

**EVALUATING THE METHODS OF
ESTIMATING
EVAPOTRANSPIRATION
POTENTIAL IN HUMID AND
SUB HUMID STATIONS OF NIGERIA**

BY



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CERTIFICATION

This is to certify that this thesis has been read and approved as meeting the requirements of the Department of Agricultural Engineering, Federal University of Technology, Akure for the award of Master of Engineering in Soil and Water Conservation Engineering.



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DECLARATION

I hereby declare that this Thesis is a record of my research work. It has neither been presented nor accepted in any previous application for a higher degree. All sources of information have been specifically acknowledged.

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DEDICATION

To the Lord "The author of my life, finisher of my faith", and the source of my wisdom".

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"Blessed be the Lord my Rock, who trains my hands for war, and my fingers for battle". Lord my God you are very great: You are clothed with honour and majesty" (Psalm 144:1; 104:1). To God be the glory for all He has done

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LIST OF SYMBOLS

SYMBOL	UNIT	NOMENCLATURE
AET	mm of water	Actual Evapotranspiration
MET	mm of water	Maximum Evapotranspiration
RET	mm of water	Reference Evapotranspiration
PET	mm of water	Potential Evapotranspiration
R_0	mm of water	Runoff
S_i and S_f	mm of water	Initial and final stored water
D	MJ / m ² .day	deep percolation or capillary rise
R_n	MJ / m ² .day	Net radiation
G	MJ / m ² .day	Soil heat flux
LE	°C	Latent heat flux
H	-	Sensible heat flux
T	mmHg	air temperature
K_p	mmHg	Pan coefficient
e_a	-	Saturation vapour pressure of water at air temp.
e_d	-	Saturation vapour pressure at dew point
U	mm/day	Wind speed
R_i	-	Incoming solar radiation
R_b	-	Outgoing terrestrial radiation
R_s	-	Short-wave radiation
α	-	Albedo or reflection coefficient
n		Actual hour of bright sunshine
N		Possible hour of bright sunshine
σ		Stefan's constant
γ	mmHg/°C	Psychometric constant
Δ	mmHg/°C	Slope of saturation vapour pressure curve

SYMBOL	UNIT	NOMENCLATURE
P	mbar	Mean atmospheric pressure
L	J/g	Latent heat of vapourization
E	m	elevation above sea level
ρ	Kg/m ³	air density
C _p	J/Kg °C	specific heat of the air
r _a	s/m	aerodynamic resistance
r _s	s/m	bulk stomata resistance
R _{aw}	s/m	effective aerodynamic resistance
I	/-	annul heat index
m	-	cubit function of I
l	-	monthly heat index
r _f	-	radiation ratio
RH	%	relative humidity
r _c	s/m	average canopy resistance
LAI	-	Leaf area index
h _c	m	mean grass height
THON	-	Thornthwaite method
BMN	-	Blamey-Morin-Nigeria model
PEN	-	Penman formula
PM	-	Penman-Monteith method
Epan	-	Class A evaporation pan
Y	mm	Predicted PET
X	mm	Observed PET
AAD	mm	absolute average deviation
RMSE	mm	root-mean-square-error
R	-	coefficient of correlation
Z	-	test statistic

ABSTRACT

Potential Evapotranspiration (PET) is essential to soil and water studies and design of hydraulic structures, e.t.c. This study was conducted to evaluate the relative performance of four commonly used methods of estimating potential evapotranspiration. These are: Thornthwaite method (THON), Blaney-Morin-Nigeria model (BMN), Penman method (PEN) and Penman-Monteith method (PM).

Data used for computation of PET were collected from IITA stations. The PET values were compared on annual, monthly and decadal basis using Pan evaporation values as reference. The PET values from each of the model was regressed with Pan values using a linear regression model.

Penman-Monteith closely followed by Blaney-Morin-Nigeria model were highly correlated (on annual, monthly and decadal basis) with the observed values (Epan). PM overpredicted Epan by about 2.1% in the humid zone, by 0.42% in the sub-humid environment while BMN overpredicted Epan by about 20%-33%, PEN by about 32%-34%. For THON the range of overprediction was between 38% and 69% at Onne and Ibadan. The results showed that PM, PEN and BMN gave comparable estimates of PET. However BMN has the advantage of fewer numbers of input data required.

While the Thornthwaite method is most affected by temperature, the BMN is highly sensitive to solar radiation and relative humidity.

Simple models relating PET(obtained by each of the method) to Epan and the relative humidity, were developed. The models were tested with independent data sets.

The results of this study are useful in the management of irrigation systems, crop simulation models, planning and operation of water resource projects.

CHAPTER ONE

GENERAL INTRODUCTION

1.0 Introduction

Evapotranspiration is one of the important components of hydrological cycle from the time water falls upon the land as precipitation until it reaches the ocean or is returned to the atmosphere. Evapotranspiration studies is of interest to agronomists, meteorologists, hydrologists and irrigation project managers, and engineers, e.t.c. It is used in the design of hydraulic structures, planning and operation of water resource projects.

In developed countries of the world Evapotranspiration is an important factor in negotiating compacts and treaties and in the litigation and the adjudication of water rights of major water systems, in which the welfare of people, cities, valleys, states and even nations is involved (Blaney and Criddle, 1949). Before an equitable division of the waters of a developing river basin can be made, careful consideration must be given to the Evapotranspiration requirements in the sub-basins. In developing countries, attempts are made to reasonably estimate evapotranspiration in spite of inadequate reliable data for the design of hydraulic structures.

Most of the current hydrologic, water-management and crop-growth models require an accurate estimate of potential

evapotranspiration (PET) for reliable applications (Choisnel et. al, 1992). Evapotranspiration data are also used for estimating irrigation requirements, safe yields of groundwater basins, water yields from mountain watersheds, soil water balance and stream flow depletion in river basins.

In water resource investigations, the need to be able to compute evapotranspiration rapidly and accurately remains indisputable as direct measurements of evapotranspiration are time-consuming and expensive. Thus, rapid and reliable methods are needed by engineers, basically to transpose the results of observed ET data in one area to the other areas for which only climatological data, elevation and latitude are available.

Potential evapotranspiration can be determined by water balance methods, evaporimeters and from purely empirical techniques. A number of formulae for quantitative estimation of PET have been used by scientists over the years. Each of the models has its peculiarities which make it more adaptable and suited for a particular location than the others. In view of the wide applicability of potential evapotranspiration data in solving different hydrological problems, it is important to evaluate the accuracy and reliability of these in predicting ET.

In this study, a comparative evaluation of some frequently used models is undertaken. They are: Thornthwaite, Blaney-Morin- Nigeria model, Penman and Penman-Monteith. Thornthwaite method is still widely used, because temperature data are available for most of the stations, for estimating PET (Smajstrla et al, 1984; Amatya et al, 1995).

The three other formulae are selected based on their good performance particularly when the required input parameters are available (Jensen,1973; Jagtap and Alabi, 1997b). Since reliable and appropriate lysimeter measurements data are not available, class A pan is selected as basis of comparison. This approach has been used by some workers (Von Bavel, 1966; Jensen,1973; and Duru, 1984).

1.1 Objectives

The objectives of this study are therefore to:

- (i) evaluate the relative performance of the selected models in accurately predicting the potential evapotranspiration (PET) in the study area;
- (ii) to develop a simplified model for predicting potential evapotranspiration.

1.2 Justification Of The Study

The importance of ET data in water related development projects can not be over-emphasised, hence the reliability of the estimating models should be ascertained. Mohammed (1978) and Smajstrla et al,(1984) conducted similar studies for eastern North Carolina and the humid conditions in Florida, respectively.

In Nigeria, very little work has been done in the area of comparing and evaluating evapotranspiration (ET) models. Perhaps, the most outstanding work is that presented by Duru (1984). It is quite

unfortunate that across the width of Nigeria, only a few references can be made to research works on accurate lysimetric measurements of ET. The practice of using foreign developed empirical models therefore continues.

In Nigeria, like in other developing countries, there is need to compute ET from meteorological parameters which can be easily measured. This will lead to greater accuracy in estimating ET for a particular need and also reduce cost. The failure of our developing River Basin projects, poor performance of irrigation schemes and other water-related development projects could be attributed, in part, to lack of adequate and relevant data from which ET can be estimated.

1.3 ET Definitions

Evapotranspiration is the combined effect of evaporation of water from soil and transpiration of water by a growing crop. Some form of ET terms that are frequently used include potential evapotranspiration (PET) actual evapotranspiration (AET), maximum evapotranspiration (MET) and reference evapotranspiration (RET).

The concept of potential evapotranspiration was first introduced by Thornthwaite in 1944, and according to him PET is "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of the vegetation". Penman (1948) later defined PET as the ET rate of a "short green crop, completely shading the ground, of uniform height and never short of water". This was modified by Doorenbos and Pruitt (1977)

by specifying the size range of the short grass as 8-15 cm tall. Considering these various existing definitions, one can simply define PET as the total amount of water which could be transferred from an area to the atmosphere under the existing meteorological conditions.

Actual ET is the actual amount of water given up to the atmosphere, which depends not only on the existing meteorological conditions, but also on the availability of water to meet the atmospheric demand and, the ability of the vegetation to extract moisture from the soil.

Maximum ET is the highest value of Actual ET and equals to the actual ET of a crop under no water stress (Itiz., 1996). Since individual crops have different aerodynamic properties and growth characteristics, the PET of crops will differ and hence, the ET should be calculated based on a particular reference crop. Doorenbos and Pruitt used grass and defined the Reference ET as "The rate of evapotranspiration (ET) from an extended surface of 8 to 15 cm tall green grass cover of uniform height, actively growing, completely shading the ground and not short of water". Jensen and Haise also proposed the alfalfa that is well-watered and has 30-50 cm of top growth as the reference crop. Reference ET is, essentially, equivalent to potential ET, with the exception that the leaf surfaces are typically not wet and a reference crop is specified (Jensen et al, 1990). In spite of the technical distinction, Mckenney and Rosenberg (1993) viewed potential ET and reference ET as conceptually the same.

