PREDICTION OF MODIFIED CLASS A PAN EVAPORATION USING RADIATION, TEMPERATURE AND WIND SPEED DATA

BY

JOSEPH LUHANGA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT FOR THE
DEGREE OF MASTER OF SCIENCE (AGRICULTURAL ENGINEERING)
SOKOINE UNIVERSITY OF AGRICULTURE

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ABSTRACT

A simple evaporation model relating pan evaporation (E_p) to shortwave solar radiation (R_s), mean daily temperature (T) and wind speed (W) developed for different climatic conditions was calibrated for the Malawi conditions. The objectives of the study were to examine the possibility of using the model to estimate pan evaporation where such data are missing either because no such readings are recorded or a very short record is available whose extension is sort for various purposes. The model was also examined for use in areas where no shortwave solar radiation is measured and also for the possibility of using the model to estimate reference evapotranspiration (ET_o) for such areas.

Three stations, Bvumbwe, Chitedze and Ngabu were used in this study. The stations represent different climatic conditions within Malawi. Five-day averages of pan evaporation, shortwave radiation, mean daily temparature and wind speed were computed from data collected by the Meteorological Department between 1985 and 1988 inclusive. Data for 1985 and 1986 were used to calibrate the models and the rest were used for validation. A statistical software package (MSTATC) was used to calibrate the models using regression techniques while a climate version of INSTANT package was used for computing R_s and ET_o by the modified Penman equation as presented by Doorenbos and Pruitt (1977). The models calibrated from measured R_s were found to be adequate for the three stations used in the study. All the models estimated pan evaporation to within 6%. Models developed from R_s

computed from tables were found to be slightly superior to models developed from measured solar radiation in that the variables included accounted for an average of 75% and 66% of the variability in the response for Ngabu and Chitedze respectively, as opposed to 74% and 56% for measured R_s, despite the fact that only one year of data was available for their calibration. Correlation coefficients between observed pan evaporation and computed evaporation were high. High correlation coefficients (r=95%) were also observed between reference evapotranspiration and evaporation computed from models derived from tabulated solar radiation indicating that computed evaporation represents ET_o well.

These results indicate that the model is suitable for the Malawian climatic conditions and can be used to estimate evaporation where no such measurements are made and also to estimate both missing pan evaporation and ET_o.

DECLARATION

I, JOSEPH LUHANGA, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has never been submitted for a degree at any other university.

Signature:......................................

Date:...26/10/93......

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ACKNOWLEDGEMENTS

I wish to convey my sincere and heartfelt gratitude to my supervisor Dr.N.I. Kihupi for his tireless assistance, guidance and encouragement throughout the course of my study. Special thanks go to the Agricultural Engineering departmental postgraduate committee for their critical comments and encouragement which helped in shaping this report and also to the Meteorological Department at Chileka for providing the data. Mr. B.A. Salim and Ms. M. Banda deserve special thanks for the assistance given in the use of computers and for typing much of the manuscript respectively. I would also like to thank SACCAR/GTZ for providing the funds and facilities for this study tour. Last but not least, I wish to convey my thanks to my beloved mother, brothers and sisters in Christ, brothers and sisters, in-laws and the many friends and relatives whose prayers and encouragement throughout my endeavour to attain higher education are greatly appreciated. May the LORD of Grace be with you all.

DEDICATION

To my beloved wife Getrude, and my children Tiyezge, Mbachi and Tapona, who I thank for persevering for two years while I pursued my studies. May God bless you.

TABLE OF CONTENTS

LIST OF TABLES

Table No.

LIST OF FIGURES

Figure No

LIST OF APPENDICES

Appendix A

Appendix B

Appendix C

Appendix D

Appendix E.

Appendix F

ABBREVIATIONS

Abbreviation	meaning
a, b, c, b_i	Model parameters.
E_t	Evapotranspiration
ET_o	Reference evapotranspiration
E	Evaporation
e_s	Saturated vapour pressure
e_o	Actual vapour pressure of air
U,W	Wind speed
E_p	Pan evaporation
R_s	Shortwave solar radiation
T	Mean daily temperature
LE,El	Latent evaporation
zo	Roughness length parameter
ly	Langleys
ml	Miles
in	Inches
mbar	Millibars
mm Hg	Millimeters of mercury
cm	Centimeter
mm	Millimeter
km	Kilometer

%	Percent
°C	Degree Celcius
°F	Degree Fahrenheit
n	Number of observations
V.P.D	Vapour pressure deficit
z_a	Wind profile parameter
r	Simple correlation coefficient
R	Multiple correlation coefficient
R^2	Coefficient of determination
a.m.s.l	Above mean sea level
COVA	Coefficient variance covariance matrix
E_{oi}	Observed evaporation in period i
E_{si}	Simulated evaporation in period i
E_o	Mean of observed evaporation
E_s	Mean of simulated evaporation
RE	Coefficint of efficiency
SSE	Sum of squared errors
SD_o	Standard deviation of observed pan evaporation
SD_s	Standard deviation of simulated pan evaporation
δE_p	Small change in pan evaporation

δT	Small change in mean daily temperature
δW	Small change in wind speed
δR_s	Small change in solar radiation
dE_p/dR_s	Partial differentiation of E_p with respect to R_s
dE_p/dT	Partial differentiation of E_p with respect to T
dE_p/dW	Partial differentiation of E_p with respect to W

1. INTRODUCTION

Evapotranspiration (E_t) is an essential parameter in the design and management of irrigation systems (Heermann, 1988). The irrigation of crops consists of supplementing the natural rainfall to compensate for what is lost by runoff, drainage, evaporation, etc. Because evaporation generally causes the greatest loss of water, it is useful to know what quantity of water has evaporated from the crop when deciding how much irrigation water to apply (Linacre, 1967). Estimates of evapotranspiration, were required for construction of early irrigation projects (Jensen and Haise, 1963), the same estimates are needed today but greater accuracy is required. There are several reasons for the increased accuracy requirements: (a) growing competition for limited water supplies; (b) higher construction costs of new projects demand closer tolerances and less leeway in design to make the projects economically feasible; (c) water litigation between irrigation districts, upper and lower river basins and in some cases between countries, require more precise estimates of evapotranspiration ; (d) river basin development for maximum use of water supplies requires long range planning with reliable estimates of E_t; (e) high frequency irrigation which is possible with either sprinkler or trickle irrigation systems, may require estimates of E_t for periods as short as daily; (f) many drainage problems can be avoided or time of their occurrence predicted in advance if accurate estimates of E_t are available; and (g) existing projects can often reduce operational wastes by predicting water deliveries several days in advance (Jensen and Haise, 1963; Heermann, 1988). Thus the need for accurate information on evapotranspiration by crops has become more important today than ever before. From the irrigation point of view, evapotranspiration can be equated to the amount of water that has to be applied to a crop to meet the evapotranspiration processes of the soil-crop system and this water is referred to as the crop water requirement. The determination of crop water requirement essentially entails the measurement of evapotranspiration. Crop water requirement can be measured directly (using lysimeters) by measuring the real evapotranspiration of the soil-crop system, however it is normally determined indirectly by empirical relationships. These theoretical relationships are correlated or validated against a specific reference condition (Abdulmumin et al., 1990). The relationships can be grouped under two categories; (a) pan evaporation; and (b) empirical formulae. All these methods require climatic data. The type and number of measured or estimated data required by each method vary. Therefore the availability and the possibility of estimating the data form the basis upon which the relevant method for determining reference evapotranspiration (ET_o) is selected (Doorenbos and Pruitt, 1977). Because of their ease of operation, evaporation pans have become the most widely adopted evaporation instruments throughout the world (Hounam, 1977).

In Malawi, evaporation pans are commonly used for collecting evaporation data. The Meteorological Department has a number of evaporation pans installed at most of the weather observation stations as part of a range of instrumentation for collecting climatic data. There is also a small number of pans installed and run by the Water

Department for specific water resources studies (SADCC, 1987; Laisi, E.Z. personal communication, 1990). However the reliability of evaporation data collected by the Water Department is questionable. Moreover there are large gaps of missing data at most stations run by both the Water Department and the Meteorological Department, caused by prolonged delays in repairing pan leakages, poor station maintenance programmes, negligence of observers, etc. The accuracy requirements of present and future irrigation projects render this data unsuitable for most design and management applications in general, and for determining crop water requirements in particular.

Consequently, the main objective of this study is to develop location specific models that relate pan evaporation as a dependent variable to radiation, mean daily temperature and wind speed. The specific objectives of the study include:

(a) to estimate missing evaporation data and test the data reliability.

(b) to evaluate the relative influence of each of the variables in determining pan evaporation.

(c) to evaluate the use of radiation data computed from Smithsonian tables in determining pan evaporation.

(d) to compare the reference evapotranspiration data calculated using the modified Penman method with evaporation data simulated by models developed using radiation from tables.

2. LITERATURE REVIEW.

2.1 Theoretical background behind pan evaporation.

Pan evaporation is a measure of the integrated effects of radiation, wind, temperature and humidity on evaporation from a specific open water surface. As such pan evaporation data can be used to estimate ET_o (Doorenbos and Pruitt, 1977). There are however physical differences between pan and grass which make the adjustment of pan evaporation data necessary. The main differences as reported by many authors (e.g. Doorenbos and Pruitt, 1977; Hounam, 1977; Robertson, 1970) are: (a) the albedo or reflectivity of water in the pan is 5-8%, whereas for grass it is 20-25%; (b) pans can store heat which can be used to evaporate water even at night, whereas crops transpire only during daytime; (c) there are differences in microclimate (wind turbulence, humidity and temperature) around the pan compared to a crop; (d) some heat can be transferred from the environment to the pan, especially in sunken pans. This can enhance evaporation; (e) local advection of heat which depends on the siting of the pan can affect evaporation. The nature of the local climate in terms of characteristic air temperatures, levels of humidity, wind speeds and available solar radiation determines the evaporative capacity of the environment. Generally high levels of solar radiation, temperatures and wind, associated with low humidities give high levels of evaporative demand. Low evaporative demands are associated with low radiation, low temperatures, high humidities and low winds (Abdulmumin et al., 1990; Doorenbos and Pruitt, 1977).

2.2 Radiation, mean daily temperature and wind speed vis a vis pan evaporation.

Many researchers have modelled pan evaporation and various climatic factors (e.g. Linsley et al., 1982; Doorenbos and Pruitt, 1977; Jensen, 1983; Linacre, 1967). One of the earlier models developed by Kohler et al.(1955) related the open water pan evaporation with the climatic variables wind and vapour pressure deficit and as reported by Linsey et al.(1982), the equation was of the aerodynamic form suggested by Dalton(1802) thus:

$$E = (a+b)\ (e_s - e_o)^n \qquad (2.1)$$

Where U = wind speed in miles/day taken at 1.9 ft. above ground level.

e_s = saturated vapour pressure.

e_o = actual vapour of the air.

a,b & n = location specific constants.

This model was used to study evaporation of lakes Hefner, Mead and Felt in USA and elsewhere worldwide (Linsley et al., 1982). Since then numerous relationships have been developed between pan evaporation and climatic variables (Pelton, 1964; Hounam, 1971; Halstead and Covey, 1963; Fitzpatrick, 1963; Shnitnikov, 1974).

Fitzpatrick (1963) studied and developed a relationship between mean temperature and vapour pressure deficit. He found that the vapour pressure deficit calculated from maximum temperature is a more deficient indicator of evaporation than simple saturation deficit (Krishnan and Kushwaha, 1973). Linacre (1967) believes that the evaporation rate can be estimated from radiation measurements and ambient temperature and that ignoring humidity and wind speed would be less serious. As reported by Linacre (1967), Stephen and Steward (1963) were the first to specifically associate the ratio of latent evaporation and shortwave solar radiation (LE/R_s) with the mean ambient temperature (T). Correlation coefficients of above 80% were found for varied climates and locations in USA and elsewhere. Using the E_t data and estimates of solar radiation, Jensen and Haise (1963) calculated E_t/R_s ratios for approximately 1000 individual sampling periods during the growing season of fifteen crops. Jensen and Haise (1963) derived a linear equation relating E_t/R_s to mean air temperature (r=0.86):

$$E_t/R_s = 0.014T - 0.37 \tag{2.2}$$

where E_t = evapotranspiration (in./day)

R_s = solar radiation (in./day)

T = mean air temperature (°F)

Jensen and Haise (1963) concluded that this ratio reflected the combined effect of reflectance or albedo, and relative effects of effective thermal radiation, sensible heat flux to the air and soil, plus other minor energy balance components. They also suggested that the ratio may be used for estimating mean weekly, monthly or seasonal evapotranspiration.

Tanner (1968) did a lot of excellent review on the subject and remarked that radiation methods of determining evaporation are among the better empirical methods and that their success rests on the fact that the radiation term of the combination approach is rarely smaller than the convective term (Krishnan and Kushwaha, 1973). However while studying evaporation at Jodhpur (India), Krishnan and Kushwaha (1971) showed that not only was the aerodynamic term in general numerically greater than the energy balance term but also is more important in depicting the observed evaporation.

In later studies at Jodhpur in the Indian arid zone using multiple regression of pan evaporation on climatological factors, Krishnan and Kushwaha (1973) developed the following relationships:

$$Y = 0.0122X_1 + 0.2559X_2 + 0.5677X_4 - 9.0657 \qquad (2.3)$$

and

$$Y = 0.0066X_2 + 0.3260X_3 + 0.5150X_4 - 6.3571 \qquad (2.4)$$

Where Y = pan evaporation (mm/day)

X_1 = total global radiation (cal/sq. cm. day)

X_2 = estimated net radiation (cal/sq. cm. day)

X_3 = saturation deficit at maximum temperature (mm of Hg)

X_4 = mean daily wind speed (km/h)

They found that the aerodynamic factors are important in the Jodhpur climate and that saturation deficit at maximum temperature and daily mean wind speed explain 83% of the variance. The total global radiation or the estimated net radiation terms increased the explained variance by only 5% and 1% respectively. The correlation coefficients of the models were 0.94 and 0.92 respectively.

Using pattern search optimization technique, Hanson (1989) modelled pan evaporation in southwest Idaho at three separate sites. The algorithm he used to describe daily evaporation amounts to a modification of the frictional evaporation-equivalent method used by Stephens and Stewart (1963) and Linacre (1967). Hanson (1989) used this equation because the values for the variables are widely available or can be estimated in case of radiation.

The models he came up with for the combined sites were:

$$E_p = R_s\,(0.102 + 0.023T) + 0.0045W \qquad (2.5)$$

if the wind term is included and

$$E_p = R_s\,(0.281 + 0.030T) \qquad (2.6)$$

if the wind term is ignored.

where E_p = pan evaporation (mm/day)

R_s = shortwave solar radiation (mm/day)

T = mean daily temperature (°C)

W = wind speed (km/day)

Without the wind term the correlation coefficients were 0.84 for the combined sites and 0.86, 0.86 and 0.79 for the individual sites. However when the wind term was included the correlation coefficient improved to 0.87 for the combined sites and 0.88, 0.90 and 0.84 respectively for individual sites, thereby indicating a better representation of the pan evaporation.

Campbell and Phene (1975) investigated the effect of a 5 cm mesh wire screen traditionally placed on class A pans to prevent animals from consuming or polluting the water. They found that evaporation was reduced by 12.8% compared to that of an open pan. A near 1:1 relationship was observed between screen pan evaporation and potential evapotranspiration computed from the combination equation as used by Van Bavel (1966) and Tanner and Pelton (1960) using the roughness length parameter of Z_0 = 1 in the wind term. They concluded that the screens reduced absorption of radiant energy and introduced an element of roughness that increases the thickness of the diffusion boundary layer, which in effect may be similar to the roughness introduced by crops growing on wet soil. They suggested that the screened pan can be a more practical tool for estimating crop water requirements than an open evaporation pan.

