - SVPDP)))
C
C END OF SUBROUTINE, NOW RETURN TO THE MAIN PROGRAM
C
      RETURN
      END
```

```
      SUBROUTINE WRIGHT(WRGHT)
      IMPLICIT REAL (A-Z)
      COMMON/ONE/Ta,RHa,WIND,SUNR
      COMMON/TWO/SLPVP,PRESS,Tmax,Tmin,G
      COMMON/FOUR/DOY,LAT,RSO,RA,ASUNHR
      COMMON/FIVE/MONTH,DAY
C
C CALCULATION OF LATENT HEAT OF VAPORIZATION AND PSYCHROMETRIC
C CONSTANT .
C
      LATHIT = (595 - (0.51 * Ta))
      PSYCH  = (0.24 * PRESS) / (0.622 * LATHIT)
C
C CALCULATION OF MAXIMUM AND MINIMUM SATURATION VAPOR PRESSURE C
AND VAPOR PRESSURE DEFICIT.
C
      SVPMAX=6.105+(4.44 E-1*Tmax)+(1.434 E-2*(Tmax**2))
     +       +(2.623 E-4 * (Tmax**3))+(2.953 E-6*(Tmax**4))
+         +(2.559 E-8*(Tmax**5))
C
      SVPMIN=6.105+(4.44 E-1*Tmin)+(1.434 E-2*(Tmin**2))
     +       +(2.623 E-4 * (Tmin**3))+(2.953 E-6*(Tmin**4))
     +       +(2.559 E-8*(Tmin**5))
C
      SVP = (SVPMAX + SVPMIN) / 2
C
      SVPDP = SVP * (RHa / 100)
C
C
      SVPDF = SVP - SVPDP
C
C CALCULATION OF NET RADIATION
C
C
      SHORAD = (0.35 + ( 0.61 * SUNR)) * RSO
      RSORAT = SHORAD / RSO
      IF (RSORAT .GT. 0.7) THEN
         A = 1.126
         B = -0.07
      ELSE
         A = 1.017
         B = -0.06
      END IF
      A1 = 0.26+(0.1*EXP(-1.0*((0.0154*((30.0*MONTH)
     +     +DAY-207.0))**2)))
C
C DETERMINATION OF ALBEDO
C
      DG = 3.14159265 / 180
      IF (MONTH .LT. 4) THEN
              ALBEDO = 0.25
      ELSE IF (MONTH .GT. 10) THEN
```

```
                ALBEDO = 0.25
         ELSE
            ALBEDO =0.29+(0.06*(SIN(DG*30*(MONTH+(0.0333*DAY)
+              +2.25))))
      END IF
C
      RBO=(A1-(0.044*SQRT(SVPDP)))*(11.71E-8*(((Tmax+273)**4)+
    +     ((Tmin+273)**4))/2)
C
C DETERMINATION OF NET LONG WAVE
C
      LONRAD = ((A * RSORAT) + B) * RBO
C
C DETERMINATION OF NET RADIATION
C
      NETRAD = ((1 - ALBEDO) * SHORAD) - LONRAD
C
C CALCULATION OF WIND FUNCTION
C
C
C
      AW = 0.4 + (1.4 * EXP(-1.0*(((DOY - 173.0) / 58.0)**2)))
      BW = 0.007 + (0.004 * EXP(-1.0*(((DOY - 243.0)/80.0)**2)))
      WF = AW + (BW * WIND)
      W  = SLPVP/(SLPVP+PSYCH)
C
C CALCULATION OF REFERENCE EVAPOTRANSPIRATION
C
WRGHT=((W*(NETRAD-G))+((1-W)*15.36*(WF*SVPDF)))/(LATHIT*0.1)
C
      RETURN
      END
```

```
      SUBROUTINE DOFY(DOY)
      IMPLICIT INTEGER (A-Z)
      COMMON/FIVE/MONTH,DAY
      DIMENSION NOD(12)
C
C     DATA
C
      DATA NOD(1),NOD(2),NOD(3),NOD(4)/0,31,59,90/
      DATA NOD(5),NOD(6),NOD(7),NOD(8)/120,151,181,212/
      DATA NOD(9),NOD(10),NOD(11),NOD(12)/243,273,304,334/
C
C     CALCULATE DAY NUMBER
C
      DOY = NOD(MONTH)+DAY
      RETURN
      END
```

```
      SUBROUTINE RRS(RSO,RA,ASUNHR)
      IMPLICIT REAL (A-Z)
      INTEGER DOY
      COMMON/FOUR/DOY,LAT
C
      OPEN(UNIT=3,FILE='RRS.TBL',ACCESS='DIRECT',RECL=60,
     +     STATUS='OLD')
      READ (3,REC=DOY)RSO1,RSO2,RA1,RA2,SUN1,SUN2
      L1     = 25
      L2     = LAT
      L3     = 30
      RSO    = RSO2 - ((L3 - L2) * (RSO2 - RSO1) / (L3 - L1))
      RA     = RA2 - ((L3 - L2) * (RA2 - RA1) / (L3 - L1))
      ASUNHR = SUN2 - ((L3 - L2) * (SUN2 - SUN1) / (L3 - L1))
      RETURN
      END
```

4. SOLAR RADIATION DATA

This program reads the solar radiation data (clear day solar radiation RSO, extra-terrestrial radiation RA and maximum possible sunshine hours SUN) from file called "RRS.TBL". This file must be written in direct access format. The following is some consideration that must be given in writing this file:

1. Interpolation between months must be made for daily values, assuming the mean value falls in the meddle of the month.
2. The first column in the file must be the day number in the year (1 - 365).
3. For the interpolation between the latitudes; write the both values of each data set (at the lower and the higher latitudes).
4. Example of solar radiation file :

```
(1) (2) (3) (4)  (5)  (6)  (7)

001 448 395 09.9 08.6 10.7 09.8
002 447 394 09.8 08.5 10.6 09.7
... ... ... .... .... .... ....
... ... ... .... .... .... ....
... ... ... .... .... .... ....
365 419 358 09.4 08.5 10.5 09.2
```

(1) = the day number in the year

(2 and 3) = RSO values at lower and higher latitudes respectively

(4 and 5) = RA values at lower and higher latitudes respectively

(6 and 7) = SUN values at lower and higher latitudes respectively

5. SAMPLE OF INPUT DATA

(1)		(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
07	01	42.0	26.0	90	1	67.0	6.8	0.0	2.0
07	02	41.0	25.0	89	18	55.8	10.0	0.0	2.0
07	03	43.2	24.2	90	1	66.5	10.9	0.0	2.0
07	04	43.8	24.0	90	1	52.8	10.8	0.0	2.0
07	05	44.0	23.4	71	1	71.2	11.0	0.0	2.0
07	06	44.2	24.6	89	1	80.8	11.5	0.0	2.0
07	07	43.2	23.4	91	1	100.0	11.0	0.0	2.0
07	08	41.4	28.6	90	11	99.2	11.7	0.0	2.0
07	09	41.0	24.0	92	5	51.5	11.7	0.0	2.0
07	10	42.0	22.0	94	1	46.0	11.4	0.0	2.0
07	11	45.8	24.4	90	1	53.5	11.4	0.0	2.0
07	12	45.0	26.4	89	1	36.2	7.5	0.0	2.0
07	13	46.4	27.0	92	1	50.0	10.8	0.0	2.0
07	14	44.4	26.6	88	1	78.5	10.7	0.0	2.0
07	15	44.0	26.6	90	1	80.4	10.8	0.0	2.0
07	16	40.0	23.0	91	19	46.5	11.4	0.0	2.0
07	17	40.4	23.5	90	11	57.5	11.0	0.0	2.0
07	18	40.0	25.0	90	24	53.8	11.2	0.0	2.0
07	19	45.2	24.0	90	1	37.0	11.4	0.0	2.0
07	20	45.4	24.0	90	1	83.2	11.4	0.0	2.0

(1) = Date (month, day)

(2) = Maximum air temperature

(3) = Minimum air temperature

(4) = Maximum relative humidity

(5) = Minimum relative humidity

(6) = Wind movement at 2m height, km/day

(7) = Sunshine duration,hr

(8) = Soil heat flux

(9) = ratio of day to night wind run

6. SAMPLE OF OUTPUT DATA

DIGDAGA U.A.E. 1982

DATE	FAO	WRIGHT
7/ 1	7.08	7.78
7/ 2	7.78	8.04
7/ 3	8.57	8.99
7/ 4	8.35	8.81
7/ 5	8.37	9.50
7/ 6	9.14	9.49
7/ 7	9.09	9.41
7/ 8	9.50	9.29
7/ 9	8.46	8.46
7/10	8.24	8.38
7/11	8.78	9.14
7/12	7.08	7.69
7/13	8.78	8.99
7/14	8.94	9.16
7/15	9.01	9.11
7/16	7.99	7.80
7/17	8.09	8.02
7/18	8.09	7.81
7/19	8.40	8.56
7/20	9.16	9.34

APPENDIX B

Graphical Results of the Regression Analyses

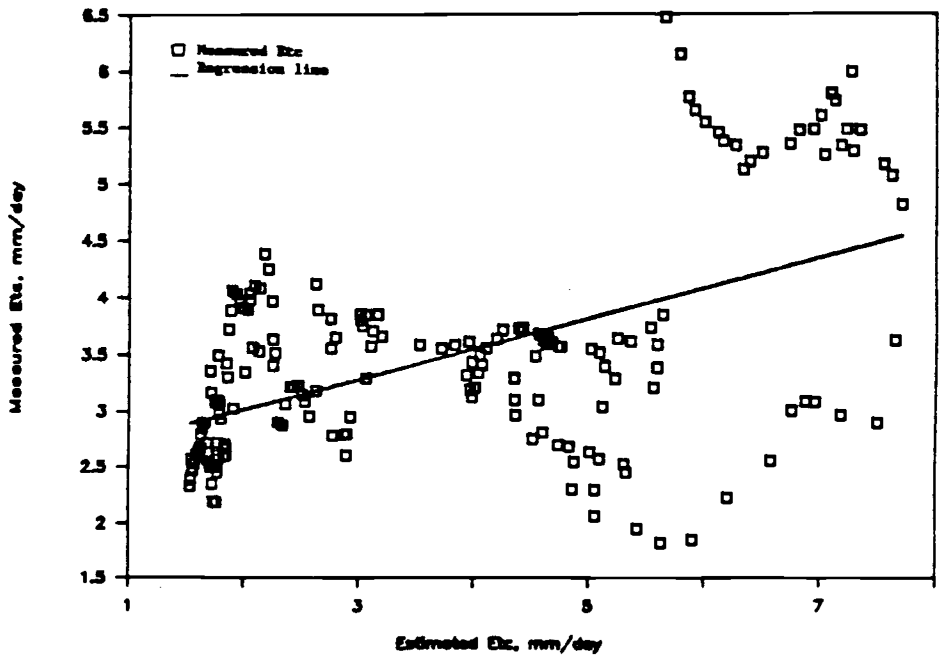

Figure B.1 The relationship between measured E_{tc} and Predicted E_{tc} for Tomato. 1983 season, for FAO version.