It is important to note that there are slight differences in the definitions of ET in literature. Hence, definitions presented by FAO

experts and consultation group (Doorenbos and Pruitt, 1977) are retained and referred to in this report.

CHAPTER TWO

EVAPOTRANSPIRATION

2.0 Basic Concepts

'Evaporation' is the term used to describe water loss from water and bare-ground surfaces. It is a process by which moisture is converted into water vapour and removed and transported upward into the atmosphere. On vegetated surface where transpiration is an important component of water loss, the term 'evapotranspiration' is used. Evapotranspiration is thus the combined process of evaporation and transpiration.

Evapotranspiration is a complete process involving the following four sequential but distinct processes (Ayoade, 1988):

- (i) Movement of water within the soil towards the ground surface or zone of absorption around the roots of plants,
- (ii) Transpiration,
- (iii) Vaporisation of water at the soil or plant surface of the stomata leaves,
- (iv) Removal and transport of the evaporated water, now in gaseous form, into the atmosphere.

The rate of evaporation or evapotranspiration over any given surface is dependent on the availability of moisture and the ability of the atmosphere to vaporise and remove the vapour from the given surfaces.

If moisture is always available in sufficient quantities at the evaporating surface, evaporation will occur at the maximum rate possible. This is the basis for the concept of potential evapotranspiration outlined by Thornthwaite (1944). The fact that moisture is not always available sufficiently at the evaporating surface underlies the idea of actual evapotranspiration - whose values are either equal to or below those of potential evapotranspiration for any given environment.

2.1 Factors Affecting Rates Of Evapotranspiration

Several factors influencing the rate of evapotranspiration can be grouped into two categories: climatological and non-climatological factors. Non-climatological factors are only important in respect of actual evapotranspiration and include: surface characteristics (i.e. soil or water, vegetated or bare surface) ; the type of soil and land management; the moisture condition of the soil profile; and the degree of plant cover and type. In contrast, potential evapotranspiration is independent of all surface control except for differences in albedo (radiation reflection due to type of surface) and is influenced solely by climatic factors. According to the definitions presented by both Thornthwaite (1944) and Penman (1963), the effect of surface characteristics on the rate of PE is generally insignificant.

There are three major climatic factors influencing the rate of evapotranspiration whether potential or actual (Ayoade, 1988):

- (i) The amount of energy available to vaporise water (which depends on air temperature, solar radiation, sunshine duration);

- (ii) air humidity that indicates the capacity of the air to hold moisture, and
- (iii) wind speed – helps to maintain the continuity of the evapotranspiration process.

2.2 Estimation Of Actual Evapotranspiration

Direct and indirect measurements or estimation of actual evapotranspiration are carried out in several ways (Tier, 1996). They include: water balance approach, energy balance approach and aerodynamics approach.

2.2.1 Water Balance Approach

Evapotranspiration from vegetated surface can be estimated using the water balance equation:

$$ET = P - R_r + S_i - S_f \pm D \dots \dots \dots (1)$$

where ET is evapotranspiration (mm), P is precipitation (mm), R_r is runoff and S_i and S_f are the initial and final amounts of stored water respectively (mm), D is deep percolation or capillary rise (mm). Difficulty in measuring seepage losses and the cumulative errors involved in the separate determination of the other terms of the equation limits the reliability of this method.

Lysimeter studies, for example, involve the growing of crop in a large container and measuring water losses and gains. There are basically two types of lysimeter: weighing and non-weighing (drainage)

lysimeters. The weighing lysimeter is an equipment consisting of a tank filled with soil and vegetation similar to that in the surrounding and supported by a weighing mechanism. Evapotranspiration values are obtained by calculating the changes in the weight of the soil-vegetation system within the tank. Weighing lysimeters are often used to measure actual evapotranspiration and therefore not necessarily at field capacity, unlike the drainage lysimeter, which is used for measuring potential evapotranspiration. The latter is discussed in section 2.3.

2.2.2 Energy Balance Approach

In view of the difficulties of measuring evaporation and evapotranspiration accurately on the field, attempt has been made to use indirect methods which involve meteorological data.

Energy balance approach is based on the fact that evapotranspiration of water either directly at the soil level or transpired through plants stomata is associated with energy consumption through latent heat of vaporisation. This energy consumption corresponds to the latent heat flux and over a surface covered with an active growing crop, it represents the major part of the use of available energy due to radiation balance. It is generally written as:

$$R_n - G = H + LE \dots\dots\dots(2)$$

where

R_n = net radiation ($MJ/m^2.d$), G = The soil heat flux ($MJ/m^2.d$)

H = Sensible heat flux ($MJ/m^2.d$), and LE is the latent heat flux ($MJ/m^2.d$).

Bowen (1926), as cited by Jensen (1973), showed that the partitioning of the net radiation between sensible heat used for warming the air (H) and latent heat of evaporation (LE) is given by

$$B = \frac{H}{LE} = \frac{0.659 (k_h) (T_s + T_a)}{(K_e) (e_s + e_a)} \dots\dots\dots(3)$$

where

B : The bowen ratio, K_h and K_e are eddy diffusivities of heat and vapour respectively. T_s is the temperature of the evaporating surface, e_s is the vapour pressure at evaporating surface (mb), T_a is air temperature ($^{\circ}$ C), e_a is the vapour pressure of the air (mb), H and LE are as defined above.

By assuming that $K_h = K_e$, B can easily be solved from measurements of temperature and vapour pressure gradients. Thus the amount of evapotranspiration can be obtained using the equation of the form:

$$E = \frac{R_n + H}{1 + B} \dots\dots\dots(4)$$

where E is evapotranspiration in mm of H_2O .

2.2.3 The Aerodynamic Approach

If other factors remained constant, evaporation would be proportional to the wind speed and the vapour pressure deficits. This relationship provides the basic foundation of the several aerodynamic formulae for estimating values of evapotranspiration. For example Thornthwaite and Holzman (1939) defined evapotranspiration as:

$$E = 17.1 \frac{(e_1 - e_2)(u_2 - u_1)}{(T + 459.4)} \dots\dots\dots(5)$$

where:

E is evapotranspiration of a short vegetation, e_1 and e_2 are vapour pressure in inches Hg at heights of 2ft and 28.6ft above the ground, u_1 and u_2 are wind velocities in miles per hour at the same two levels and T is the air temperature in °F.

2.3 Estimation of PET

Potential evapotranspiration could be measured directly using drainage lysimeter or estimated by the use of various formulae based on meteorological data.

2.3.1 Measurement of PET with Lysimeter

Both weighing and non-weighing lysimeters can be used to determine PET depending on scale of measurements. The drainage lysimeter is normally used to measure PET. It operates on the basis of simple water balance equation. There is need to keep the soil around the instrument always saturated with moisture. Daily measurements are taken and PET is estimated using :

$$PET = I - O \dots\dots\dots(6)$$

where

PET is potential evapotranspiration (mm), I is amount of water applied by irrigation and/or rainfall (mm), and O is water output or runoff

which is collected in the bucket (mm). The storage term is assumed to be zero since the soil column is always saturated with moisture.

Comprehensive report on lysimeters uses and limitations are discussed by Itier (1996), Ayoade (1988) and Jensen (1973).

2.3.2 Estimation of PET with Pan Evaporimeters

Many researchers have suggested the use of pan evaporimeter to estimate PET using a simple relationship.

$$PET = K_p * E_{pan} \dots \dots \dots (7)$$

Where:

K_p is the pan coefficient depending on reference crop, type of pan and the prevailing climatic conditions.

Despite major differences in the energy balance and aerodynamics of pans and crops, pan evaporimeters are still in use all over the world (Brustsaert, 1962). This is due to their simplicity. Pan coefficients, depending on the type of pan, wind velocity, air humidity and the nature of the surroundings, are provided by Doorenbos and Pruitt (1977).

In Nigeria, the following formula is used to obtain estimates of pan evaporation in units of depth (Ayoade, 1988).

$$E_{pan} = r + 0.51(a-w) \dots \dots \dots (8)$$

where:

E_{pan} is pan evaporation in mm, r is rainfall in mm, a is the number of cups of water added and w is the number of cups of water withdrawn to reset the instrument.

2.3.3 Calculating PET Using Meteorological Data

Since potential evapotranspiration is based on atmospheric demand, attempts to establish PET formulae based on climatological observations have been made. The formulae range from complex physically based one to simple empirical formulae; they include Penman, Penman-Monteith, Jensen-Haise, Thornthwaite, Turc, Blaney-Cridde, etc.

(I) *Penman Approach*

Penman(1948) combined the energy-budget and aerodynamic approaches to eliminate the theoretical difficulties and measurement problems inherent in the use of either of the two approaches.

Basically, there are three equations in Penman's treatment. The first equation is of the aerodynamic type and is a measure of the drying power of the air. It is given as:

$$E_a = 0.35 (e_s - E_d) (1 + u_2/100) \dots\dots\dots(9)$$

where e_s is the saturation vapour pressure of water at the mean air-temperature in mm of mercury, e_d is the saturation vapour pressure of water at the dew point temperature, and u_2 is wind speed in miles per day at 2 meters above the ground.

The second equation is for estimating values of net radiation where measured value is not available and is of the form.

$$R_n = R_i - R_B \dots\dots\dots(10)$$

where : R_n is the net radiation (mm /day), R_i is the incoming solar radiation (mm/day), and R_B is the outgoing terrestrial radiation (mm/day).