Pelton (1964) compared evaporation measured by four methods including the U.S. Weather Bureau Class A pan and made the observations on 124 consecutive days. He found that the maximum single day evaporation from the class A pan was 0.93 in. (23.6 mm) and that every evaporimeter had recorded the maximum evaporation on the day. This particular day was further characterised by high values of radiation of 590 ly.(9.9mm), wind speed of 286 mi.(457.6Km), vapour pressure deficit of 18.4 mb.(13.8mm Hg) and a mean air temperature of 85°F. The temperature on the day was 100°F for approximately 6 hours during the day. Simple correlation coefficients (Table 2.1) were well above those required for significance at the 1% level except for wind speed. The coefficients for wind against evaporation from the class A pan were statistically significant at the 1% level. This indicates that less than 10% of the evaporation from the pan can be attributed to the effects of wind alone. Mean temperature appeared to correlate better with class A pan evaporation than the other meteorological factors. The correlation coefficient between mean air temperature and vapour pressure deficit was high as was expected because air temperature formed a basis of one of the vapour pressure components. Wind was negatively correlated with each of the other variables (Table 2.2b). The multiple correlation coefficients, R, for each of the four linear regression equations were highly significant. The R^2 values indicated that 86% of the variability in pan evaporation could be accounted for by the four meteorological factors included in the regressions.

In Canada, Baier and Robertson (1965) developed a technique of estimating latent evaporation at six agricultural research establishments from a given set of meterological data. They primarily evaluated the single or combined influence of several meterological parameters ordinarily available at weather stations. They found that on average over all the stations and years used in their study, variations in solar energy alone accounted for 50% of the variations in latent evaporation, E_l. This is in agreement with the findings of Pelton (1964) at Swift Current, Canada. Because solar radiation data are not always available, they were able to explain 46% of the variations of E_l by using maximum temperature, temperature range and extraterrestrial radiation from tables. They further reported that if records of any of the additional variables viz. solar energy, vapour pressure deficit or wind speed are included, approximately 57% of the variability of E_l were accounted for by variations in the meteorological parameters involved. With a suitable combination of five meteorological variables 64% to 66% of the variability in latent evaporation was accounted for and with six variables this value increases to 70%. This is the result Pelton (1964) got for a multiple correlation between disk atmometer evaporation and the four meteorological variables temperature, radiation, vapour pressure deficit and wind speed at Swift Current. Baier and Robertson (1965) concluded from their findings that it is feasible for daily E_l to be estimated from meteorological data and astronomical data readily obtainable from tables. With extraterrestrial radiation from tables, the correlation coefficient with latent evaporation was highly significant ($r = 0.68$). The inclusion of any one or two of the variables solar energy, vapour pressure deficit and wind resulted in correlation coefficients ranging from 0.75 to 0.81.

Merva and Fernandez (1985) examined the response of Penman's equation to errors in the estimation of the input parameters of extraterrestrial radiation, temperature, albedo, percent sun and wind. They plotted the parameters versus the percent variation of the parameter. If the percent fluctuation of a given parameter showed a relatively small percent response, or if the parameter value was one which was not readily available, the parameter used in the Penman equation was modified. They found that the Penman model responded least to variation in wind speed, irrespective of the estimated value of the wind speed around which the fluctuation was varied. For the conditions chosen, a variation of plus or minus 20% of the wind speed caused less than 2.5% change in the result. Similarly, the variations in dew point temperature appeared to have relatively little effect on the results obtained by applying the Penman model. The maximum variation in model response due to a plus or minus 20% variation in dew point temperature was about 2.3%. The maximum change due to maximum temperature when varied 20% was 9%, albedo changes showed a negative slope and a maximum of 8% was achieved, percent sunshine showed an 11.5% and radiation showed a 30% change.

Saxton (1975) derived the sensitivity equation by differentiating the combination energy budget-aerodynamic evapotranspiration equation with respect to each variable. The sensitivity coefficients of these equations define the change in computed potential evapotranspiration due to a change in the variable. Daily sensitivity coefficients were determined by applying two years of data, March through November, obtained in western Iowa over corn and grass. The results showed computed evapotranspiration to be most sensitive to net radiation. He also found that during mid-year potential evapotranspiration values usually changed 50-90 % of any radiation change or error, whereas only 20-30 % of any change in pressure deficit or wind travel transfers to potential evapotranspiration value.

Table 2.1 Simple correlation coefficients of meteorological observations against evaporation from four instruments.

	Evaporimeter			
Meteorological factor	Black Bellani	Porous disk	Class A Pan	Buried tank
Daily total radiation	0.725	0.675	0.680	0.640
Mean daily temperature	0.739	0.664	0.744	0.686
Average daily vapour pressure deficit	0.751	0.659	0.692	0.676
Daily wind travel	0.138	0.177	0.280	0.296

Source: Pelton (1964)

Table 2.2a: Simple correlation coefficients between evaporimeters.

	Evaporimeters			
	Tank	Pan	Plate	Disk
Disk	0.77	0.83	0.86	1.00
Plate	0.83	0.91	1.00	
Pan	0.88	1.00		
Tank	1.00			

Source: Pelton (1964)

Table 2.2b: Simple correlation coeficients between meteorological variables.

	Meteorological variables			
	Wind	V.P.D	Rad	Temp
Temp	-0.108	0.763	0.459	1.000
Rad	-0.063	0.574	1.000	
V.P.D	-0.241	1.000		
Wind	1.000			

Source: Pelton (1964)

In the spring and fall months the aerodynamic portion of the equation played a larger role; thus the net radiation coefficients decreased and the aerodynamic variable coefficients increased. Furthermore, he found that the calculated potential evapotranspiration values were not largely sensitive to the wind profile parameters z_a, d and z_o. However experience has shown that large errors can occur in the measurement or prediction of these variables; thus their effect on the potential evapotranspiration can still be significant in many cases.

3. MATERIALS AND METHODS

3.1 Study sites

This study was conducted at Chitedze, Ngabu and Bvumbwe agricultural research stations located in three different agricultural development divisions. All the sites are full meteorological stations under the World Meteorological Organisation (WMO) classification and as such, the Meteorological Department abides by the standards and regulations of WMO in the installation of instruments and in taking readings (G.Munthali, personal communication, 1991). The sites are in different physiographical zones (Fig.3.1). Chitedze is at an altitude of 1149m above mean sea level (a.m.s.l.), Bvumbwe is at an altitude of 1146m a.m.s.l. and Ngabu is at an altitude of 107m a.m.s.l.

3.2 Measurement of pan evaporation, radiation, daily temperature and wind speed

3.2.1 Pan evaporation

Pan evaporation at all sites is measured by modified class A pans. The pans are made of galvanised iron 25.40 cm deep and
120.60 cm inside diameter.

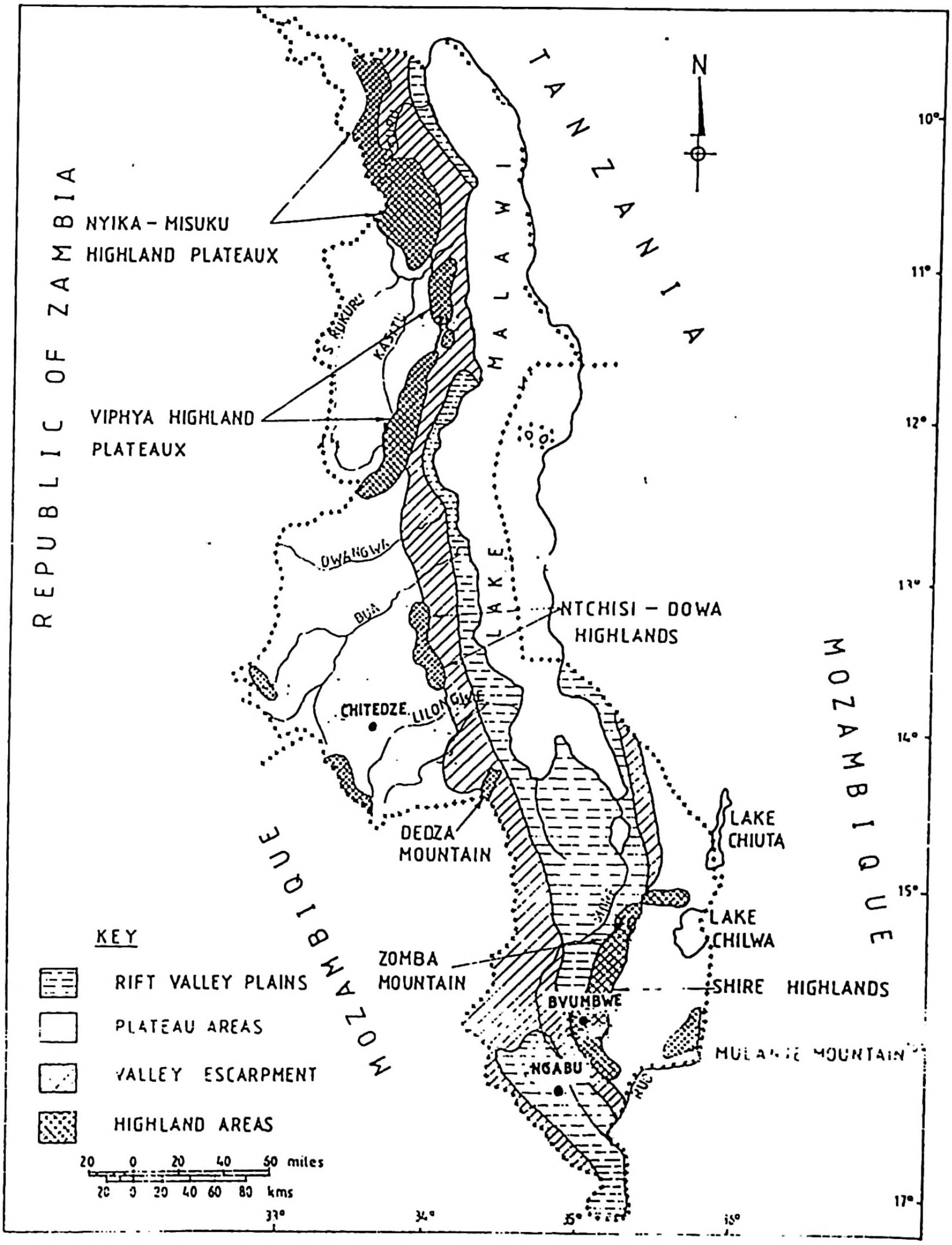

Fig.3.1 Physiographical Zones of Malawi.

They are coated with aluminum paint and mounted on wooden grating 15 cm above ground to allow air circulation underneath. Readings are taken using the hook gauge mounted in the stilling well. The depth of water needed to bring the water level to the gauge point is equivalent to the amount of water evaporated. Adjustments for rainfall if any is made appropriately.

3.2.2 Radiation

Gunn-Bellani radiation integrators are used at the sites to measure radiation. They consist of a blackened copper sphere filled with water or alcohol, into which a graduated tube protrudes. Falling short-wave radiation passes through the glass dome enclosing the sphere and is converted into heat upon interception by the sphere. The heat is used to evaporate the liquid inside the sphere and the vapour condenses at the lower cooler end of the graduated tube. The amount of the liquid condensed is proportional to short-wave radiation in langleys received on the sphere (Rijks, 1971).

3.2.3 Temperature

Temperature is measured with thermometers. All sites have ordinary mercury-in-glass thermometers for measuring maximum daily temperature and alcohol-in-glass thermometers for measuring minimum daily temperature. They are all kept in Stevenson screens to protect them from direct solar heating, precipitation and strong winds. Readings are recorded at appropriate intervals and compared with the thermograph readings. Temperature is measured in degrees celcius to the nearest 0.1°C.

3.2.4 Wind speed

Wind speed is measured with cup anemometers. They consist of a rotor and a signal generator. The cup is turned by the force of the wind passing by it and the resulting angular velocity is proportional to wind speed. Wind speed is measured at 2 m above ground in units of meters per second.

3.2.5 Other climatic variables measured

The other climatic variables measured are wet and dry bulb temperature, relative humidity, cloudness, sunshine hours and rainfall in units of degrees celcius, percent, octas, hours and millimeters respectively.

3.3 Data analysis

3.3.1 Parameter estimation

Four years of the most recent (1985-88) pan evaporation, radiation, wind speed and mean daily temperature and all data required for computation of evapotranspiration using the Penman method were collected, where available, from the historical records kept by the Meteorological Department. Five-day averages were computed for each variable and analyzed using the model developed by Stephen and Steward (1963) because it requires climatic variables most easily obtainable viz. mean daily temperature, wind and radiation. Estimated radiation using methods suggested by Jensen (1983) could be used where measured radiation is not available. The model has the advantage that it can be used where very little or no data are available and can thus be written as:

$$E_p = R_s (a+bT) + cW \qquad (3.1)$$

including the wind term, and

$$E_p = R_s (a+bT) \qquad (3.2)$$

excluding the wind term.

where E_p = pan evaporation (mm/day)

R_s = solar radiation (mm/day)

T = mean daily temperature (°C)

W = wind speed (km/day

a,b & c = fitting constants.

The solution of the equation was found by converting the model into a dimensionless equation by dividing it by radiation, R_s as follows:

$$E_p/R_s = a + bT + cW/R_s \tag{3.3}$$

including the wind term, and

$$E_p/R_s = a + bT \tag{3.4}$$

excluding the wind term

where E_p, R_s, T, W, a, b and c are as previously defined.

Multiple regression procedures incorporated in a statistical software package called MSTAT-C were used to solve for the fitting parameters a, b and c (Linacre, 1967; Jensen and Haise, 1963) and for completeness sake, the Simplex optimization procedure was also used to estimate the values of the parameters to facilitate comparison. Data for 1985 and 1986 for each station were used for model calibration and the remaining data were used for model validation. The data was further divided into dry and wet seasons. Data for wet season in 1985 was combined with that for 1986 and used as one input to calibrate the wet season models for each station. The same was done for dry season.

The demarcation between seasons was arbitrary but as a rule of thumb, six months of the least monthly total rainfall were regarded as dry season.

3.3.2 Sensitivity Analysis of Model Parameters.

Modelling process would be incomplete without a thorough sensitivity analysis to examine the effects of small changes in the parameter values on the model performance. Sensitivity analysis was carried out by perturbating one parameter while holding the other two parameters constant. If small perturbations of the parameter resulted in large changes in the model performance, then the system was considered sensitive to that parameter. This therefore gave a measure of how accurate that parameter must be estimated. Conversely, if the perturbated parameter did not create substantial change on the model performance, then the system was considered insensitive to that parameter and hence extremely accurate estimation of the parameter was considered unnecessary. In cases where the system is extremely insensitive to the perturbated parameter, the parameter and its associated system component are deemed redundant and dropped from the model. Thus sensitivity analysis not only provides measures of how accurate a model parameter must be estimated but also renders justification on the inclusion or non-inclusion of some of the model parameters or components (Wyseure, 1986).

3.3.3 Adequacy of the regression model and statistical inferences on model parameters.

The approach adopted is that of determining how much of the variability in the dependent variable is explained by the regression. The variability in the dependent variable is quantified as a sum of squares. The total sum of squares corrected for the mean is made up of two components, thus the residual sum of squares and the regression sum of squares. Details of the derivations of the necessary expressions representing the sums of squares are given in Haan (1977). The larger the regression sum of squares compared to the residual sum of squares, the more the total sum of squares corrected for the mean is explained by the regression equation. The ratio of the sum of squares due to regression to the total sum of squares corrected for the mean can be used as a measure of the ability of the regression model to explain variations in the dependent variable. This ratio is commonly noted as R^2 and is called the multiple coefficient of determination when more than one independent variable are involved and simply the coefficient of determination when only one independent variable is involved. Frequently the partitioning of the sum of squares is shown in form of an analysis of variance (ANOVA) table and will be so shown in this study.