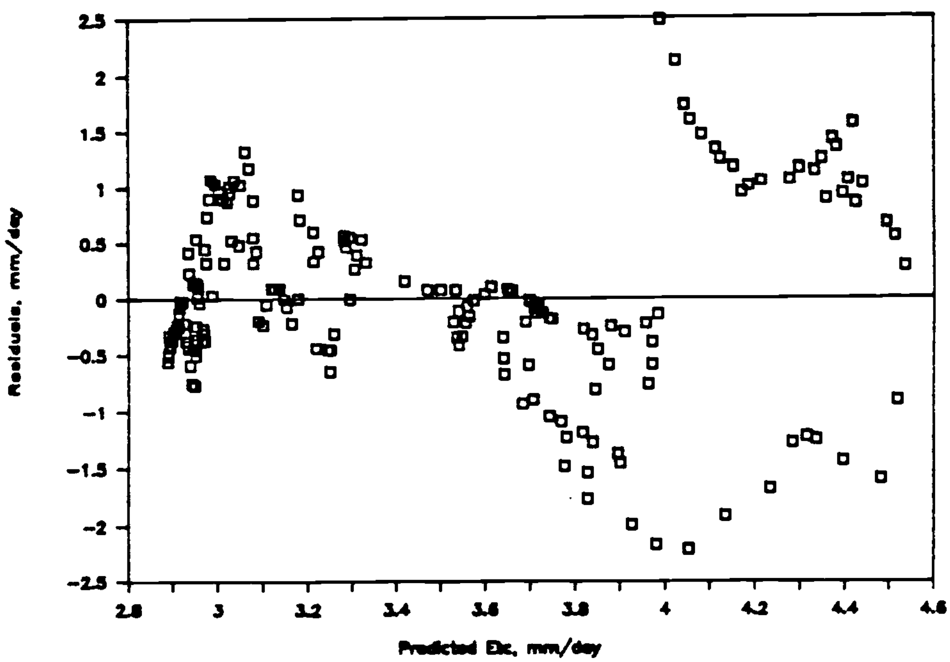

Figure B.2 Residuals plot for predicted E_{tc} for Tomato. 1983 season, for FAO version.

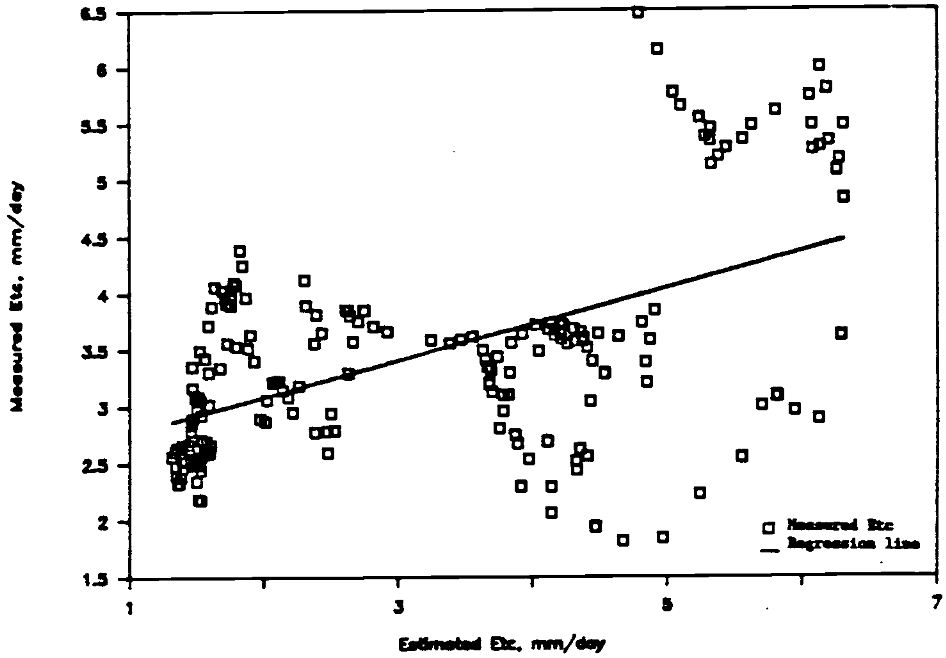

Figure B.3 The relationship between measured E_{tc} and predicted E_{tc} for Tomato. 1983 season, for Wright version.

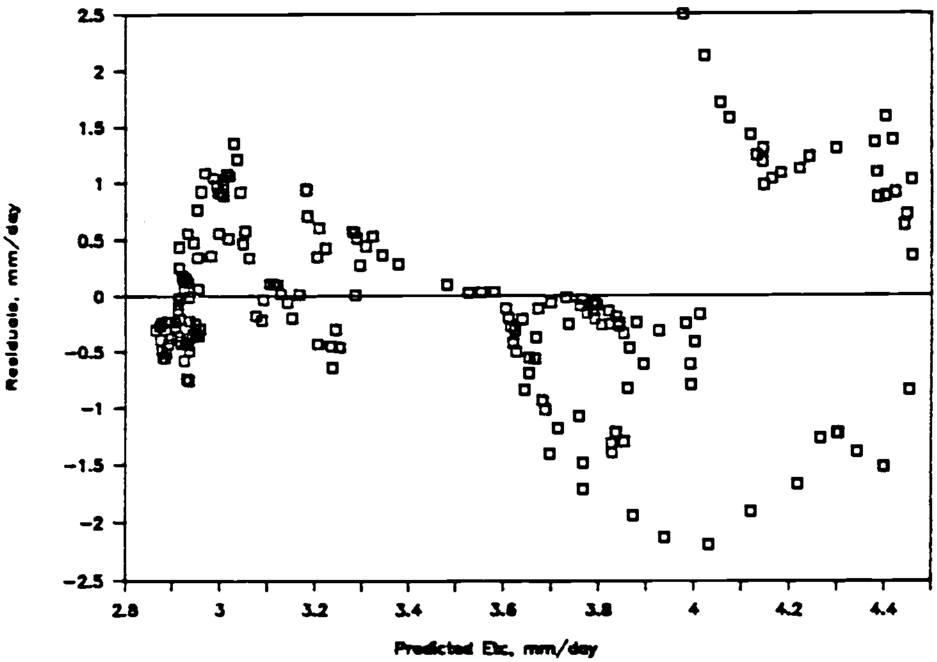

Figure B.4 Residuals plot for predicted E_{tc} for Tomato. 1983 season, for Wright version.

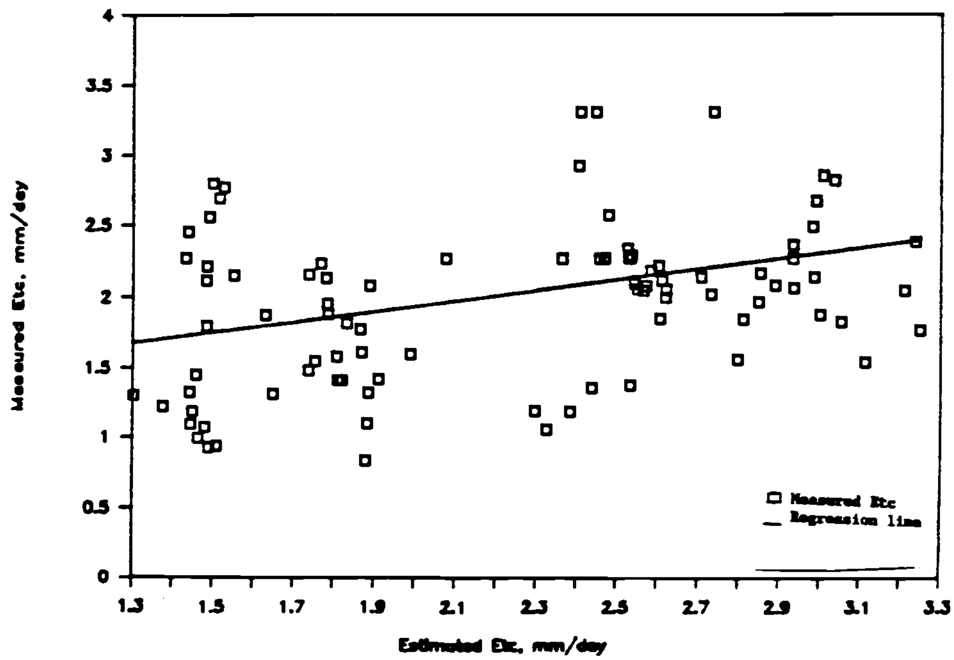

Figure B.5 The relationship between measured E_{tc} and predicted E_{tc} for Cabbage. 1982 season, for FAO version.