For estimating values of R_i Penman gave the equation of the form:

$$R_i = (1 - \alpha) R_0(0.18 + 0.55n/N) \text{ mm/day} \dots\dots\dots(11)$$

where:

R_0 is the theoretical radiation that would be received at the ground surface in the absence of an atmosphere, α is albedo or reflection coefficient of the evaporating surface and n/N is the ratio of actual (n) to possible (N) hours of bright sunshine.

The equation for estimating R_B is

$$R_B = \sigma T_a^4(0.56 - 0.09e_d) (0.10 + 0.90n/ N) \text{ mm/day} \dots\dots\dots(12)$$

where : σT_a^4 is the theoretical back radiation which would leave the surface in the absence of an atmosphere, T_a is the mean air temperature, σ is the stefan's constant, and e_d is the saturation vapour pressure of water at the dew point temperature.

Penman (1948) combined the above equations and came out with an evapotranspiration equation of the form:

$$PET = \frac{R_n + \gamma E_a}{\Delta + \gamma} \dots \dots \dots (13)$$

Where PET is the potential evapotranspiration (mm), Δ is the slope of the saturation vapour pressure curve for water at the mean air temperature in mm Hg/ $^{\circ}$ C γ is the constant of wet and dry bulb psychrometer equation in mmHg/ $^{\circ}$ C. R_n is the net radiation and E_a is as previously defined.

Performance of the classical Penman equation has been improved by a group of FAO experts resulting in the world-wide known "FAO 24 corrected Penman method" (Doorenbos and Pruitt, 1977). The equation is given as:

$$PET = \frac{(\rho_0 / \rho) \Delta (0.75R_n(a + b n/N) - \alpha T_a^4(0.56 - 0.079e_d) (0.10 + 0.40 n/N) + 0.26(e_a - e_d) (1.00 + 0.54u))}{(P_0 / P) (\Delta / \gamma) + 1.00} \dots \dots \dots (14)$$

where

P_0 is the mean atmospheric pressure expressed in millibar-at sea level,

P = mean atmospheric pressure expressed in millibar based on elevation of the station;

R_n = short-wave radiation received at the limit of the atmosphere expressed in mm of evaporated water;

a & b = coefficients for the estimation of total radiation from the sunshine duration.

PET, Δ , γ , e_a , δT_a^4 , T_a , e_d , and u are as previously defined.

A review of literature clearly indicates that Penman method is superior (when the required data are available) to all other commonly used methods. The performances of classical Penman and FAO Penman in USA and Europe are reported in Seguin (1975), Jensen et al. (1990), Allen et al. (1994) Choisnel et al. (1992), Jagtab and Alabi (1997a).

Expressions to obtain some of the parameters in the above equations are proposed as follows:

e_s and Δ are given as a function of temperature by Bosen (1960) as

$$e_s = 33.8639 [(0.00738T_s + 0.8072)^8 - 0.000019(1.8T_s + 48) + 0.001316] \dots \dots \dots (15)$$

and

$$\Delta = 3.8639 [0.05904(0.00738T_s + 0.8072)^7 - 0.0000342] \dots \dots \dots (16)$$

The Psychometric constant according to Weiss (1983) is

$$\gamma = 1.61452P/L \dots \dots \dots (17)$$

where: 1.61452 (J/gram) is the ratio of the specific heat of dry air to the ratio of the mass of water vapour to dry air, P is the barometric pressure of the air (mbar), and L the latent heat of vaporisation of water (J/gram). L is calculated as follows (Jensen 1981):

$$L = 4.1855(595 - 0.51T_s) \dots \dots \dots (18)$$

P for given altitude was proposed by List (1971) as:

$$P = 1013 - 0.1093E \dots\dots\dots(19)$$

where E is the elevation above sea level in metres.

(ii) ***Penman-Monteith approach.***

This is the most physically sound combination equation known in recent times. In P M equation, the "Physics" and " physiology" were combined just as Penman equation combined "Energy" and "aerodynamics" (Monteith, 1965; Jensen, 1966; Ostromecki, 1965; Rijtema, 1965 and Jackson et. al. 1988). The underlying principle is in the fact that under no condition should a reference crop be considered as a wet surface. Hence, there is the inclusion of an additional resistance to water vapour transfer parameter, r_c - called stomata resistance. The resulting PET equation is given as:

$$PET = \frac{\Delta(R_n - G) + \rho C_p VPD/r_a \dots\dots\dots(20)}{\Delta + \gamma (1 + r_c/r_a)}$$

where:

ρ is the air density (kg/m^3), G is the soil heat flux density ($J/m^2.d$), C_p is the specific heat of the air ($J/kg^{\circ}C$), VPD vapour pressure deficit ($e_a - e_d$), r_a is the aerodynamic resistance to vapour and heat diffusion (s/m), and r_c is the bulk stomata (canopy) resistance (t/m). Variable t is the time scale for which the vapour flux is to be estimated.

Wright and Jensen(1972) approximated average daily soil heat flux as

$$G = (T_a - T_p) C_s \dots\dots\dots(21)$$

where T_a is the average air temperature ($^{\circ}\text{C}$) and T_p is the average daily air temperature ($^{\circ}\text{C}$) for the previous three days. Parameter C_s is the general heat conductance for the soil surface, equal to about $0.38\text{MJm}^{-2}/\text{d}^{\circ}\text{C}$ for a silt loam soil. Thom and Oliver (1977) proposed a semi-empirically based equation for r_c that reaches a finite limit as $U \rightarrow 0$. Their equation is

$$R_{ae} = \frac{4.72 (1n((z-d)/Z_0))^2}{(1 + 0.54U)} \dots\dots\dots(22)$$

where R_{ae} is the effective aerodynamic resistance (s/m), Z is the reference height (m), d is displacement height (m), Z_0 the roughness length (m), U is the wind speed (ms^{-1}). The terms Z_0 and d can be represented as functions of the vegetation height (h). $Z_0 \approx 0.13h$, and $d \approx 0.63h$ for plant canopies with full cover.

In recent works, PM equation has been acclaimed superior to the classical Penman, particularly when PM is used with a site calibrated value of crop resistance. A standardised FAO - PM was also recommended in place of FAO-PENMAN for use in the nearest future (Smith et al. 1991; Choisnel et al., 1992; and Allen et al., 1994).

(iii) **Thornthwaite approach**

The concept of PET was first introduced into climatological literature by Thornthwaite in 1944. Thornthwaite (1948) correlated mean monthly air temperature with evapotranspiration as determined by water balance studies in valleys of east central USA. His concept has had a major influence on the geographical studies of world climate.

In his formula, potential evapotranspiration is expressed as an exponential function of mean monthly air temperature. A day length factor is then applied to correct for season and latitude. The formula is of the form

$$PET = 1.6(10Ta/I)^m \dots\dots\dots(23)$$

where T_a is the mean monthly air temperature in $^{\circ}C$, I is the annual heat index and m is the cubic function of I empirically determined as:

$$m = (0.675 \cdot I^3 - 77 \cdot I^2 + 17920 \cdot I + 492,390) \times 10^{-6} \dots\dots\dots(24)$$

The annual heat index is a summation of the values of the monthly heat index and is given by the expression

$$I = \sum_{i=1}^{12} i \dots\dots\dots(25)$$

$$i = \frac{\{T_a\}^{1.514}}{5} \dots\dots\dots(26)$$

PET is the unadjusted potential evapotranspiration based on a 12 hour day and 30 day month. By adjusting for the actual day length (L) and days in the month (D), the real value of potential evapotranspiration is obtained as

$$PET^* = PET (L/12) (D/30) \dots\dots\dots(27)$$

where PET* is the adjusted value of the PET.

2.4.2.4.2. Estimating PET

(iv) **Blaney-Morin-Nigeria ET model**

Blaney and Morin (1942) proposed a simple evapotranspiration model, in S. I. Unit of measurement:

$$PET = p(0.45 T + 8) (H - R^m)/100 \dots\dots\dots(28)$$

where PET is the potential evapotranspiration (mm/day) when T and R are daily values of temperature (⁰C) and relative humidity; H and m are empirical constants, and P is the ratio of maximum possible hours of sunshine to the annual maximum. This formula was later abandoned in favour of Blaney-Criddle (1950) model formulated later. Having identified the weakness of the Blaney-Criddle model for Nigeria, Duru (1984) proposed a Nigeria model based on the original equation of Blaney and Morin (1942) and locally determined empirical constants H and m. He

CHAPTER THREE

discovered that by replacing p - the ratio of maximum possible hours of sunshine to the annual maximum, with r_r - the ratio of monthly radiation to annual radiation, the performance of the model was enhanced. The resulting model is given as:

$$PET = r_f(0.45T_m + 8) (520 - R^{1.31})/100 \dots\dots\dots(29)$$

where T_m is the mean monthly temperature in $^{\circ}\text{C}$ and R is the mean monthly relative humidity and other parameters as defined earlier.

2.4 Other Methods of Estimating PET

Other methods of estimating PET as cited in Doorenbos and Pruitt(1977); Jensen (1973); Svehlik(1982); McKenney and Rosenberg(1993) and Amatya et. al. (1995), include: Lowry - Johnson (1942), Makkink (1957), Blaney-Morin (1942), Turc (1961), Papadakis (1966), Jensen-Haise (1963), Priestley and Taylor (1972) Hargreaves (1974), Samani (1985); These are not discussed here because they are rarely used in this part of the world . They are therefore not within the scope of this study.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Study Area

The study area consists of Ibadan (Southwest) and Onne near Port-Harcourt (Southeast). Ibadan lies on the latitude $7^{\circ}30'N$ and longitude $3^{\circ}54'E$ and serve as the main research station of the International Institute of Tropical Agriculture (IITA) while Onne ($4^{\circ}43'N, 7^{\circ}01'E$) is IITA research centre near Port Harcourt. The 24 years mean annual rainfall at Ibadan city (sub-humid zone) is 1250 mm and 2400 mm at Onne (Humid region). The long-term mean annual temperatures in the two areas are not very significantly different. The normal annual maximum temperature varies between 27° and 32° for Onne while minimum temperature ranges from 20 to $23^{\circ}C$ and 21° to $23^{\circ}C$ for both stations, respectively. Wind speed is relatively light in both sites and vegetation varies from mild-hot farm-land/settlements to farm-land/swamp in Ibadan and Onne, respectively.