After evaluating the model parameters, it becomes imperative to provide some statistical information regarding their reliability. The covariance matrix and correlation matrix of estimated parameters are usually helpful (Moussavi, 1988) and are used in this study to statistically evaluate the parameter estimators. The covariance matrix of the estimated parameters provides information regarding the reliability of the estimated parameters. A well estimated parameter is generally characterized by a small variance as compared to an insensitive parameter that is associated with a large variance. However the covariance matrix of the estimated parameter was part of the output of the statistical package used in this study.

Model parameter estimators tend to be negatively correlated if simultaneous increases (or decreases) of both parameters result in very similar effects on simulated output. If parameter changes have opposing effects on simulated output, then parameter estimators tend to be positively correlated (Moussavi, 1988). A correlation analysis of the estimated parameters would indicate the degree of interdependence among the parameters with respect to the objective function.

The confidence limits of parameter estimators were calculated using

$$\text{Upper limit} = bi + (t.\sqrt{COVA(i,i)}) \qquad (3.6)$$

$$\text{Lower limit} = bi - (t.\sqrt{COVA(i,i)}) \qquad (3.7)$$

where t = the t distribution score for corresponding probability and degree of freedom.

bi = the estimated parameter value i.

COVA(i,i) = the i,ith element of the covariance matrix of the estimated parameters.

3.3.4 Model validation

Apparently an important element of modelling, model validation involves the testing and evaluation of the performance of the calibrated model using a set of data other than those used in model identification and parameter estimation.

The model is considered to be conditionally acceptable if the results of the model on the independent set of test data prove to be acceptable for the intended purposes and within the desired accuracy. If this is not the case, the model parameters will need to be updated or the basic model structure will need to be modified all together.

Model validation should be a continuous process and is encouraged as additional information likely to affect the model performance becomes available.

3.3.5 Evaluation criteria of the results for the goodness of fit.

Besides visual displays such as graphs and scattergrams of observed and simulated evaporation, some of the statistical parameters discussed hereunder were used to objectively evaluate the goodness of fit of the simulation.

3.3.5.1 Sum of squared errors.

$$SSE = \sum_{i=1}^{n}(E_{oi} - E_{si})^2 \qquad (3.8)$$

where E_{oi} = observed evaporation in period i.

E_{si} = simulated evaporation in period i.

n = number of time periods being considered.

The lower the value of SSE, the lower is the magnitude of the simulation discrepancy and the better the fit. The standard error is obtained by dividing SSE by the degrees of freedom and taking the square root of the result.

3.3.5.2 Coefficient of Efficiency.

$$RE = \left\{\sum_{i=1}^{n}(E_{oi} - E_o)^2 - \sum_{i=1}^{n}(E_{oi} - E_{si})^2\right\} / \sum_{i=1}^{n}(E_{oi} - E_o)^2 \qquad (3.9)$$

where E_o is the mean of the observed pan evaporation values, and the other symbols are as previously defined.

The coefficient of efficiency indicates how much of the variance is explained by the model. This is sometimes referred to as the model explained variance. RE is analogous to the coefficient of determination, R^2 with a minor difference in the second term of the numerator. While the coefficient of determination is based on systematic error, the coefficient of efficiency is based on random error. That is, in the coefficient of efficiency, the error given by the second term of the numerator is reckoned from the simulated values instead of the regressed values (Ella,1988).

Another property of the coefficient of efficiency is that it gives an indication of the degree of performance of the model as compared to a "mean model" as can be seen in the numerator. For instance, if the simulated values equal the mean of the observed values, then RE becomes zero which indicates that the model performance is only as satisfactory as the performance of the "mean model" and therefore the model does not perform well (Ella,1988). In this study, R^2 was used as a measure of goodness of fit.

3.3.5.3 Correlation coefficient.

$$R = \left\{\sum_{i=1}^{n}(E_{oi} - E_o)(E_{si} - E_s) / n-1\right\} / (SD_o)(SD_s) \tag{3.10}$$

where SD_o and SD_s are the standard deviation of the observed and simulated pan evaporation respectively, E_s is the mean of the simulated values and E_{oi}, E_{si}, E_o and n are as previously defined.

The value of R varies from -1 to +1. A high degree of agreement in simulation is indicated by R of close to +1 which indicates a high degree of linear dependence between the observed and simulated evaporation treated as random variables.

3.3.5.4 Slope of the regression line relating observed and simulated values.

$$SLOPE = \{\sum_{i=1}^{n}(E_{si} - E_s)(E_{oi} - E_o)\} / \sum_{i=1}^{n}(E_{si} - E_s)^2 \qquad (3.11)$$

where all terms are as previously defined.

This formula is convenient for computational purposes (Haan,1977). The simulated values are considered to be lying on the horizontal axis and the observed values on the vertical axis.

Apparently, the value of the slope of the regression line between the observed and simulated values will be close to unity, i.e. the line will form a 45° angle with either axis if there is a high degree of agreement between the two variables. This parameter also gives an indication on which variable is more heavily weighted.

3.3.5.5 Mean and Standard Deviation of observed and Simulated Values.

$$E_o = \sum_{i=1}^{n} E_{oi}/n \qquad (3.12)$$

$$E_s = \sum_{i=1}^{n} E_{si}/n \tag{3.13}$$

$$SD_o = \surd\{\sum_{i=1}^{n}(E_{oi} - E_o)^2 \;/\; n\text{-}1\} \tag{3.14}$$

$$SD_s = \surd\{\sum_{i=1}^{n}(E_{si} - E_s)^2 \;/\; n\text{-}1\} \tag{3.15}$$

where all terms are as previously defined.

Similarity of the statistical distribution between the observed and simulated values where treated as random variables can be checked by comparison between the mean and standard deviation of the two series. All the above statistical measures provide a basis for good scientific judgement and evaluation of the model performance at calibration or validation stage. Irrespective of the number of statistical parameters used, it is imperative to note that attention should not be directed at only one measure of goodness of fit since while this parameter could indicate an unsatisfactory model performance, other parameters, could on the contrary show highly acceptable performance and vice versa. Thus, the various statistical measures should be taken collectively to provide an overall basis for objective evaluation of the model performance (Wyseure, 1986).

3.3.6 Influence of radiation, mean daily temperature and wind speed on pan evaporation.

Partial differentiation techniques were employed on each of the models to determine the relative influence of each of the variables in determining pan evaporation, by considering the change in E_p brought by allowing small changes in R_s and T.
If δE_p is the change in E_p due to changes δR_s and δT in R_s and T, and letting dE_p/dR_s represent a partial differentiation of $E_p(R_s,T)$ with respect to R_s, then

$$\delta E_p \approx dE_p(R_s,T)\delta R_s/dR_s + dE_p(R_s,T)\delta T/dT \qquad (3.16)$$

The first term in (3.16) represents the change in $E_p(R_s,T)$ due to a change δR_s in R_s keeping T constant. Similarly the second term is the change in $E_p(R_s,T)$ due to a change δT in T keeping R_s constant. The sum of the two effects is the total differential (Stephenson,1983).

In the case of this study with three variables R_s, T and W a differential of the form:

$$\delta E_p \approx dE_p \delta R_s / dR_s + dE_p \delta T / dT + dE_p \delta W / dW \qquad (3.17)$$

was used to determine the effect on E_p of a change in anyone of the three independent variables keeping the other two constant.

Five-day averages of each of the three variables including pan evaporation were computed for the two year period used in building the model. The mean values of radiation, mean daily temperature and wind speed were used to compute the mean value of pan evaporation using the resulting models. Variations of plus or minus 20% were made about the mean value of the data used in calibrating the model to determine the relative influence of each of the climatic variables on pan evaporation.

3.3.7 Estimation of missing pan evaporation data.

Baier and Robertson (1965) reported that the evaporation models can be used to estimate pan evaporation data and test their reliability. By assuming that the 1988 pan evaporation data for Ngabu and Bvumbwe were missing, the ability of the models to estimate missing data was tried by computing pan evaporation from the recorded climatic data. Since data to facilitate comparison for Chitedze was missing the station was not included in this analysis. Statistical methods outlined in Section 3.3.5 were employed to evaluate the closeness with which the models estimate the observed pan evaporation. Trend graphs were used to compare the similarity of the two data series.

3.3.8 Evaluation of the use of radiation Computed from Smithsonian tables on pan evaporation.

Using estimated radiation from the method suggested by Jensen (1983) and obtained from the software package INSTAT for 1986 for Chitedze and Ngabu models (3.1) and (3.2) were fitted. The 1987 evaporation data simulated by this method using computed radiation were correlated with measured pan evaporation data and compared. This analysis was confined to Chitedze and Ngabu due to some data input constraints into the software package INSTAT which made it difficult to compute shortwave solar radiation as well as the reference evapotranspiration for Bvumbwe.

3.3.9 Comparison of reference evapotranspiration with evaporation computed from models using tabulated radiation.

To evaluate the use of models developed from tabulated radiation for localities without adequate meteorological data for the computation of evapotranspiration, reference evapotranspiration was computed using the software INSTAT which employs the modified Penman model as suggested by Doorenbos and Pruit (1977).

Evaporation simulated in section 3.3.8 for 1987 from models developed from tabulated solar radiation was compared with reference evapotranspiration. Appropriate goodness of fit techniques suggested in section 3.3.5 were employed to evaluate the performance of the models. Scattergrams relating simulated evaporation and evapotranspiration were also drawn to show how well simulated evaporation fits reference evapotranspiration to be able to predict ET_o. Because some of the variables for computing ET_o for Bvumbwe were not available the station could not be used in this analysis.

4. RESULTS AND DISCUSSION

4.1 Evaluation of the Location Specific Models

Table 4.1 and 4.2 show the multiple regression models which resulted from relating the ratio between observed pan evaporation and shortwave solar radiation (E_p/R_s) to mean daily temperature (T) and the ratio between wind speed and shortwave solar radiation (W/R_s). Both the dry and wet season models showed a high correlation of $R = 0.909$ and $R = 0.814$ at $P < 0.001$ respectively between the E_p/R_s ratio and the temperature term and the W/R_s term. Chitedze also showed a similar pattern except that the parameters were less highly correlated with the E_p/R_s ratio at $P < 0.001$. On the other hand, the correlation between model parameters and the E_p/R_s ratio during the wet season at Bvumbwe was much less than for the other stations. The dry season model parameters correlated well with the E_p/R_s ratio $R=0.63$ at $p<0.001$. These results agree with the findings of Linacre (1967) who got correlation coefficients of above 0.8.

The terms included in the dimensionless equations accounted for 65% and 50% of the variations in the E_p/R_s ratio for Ngabu and Chitedze respectively during the wet season. During the dry season, the terms accounted for over 80% of the variation in the E_p/R_s ratio for both Ngabu and Chitedze. For Bvumbwe the terms accounted for only 4.8% of the variations in E_p/R_s ratio during the wet season and 37.9% during the dry season (Tables 4.1 and 4.2).

Table 4.1: Regression models including the wind term.

Location	Season	Model	R^2	R
Ngabu	Wet	$E_p=R_s(-1.346+0.0647T)+0.01664W$	0.654	0.814
	Dry	$E_p=R_s(-0.641+0.04434T)+0.01587W$	0.821	0.909
Chitedze	Wet	$E_p=R_s(-1.193+0.06616T)+0.0153W$	0.503	0.719
	Dry	$E_p=R_s(-0.236+0.03152T)+0.01337W$	0.627	0.798
Bvumbwe	Wet	$E_p=R_s(-0.021+0.01847T)+0.00305W$	0.048	0.273
	Dry	$E_p=R_s(-0.078+0.02700T)+0.00259W$	0.379	0.630

Table 4.2: Regression models excluding the wind term.

Location	Season	Model	E_p/R_s	R^2	R
Ngabu	Wet	$E_p=R_s(-1.229+0.07201T)$	0.773	0.389	0.630
	Dry	$E_p=R_s(-1.264+0.08617T)$	0.806	0.634	0.799
Chitedze	Wet	$E_p=R_s(-0.375+0.04129T)$	0.533	0.128	0.375
	Dry	$E_p=R_s(0.070+0.03067T)$	0.636	0.275	0.534
Bvumbwe	Wet	$E_p=R_s(0.235+0.00984T)$	0.442	0.006	0.140
	Dry	$E_p=R_s(0.003+0.02651)$	0.473	0.348	0.598

This indicates that a substantial variation in E_p/R_s is accounted for by factors not included in the models for Bvumbwe. There was a general reduction on both the coefficient of determination and the correlation coefficients between the model parameters and the E_p/R_s ratio at all stations when the wind term was excluded from the models (Table 4.2).

Table 4.2 shows the E_p/R_s values for the data used in building the models. The ratios ranged between a high of 0.806 and the low value of 0.442. Again the results agree well with the results obtained by Jensen and Haise (1963) who for potential evapotranspiration suggested values within the range of 0.55 to 0.60 for the upper limit for areas where additional heat may be received from the air and cause the advection of energy to occur. Since potential evapotranspiration is generally lower than open water evaporation, the results obtained here are considered to be within limits of those obtained by Jensen and Haise (1963).

4.1.1 Results of the sensitivity analysis of parameters.

Fig. D1 to Fig. D6 in Appendix D show plots of the results of the sensitivity analyses performed on the parameters used in the models. Overall parameter b is the most sensitive of all. This is revealed by the gradient of the lines repesenting the parameter. For every small change in the parameter there is a relatively larger change in the objective function. All parameters are symmetrically sensitive, that is, the effect on the objective function is the same on each side of the optimum

(Wyseure,1986). Parameter a is the second most sensitive. However parameter c appears more sensitive than parameter a for Chitedze dry season model. The results indicate that parameter c can safely be dropped from the models without seriously affecting their performance.

The optimized and the regressed values of parameters a, b and c are shown in Appendix B. The parameters are all within the limits of the 95% confidence intervals indicating that the optimized parameters are close to the regressed values and in fact not significantly different from them at p=5%

4.2 The influence of radiation, mean daily temperature and wind speed on pan evaporation.

4.2.1 Influence of Radiation on pan Evaporation.

As indicated in the Tables 4.4 to 4.9 the linear correlations between radiation and pan evaporation were generally high for all stations for both the wet and dry seasons. Radiation appears to influence pan evaporation more at Chitedze and Bvumbwe during the wet season than at Ngabu. The correlation between radiation and pan evaporation was best at Bvumbwe than at the other two stations. Coincidentally, Bvumbwe also had the highest mean daily radiation of 8.1 mm/day compared with the other stations (Table 4.3). Chitedze pan evaporation correlated better with radiation and the mean daily radiation of 7.9 mm/day was also higher than 7.6 mm/day for Ngabu. Since solar radiation is the major supplier of energy for evaporation, it is expected to correlate well with the amount of water expected to evaporate if all other factors affecting evaporation remain constant. Radiation correlated better with pan evaporation during the wet season than during the dry season at all the three stations. The results are supported by the findings of Pelton (1964) at Shift Current who found a correlation coefficient of 0.680 between daily total radiation and pan evaporation from a United States Weather Bureau (USWB) class A pan.