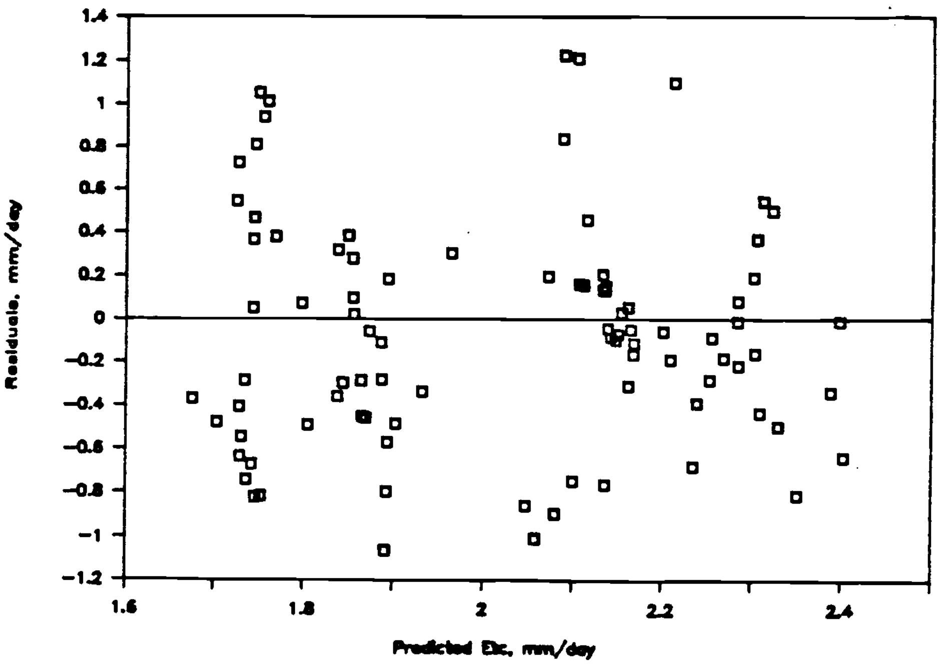

Figure B.6 Residuals plot for predicted E_{tc} for Cabbage 1982 season, for FAO version.

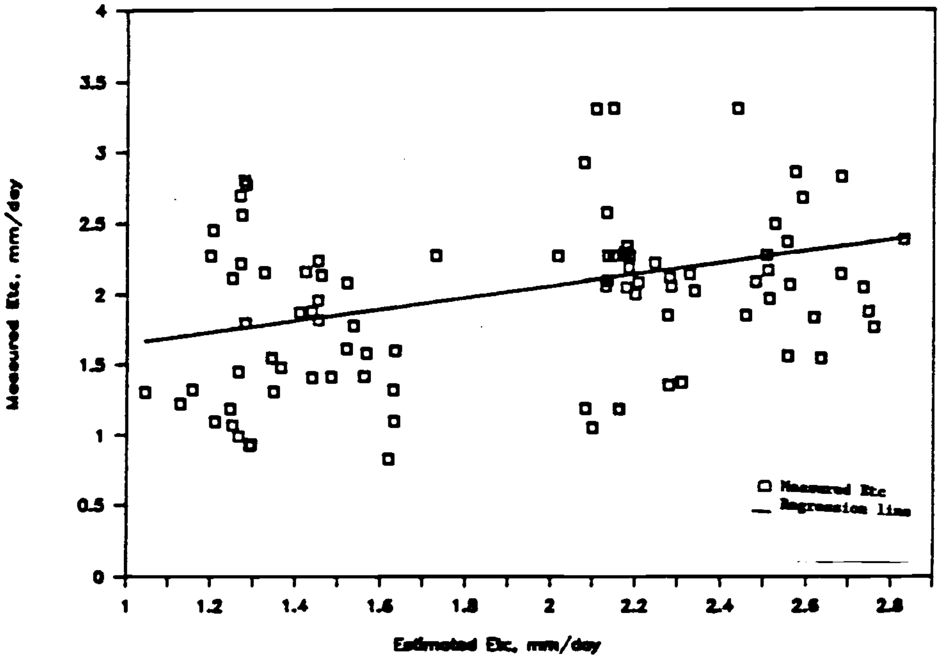

Figure B.7 The relationship between measured E_{tc} and predicted E_{tc} for Cabbage. 1982 season, for Wright version.

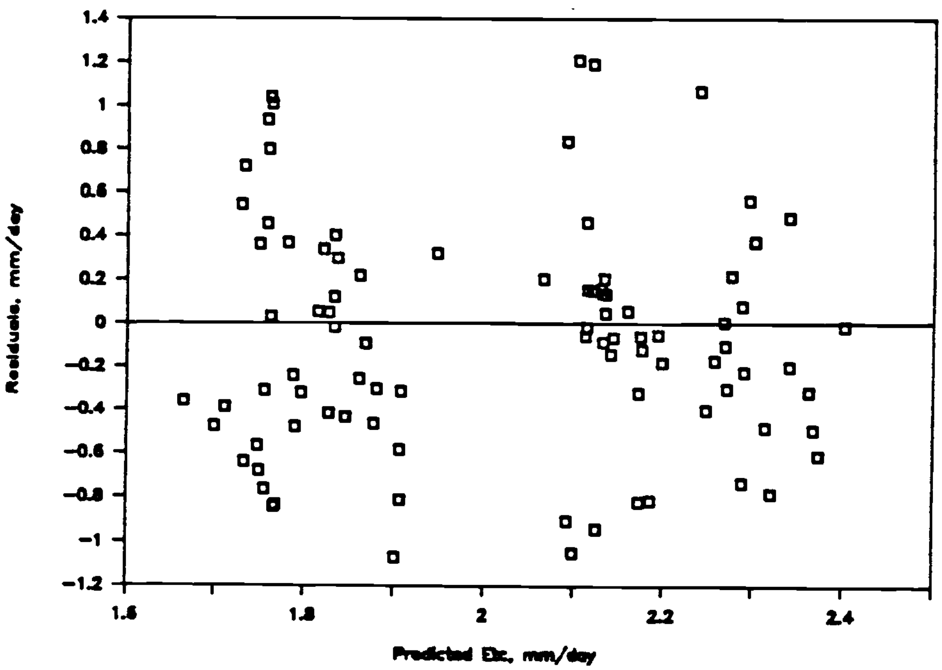

Figure B.8 Residuals plot for predicted E_{tc} for Cabbage, 1982 season, for Wright version.

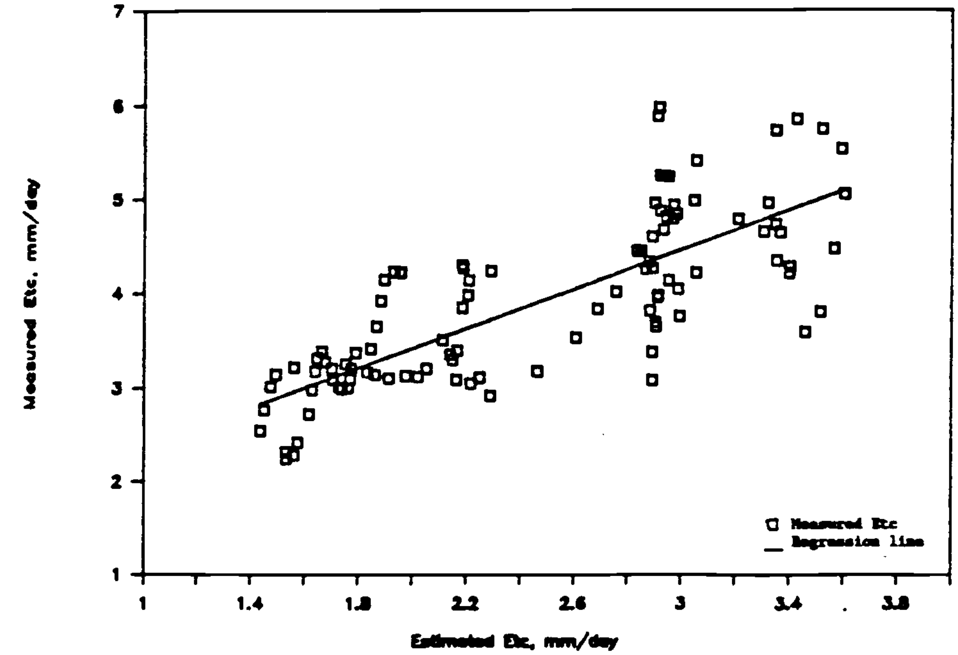

Figure B.9 The relationship between measured E_{tc} and predicted E_{tc} for Cabbage. 1983 season, for FAO version.