The soil type for Ibadan is Ferric luvisols while that of Onne is Thionic Fluvisols (Jagtab and Alabi, 1997a). The agroecological features, type and accuracies of meteorological instruments in both location are presented in Tables 1 and 2.

Table 1: Agroecological and Weather Characteristics at Ibadan and Onne

Agroecological Features	Ibadan	Onne
Latitude	7° 30'N	4° 43'N
Longitude	3° 54'E	7° 01'E
Zone	Sub-humid	Humid
Rainfall Pattern	Bimodal	Unimodal
First Season	April-July	March-November
Second Season	August-Nov.	—
Soil Type	Ferric Luvisols	Thionic fluvisols
Vegetation	Mild-hot farm land & Settlement	farmland & swamp
Maximum Temperature		
Range (°C)	27-34	28-32
Minimum Temperature		
Range (°C)	20-23	21-23
Mean Annual Rainfall (mm)	1250	2400

Source: adapted from Jagtab and Alabi 1997 a, b

Table 2: Instrumentation at both sites and their accuracies

Parameter	Instrument	Accuracy	Unit
Evaporation	U.S. Class A Pan	0.01	mm
Temperature	Casella Min. & Max. Thermometer	0.1	°C
Rel. Humidity	HMP35C Temp/RH Probe	2%	%
Solar Radiation	LI200X Pyranometer	3%	MJ/m ² .d
Rainfall	Universal Self-recording Rainguage	0.1	mm
Wind Speed	MET-ONE 014A Wind Speed Sensor	1.5%	m/s

Source: Jagtab and Alabi (1997b)

3.1 Data: Sources and Collection

Meteorological data used in this study were obtained from the IITA data base at Ibadan and Onne. Twenty four years of daily data were available from Ibadan while 10 were available for Onne. The available data at both stations include rainfall, pan evaporation, wind speed, temperature (minimum and maximum), solar radiation, relative humidity (minimum and maximum). These data were collected by trained personnel of the Crop Ecology and Modelling Unit of the International Institute of Tropical Agriculture in Nigeria. The data were found to be consistent and reliable, although there were few cases of missing data mainly due to instrumental failure.

3.2 PET Computations

Data Validation

Validation of data was done particularly for missing data of shorter duration by using regression method of data validation (Shih and Cheng, 1991). Longer periods of omission data were eliminated. Data processing was carried out on a 486 personal computer. A Microsoft Excel version 5.0 software was used to compute decadal, monthly and annual PET from Blaney-Morin-Nigeria model (BMN), Thornthwaite (THON) Penman (PEN) and Penman-Monteith (PM) Formulae. PET was also estimated from pan evaporation by the use of appropriate coefficient (0.8) as recommended by FAO (1986) for sub-humid and humid Tropics. The first two methods are easy to compute while the precise procedures for computing the others are summarised below.

Computational Procedure: BMN and PEN

BMN model was used following the steps outlined by Duru (1984). Sunshine duration needed to compute correction factor to adjust Thornthwaite estimate are interpolated from Tables (FAO, 1986). Thornthwaite model, although developed for total annual estimate of PET, have been widely used for daily, weekly and monthly periods (Amatya et al, 1995, Jensen et al., 1990 and Mohammed, 1978). The method by Penman (1963) was used instead of the well acclaimed FAO-24 Penman since Jagtab and Alabi (1997a) showed that the former is

more accurate in predicting daily, weekly and monthly PET in the study area.

Computation Procedure: Penman-Monteith

Of the methods considered here, PM is the most soundly based on physical principles as well as the most data demanding, (table 3) It requires information on temperature, radiation, humidity, wind speed and vegetation characteristics (stomata resistance, leaf area index and vegetation height). These vegetal characteristics are very difficult to measure, and hence average values drawn from the literature are relied upon for the purpose of PET computations.

The equation used for P-M is stated in equation (20) The procedure outlined by Allen et al., (1989) were followed for computing all terms in the equation.

$$r_c = \frac{r_s}{0.5 \text{ LAI}} \dots\dots\dots(30)$$

where r_c is the average canopy resistance (S/m)

r_s is the average stomata resistance (s/m) and LAI is the Leaf Area Index. To represent a well-watered short grass canopies, $r_s = 100$ s/m was used (Monteith, 1965, Allen et al., 1989).

Leaf Area Index was computed as

$$\text{LAI} = 24 * h_c \dots\dots\dots(31)$$

where h_c is mean grass height (m).

$h_c = 15$ cm was used to represent the upper limit of height as contained in the PET definition.

Data requirement for ET Computations

Four methods of computing PET examined in this study, are classified according to their data requirements (Table 3). Other relevant equations relevant for the use of each of the methods are as outlined in chapter two of this report. PET was computed in the unit of millimetre equivalent of water. f

Table 3: Features of the selected formulae for estimating PET

Method	Main Parameter Required						Period
	T	R _s	RH	U	Lat.	Crop Para.	Recommended
THON	x				x		Annual
BMN	x	x	x				Monthly
PEN	x	x	x	x			Daily, weekly, Monthly
PM	x	x	x	x		x	Daily, weekly, Monthly

T: Temperature; R_s: Solar radiation; RH: relative humidity; U: wind speed;

3.3 Statistical Analysis

Decadal, mean monthly and Total Annual PET were computed using pan evaporation data and the four formulae described above. Regression and Correlation analysis were carried out using the values obtained from the formulae and US class A pan. The Statistical analysis System (SAS) was used at 95% level of significance.

A linear regression model was used:

$$Y = a + bX \dots\dots\dots(32)$$

where Y represent the predicted PET as estimated by each of the methods; X is the observed PET estimated from $0.8 \cdot E_{pan}$ and b and a are slope and intercept, respectively. Decadal data of 360 observations (1985-94) were used, for Ibadan and Onne, for the regressions. Similarly, 120 observations were used for regression of mean monthly estimates versus the mean monthly values of $0.8 \cdot E_{pan}$. The root-mean-square-error (RMSE) parameter, Coefficient of Correlation (R), the slope of the regression, the intercept and the absolute average deviation (AAD) between the calculated and observed PET were used to indicate the goodness-of-fit of PET estimates as compared to the observed US class A PET. Root-mean square error (RMSE) was also used as the main parameter for evaluating the reliability of methods in predicting PET at each location. A close fit is indicated by low AAD, Intercept close to zero; slope approaching unity, and high value of R (Parmele and McGuinness, 1974, Amatya et. al., 1995)

Average Absolute Deviation (ADD) is defined in this work as:

$$ADD(\text{mm/day}) = 1/N_o \sum \text{ABS}(\text{PET}_{\text{pan}} - \text{PET}_{\text{estimated}}) \dots \dots \dots (33)$$

Where, N_o is the number of observations.

The methods of sensitivity analysis outlined in Campbell and Norman (1990) and Mc Kenney and Rosenberg (1993) were used.

3.4 Model Development

In this study, we attempted to relate evaporation of class A pan (E_p) with PET from estimating models and relative humidity. This is with a view of developing a simplified model for generating PET with an acceptable level of accuracy. A similar work was carried out by Baldy (1978) for Sudano-Sahelian countries using Burkina Faso as a case study.

In this study, we used a MicroCal-Origin Version 2.75 software for model fitting. Testing and validation were done using a separate set of data from that used for model fitting. The reliability was therefore ascertained by comparing the output of the predicted values from the simplified model with the observed data. The simplified model is of the form:

$$\text{PET} = f(E_p, \text{RH}) \dots \dots \dots (34)$$

The equation obtained by of Baldy (1978) for Burkina Faso is given as

$$\frac{E_{\text{pan}}}{\text{PEN}} = 2 - 1.55 \cdot \text{RH} \dots \dots \dots (35)$$

where 2 and 1.25 are fitted constants.

The general form of the equation fitted here is :

$$PET_i = \frac{E_{pan}}{p - q \cdot RH} \dots\dots\dots(36)$$

Where PET_i represent any of the four estimating methods; p and q are the constant that must be evaluated and other parameters as previously defined

CHAPTER FOUR

RESULTS AND DISCUSSION

This section deals with the assessment of four methods of estimating potential evapotranspiration in the humid and sub-humid regions of Nigeria. Firstly, the number and the ease of measurement of input parameters required by each of the formulae were compared. Secondly, the results obtained using these formulae were statistically analysed.

4.0 A Brief Comparison of Input Parameters

Table 3 summarises the input parameters required by each method. In this study, these four models were compared:

(i) Thornthwaite (THON), (ii) Blaney-Morin-Nigeria-model (BMN), (iii) Penman (PEN) and (iv) Penman-Monteith (PM). Penman-Monteith followed by Penman are the most data demanding. Thornthwaite required only the mean air temperature. Most of the inputs required by PM and PEN are difficult and/or costly to measure. Apart from the inherent errors generally common with empirical and semi-empirical models, there is, in addition, the cumulative effect of instrumental errors which can be important. Stomata resistance for example, is very difficult to measure in a developing country such as Nigeria where instrumentation is very poor.

The methods which require fewer input parameters, but high comparable accuracy is therefore preferred to others. In this regard BMN model seemed

outstanding since its accuracy judging from the results (showed later in this study), was high comparable to PM's and atimes, equalled or better that of the PEN. Furthermore BMN required less than 50% of the inputs required by PEN and PM. BMN was the most easily computed of all the four methods as its computation was even more straight-forward than THON which is the most empirically based.