Baier and Robertson (1965) also found a similar result in Canada and this read them to conclude that on average over all stations and years used in their study, variations in solar energy alone accounted for 50% of the variations in latent evaporation. The results of the analysis outlined in section 3.3.6 show that a 20% change in solar radiation resulted in a 9.1% change in evaporation for Ngabu wet season model, a 4.5% change in evaporation for Chitedze wet season and a 7.3% change for Bvumbwe wet season models. The 20% change in solar radiation resulted in 8.5% change in evaporation for Ngabu dry season model, slightly less than the wet season. Chitedze and Bvumbwe dry season models showed increases of 2.4% and 0.8% respectively, in the change in evaporation induced by a 20% change in solar radiation over their wet season counterpart models. The

Table 4.3: **Mean values of data used in developing the regression models.**

Location	Season	Daily Evaporation (mm/day)	Mean daily Radiation (mm/day)	Mean Daily Temperature (oC)	Mean Daily Wind Speed (km/day
Ngabu	Wet	6.3	8.0	27.8	153.0
	Dry	5.8	7.1	24.0	172.2
Average		6.1	7.6	25.9	162.6
Chitedze	Wet	4.1	7.7	22.0	130.5
	Dry	5.2	8.1	18.4	172.5
Average		4.7	7.9	20.2	151.5
Bvumbwe	Wet	3.6	8.2	21.0	189.0
	Dry	3.8	8.0	17.8	217.2
Average		3.7	8.1	19.4	203.1

The results agree with those obtained by Saxton(1975) on the combination evapotranspiration model. Merva and Fernandez (1985) found that a 20% change in radiation caused a 30% change in evapotranspiration on the Penman equation. Details of the computations of this analysis are given in Appendix C.

4.2.2 Influence of mean daily temperature on pan evaporation.

The simple linear correlation coefficients between mean daily temperature and pan evaporation are shown in Tables 4.4 to 4.9. The correlations were all significant at $p<0.001$. The mean daily temperature and pan evaporation correlated better for Ngabu than for Chitedze and Bvumbwe for both the wet and dry season. At all stations mean daily temperature correlated better with pan evaporation during the dry season than during the wet season. This may be because humidity which tends to retard evaporation is higher during the wet season. Ngabu evaporation showed a better correlation with mean daily temperature than evaporation at Chitedze and Bvumbwe. Ngabu also had the highest mean daily temperature of 25.9°C compared to 20.2°C and 19.4°C for Chitedze and Bvumbwe respectively. Again as expected Chitedze evaporation correlated better with mean daily temperature than Bvumbwe since if all other climatic factors affecting or influencing evaporation remain constant, an increase in mean daily temperature would result in an increase in the amount of water evaporated (Abdulmunin et al., 1990). Wet season evaporation at Ngabu and Chitedze appear to be more sensitive to mean daily temperature than to the other variables. A 20% change in mean daily temperature induced a 10.4% change in evaporation at Ngabu and a 10.2% change at Chitedze. In comparison, temperature had the least effect at Bvumbwe during both the dry and wet season because a 20% change in mean daily temperature caused only 3.0% and 4.3% change in evaporation during the wet and dry season respectively. Evaporation appears to be more sensitive to temperature at Bvumbwe during the dry season than during the wet season. During the dry season solar radiation appears to be more influencial in inducing evaporation than temperature.

4.2.3 Influence of wind speed on pan evaporation.

Simple linear correlations between wind speed and pan evaporation was good for all stations as can be seen from the Tables 4.4 to 4.9. The correlation coefficient was highest for Ngabu dry season evaporation ($r = 0.88$) than for the other stations. Ngabu evaporation also showed a higher correlation than the other stations during the wet season ($r = 0.689$). The wet season pan evaporation at Chitedze correlated better with wind speed than did the dry season evaporation although the difference was for all practical purposes insignificant. There was reasonably low correlation between wind speed and dry season pan evaporation at Bvumbwe. Wet season evaporation practically showed a low correlation with wind speed. These results bring out the conclusions found by other researchers such as Pelton (1964) who found that pan evaporation and wind speed had a correlation of $r = 0.280$ (Table 2.1). The findings of Saxton (1975) and Merva and Fernandez (1985) that wind speed has a relatively lesser influence on the amount of water evaporated supports the results of this research. Table 4.3 shows that Bvumbwe had the highest daily mean wind speed and yet the smallest amount of evaporation of the three stations. Further examination of the table indicates that Bvumbwe also had the highest values of radiation and wind speed but the least mean daily temperature. Chitedze had the least wind speed but had the second highest values of mean daily radiation and mean daily temperature. Ngabu had the highest mean daily temperature value but the least radiation value and the second largest mean daily wind speed. Pan evaporation was however highest at Ngabu seconded by Chitedze and Bvumbwe which had the least of the three. Wind speed appears to be the least influencial of the other variables. A 20% change in wind speed caused only about 0.3% change in evaporation at Ngabu and Chitedze, and slightly less than 0.1% change in evaporation at Bvumbwe. These results are in agreement with those of Saxton (1975) and Merva and Fernandez (1985) who found wind to be the least influencial. The results also agree with those of the sensitivity analysis discussed above.

Table 4.4: Simple correlation coefficients for Ngabu wet season model.

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.689	1.000		
Mean daily temperature	0.744	0.398	1.000	
Solar radiation	0.692	0.317	0.611	1.000

Table 4.5: Simple correlation coefficients for the Ngabu dry season model

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.875	1.000		
Mean daily temperature	0.828	0.758	1.000	
Solar radiation	0.591	0.418	0.541	1.000

Table 4.6: Simple correlation coefficients for Chitedze wet season model.

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.601	1.000		
Mean daily temperature	0.665	0.153	1.000	
Solar radiation	0.724	0.209	0.594	1.000

Table 4.7: Simple correlation coefficients for Chitedze dry season model.

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.589	1.000		
Mean daily temperature	0.729	0.301	1.000	
Solar radiation	0.635	0.005	0.624	1.000

Table 4.8: Simple correlation coefficients for Bvumbwe wet season model.

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.027	1.000		
Mean daily temperature	0.489	-0.187	1.000	
Solar radiation	0.757	-0.220	0.507	1.000

Table 4.9: Simple correlation coefficients for Bvumbwe dry season model.

	Pan evaporation	Wind speed	Mean daily temperature	Solar radiation
Pan evaporation	1.000			
Wind speed	0.416	1.000		
Mean daily temperature	0.671	0.377	1.000	
Solar radiation	0.699	0.047	0.434	1.000

4.2.4 Correlation amongst climatic variables.

Simple linear correlation between mean daily temperature and solar radiation was quite good for all stations. This was expected since solar radiation is the source of heat energy received by the earth's surface and the energy directly influences temperature. Wind speed and mean daily temperature correlated well (r = 0.758) at Ngabu and not surprisingly, wind speed also correlated well with solar radiation since solar radiation greatly influences temperature. This result agrees with the results Pelton (1964) got at Swift Current Canada. He found that temperature and radiation had a correlation of r = 0.459. However, Pelton (1964) found a negative correlation of r = -0.063 between wind speed and radiation. There was some correlation between wind speed and mean daily temperature and also between wind speed and radiation although not much at various probability levels (Tables 4.4 to

4.9). The correlation between wind speed and mean daily temperature and wind speed and solar radiation was negative for Bvumbwe during the wet season.

4.3 Validation of the location specific models.

4.3.1 Models that included the Wind term.

Table 4.10 shows observed pan evaporation and evaporation computed using each of the prediction models shown in Table 4.1. For the periods used, the models for Ngabu and Chitedze overestimated evaporation by 7.8% and 3.8% respectively, during the wet season, while that at Bvumbwe underestimated evaporation by 8.3%. The dry season models appeared to be more accurate in estimating evaporation at all the sites because a larger proportion of the variance is explained by the models during the dry season than during the wet season. Inaccuracy in correcting evaporation for the added rainfall is usually the cause of this. The Bvumbwe dry season model underestimated evaporation by 2.4% while the Ngabu and Chitedze models underestimated it by 1.3% and 1.2% respectively. Overall all the models estimated observed pan evaporation to within 5%

4.3.2 Models that exclude the wind term.

Table 4.11 shows observed pan evaporation and evaporation computed using models that excluded the wind term (Table 4.2). For the periods used, the wet season model for Ngabu and the dry season model for Chitedze very closely approximated the observed pan evaporation to within 0.2% and 0.3% respectively. The dry season model for Bvumbwe estimated evaporation to within 2.5% of the observed pan evaporation. However the dry season model for Ngabu and the wet season models for Bvumbwe and Chitedze estimated pan evaporation to within 10.5%, 8.6% and 8.3% respectively. Overall all the models estimated evaporation to within 5% of the observed pan evaporation.

4.3.3 The effect of wind speed on evaporation at each station.

Table 4.12 summarizes estimated evaporation using models with and without the wind term. Wind appears to contribute 8.1% of evaporation at Ngabu when the wet and dry season evaporation are considered together. Surprisingly wind speed appears to have a negative effect on evaporation at Chitedze in that evaporation increased when the wind term was excluded. This effect appears to be more pronounced during the wet season when evaporation increased by 4.4% than during the dry season when it increased by 0.9% . One most likely reason for this is that there might be some anomalies within the data set chosen. The dry season evaporation for Bvumbwe appeared to be independent of the wind speed. Wind contributed virtually nothing. Similar behaviour was observed for Bvumbwe evaporation during the wet season when wind only contributed 0.3% of the evaporation. Saxton (1975) performed a sensitivity analysis to study the effect of wind speed on evaporation. He found that a 20% change in wind speed caused only 2.5% change in evaporation.

The above results agree well with these findings. Many researchers (e.g.Hanson, 1989; Linacre,1967) have reported that wind speed can be safely ignored in modelling evaporation without causing serious errors in the results.

4.4 Capability of each model to estimate missing pan evaporation data.

4.4.1 Models which include the wind speed term.

Table 4.13 shows simple linear regression equations relating observed pan evaporation and evaporation computed using the models shown in Tables 4.1. As shown in Table 4.13, the correlation coefficients between observed pan evaporation and computed evaporation are high for all the equations at $p<0.001$. Figure E1 to E8 in Appendix E show cumulative evaporation plotted against the 5-day periods used in each case and a period to period trend in evaporation. Computed evaporation and evaporation estimated from models in Table 4.1 and regression equations shown in Table 4.13 appear to closely follow the observed evaporation.

Table 4.10: Comparison of observed pan evaporation with evaporation computed by the models which include the wind term.

Location	Season	Dates	Periods	Observed	Computed	Difference	%
Ngabu	Wet	28/10/87-29/4/88a	31	1127.6	1215.5	-87.9	-7.8
	Dry	21/5/87-27/10/88c	31	1101.7	1087.9	13.0	1.3
Totals			62	2229.3	2303.4	-74.1	-3.3
Chitedze	Wet	2/11/87-4/5/88a	36	879.1	912.6	-33.5	-3.8
	Dry	1/5/87-27/10/87	36	802.3	792.7	9.6	1.2
Totals			72	1681.4	1705.3	-23.9	-1.4
Bvumbwe	Wet	28/10/87-4/4/88a	31	703.7	645.1	58.6	8.3
	Dry	16/5/87-27/10/87b	31	667.9	651.6	16.3	2.4
Totals			62	1371.6	1296.7	74.9	5.5

Note: a = excluding one 5-day period of missing data.
b = excluding two 5-day periods of missing data.
c = excluding six 5-day periods of missing data.
The negative sign represents an overestimation.

Table 4.11: Comparison of observed pan evaporation with evaporation computed by the models which exclude the wind term.

Location	Season	Dates	Periods	Observed	Computed	Difference	%
Ngabu	Dry	21/5/87-27/10/87c	31	1101.7	986.1	115.6	10.5
	Wet	28/10/87-29/4/88a	31	1127.6	1129.9	-2.3	-0.2
Totals			62	2229.3	2116.0	113.3	5.1
Chitedze	Dry	1/5/87-27/10/87	36	802.3	799.7	2.6	0.3
	Wet	2/11/87-4/5/88a	36	879.1	952.4	-73.3	-8.3
Totals			72	1681.4	1752.1	-70.7	-4.2
Bvumbwe	Dry	16/5/87-27/10/87b	31	667.9	651.3	16.6	2.5
	Wet	28/10/87-4/4/88a	31	703.7	643.4	60.3	8.6
Totals			62	1371.6	1294.7	76.9	5.6

Note: a = excluding one 5-day period of missing data.
b = excluding two 5-day periods of missing data.
c = excluding six 5-day periods of missing data.
The negative sign represents an overestimation.

Table 4.12: **Comparison of evaporation computed from models which include the wind term and those that exclude the wind term.**

Location	Season	Dates	Periods	Evaporation with wind	Evaporation without wind	Difference	%
Ngabu	Dry	21/5/87-27/10/87c	31	1087.9	986.1	101.8	9.4
	Wet	28/10/87-29/4/88a	31	1215.5	1129.9	85.6	7.0
Totals			62	2303.4	2116.0	187.4	8.1
Chitedze	Dry	1/5/87-27/10/87	36	792.7	799.7	-7.0	-0.9
	Wet	28/10/87-4/5/88a	36	912.6	952.4	-39.8	-4.4
Totals			72	1705.3	1752.1	-46.8	-2.7
Bvumbwe	Dry	16/5/87-27/10/87b	31	651.6	651.3	0.3	0
	Wet	28/10/87-4/4/88a	31	645.1	643.4	1.7	0.3
Totals			62	1296.7	1294.7	2.0	0.2

Note: a = excluding one 5-day period of missing data.
b = excluding two 5-day periods of missing data.
c = excluding six 5-day periods of missing data.
The negative sign represents an overestimation.

4.4.2 Models which exclude the wind term.

Table 4.14 shows simple linear regression equations relating observed pan evaporation and evaporation computed from models that exclude the wind term shown in Table 4.2. Again as in section 4.4.1, the observed pan evaporation is highly correlated with computed evaporation only to a lesser degree. The graphs shown in Appendix E appear to show a trend similarity between observed pan evaporation and evaporation computed from the models in Table 4.2.

4.5 Use of radiation data from tables in determining pan evaporation.

Tables 4.15 and 4.16 show regression models developed from shortwave solar radiation computed using the method suggested by Jensen and Haise (1963) and incorporated in the computer software package INSTAT for calculating potential evapotranspiration. The variables included in determining the ratio E_p/R_s were all highly significant at less than 1% probability level. The variables accounted for 82.1% of the variations in E_p/R_s for Ngabu dry season model and 67.4% for the Ngabu wet season model. The Ngabu dry season model was a bit more superior in terms of the multiple correlation and the coefficient of determination. Chitedze wet season model appeared to be just slightly superior in that the variables included in the models accounted for 68.4% of the variability in the E_p/R_s ratio while the dry season model accounted for 63.2%.

Table 4.13: Regression equations relating observed pan evaporation with evaporation computed from models which include the wind term.

Location	Season	Equation	R
Ngabu	Dry	E_p=0.474+0.945Ec	0.962
	Wet	E_p=0.270+0.893E_c	0.965
Chitedze	Dry	E_p=-0.545+1.136E_c	0.916
	Wet	E_p=-0.511+1.064E_c	0.924
Bvumbwe	Dry	E_p=-0.248+1.084E_c	0.915
	Wet	E_p=-3.339+1.893E_c	0.899

Table 4.14: Regression equations relating observed pan evaporation with evaporation computed from models which exclude the wind term.

Location	Season	Equation	R
Ngabu	Dry '	$E_p=0.778+0.995E_c$	0.972
	Wet	$E_p=-2.132+1.291E_c$	0.831
Chitedze	Dry	$E_p=-0.932+1.213E_c$	0.814
	Wet	$E_p=0.022+0.919E_c$	0.867
Bvumbwe	Dry	$E_p=-0.100+1.049E_c$	0.907
	Wet	$E_p=-3.152+1.853E_c$	0.832

The multiple correlation coefficient for the wet season model was as expected higher at $R = 0.839$ while the dry season model had a multiple correlation coefficient of $R = 0.812$. The variables included were however all highly significant at $p<0.001$.