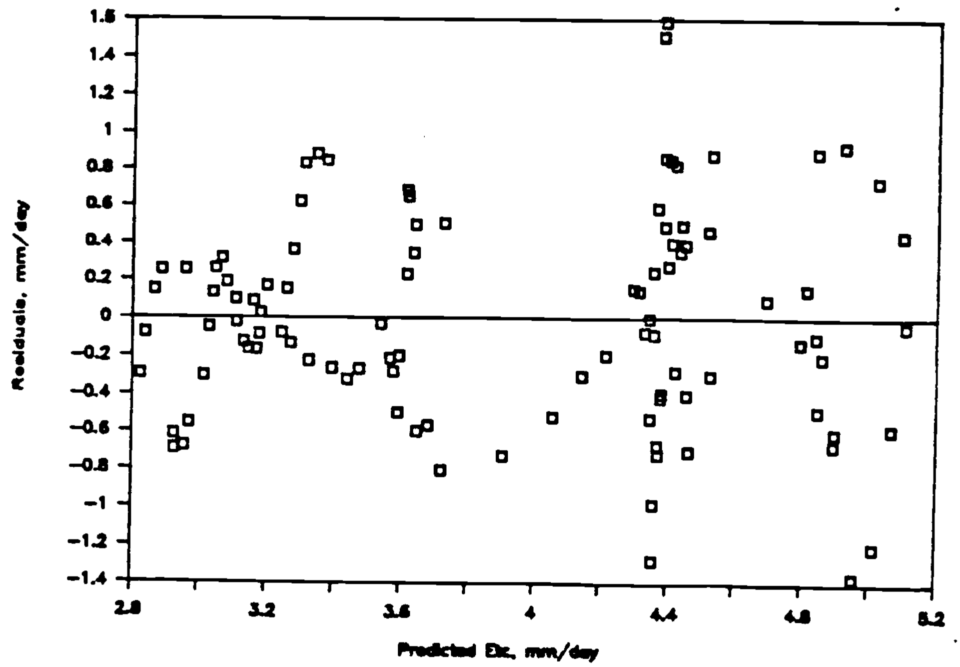

Figure B.10 Residuals plot for predicted E_{tc} for Cabbage, 1983 season, for FAO version.

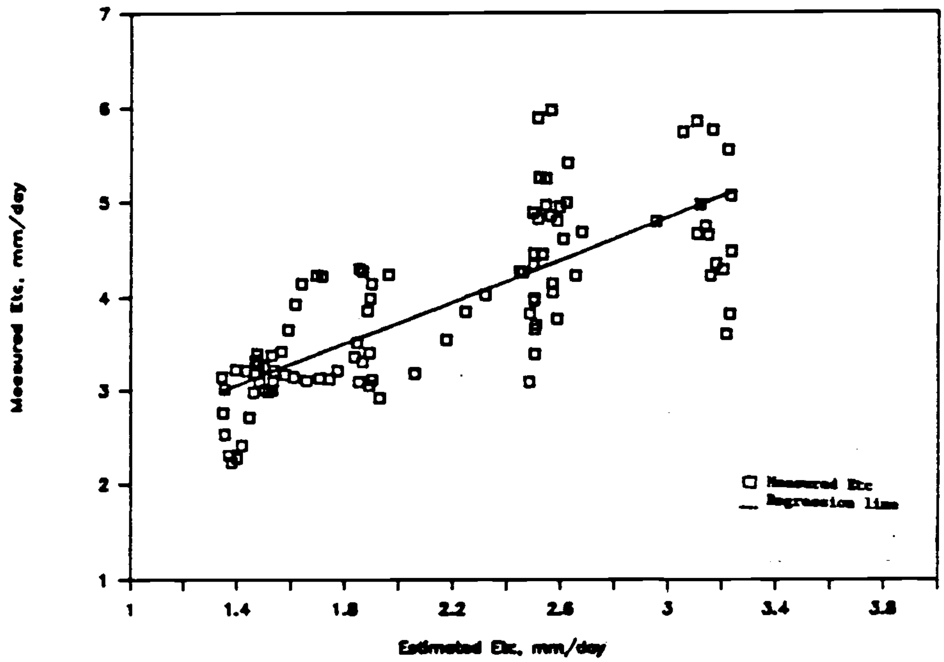

Figure B.11 The relationship between measured E_{tc} and predicted E_{tc} for Cabbage. 1983 season, for Wright version.

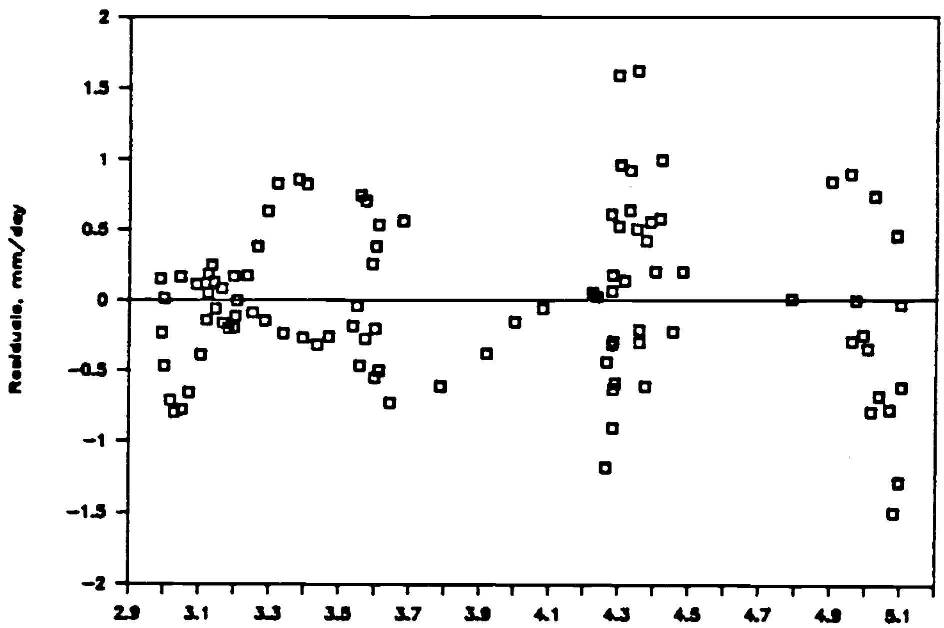

Figure B.12 Residuals plot for predicted E_{tc} for Cabbage. 1983 season, for Wright version.

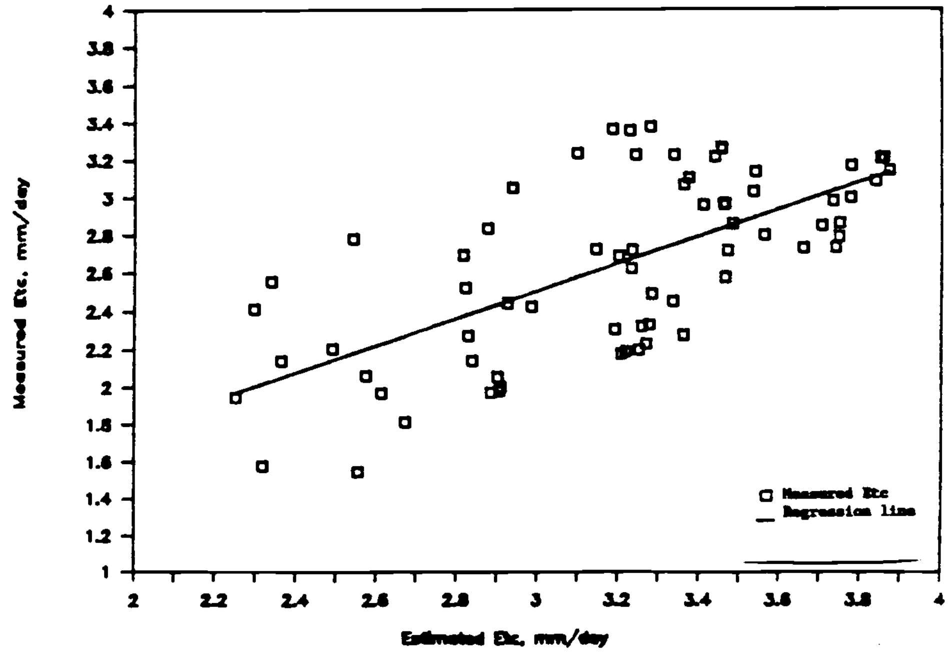

Figure B.13 The relationship between measured E_{tc} and predicted E_{tc} for Squash. 1984 season, for FAO version.

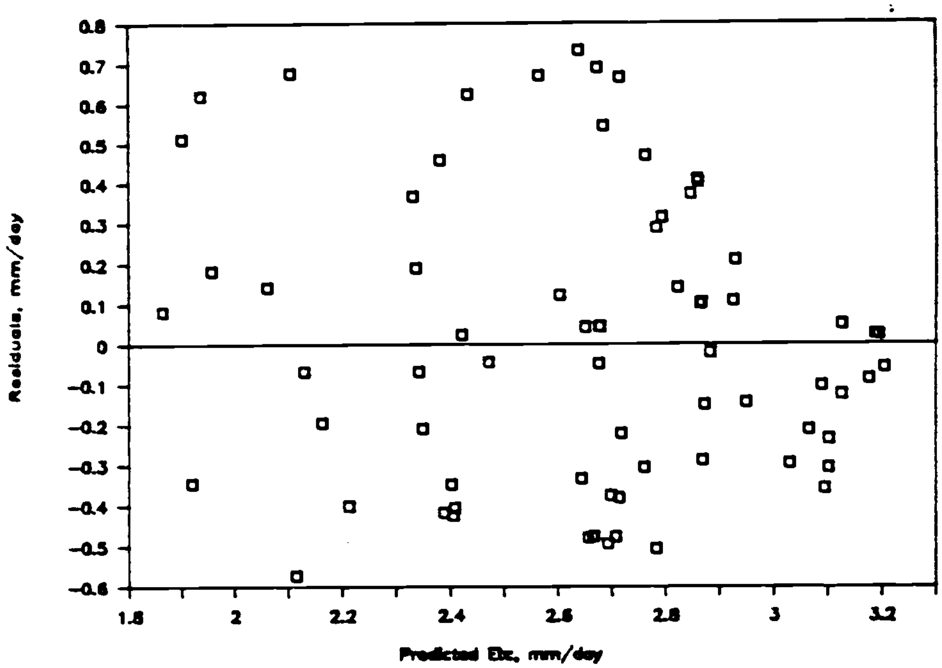

Figure B.14 Residuals plot for predicted E_{tc} for Squash. 1984 season, for FAO version.