4.1 Comparisons of PET Values:

4.1.1 On Annual Basis

The annual PET, standard deviation and coefficient of variation for both stations are summarised in Tables 4 and 5. THON model produced the highest annual values at all locations and Penman-Monteith the lowest. The difference between the relative error of THON and PM was about 67% in Onne and up to 38% in Ibadan. On the average BMN and PEN over estimated the observed PET (Epan) by 20% and 33% at both locations. At Ibadan the computed PET as given by BMN was closest to PM. The mean annual PET predicted was compared with the observed PET (Epan) as presented in Figure 1. For easy comparison, relative differences is defined as:

$$\text{Relative Difference, RD} = \frac{\text{PET}(\text{by a method}) - \text{Epan}}{\text{Epan}} \dots\dots\dots(37)$$

The values of RD obtained for each of the methods are shown in Figure 2. All the methods, except THON, estimated higher PET values in Ibadan and relatively lower values at Onne. This result was expected because Ibadan is located on a higher latitude (Duru, 1984).

Table 4: Annual total PET, the mean, standard deviation, and coefficient of variation using the four selected models at Onne

YEAR	Epan (mm)	PET FROM FOUR selected METHODS (mm)			
		THON	BMN	PEN	PM
1985	985.0	1868.0	1476.9	1448.3	1095.7
1986	1015.3	1637.0	1295.5	1276.9	1011.3
1987	925.1	1848.3	1350.3	1347.8	1047.7
1988	912.6	1745.8	1288.0	1289.1	1009.3
1989	945.3	1647.4	1341.9	1304.7	1023.6
1990	873.9	1710.9	1338.0	1319.6	1029.4
1991	911.6	1610.2	1287.3	1256.9	995.2
1992	929.8	1597.3	1328.7	1285.3	1008.6
1993	975.7	1599.2	1305.9	1270.3	1000.3
1994	937.1	1642.8	1294.0	1261.5	995.4
MEAN	941.1	1690.7	1330.5	1306.0	1020.9
STDEV	41.2	100.2	56.7	57.2	30.2
C.V.	0.044	0.059	0.043	0.044	0.030
% ERR	-	69.1	33.1	30.6	2.1

STDEV-- Standard Deviation; C.V. - Coefficient of Variation; %ERR- Percentage error;

*The symbols for the models are as defined in the list of symbols

Table 5: Annual total PET, the mean, standard deviation, and coefficient of variation for the four selected model at Ibadan

YEAR	Epan (mm)	PET FROM FOUR SELECTED METHODS (mm)			
		THON	BMN	PEN	PM
1985	1199.3	1640.5	1471.0	1591.1	1202.7
1986	1119.3	1576.5	1430.7 00	1548.9	1180.7
1987	1262.9	1813.0	1440.1	1611.9	1217.3
1988	1182.4	1672.7	1432.4	1573.3	1193.0
1989	1305.3	1596.7	1478.0	1578.8	1195.3
1990	1269.8	1688.7	1402.6	1565.3	1190.8
1991	1155.1	1671.1	1400.4	1553.7	1186.9
1992	1204.4	1623.9	1481.7	1595.4	1206.5
1993	1174.3	1639.5	1415.8	1556.8	1186.1
1994	1139.1	1619.2	1505.4	1601.4	1202.3
MEAN	1201.2	1654.2	1446.0	1577.7	1196.2
STDEV	60.7	65.8	36.1	21.7	11.1
C.V	0.051	0.040	0.025	0.014	0.009
% ERR	-	37.7	20.4	33.6	0.42

STDEV-- Standard Deviation; C.V. - Coefficient of Variation;

%ERR- Percentage Error;

*The symbols for the models are as defined in the list of symbols.

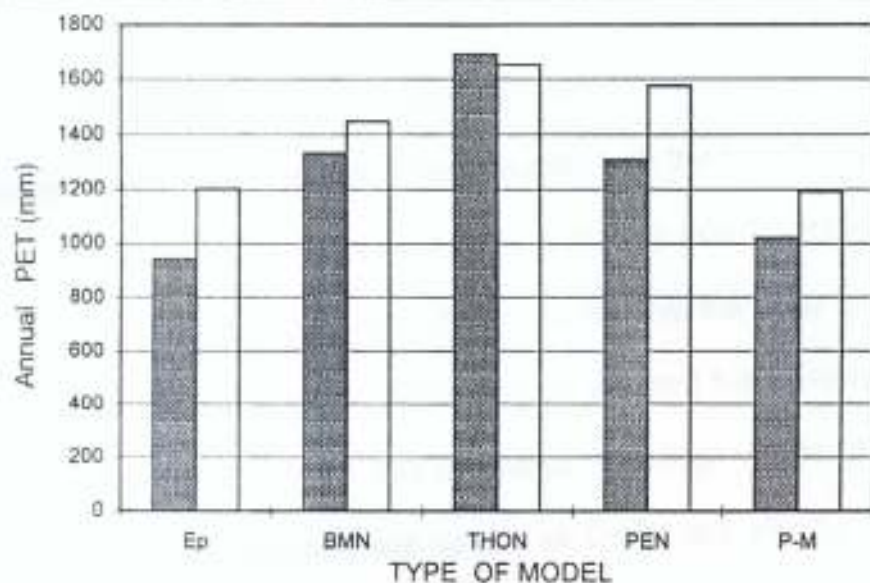


Figure 1: Mean Annual Potential Evapotranspiration (PET) predicted by the four methods against the Observed (Epan) at Onne and Ibadan

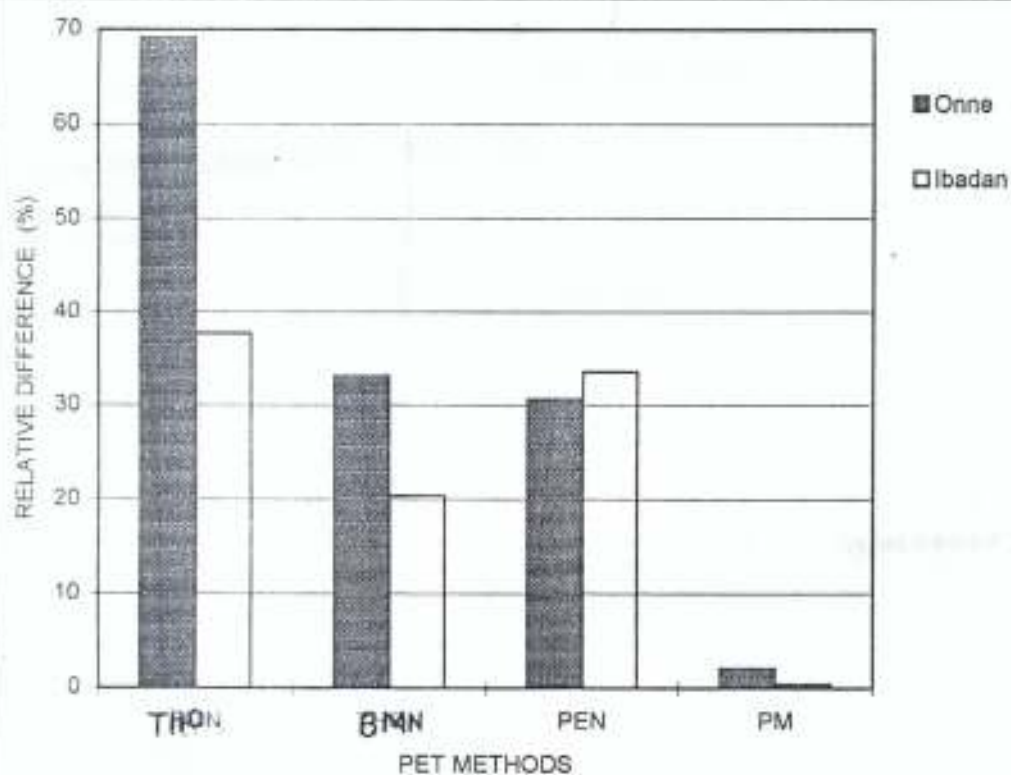


Figure 2: Relative difference of annual PET by each of the methods at Onne and Ibadan

Thornthwaite, a highly empirical model, greatly over-estimated pan PET when compared with other models. This disagrees with the results obtained by McKenney and Rosenberg (1993), and Amatya et al (1995); that Thornthwaite usually under-predicts PET. This is most likely due to the fact that the study area is humid with high degree of tropical hotness, which is quite different from a very humid environment where Thornthwaite model was calibrated. The high values of relative humidity notwithstanding the Thornthwaite values at Onne, are slightly higher than those of Ibadan, and very sensitive to increase in air temperature.

Tables 4 and 5 show that Penman-Monteith predicted PET with very high accuracy, confirming studies made by Amatya et al (1995); McKenney and Rosenberg, (1993); and Allen et al (1989). Blaney-Morin - Nigeria model ranked next to the PM using Ibadan data unlike Onne data. This sharp difference could be attributed to the fact that relative humidity is a very important input in the BMN to which is not so in the other models considered.

4.1.2 On Monthly Basis

Monthly total PET (mm) for the four methods were compared using the observed PET(Epan) as reference. Potential evapotranspiration seemed to have bimodal pattern in the study area. The two peaks occurred between January and March and between September and November. As shown in figures 3(a and b), all the 4 models consistently over-predicted PET. The values obtained using PM gave the best prediction at both sites. At Onne, the more humid region, BMN lagged behind PEN in accuracy and while in Ibadan PEN lagged behind BMN. Thornthwaite was the outlier of all the methods with highest percentage of over prediction error. There were generally lower values of PET between April and September with the lowest value occurring around May/June in Onne and April/May in Ibadan.