4.5.1 Comparison between models developed from measured radiation and computed radiation.

Models for Ngabu developed using measured radiation and computed radiation shown in Tables 4.1 and 4.15 appear to be very similar as far as the coefficient of determination and the multiple regression coefficients are concerned. Table 4.17 also appears to confirm this close similarity in that on average the evaporation computed by the models estimates the observed pan evaporation to within less than 2%. Models for Chitedze developed by the two methods appear different in that R^2 =

0.684 for the wet season model developed from computed radiation while R^2 = 0.503 for that developed from

measured radiation. The dry season models appear more similar. However on average close similarity was observed between the estimation capacity of the two models. Both estimated observed pan evaporation to within less than 2% for the data set used.

4.6 Comparison of evaporation computed by the models with reference evapotranspiration.

Tables 4.18 and 4.19 and Fig F1 to F8 in Appendix F show the relationship between evaporation computed from models developed using estimated radiation and reference evapotranspiration calculated using the modified Penman model as given by Doorenbos and Pruilt (1977).

Table 4.15: Regression Models developed from computed shortwave solar radiation including the wind term.

Location	Season	Model	R2	R
Ngabu	Wet	$E_p = R_s\,(-1.931+0.09359T)+0.01246W$	0.674	0.836
	Dry	$E_p = R_s\,(-0.413+0.03890T)+0.01622W$	0.821	0.912
Chitedze	Wet	$E_p = R_s\,(-1.174+0.07547T)+0.01027W$	0.684	0.839
	Dry	$E_p = R_s\,(0.166+0.02614T)+0.00804W$	0.632	0.812

Table 4.16: Regression Models developed from computed shortwave solar radiation excluding the wind term.

Location	Season	Model	R^2	R
Ngabu	Wet	$E_p = R_s\,(-1.863+0.10124T)$	0.493	0.715
	Dry	$E_p = R_s\,(-0.658+0.07067T)$	0.478	0.703
Chitedze	Wet	$E_p = R_s\,(-1.751+0.06814T)$	0.325	0.588
	Dry	$E_p = R_s\,(0.453+0.02420T)$	0.334	0.599

Table 4.17 Comparison of evaporation estimated using computed solar radiation (E_{cr}) with that using measured solar radiation (E_{mr}) against observed pan evaporation (E_p).

Site	Season	Dates	Periods	E_{cr}	Y%*	E_{mr}	Z%*	E_p
Ngabu	Wet	1/1/87-30/4/87a 28/10/87-31/12/87a	31	1309.1	-5.8	1282.6	-3.7	1236.9
	Dry	1/5/87-27/10/87b	34	1134.9	3.1	1151.4	1.7	1171.5
Totals			65	2444.0	-1.5	2434.0	-1.1	2408.4
Chitedze	Wet	1/1/87-30/4/87a 28/10/87-31/12/87a	31	742.6	3.0	719.7	6.0	765.4
	Dry	1/5/87-27/10/87	36	931.5	-6.0	912.6	-3.8	879.1
Totals			67	1674.1	-1.8	1632.3	0.7	1644.5

Note: a = excluding six 5-day periods.
b = excluding two 5-day periods.
The negative sign signifies an overestimation.
*$Y = (E_p - E_{cr})/E_p$
*$Z = (E_p - E_{cr})/E_p$

All the relationships show very high simple correlation coefficients between ET_0 and E_{cr}. The correlation coefficients appear higher for evaporation which include the wind contribution (Table 4.18) than the evaporation which exclude it (Table 4.19). This shows that evaporation which includes the wind term better represents ET_0 than evaporation which excludes the wind term.

Table 4.18 **Regression equations relating reference evapotranspiration with evaporation from computed solar radiation including wind speed.**

Location	Season	Equation	R
Ngabu	Wet	$ET_o = 0.871 + 0.628\ E_{cr}$	0.980
	Dry	$ET_o = 0.182 + 0.726\ E_{cr}$	0.981
Chitedze	Wet	$ET_o = 0.929 + 0.678\ E_{cr}$	0.974
	Dry	$ET_o = -1.661 + 0.997E_{cr}$	0.975

Table 4.19 **Regression equations relating reference evapotranspiration with evaporation from computed solar radiation excluding wind speed.**

Location	Season	Equation	R
Ngabu	Wet	$ET_o = 0.967 + 0.903\ E_{cr}$	0.899
	Dry	$ET_o = 1.056 + 0.910\ E_{cr}$	0.942
Chitedze	Wet	$ET_o = 0.018 + 0.808\ E_{cr}$	0.947
	Dry	$ET_o = -2.279 + 1.078\ E_{cr}$	0.902

5. CONCLUSIONS AND RECOMMENDATIONS.

This study was aimed at examining the problem of missing evaporation data within the observed pan evaporation data set important in many design applications. This involved calibrating pan evaporation models developed for climatic regions different from climatic conditions existing in Malawi and using the models in estimating pan evaporation.

Measured as well as tabulated data were used in this exercise to examine the possibility of extending the application to areas without adequate climatic data. Bvumbwe, Chitedze and Ngabu were used because the stations are in different climatic conditions within Malawi.

The study indicates that the models are adequate and can be applied for Malawi climatic conditions and therefore used to estimate pan evaporation. This would alleviate the problem of missing data at the three stations. Furthermore, the models could be used to simulate longer data series normally required for reservior designs and other applications. The models estimated pan evaporation to within 5% of the observed values. This is considered accurate enough for most design applications and other studies. Models calibrated using tabulated shortwave solar radiation data appeared to be more accurate in estimating observed pan evaporation and were also better correlated.

Wind speed was shown to contribute very little in terms of total evaporation amount, however the addition of the wind term improved the correlation between observed and estimated evaporation, thereby improving the reliability with which evaporation can be estimated.

In view of the above findings the following recommendations can be made:

1. Similar models should be developed for other stations to check the reliability of the readings recorded by observers and also to complete missing pan evaporation data during periods when evaporation pans are maintained, obervers go on leave or when pans overflow during rain storms.

2. The wet season model for Bvumbwe needs to be used with caution. Another data sample could be selected to see if the model could be improved as far as the coefficient of determinatin is concerned. As discussed in the study the Bvumbwe models give a better overall estimate of observed pan evaporation for the data set used.

3. Further studies are also recommended to determine why wind speed has a negative effect on pan evaporation at Chitedze.

4. As in the case of streamflow gauging, the models developed for each

station could be used to characterise and rate evaporation at each station. Variations in trend could be monitored periodically and adjustments or reviev of rating made in case of a shift in trend.

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APPENDICES.

APPENDIX A.

Table A1: Analysis of variance for Ngabu wet season model which include the wind term.

	SS	df	MS	F	Sign.
Regression	1.701257	2	0.85063	67.97	0.000
Residual	0.863499	69	0.01251		
Total	2.564756	71			

Table A2: Analysis of variance for Ngabu wet seaon model excluding the wind term.

	SS	df	MS	F	Signif.
Regression	1.018655	1	1.01865	46.12	0.000
Residual	1.546101	70	0.02209		
Total	2.564756	71			

Table A3: **Analysis of variance for Ngabu dry season model which include the wind term.**

	SS	df	MS	F	Signif.
Regression	5.372218	2	2.68611	163.43	0.000
Residual	1.134092	69	0.01644		
Total	6.506309	71			

Table A4: **Analysis of variance for Ngabu dry season model excluding the wind term.**

	SS	df	MS	F	Signif.
Regression	4.158198	1	4.15820	123.96	0.000
Residual	2.348111	70	0.03354		
Total	6.506309	71			

Table A5: **Analysis of variance for Bvumbwe wet season model which include the wind term.**

	SS	df	MS	F	Signif.
Regression	0.056792	2	0.02840	2.78	0.069
Residual	0.704639	69	0.01021		
Total	0.761431	71			

Table A6: **Analysis of variance for Bvumbwe wet season model excluding the wind term.**

	SS	df	MS	F	Signif.
Regression	0.014990	1	0.01499	1.41	0.240
Residual	0.746441	70	0.01066		
Total	0.761431	71			

Table A7: **Analysis of variance for Bvumbwe dry season model which include the wind term.**

	SS	df	MS	F	Signif.
Regression	0.307303	2	0.15365	22.67	0.000
Residual	0.467576	69	0.00678		
Total	0.774879	71			

Table A8: **Analysis of variance for Bvumbwe dry season model excluding the wind term.**

	SS	df	MS	F	Signif.
Regression	0.276775	1	0.27678	38.90	0.000
Residual	0.498103	70	0.00712		
Total	0.774879	71			

Table A9: **Analysis of variance for Chitedze wet season model which include the wind term.**

	SS	df	MS	F	Signif.
Regression	0.751982	2	0.37599	36.94	0.000
Residual	0.702243	69	0.01018		
Total	1.454225	71			

Table A10: **Analysis of variance for Chitedze wet season model excluding the wind term.**

	SS	df	MS	F	Signif.
Regression	0.204200	1	0.20420	11.43	0.001
Residual	1.250025	70	0.01786		
Total	1.454225	71			

Table A11: Analysis of variance for Chitedze dry season model which include the wind term.

	SS	df	MS	F	Signif.
Regression	0.942600	2	0.47130	60.58	0.000
Residual	0.536801	69	0.00778		
Total	1.479401	71			

Table A12: Analysis of variance for Chitedze dry season model excluding the wind term.

	SS	df	MS	F	Signif.
Regression	0.422602	1	0.42260	27.99	0.000
Residual	1.056799	70	0.01510		
Total	1.479401	71			

Appendix B:

Table B1: A 95% confidence interval for parameter a.

Station	Season	Regressed parameter	Optimized parameter	Lower limit	Upper limit
Ngabu	Wet	-1.346	-1.376	-1.792	-0.900
	Dry	-0.641	-0.554	-0.940	-0.342
Chitedze	Wet	-1.193	-1.453	-1.657	-0.729
	Dry	-0.236	-0.267	-0.407	-0.065
Bvumbwe	Wet	-0.021	-0.160	-0.445	0.403
	Dry	-0.078	-0.086	-0.244	0.088

Table B2: A 95% confidence interval for parameter b.

Station	Season	Regressed parameter	Optimized parameter	Lower limit	Upper limit
Ngabu	Wet	0.06470	0.06592	0.04865	0.08077
	Dry	0.04434	0.04178	0.02979	0.05889
Chitedze	Wet	0.06616	0.07852	0.04654	0.08578
	Dry	0.03152	0.03285	0.02321	0.03983
Bvumbwe	Wet	0.01847	0.02563	0.00015	0.03679
	Dry	0.02700	0.02569	0.01870	0.03530

Table B3: A 95% confidence interval for parameter c.

Station	Season	Regressed parameter	Optimized parameter	Lower limit	Upper limit
Ngabu	Wet	0.01664	0.01667	0.01214	0.02114
	Dry	0.01587	0.01574	0.01218	0.01956
Chitedze	Wet	0.01530	0.01488	0.01321	0.01739
	Dry	0.01337	0.01383	0.01010	0.01664
Bvumbwe	Wet	0.00305	0.00277	0.00004	0.00606
	Dry	0.00259	0.00383	0.00015	0.00503

Appendix C: Derivation of the total differential for determining the effect of small changes in the climatic variables, R_s, T and W on E_p.

The determination of the relative influence of each variable in determining pan evaporation by considering the change in E_p brought abuot by allowing small changes in R_s and T. If δE_p is the change in E_p due to changes δR_s and δT in R_s and T respectively, then

$$\delta E_p = E_p(R_s+\delta R_s,T+\delta T)-E_p(R_s,T) \quad (1)$$

where E_p is a function of R_s and T.

$$\delta E_p = E_p(R_s+\delta R_s,T+\delta T)-E_p(R_s,T+\delta T)+E_p(R_s,T+\delta T)-E_p(R_s,T) \quad (2)$$

But by definition, if we let dE_p/dR_s denote the partial differentiation of E_p with respect to R_s, then

$$dE_p/dR_s = \lim_{\delta R_s - 0}\{E_p(R_s+\delta R_s,T+\delta T)-E_p(R_s,T+\delta T)\}/\delta R_s \quad (3)$$

and

$$dE_p/dT = \lim_{\delta T - 0}\{E_p(R_s,T+\delta T)-E_p(R_s,T)\}/\delta T \quad (4)$$

Consequently

$$E_p(R_s+\delta R_s,T+\delta T)-E_p(R_s,T+\delta T) = \{dE_p(R_s,T+\delta T)/dR_s + \alpha\}\delta R_s \qquad (5)$$

and

$$E_p(R_s,T+\delta T)-E_p(R_s,T) = \{dE_p(R_s,T)/dT + \beta\}\delta T \qquad (6)$$

where α and ß satisfy the conditions

$\lim \alpha=0$ and $\lim \beta=0$ (7)

δR_s-0 δT-0

Substituting (5) and (6) into (2), we have

$$\delta E_p = \{dE_p(R_s,T+\delta T)/dR_s + \alpha\}\delta R_s + \{dE_p(R_s,T)/dT + \beta\}\delta T \qquad (8)$$

Moreover if the assumption that all first derivatives are continuous is upheld, the first term in (8) may be written as

$$dE_p(R_s,T+\delta T)/dR_s = dE_p(R_s,T)/dR_s + \mu \qquad (9)$$

where μ satisfies the condition

$\lim \mu=0$ (10)

δT-0

substituting (9) into (8) and simplifying, we have

$$\delta E_p = dE_p(R_s,T)\delta R_s/dR_s + dE_p(R_s,T)\delta T/dT + (\alpha+\mu)\delta R_s + \beta\delta T \qquad (11)$$

If the small terms $(\alpha+\mu)\delta R_s$ and $\beta\delta T$ in (11) are neglected, the equation becomes

$$\delta E_p \approx dE_p(R_s,T)\delta R_s/dR_s + dE_p(R_s,T)\delta T/dT \qquad (12)$$

In case of a function of n independent variables $f(x_1,x_2,\ldots,x_n)$, we have

$$\delta f \approx df\delta x_1/dx_1 + df\delta x_2/dx_2 + \ldots + df\delta x_n/dx_n = \Sigma df\delta x_r/dx_r \qquad (13)$$

In case of this research with three variables R_s, T and W a differential of the form

$$\delta E_p \approx dE_p\delta R_s/dR_s + dE_p\delta T/dT + dE_p\delta W/dW \qquad (14)$$

For instance taking the Ngabu wet season model (table 4.1) the computations for the effect on evaporation of the 20% change in each of variables are as follows:

$$E_p = R_s(-1.346 + 0.0647T) + 0.01664W \qquad (15)$$

$$\delta E_p \approx (-1.346 + 0.0647T)\delta R_s + 0.0647R_s\delta T + 0.01664\delta W \qquad (16)$$

substituting $R_s = 8.0$ mm/day and T = 27.8 °C from Table 4.3 into equation (16), we have,

$$\delta E_p \approx 0.4527\delta R_s + 0.5176\delta T + 0.01664\delta W \qquad (17)$$

Letting $\delta R_s = \delta T = \delta W = 1$ to denote no change in each of the variables R_s, T and W,

$$\delta E_p \approx 0.9869 \qquad (18)$$

Therefore a 20% change in R_s implies $\delta R_s = 0.8$ and $\delta R_s = 1.2$ when tere is a 20% reduction and increment respectively in R_s.

Taking $\delta R_s = 0.8$ and $\delta T = \delta W = 1$ and substituting into (17), we get

$$\delta E_p \approx 0.8964 \qquad (19)$$

subtracting (19) from (18), we have the required change of 9.1% in E_p. All the other results are obtained in a similar manner.

Appendix D: Sensitivity plots of model parameters.