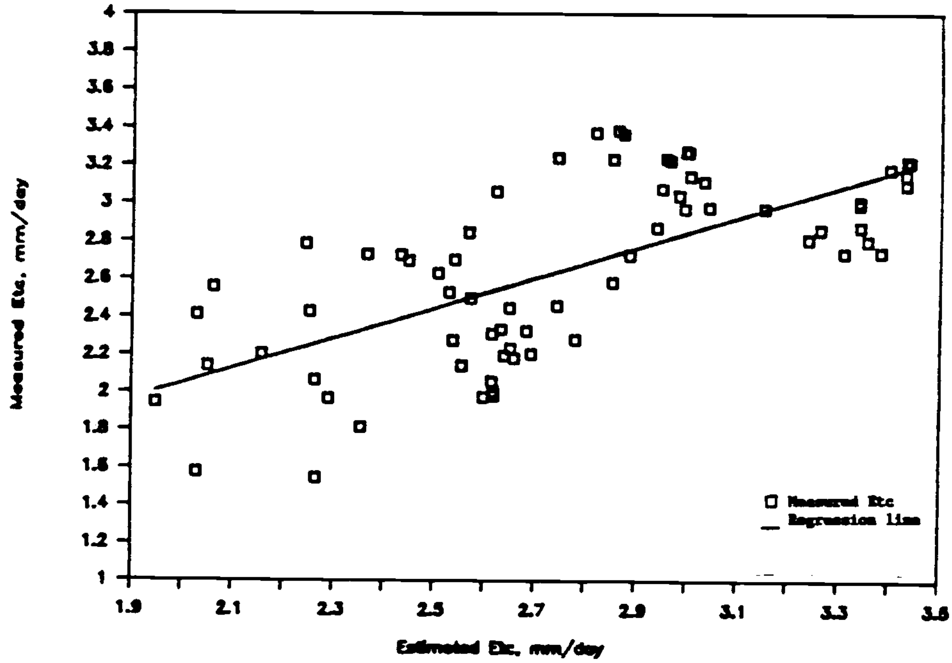

Figure B.15 The relationship between measured E_{tc} and predicted E_{tc} for Squash. 1984 season, for Wright version.

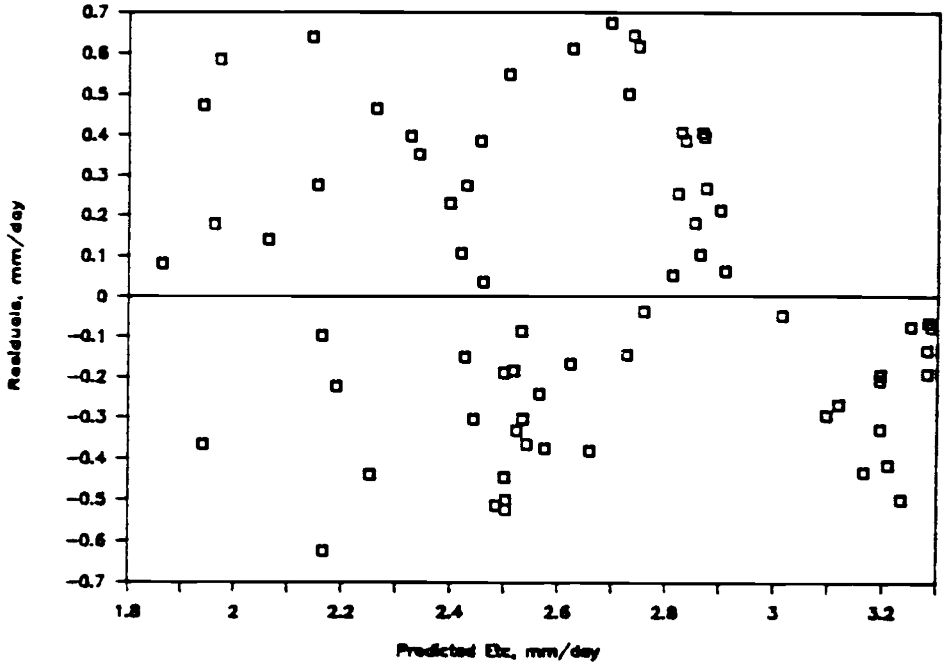

Figure B.16 Residuals plot for predicted E_{tc} for Squash. 1984 season, for Wright version.

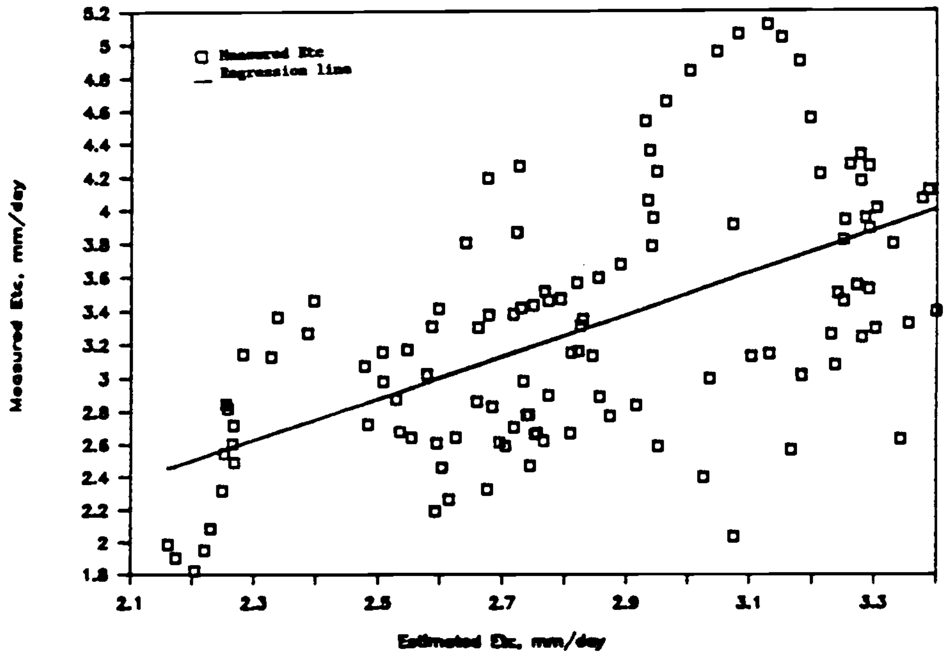

Figure B.17 The relationship between measured E_{tc} and predicted E_{tc} for Squash. 1985 season, for FAO version.

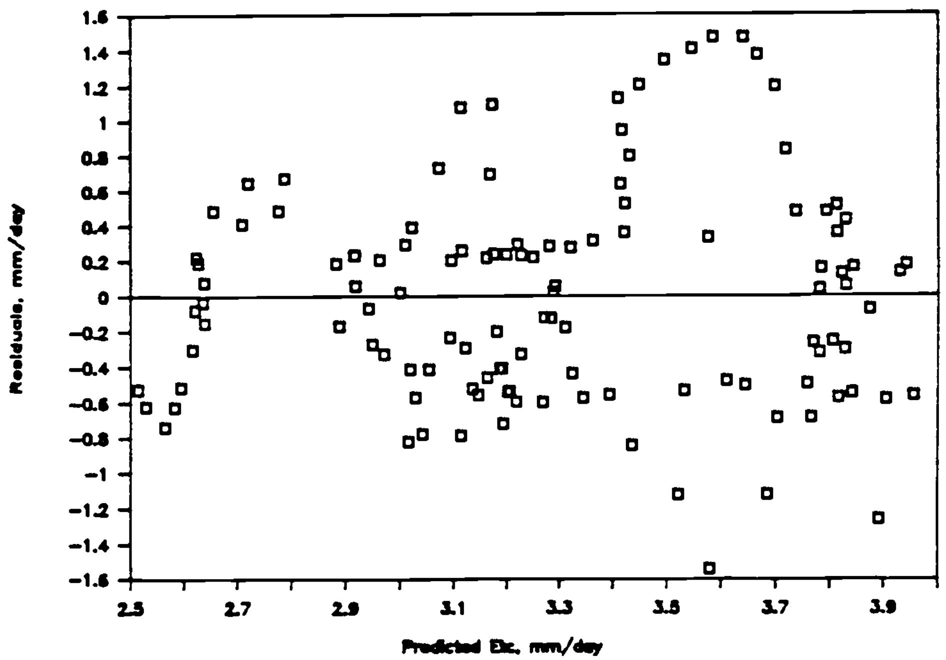

Figure B.18 Residuals plot for predicted E_{tc} for Squash. 1985 season, for FAO version.