Higher values of PET between October and March could be attributed to high solar radiation, temperature and windiness during this period. From late November to early February, there was always harmattan (Northeast trade wind) with its characteristics dry air which might explain the atmospheric demand for water as revealed by the higher values of PET. Harmattan, is usually accompanied by an intense solar radiation especially in the afternoon and clear sky or little or no cloudiness in February/March. This gives rise to high sensible heat which in turn affects evaporation. There was generally a sharp decrease in monthly PET as from April. This reduction in monthly PET extended to end of October. In the decreasing order, accuracy for total mean monthly PET over the 10 years of record (1985 - 1994) used in study areas can be expressed as:

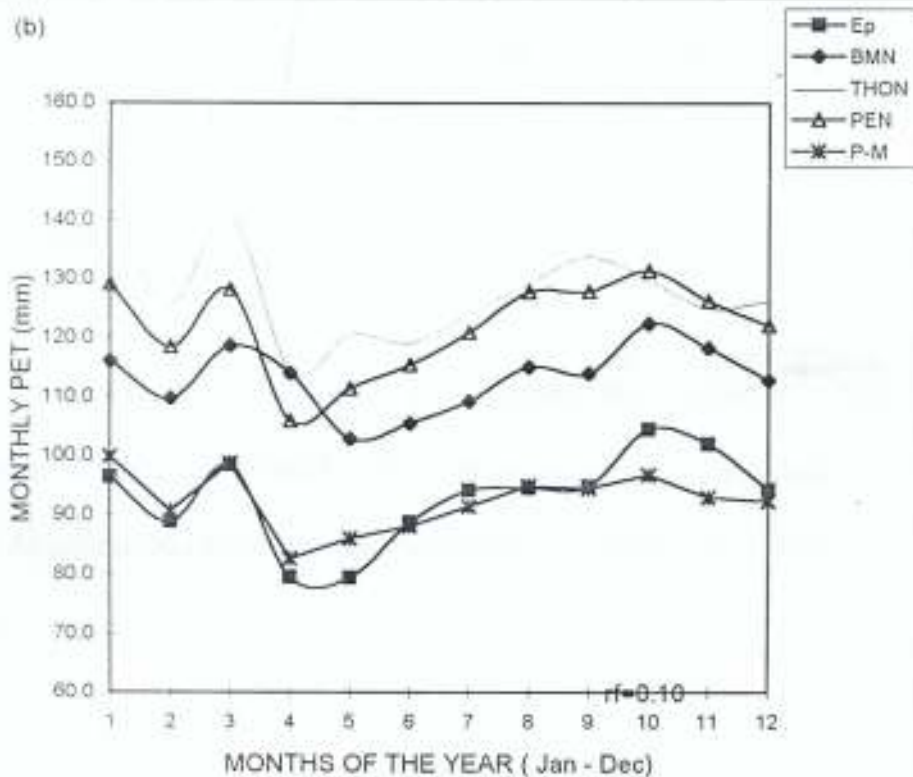
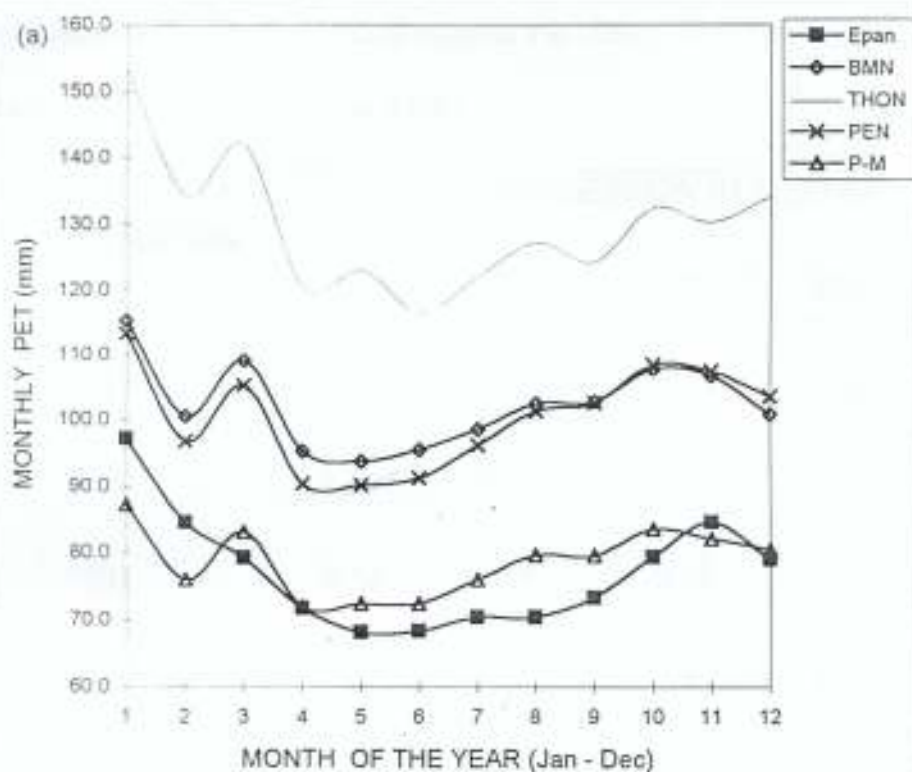


Figure 3: Monthly PET predicted by the four models at (a) Onne, (b) Ibadan

Table 6: Summary statistics for regression of mean monthly pet (daily value) estimated by the four methods against the observed pet estimated from class A evaporimeter ($Y = a + bX$).

LOCATION	METHOD OF ESTIMATION	REGRESSION STATISTICS				
		a	b	R	RMSE	AAD
ONNE	THON	2.76	0.73	0.68	0.28	0.40
	BMN	1.28	0.92	0.82	0.19	0.38
	PEN	0.56	1.17	0.82	0.31	0.44
	PM	1.01	0.70	0.81	0.12	0.28
IBADAN	THON	1.99	0.77	0.72	0.35	0.42
	BMN	1.19	0.84	0.89	0.12	0.27
	PEN	0.98	1.02	0.90	0.15	0.32
	PM	0.55	3.29	0.90	0.04	0.17

a -- Intercept of the regression model (mm); b -- Slope of the regression model;

R -- Coefficient of correlation; RMSE - Root mean square error (mm/day);

AAD - Average Absolute Deviation between predicted and observed values

(mm/day).

PM > BMN > PEN > THON

The mean monthly daily values of PET using selected models were related to the values of Epan (the observed) in linear regression. The basic statistical parameters are shown in Table 6. Penman-Monteith appeared to give the best predicting equation having the lowest Root-Mean-Square-Error (RMSE) and Average Absolute Deviation (AAD) and comparatively high correlation coefficient at both sites. Thornthwaite was poorly correlated. It gave the highest RMSE and AAD values in Ibadan while only its RMSE statistic was the second highest in Onne. The slope ranged from 0.73 - 0.77 and the intercept varied from 1.99 to 2.76. Blaney-Morin-Nigeria model performed better than Penman judging from the result of their RMSE and AAD statistics. Both have the same correlation coefficients, although Penman slopes and intercepts indicated a slightly better fit than BMN. The Root-Mean-Square error is the most important of the regression statistics on which the judgement of accuracy or fitness depends. The performances of all the estimation methods, except THON, were better at Ibadan than at Onne since RMSE and AAD were far less in magnitude in Ibadan. The RMSE lies between 0.04 and 0.35, AAD ranged from 0.17 to 0.44 while the correlation was between 0.68 and 0.90 in the study area.

These results are in agreement with that of Jensen et al (1990) and FAO (1990) who ranked PM the best performing combination equation in

Table 7. Summary statistics for regression of mean decadal PET (daily value) estimated by the four methods against the observed pet estimated from class A evaporimeter ($Y = a + bX$).

LOCATION	METHOD OF ESTIMATION	REGRESSION STATISTICS				
		a	b	R	RMSE	AAD
ONNE	THON	2.45	0.56	0.58	0.43	0.51
	BMN	0.82	1.02	0.80	0.41	0.50
	PEN	1.05	0.90	0.77	0.41	0.52
	PM	1.30	0.53	0.75	0.15	0.32
BADAN	THON	2.18	0.74	0.60	0.77	0.65
	BMN	0.85	0.98	0.76	0.53	0.57
	PEN	1.39	0.89	0.85	0.23	0.39
	PM	1.69	0.48	0.85	0.07	0.21

a -- Intercept of the regression model (mm); b -- Slope of the regression model;

R -- Coefficient of correlation; RMSE - Root mean square error (mm/day);

AAD - Average Absolute Deviation between predicted and observed values (mm/day)

the absence of the measured evaporation data. Similarly the relative better performance of BMN over PEN completely agreed with the outstanding work of Duru (1984). In contrast to the PM, Root-Mean-Square error and average absolute deviation in respect of THON is well over the overall average by over 50% and 40% respectively.

4.1.3 On Decadal Basis

Summary of statistics of mean daily PET for decadal (10 days) periods are presented in Table 7. For both locations, slopes and intercepts ranged from 0.53 - 1.02 and 0.82 - 2.45, the coefficient of correlation R for the decadal value was generally lower than the corresponding mean monthly values of R and ranged between 0.58 and 0.85 at both locations, the RMSE and ADD statistics were characterised by slightly high values, and this reduced decadal accuracy. The RMSE was between 0.07 and 0.77 whereas AAD ranged from 0.21 - 0.65.

Penman-Monteith, as usual, was rated best with lowest RMSE and AAD values and very high correlation coefficients. Based on the overall average values, P-M had about 65% and 30% lower values of RMSE and AAD respectively. Thornthwaite was the poorest performing method, with lowest R and highest values of RMSE and AAD.

The average values of RMSE and AAD were found for the four methods and compared with values for THON alone. THON gave 50% for RMSE , 40% for AAD above the average values obtained for the four methods combined . The computed statistics show

that BMN is more accurate in Onne than Ibadan and PEN performed better than BMN in Ibadan. Although their RMSE value were the same in Onne, BMN had a better AAD and R, its intercept was closer to zero and slope approaches unity. At Ibadan, PEN equation performed better than BMN, when considering its higher value of R, lower values of RMSE and AAD.