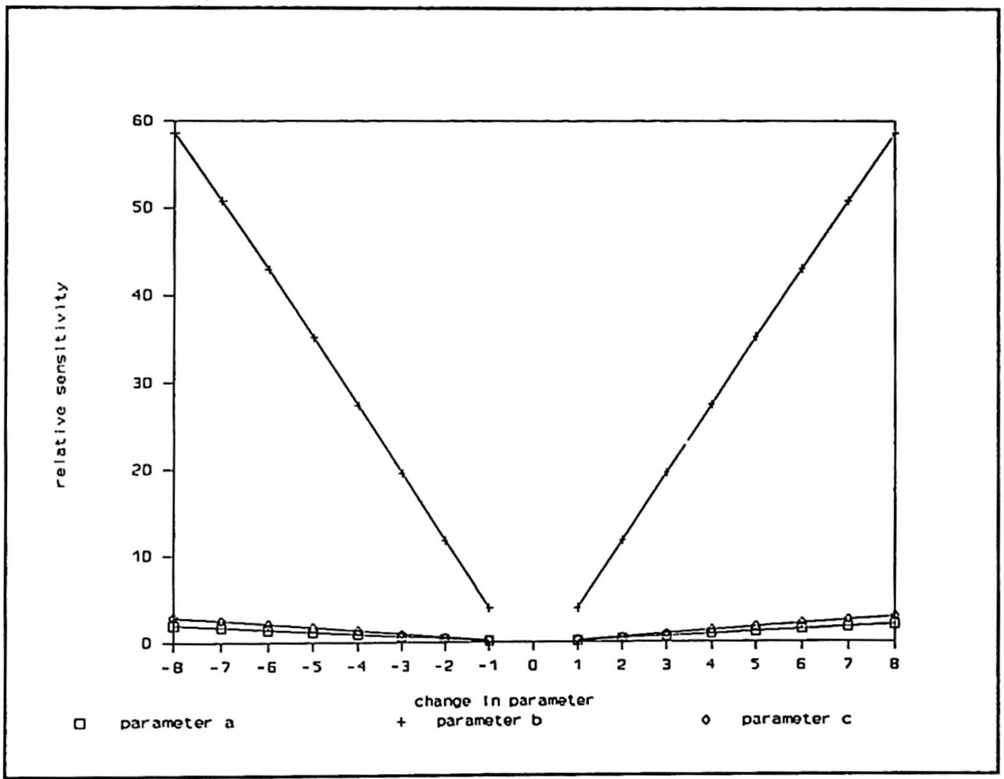

Fig. D1: A sensitivity plot of parameters for Bvumbwe dry season model.

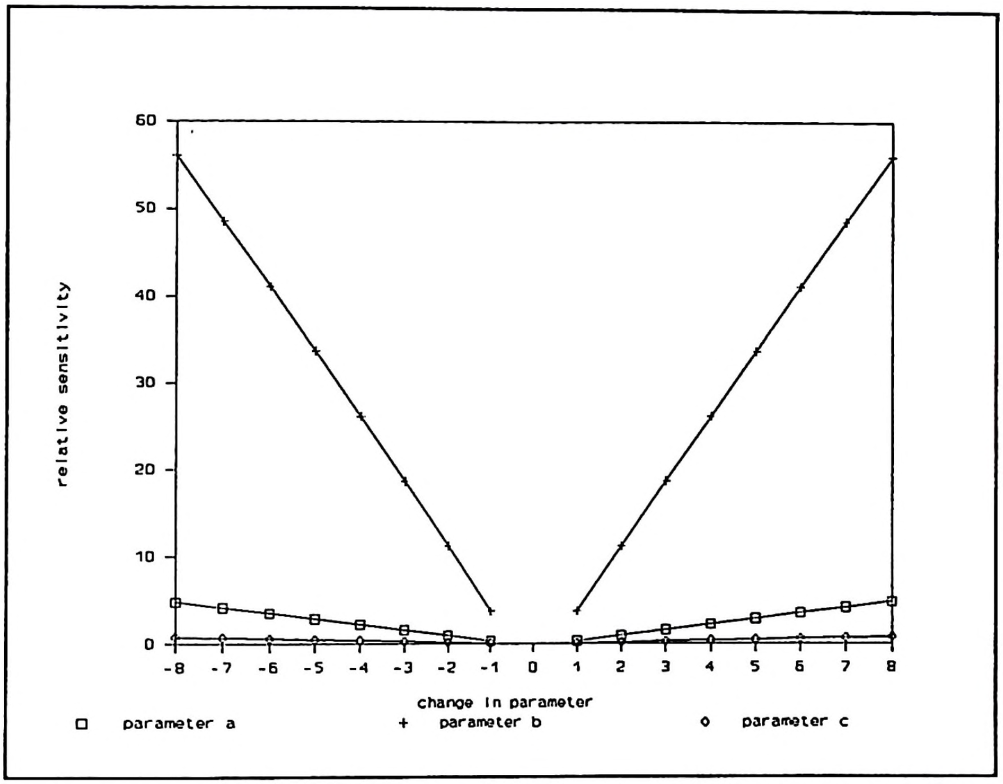

Fig.D2: A sensitivity plot of parameters for Bvumbwe wet season model.

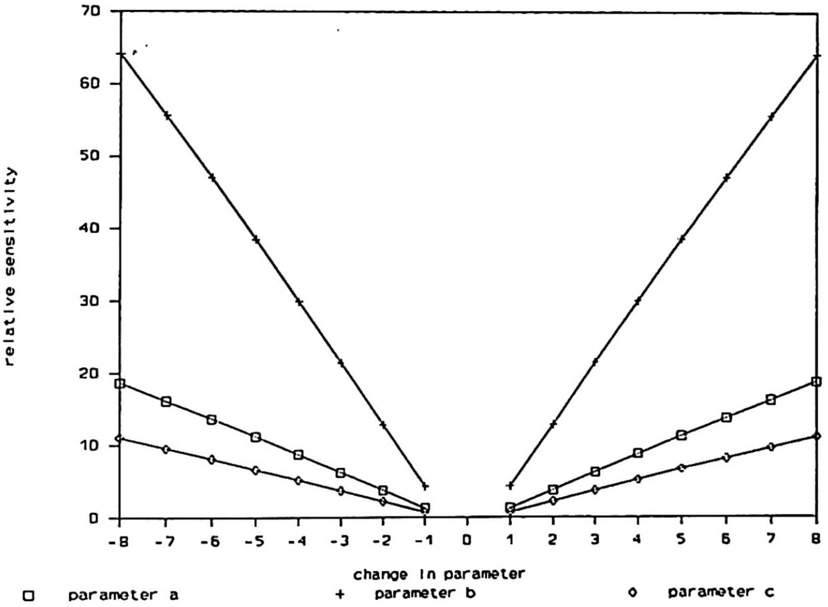

Fig.D3: A sensitivity plot of parameters for Ngabu dry season model.

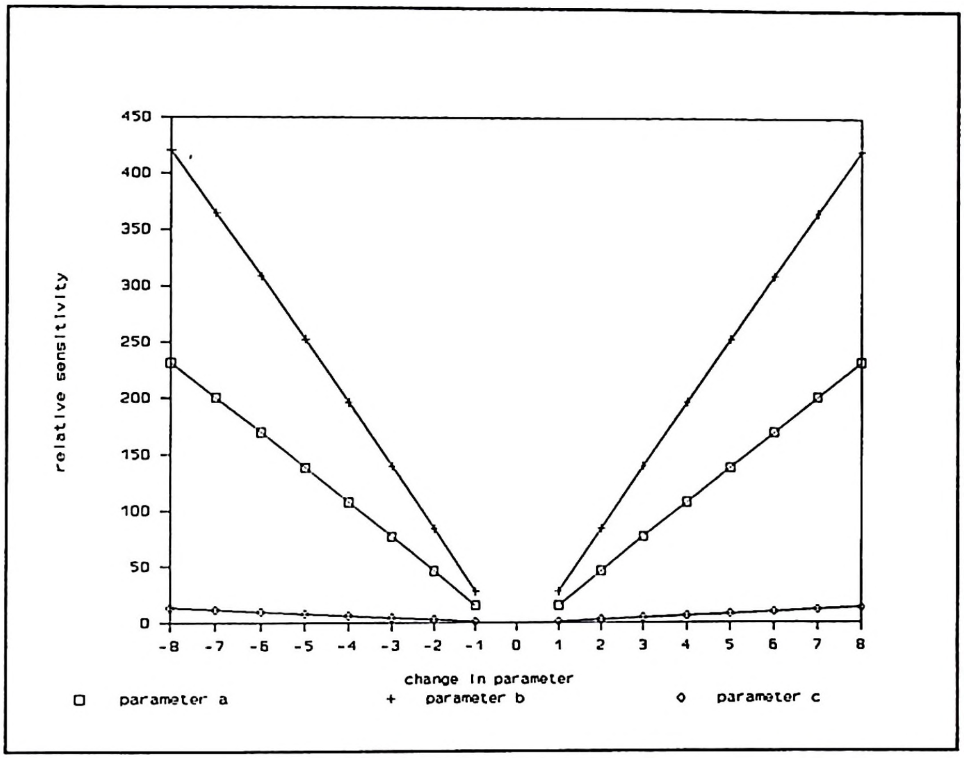

Fig.D4: A sensitivity plot of parameters for Ngabu wet season model.

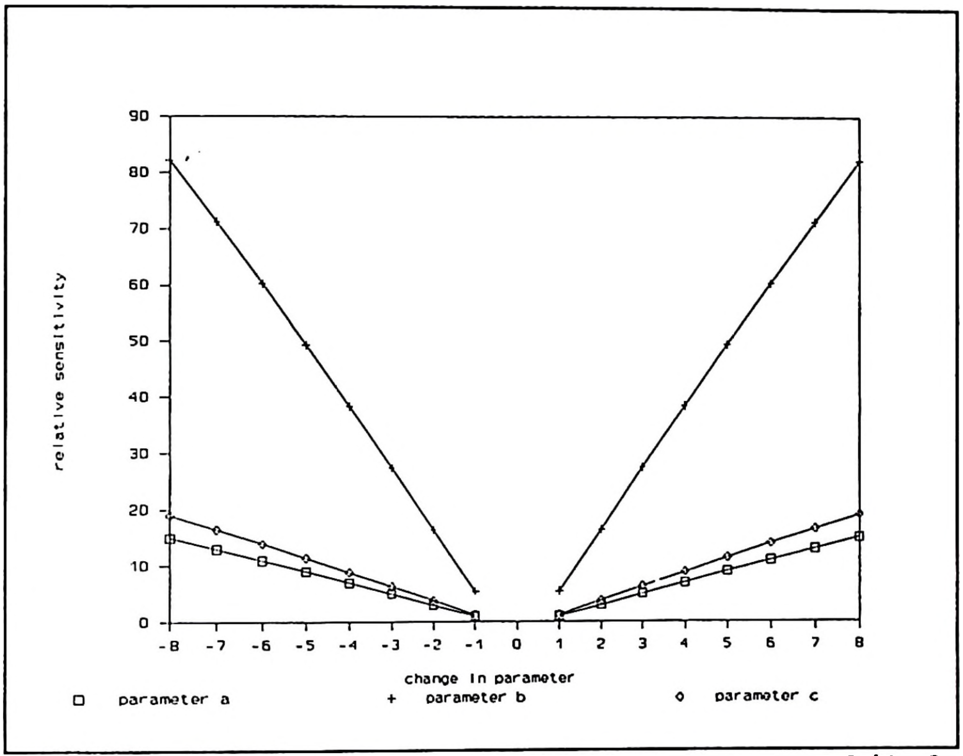

Fig.D5: A sensitivity plot of parameters for Chitedze dry season model.

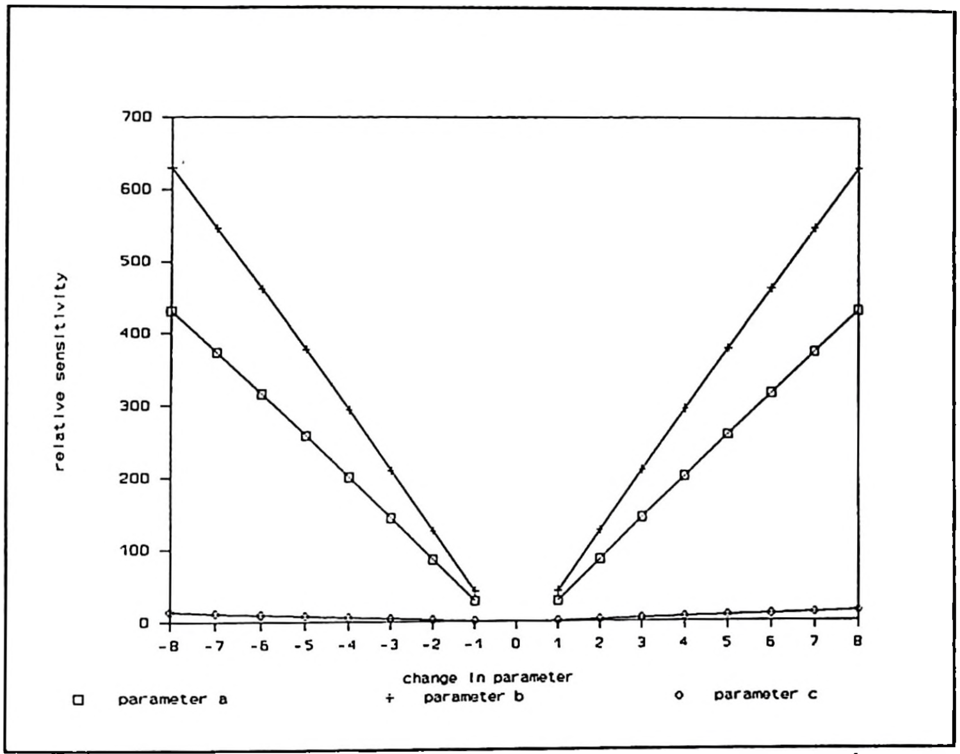

Fig.D6: A sensitivity plot of parameters for Chitedze wet season model.

Appendix E: Cumulative and trend plot of evaporation for Ngabu and Bvumbwe.

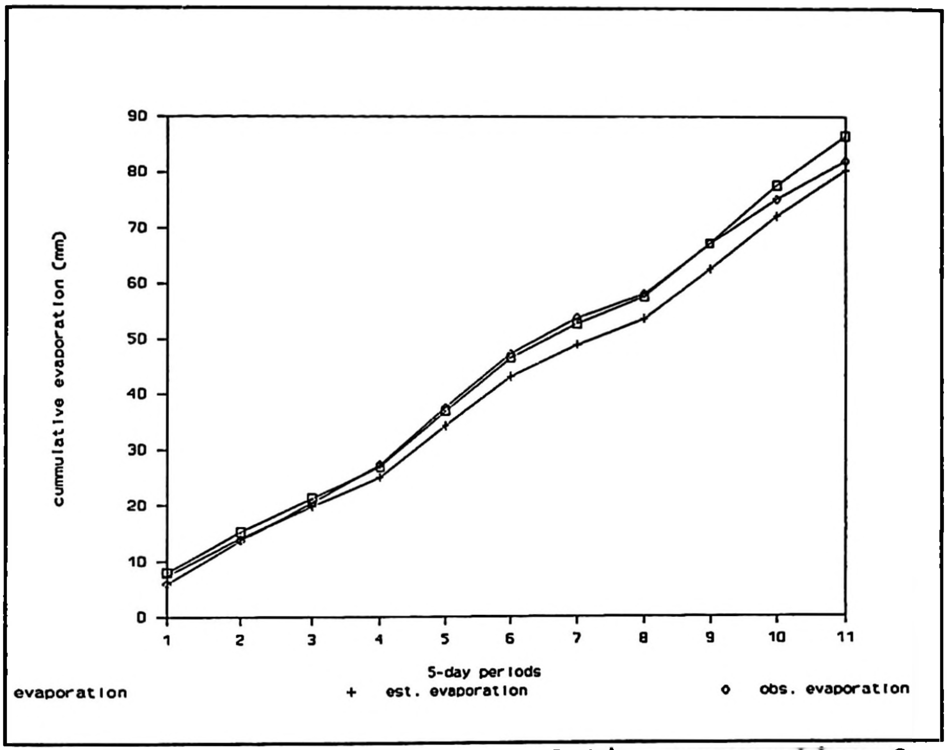

Fig. E1: A comparison of cumulative evaporation for Ngabu wet season model.