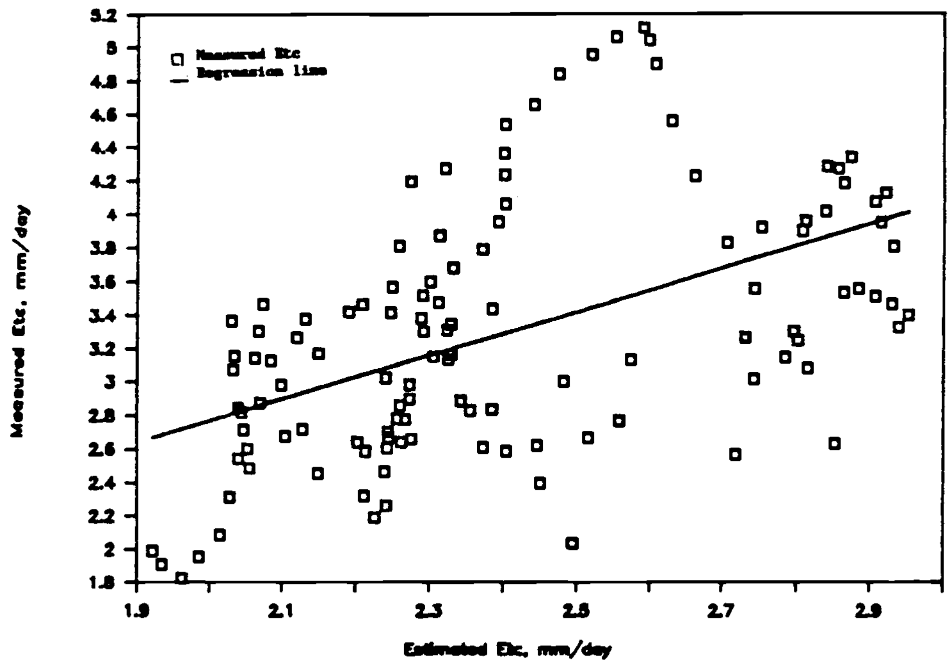

Figure B.19 The relationship between measured E_{tc} and predicted E_{tc} for Squash. 1985 season, for Wright version.

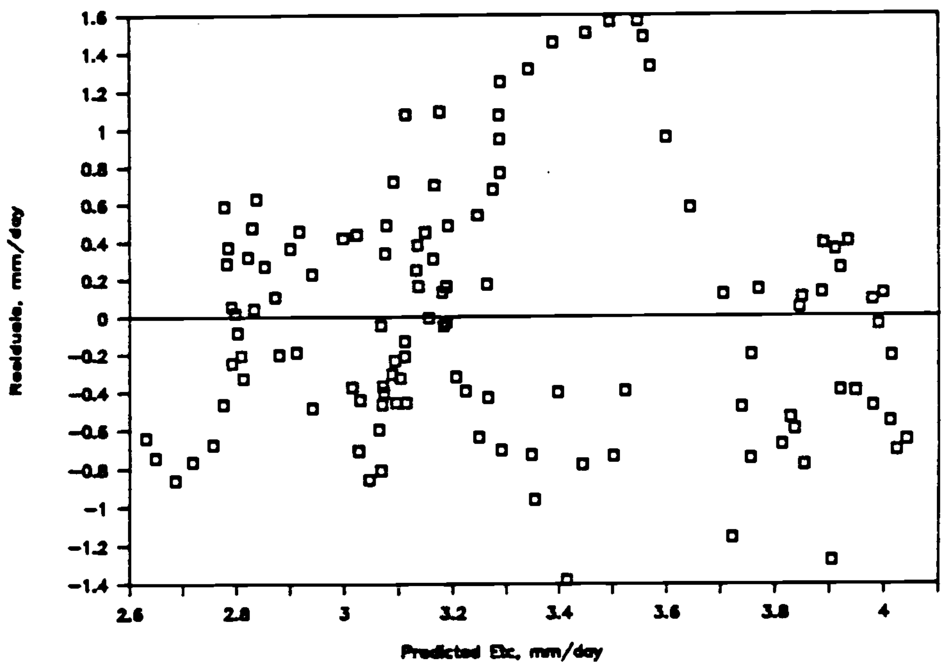

Figure B.20 Residuals plot for predicted E_{tc} for Squash. 1985 season, for Wright version.

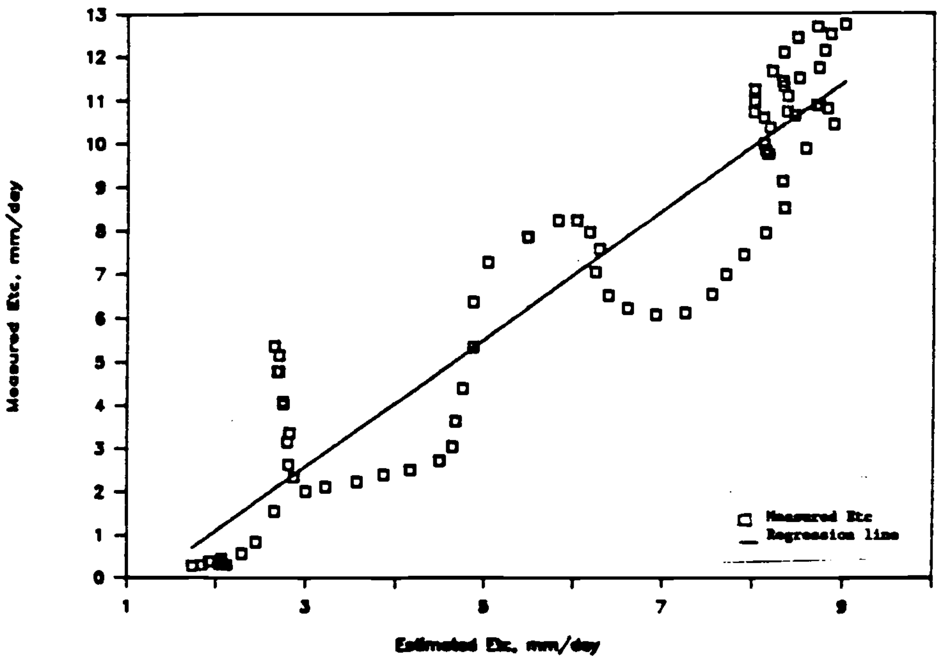

Figure B.21 The relationship between measured E_{tc} and predicted E_{tc} for Watermelon. 1983 season, for FAO version.

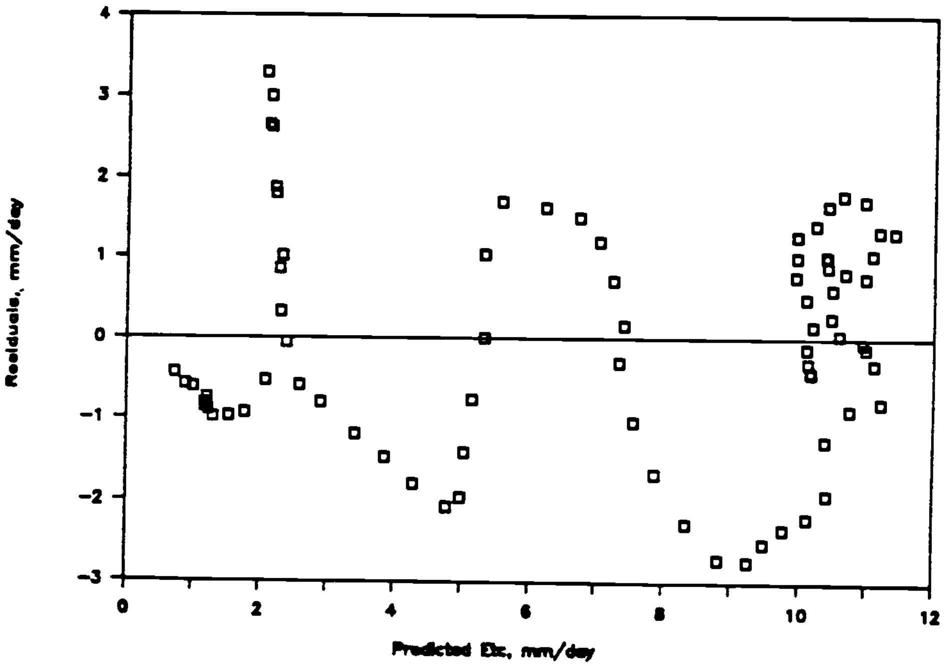

Figure B.22 Residuals plot for predicted E_{tc} for Watermelon. 1983 season, for FAO version.

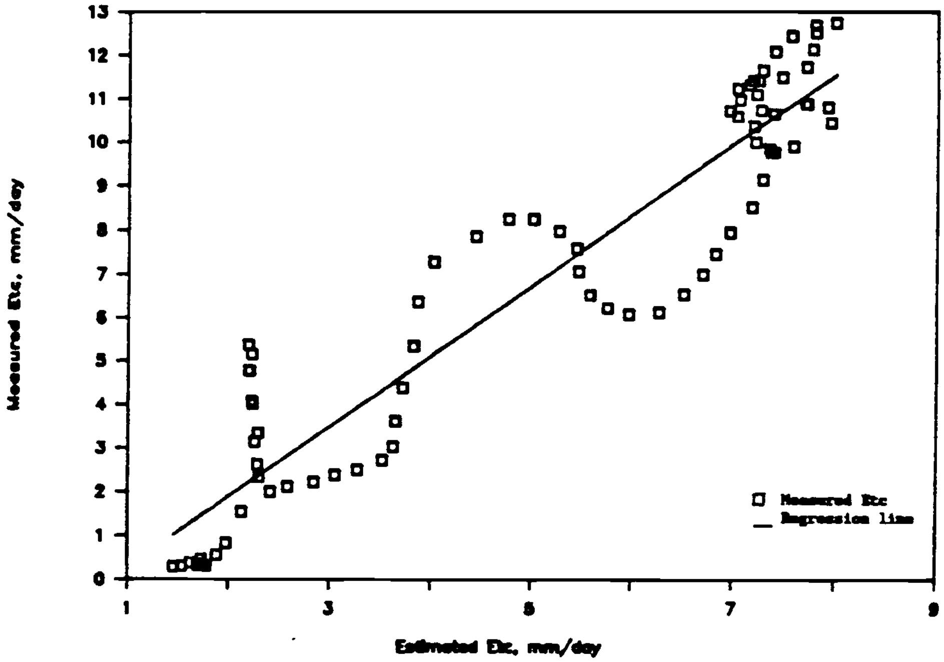

Figure B.23 The relationship between measured E_{tc} and predicted Etc for Watermelon. 1983 season, for Wright version.