The low degree of fitness in decadal PET was due to a few extreme values which are suppressed in monthly averages. The improved performance of PEN in Ibadan may be due to a slightly increase in windiness, a key parameter. Since windiness is relatively lower in Onne and thus resulted in the better performance of BMN at Onne.

4.2 Equality Of Regression Equation

The least squares regression analysis performed with Epan, and each of the four methods as the dependent variable, were compared in pairs to test their parallelism, the equality of their intercepts and that of their correlation coefficients. The models were arranged in four "Combination" two (4C_2) given six set of pairs listed in Tables 8,9 and 10.

The Z-test was used in determining the equality of regression equations (Kleinbaum and Kupper, 1978). The difference in the tested parameters, estimates of the variance of their estimated parameters as well as the computed

Table 8 : Computed parameters and test statistics to test for equality of slopes of two Regression lines

Period	Combination of Methods	Onne				Ibadan			
		DES	RSVS	Z	Rk	DES	RSVS	Z	Rk
Monthly basis (N=120)	THON&BMN	-0.19	0.0499	3.808	Re	-0.07	0.0792	0.884	Re
	THON&PEN	-0.44	0.0554	7.941	Re	-0.25	0.0824	3.034	Ac
	THON&PM	+0.03	0.0458	0.655	Ac	+0.22	0.0730	3.014	Ac
	BMN&PEN	-0.25	0.0512	4.884	Re	-0.18	0.0599	3.005	Ac
	BMN&PM	+0.22	0.0406	5.416	Re	+0.29	0.0462	6.277	Re
	PEN&PM	+0.47	0.0472	9.953	Re	-0.45	0.0514	8.758	Re
Decadal basis (N=360)	THON&BMN	-0.46	0.1001	4.593	Re	-0.24	0.0684	3.504	Re
	THON&PEN	-0.34	0.1002	3.393	Re	-0.15	0.0601	2.493	Ac
	THON&PM	+0.03	0.0837	0.358	Ac	+0.26	0.0550	4.730	Re
	BMN&PEN	+0.12	0.0987	1.215	Ac	+0.09	0.0524	1.716	Ac
	BMN&PM	+0.49	0.0820	5.977	Re	+0.50	0.0463	10.78	Re
	PEN&PM	+0.37	0.0820	4.512	Re	+0.41	0.0329	0.080	Ac

Z (tabulated value of the statistic at $\alpha = 0.001$) = 3.291

DES -- Difference in Estimated Slopes ; RSVS -- Root-sum-of the variances of the slopes; Z - Absolute value of the computed test statistics; Re - Reject the null hypothesis (H_0); Ac-Accept the null hypothesis; Rk -- Remarks

Table 9: Computed parameters and test statistics to test for equality of intercepts of two regression lines

Period	Combination of Methods	Onne				Ibadan			
		DEI	RSVS	Z	Rk	DEI	RSVS	Z	Rk
Monthly basis (N=120)	THON&BMN	+1.48	0.2462	6.012	Re	+0.80	0.2680	0.999	Ac
	THON&PEN	+2.20	0.2735	8.044	Re	+1.01	0.2787	3.623	Re
	THON&PM	+1.75	0.2261	7.742	Re	+0.52	0.2470	2.105	Ac
	BMN&PEN	+0.72	0.2526	2.851	Ac	+0.21	0.2025	4.939	Re
	BMN&PM	+0.27	0.2002	1.3481	Ac	-0.28	0.1559	6.415	Re
	PEN&PM	-0.45	0.2330	1.931	Ac	-0.49	0.1735	5.764	Re
Decadal basis (N=360)	THON&BMN	+1.63	0.1658	9.829	Re	+1.33	0.2983	4.458	Re
	THON&PEN	+1.40	0.1658	8.442	Re	+0.79	0.2621	3.014	Ac
	THON&PM	+1.15	0.1386	8.299	Re	+0.49	0.2396	2.045	Ac
	BMN&PEN	-0.23	0.1637	1.405	Ac	-0.54	0.2283	2.366	Ac
	BMN&PM	-0.48	0.1360	3.529	Re	-0.84	0.2020	4.159	Re
	PEN&PM	-0.25	0.1360	1.838	Ac	-0.30	0.1432	2.095	Ac

Z (tabulated value of the statistic at $\alpha = 0.001$) = 3.291

DEI -- Difference in Estimated Intercepts; RSVS - Root-sum-of the variances of the Intercepts; Z -- Absolute value of the computed test statistics; Re -- Reject the null hypothesis (H_0); Ac -- Accept the null hypothesis; Rk -- Remarks

Table 10: Computed parameters and test statistics to test for equality of correlation coefficients of two regression lines

Period	Combination of Methods	Onne				Ibadan			
		DFT	RSVR	Z	Rk	DFT	RSVr	Z	Rk
Monthly basis (N=120)	THON&BMN	-0.31	0.131	2.394	Ac	-0.53	0.131	4.094	Re
	THON&PEN	-0.32	0.131	2.487	Ac	-0.57	0.131	4.431	Re
	THON&PM	-0.28	0.131	2.170	Ac	-0.58	0.131	4.431	Re
	BMN&PEN	-0.01	0.131	0.093	Ac	-0.04	0.131	0.305	Ac
	BMN&PM	+0.29	0.131	0.224	Ac	-0.05	0.131	0.392	Ac
	PEN&PM	+0.04	0.131	0.317	Ac	-0.01	0.131	0.081	Ac
Decadal basis (N=360)	THON&BMN	-0.44	0.075	5.879	Re	-0.32	0.075	4.27	Re
	THON&PEN	-0.34	0.075	4.550	Re	-0.58	0.075	7.706	Re
	THON&PM	-0.31	0.075	4.140	Re	-0.58	0.075	7.755	Re
	BMN&PEN	+0.10	0.075	1.317	Ac	-0.26	0.075	3.442	Re
	BMN&PM	+0.13	0.075	1.727	Re	-0.26	0.075	3.490	Re
	PEN&PM	+0.03	0.075	0.413	Ac	-0.003	0.075	0.048	Ac

Z (tabulated value of the statistic at $\alpha = 0.001$) = 3.291

DFT -- Difference in Fisher's Transformation for the Regression Coefficients;
 RSVS -- Root-sum-of the variances of the Correlation Coefficients; Z -- Absolute
 value of the computed test statistics; Re -- Reject the null hypothesis (Ho); Ac --
 Accept the null hypothesis; Rk -- Remarks.

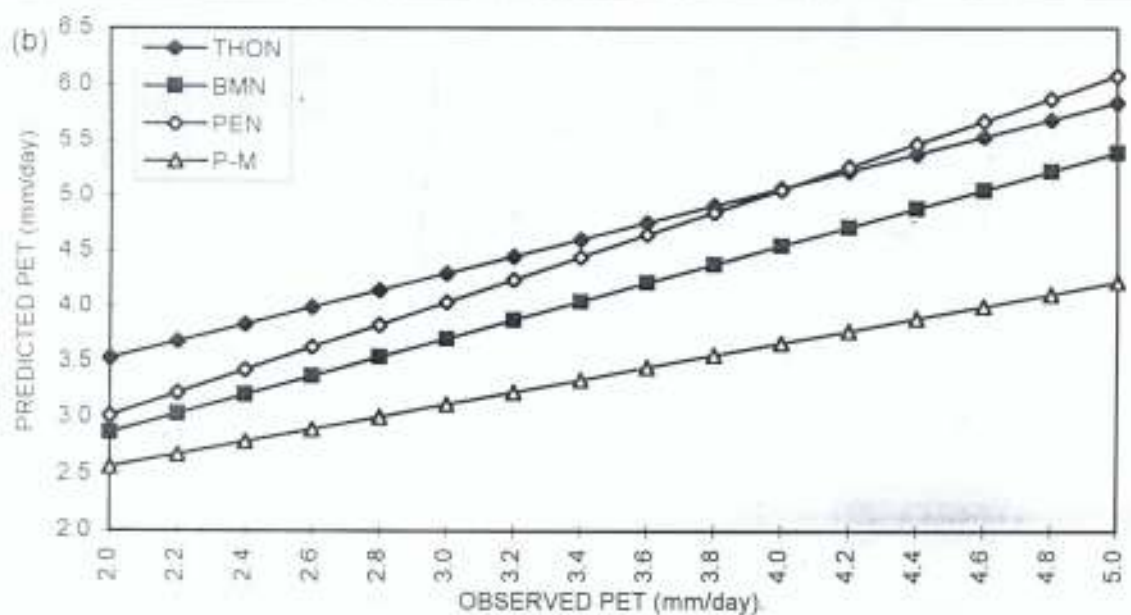
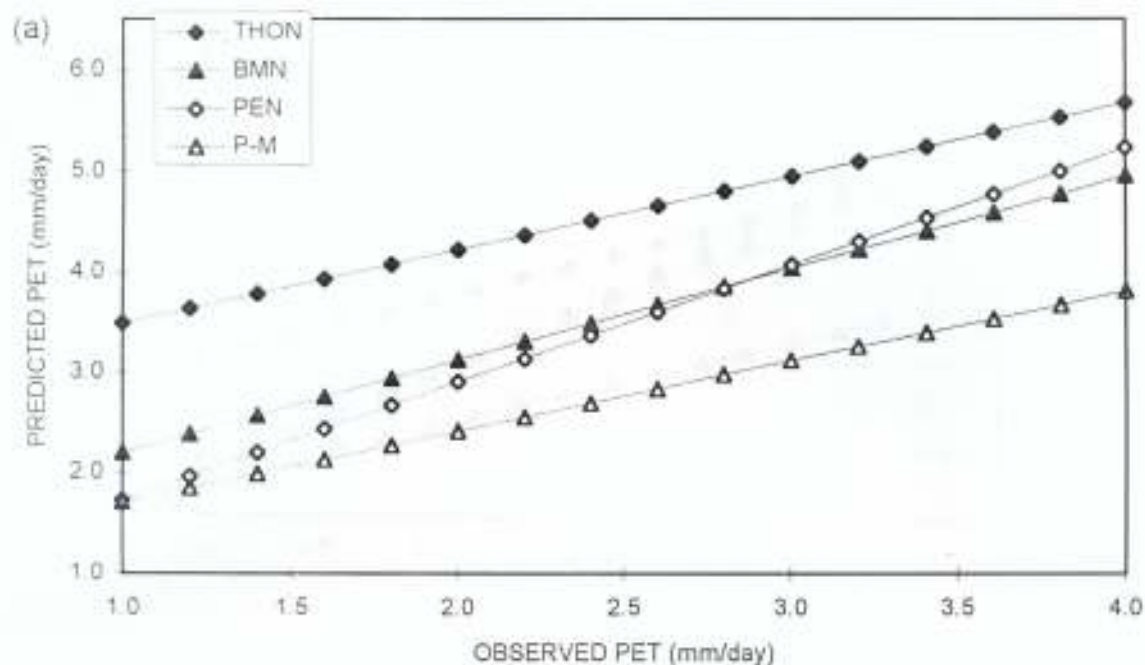


Figure 4: Comparison of regression lines for the four models using monthly data at (a) Onne, (b) Ibadan.