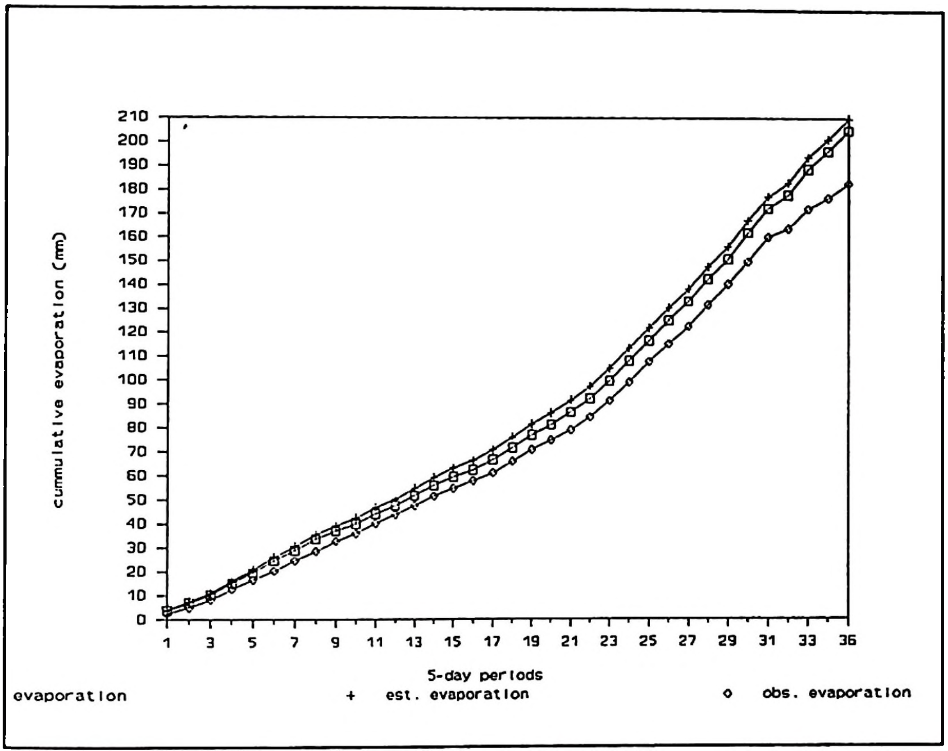

Fig. E2: A comparison of cumulative evaporation for Ngabu dry season model.

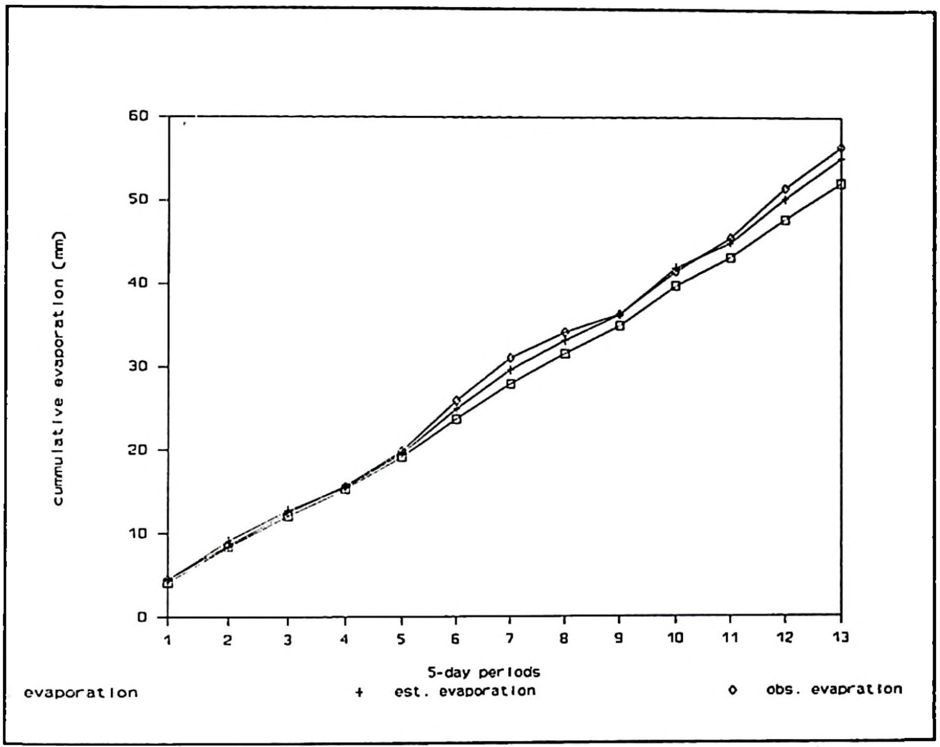

Fig. E3: A comparison of cumulative evaporation for Bvumbwe wet season model.

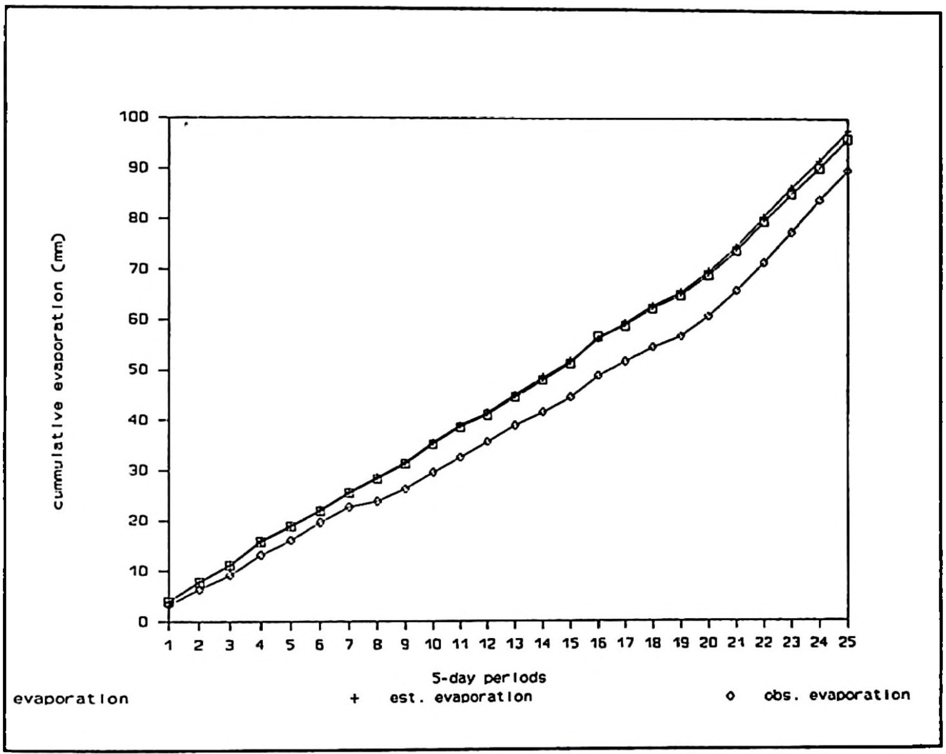

Fig. E4: A comparison of evaporation for Bvumbwe dry season model.

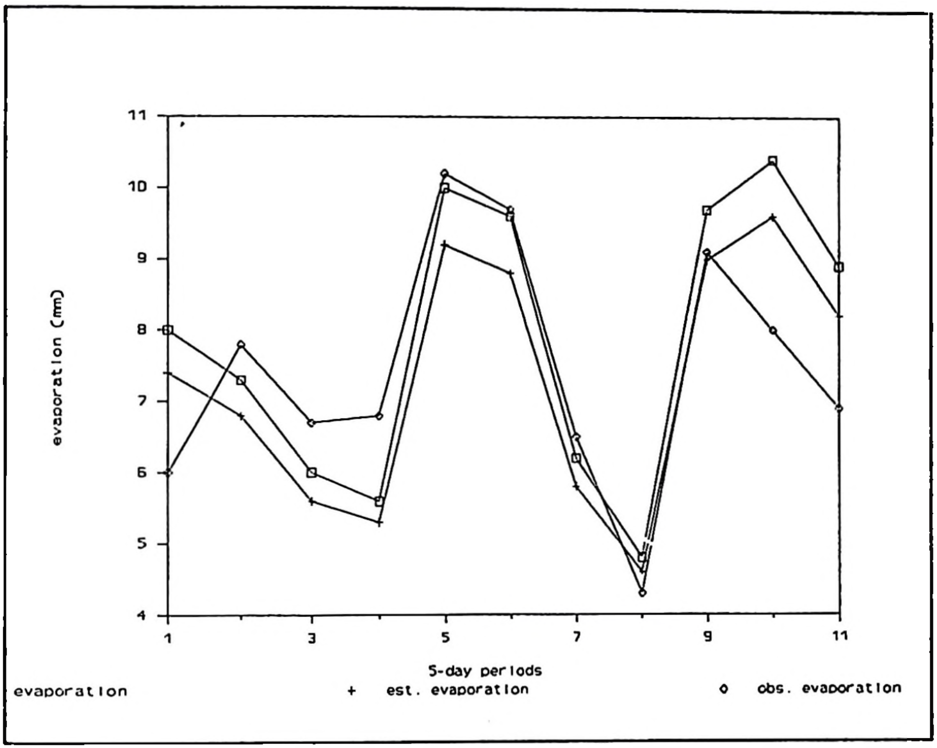

Fig. E5: A trend graph for Ngabu wet season evaporation.

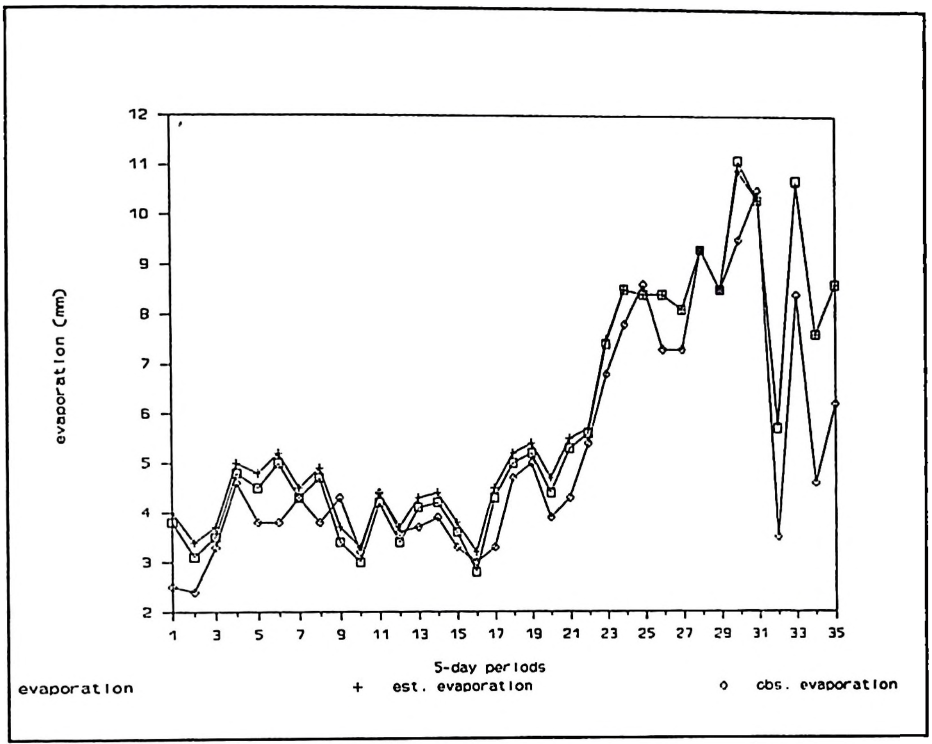

Fig. E6: A trend graph for Ngabu dry season evaporation.

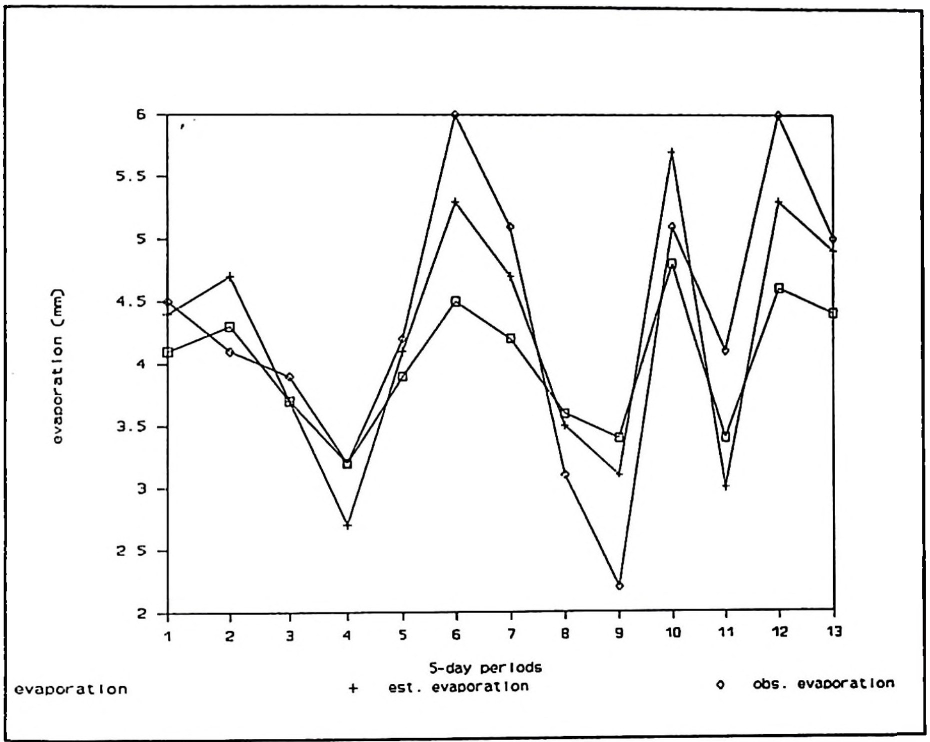

Fig. E7: A trend graph for Bvumbwe wet season evaporation.