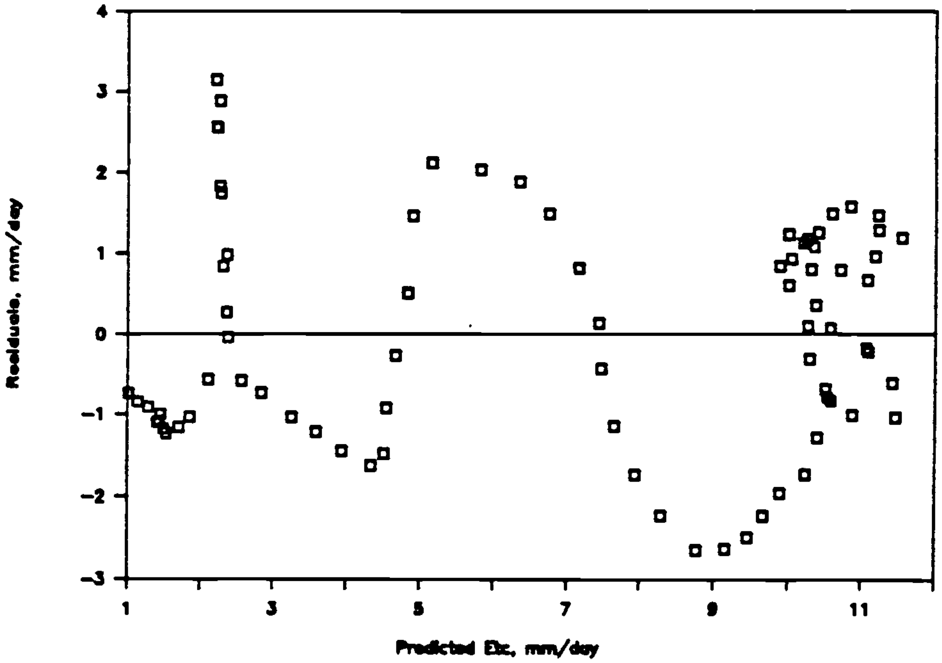

Figure B.24 Residuals for predicted E_{tc} for Watermelon. 1983 season, for Wright version.

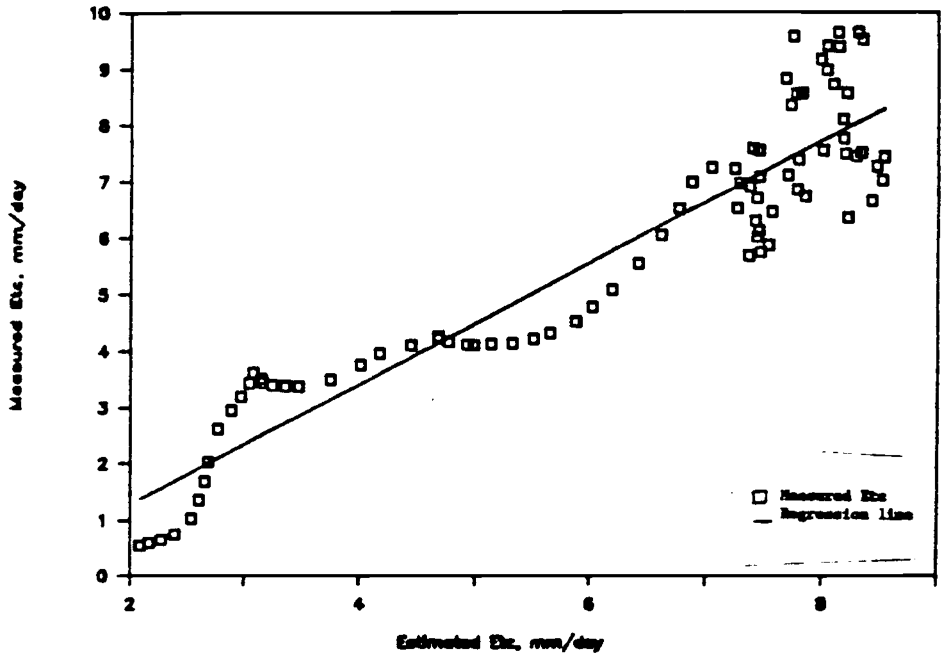

Figure B.25 The relationship between measured E_{tc} and predicted E_{tc} for Watermelon. 1984 season, for FAO version.

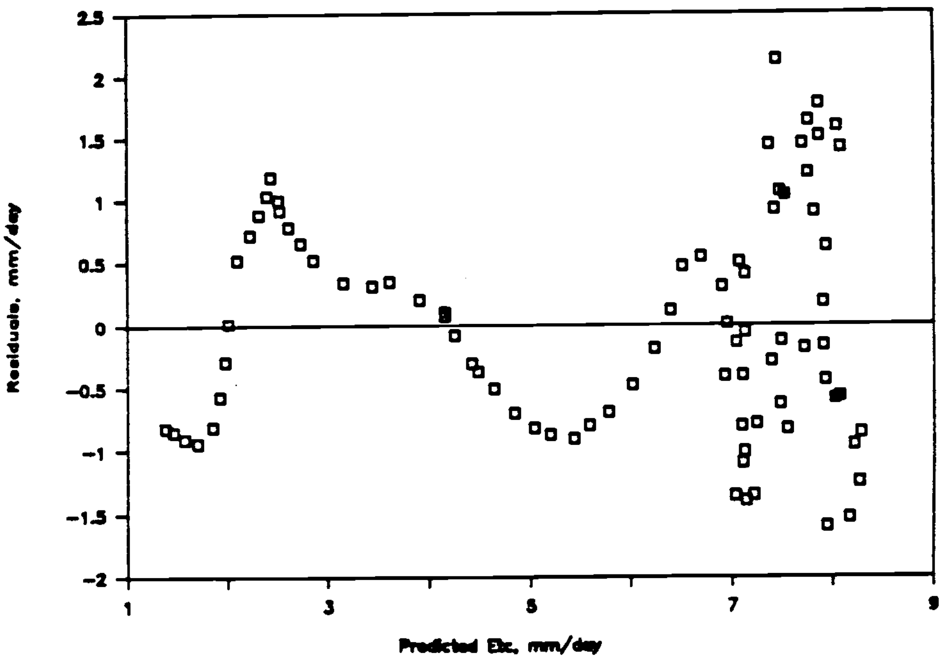

Figure B.26 Residuals plot for predicted E_{tc} for Watermelon. 1984 season, for FAO version.

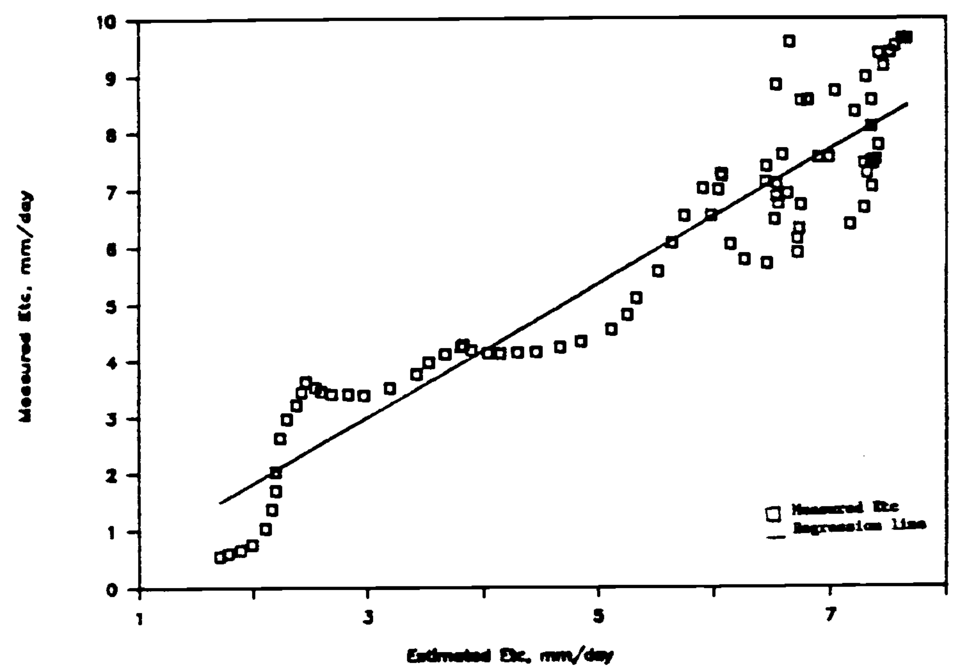

Figure B.27 The relationship between measured E_{tc} and predicted E_{tc} for Watermelon. 1984 season, for Wright version.