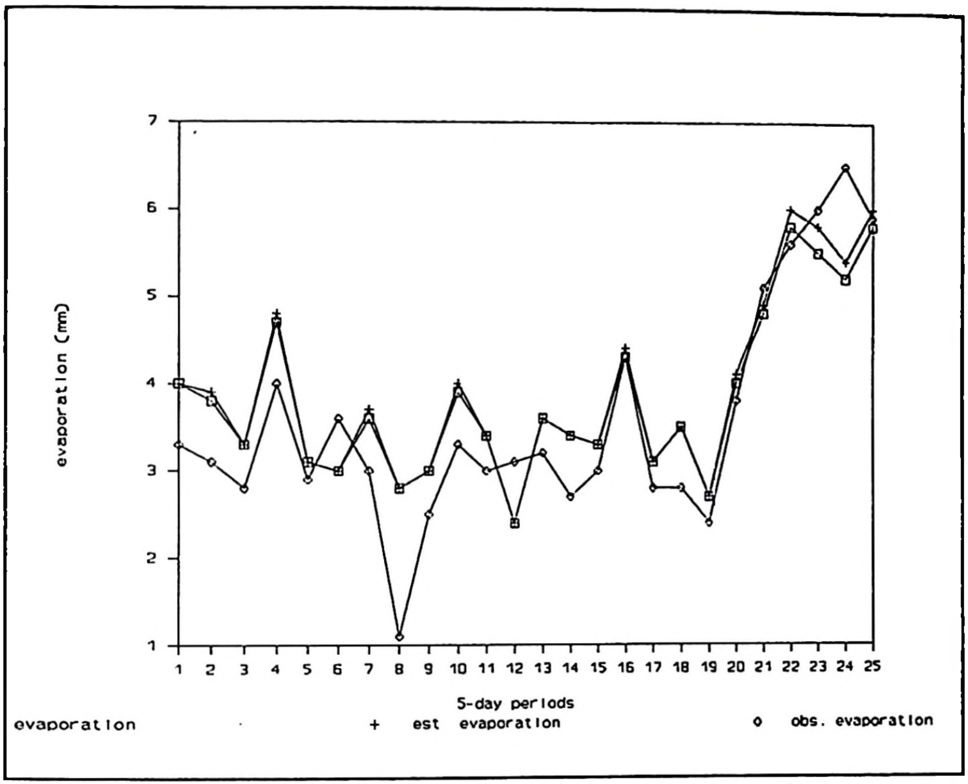

Fig. E8: A trend graph for Bvumbwe dry season evaporation.

Appendix F: Scattergram relating reference evapotranspiration to evaporation computed from models developed using tabulated solar radiation.

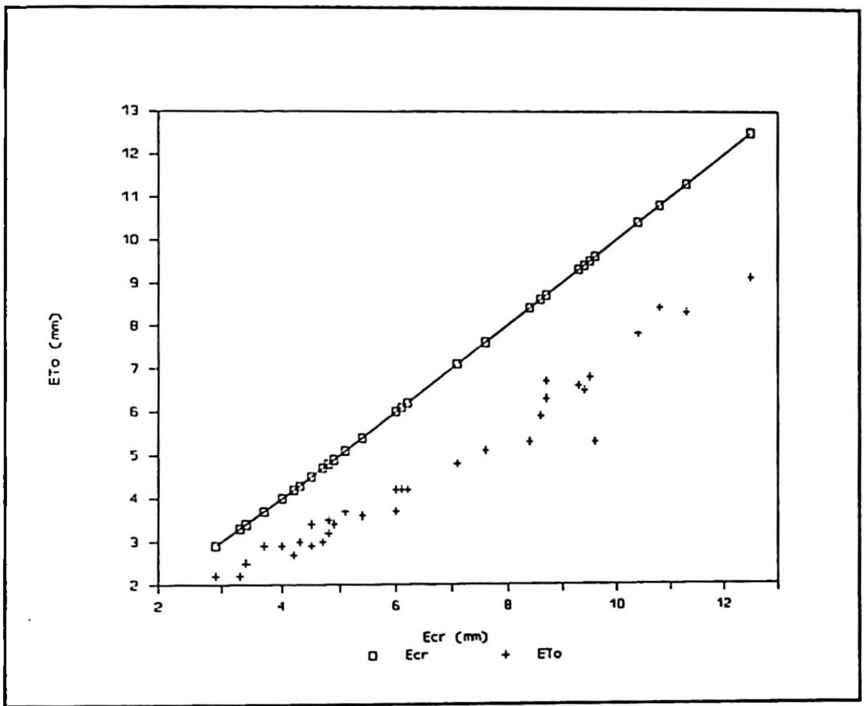

Fig. F1: A scattergram relating ETo and Ecr for Ngabu dry season model including wind speed.

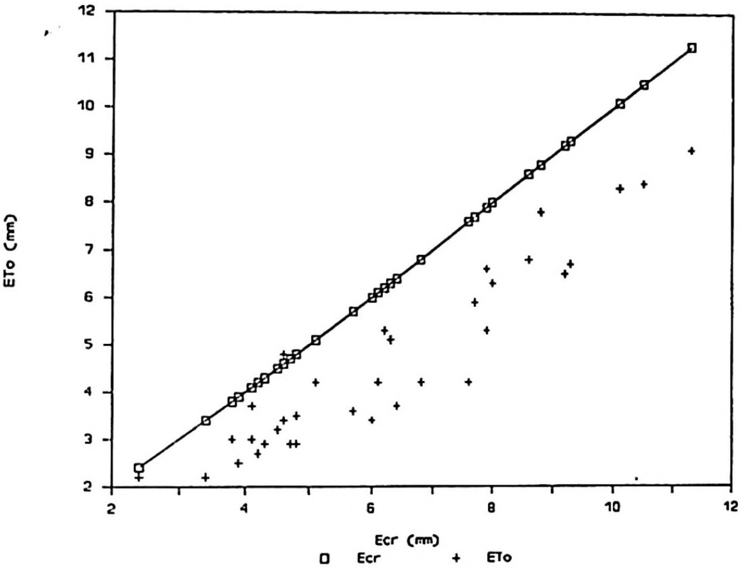

Fig. F2: A scattergram relating ETo and Ecr for Ngabu dry season model excluding wind speed.

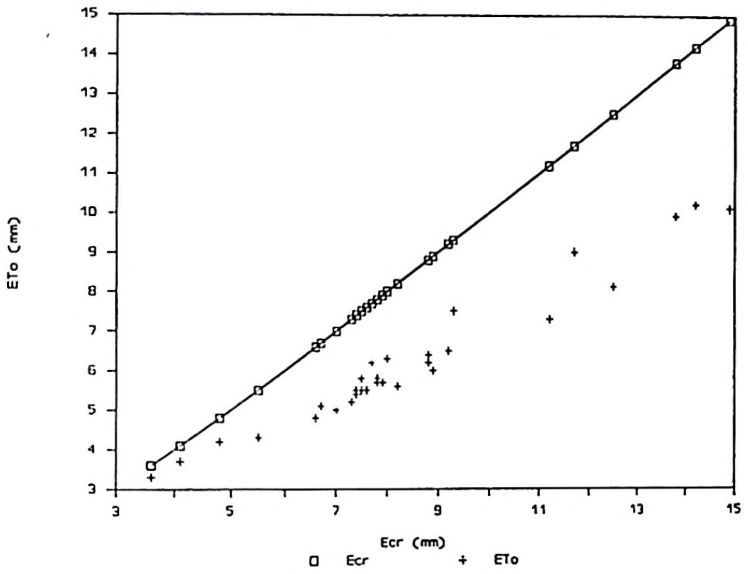

Fig. F3: A scattergram relating ETo and Ecr for Ngabu wet season model including wind speed.

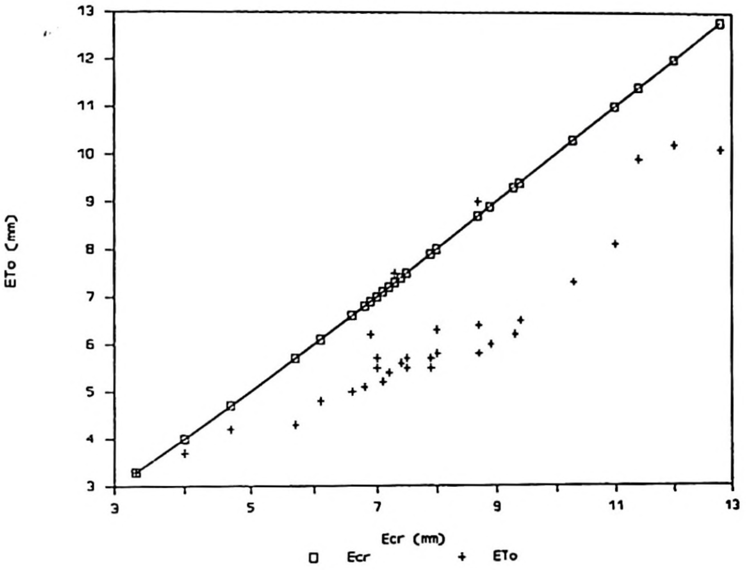

Fig. F4: A scattergram relating ETo and Ecr for Ngabu wet season model excluding wind speed.

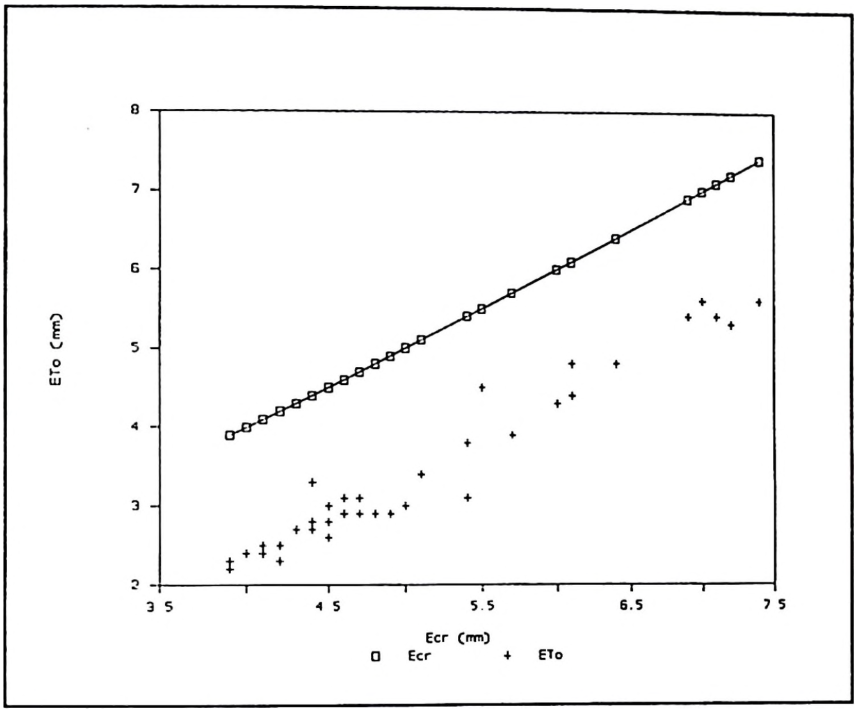

Fig. F5: A scattergram relating ETo and Ecr for Chitedze dry season model including wind speed.

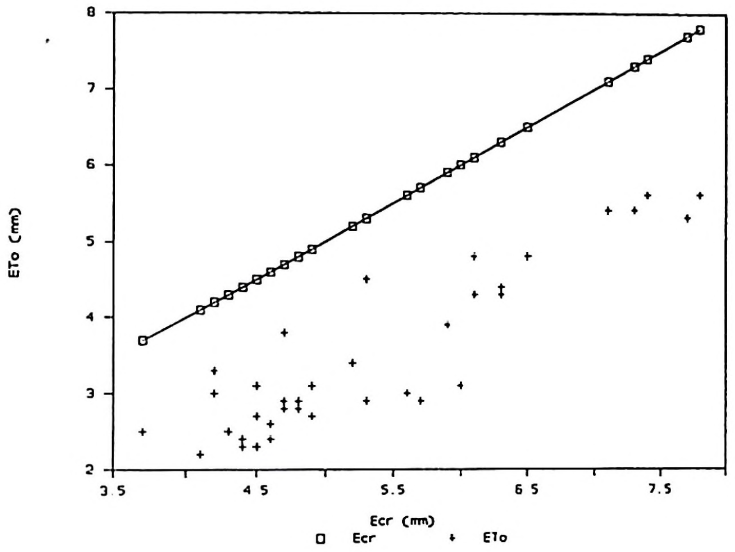

Fig. F6: A scattergram relating ETo and Ecr for Chitedze dry season model excluding wind speed.

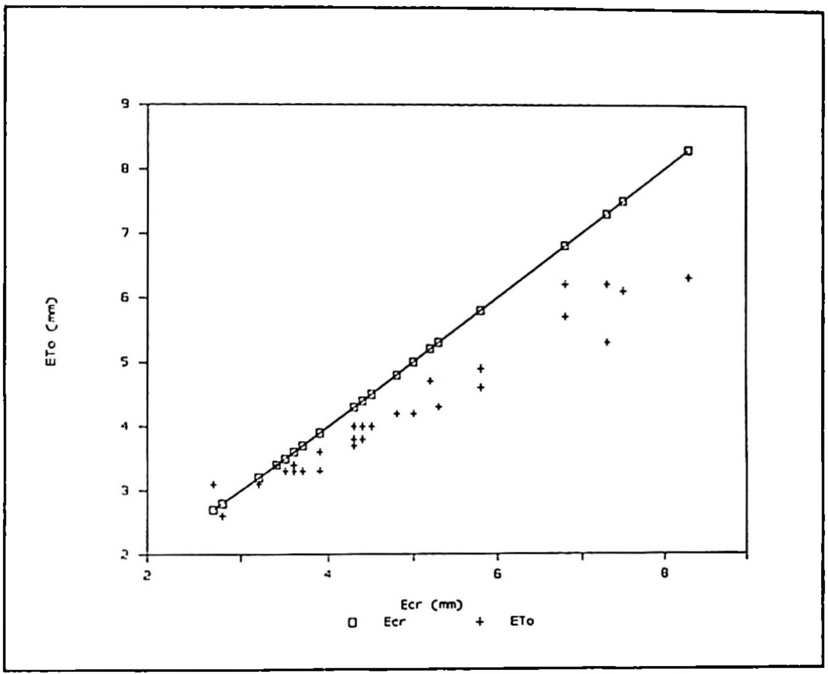

Fig. F7: A scattergram relating ETo and Ecr for Chitedze wet season model including wind speed.

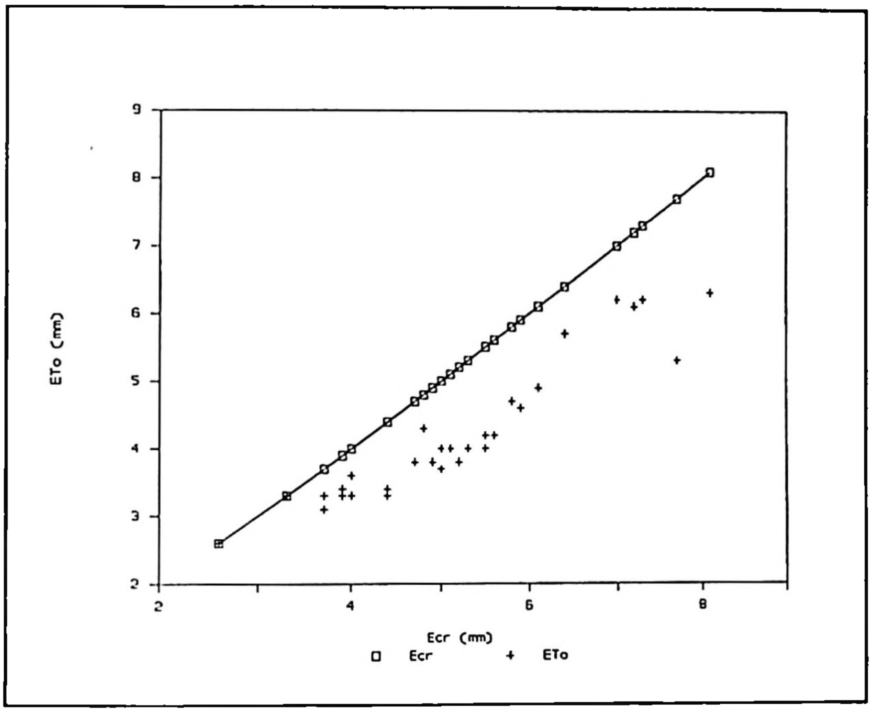

Fig. F8: A scattergram relating ETo and Ecr for Chitedze wet season model excluding wind speed.