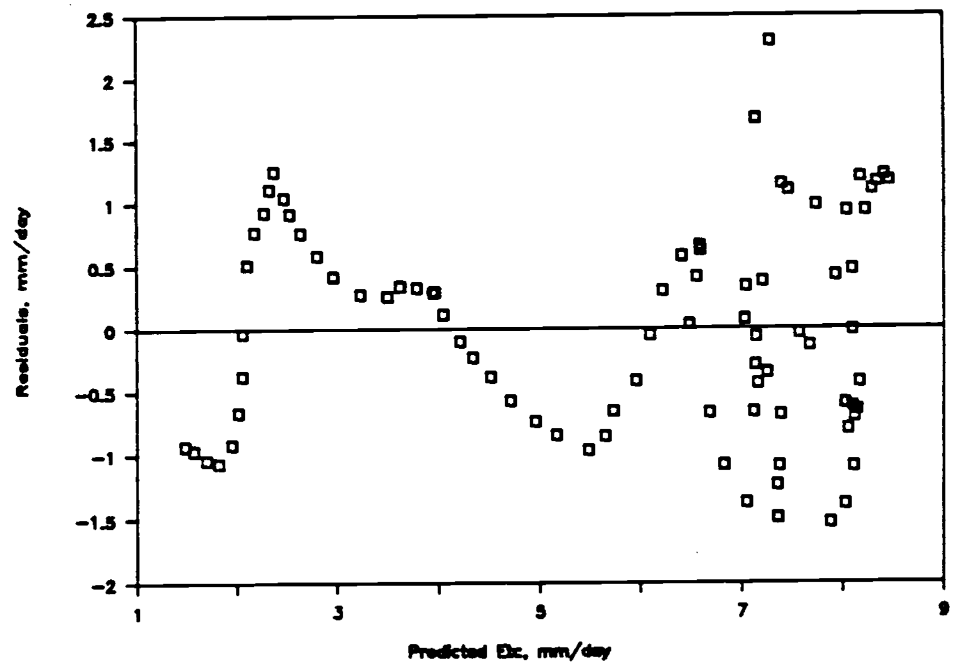

Figure B.28 Residuals plot for predicted E_{tc} for Watermelon. 1984 season, for Wright version.

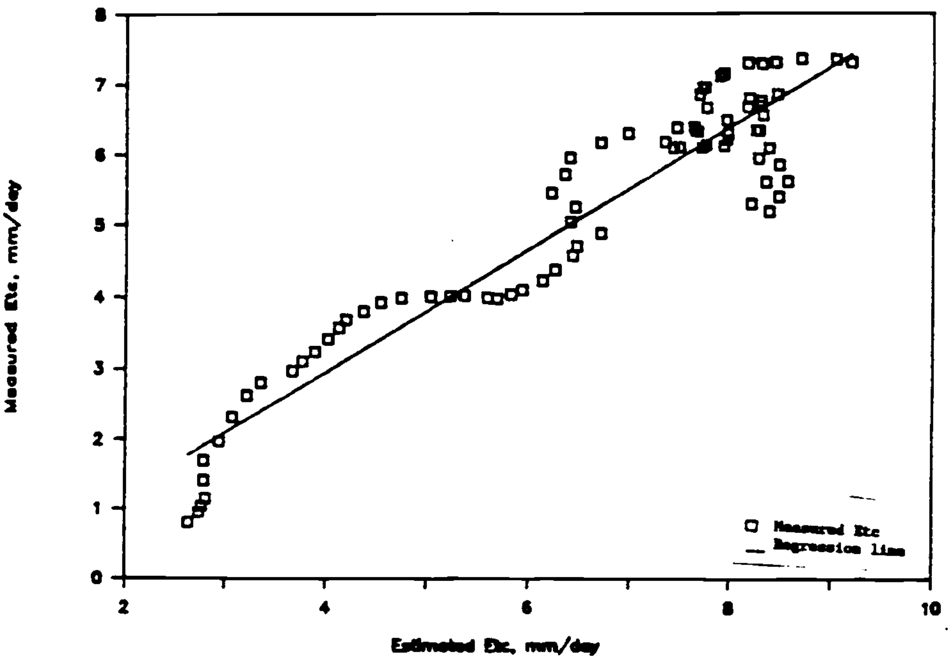

Figure B.29 The relationship between measured E_{tc} and predicted E_{tc} for Watermelon. 1985 season, for FAO version.

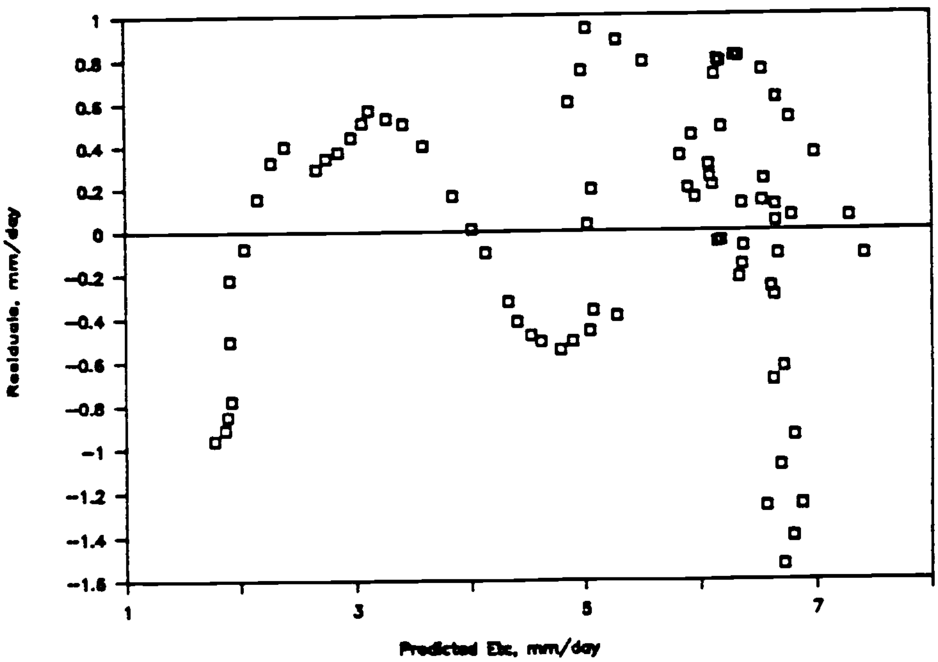

Figure B.30 Residuals plot for predicted E_{tc} for Watermelon. 1985 season, for FAO version.

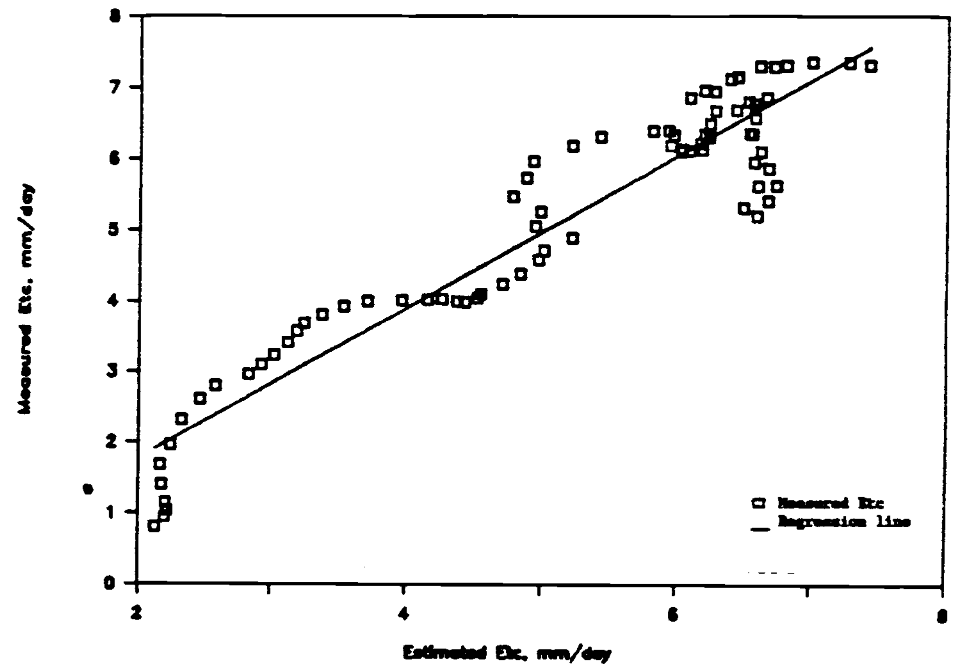

Figure B.31 The relationship between measured E_{tc} and predicted E_{tc} for Watermelon. 1985 season, for Wright version.

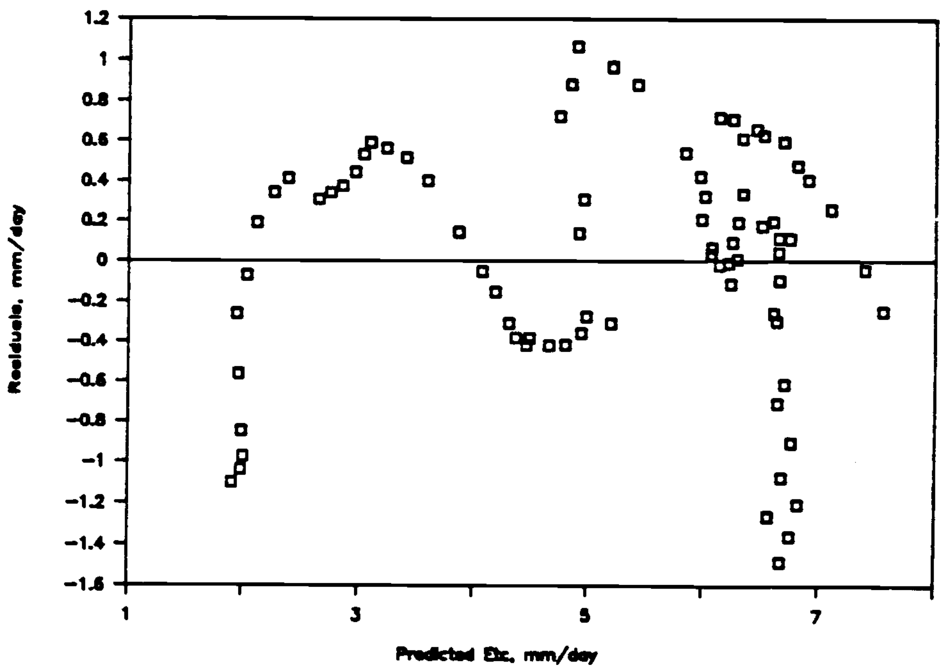

Figure B.32 Residuals plot for predicted E_{tc} for Watermelon. 1985 season, for Wright version.