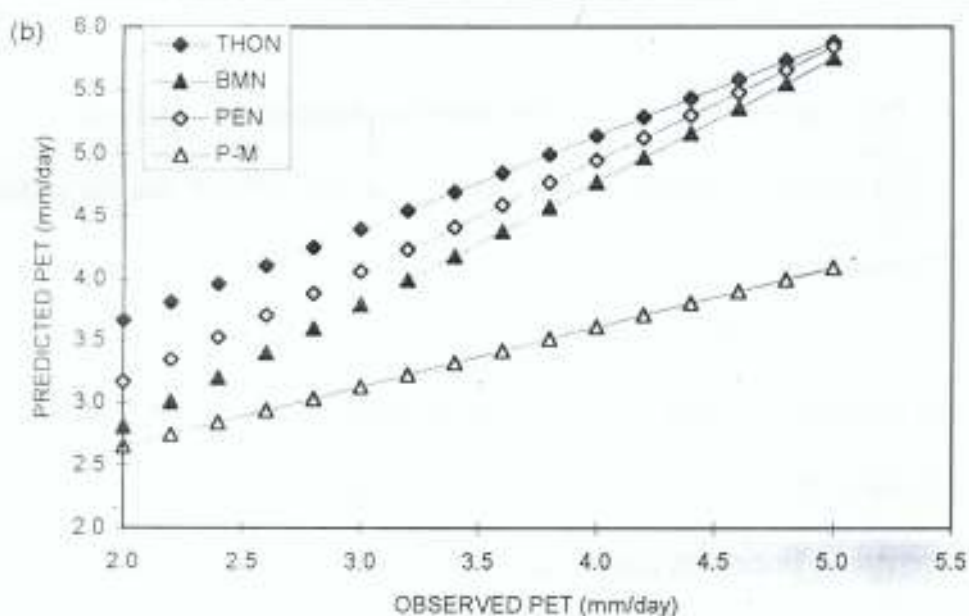
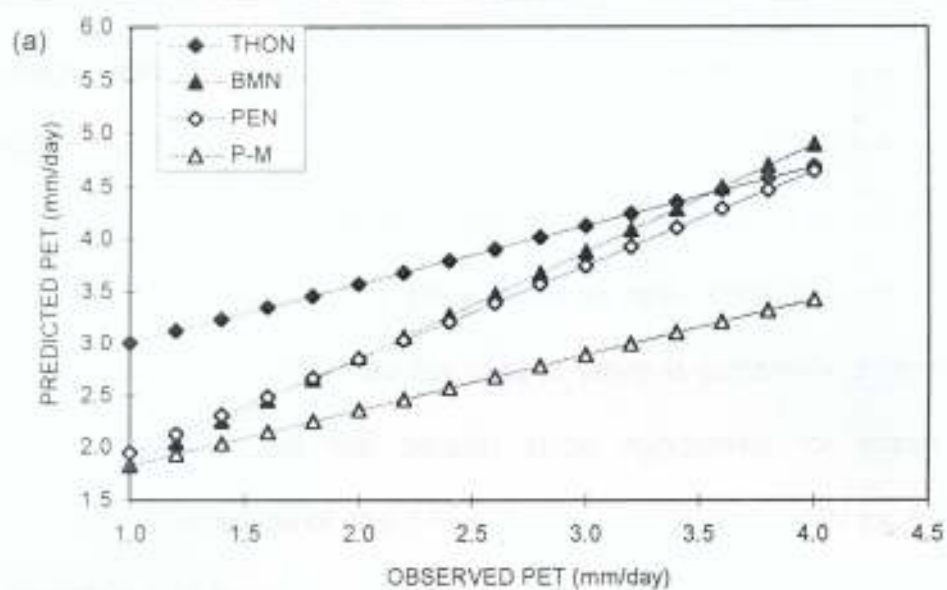


Figure 5: Comparison of regression lines for the four models using decadal data at (a) Onne, (b) Ibadan

Z-statistic are presented in Tables 8, 9 and 10. Formulae used in computing the Z-statistic and the hypotheses proposed are stated in Appendix I. The comparison between the regression lines are presented in Figures 4 and 5.

At 0.001 level of significance, the slopes of BMN vs. P M and PEN vs. PM reject the hypothesis of equal slope while all other combinations accept the hypothesis at Ibadan. However the case in Onne is extremely different as only THON vs. P M accept the parallel slope hypothesis for mean monthly comparison. The results of the Z-test, THON vs. PM and BMN vs. PEN accept the hypothesis of equal slopes for mean decadal value at Onne while THON-PEN, BMN-PEN, and PEN-P·M have their slopes statistically similar in Ibadan (Figure 4).

Similarly, the equality of intercepts were also investigated. For mean monthly values, THON-BMN and THON-PM, at Ibadan accepted null hypothesis H_0 of equality of intercept whereas other combinations rejected the null hypothesis. However, at Onne, THON-BMN, THON-PEN and THON-PM combination accepted the alternative hypothesis(H_a). On decadal basis , both BMN-PEN and PEN-PM accepted null hypothesis at Onne while THON-BMN and BMN-PM combination rejected null hypothesis at Ibadan.

The degrees of linearity, as indicated by the values of regression coefficient, were also compared. Fisher's Z transformation was used to compute the test statistic (Appendix I). Table 10 shows the difference in Z-transformation as well as the test statistic. The table of standard normal cumulative probabilities for the tabulated test statistic is shown in appendix II. The degrees of linearity

are relatively higher with monthly value at both sites than for decadal values. For monthly and decadal periods, all the methods showed higher R values in Ibadan than Onne except for BMN (decadal) which is an outlier. At 0.001 level of significance, the regression coefficients are statistically similar in the study area except: THON&BMN, THON&PEN and THON&PM in Ibadan, and for decadal values at Onne, there is no significant difference in the regression coefficients of PEN and PM lines but for the other combinations.

These results show that, Thornthwaite method consistently predicted higher values of PET than PM, but the rate of change in PET with respect to Epan was the same for both equations. In addition, there was significant difference in the strength of linearity for both methods. This is evident in that evaporation process is not analytically accounted for in THON compared with PM. Penman, Penman-Monteith and Blaney-Morin- Nigeria model have statistically similar correlation coefficient except BMN at Ibadan for decadal values. This is likely due to resemblance in data requirement of PEN and PM and the fact that BMN is a locally calibrated formula. Equality statistics shows an irregular pattern for THON, BMN and PEN since there are differences in slopes and intercepts and correlation coefficients (Figures 4 a, b and 5 a, b). This means that the relationship between PET and Epan is different for different methods in the sense that both have different origins and rates of change. The trend is most likely due to their varied structures, input requirements, and place of calibration of each of the formulae.

4.3 Sensitivity Analysis

The responses of the selected models to changes in their input parameters were examined. Five input parameters (Temperature, wind speed, relative humidity, solar radiation and radiation ratio) were varied to simulate the climatic change over the study area (Table 11). While higher mean values of wind speed and radiation ratio are found in Ibadan, other three parameters have higher values at Onne. Generally, the degree of variability and extreme values in Onne was lower than at Ibadan as shown by their standard deviations. This is so because solar radiation and wind speed decrease with increase in humidity (Jagtab and Alabi, 1997a). Difference of about 1^oC in temperature between the two zones agreed with the report of Duru (1984) that temperature does not vary widely over Nigeria. The effect of each outlined parameters on the respective PET estimation models was evaluated following the baseline values of PET computed for each of the locations.

4.3.1 Effect Of Change in Temperature On PET

Figures 6a, b show the percentage change in PET in response to a change in temperature for Onne and Ibadan . Sensitivity to temperature change was assessed for each of the methods by varying temperature over a wide range of -4 to + 6^o C in 2^o C increments. The values are computed as a percentage change to allow the slope to be more easily compared and to remove any differences in the choice of baseline values. Thornthwaite is most sensitive to temperature change while Blaney-Morin-Nigeria model is the least. Penman

Table 11 Mean climatic parameters showing the average (Ave), maximum (Max.), minimum (Min) value and standard deviation (Std) over a period of ten years (1985-1994) in the study area.

Parameter	Unit	Onne				Ibadan			
		Max.	Min	Ave.	Std	Max.	Min	Ave.	Std
Temperature	°C	29.7	24.4	26.7	1.09	28.6	24.9	26.5	1.26
Wind Speed	Km/h	4.65	0.91	3.25	0.71	4.84	2.98	3.87	0.65
Relative Humidity	%	88.4	63.5	78.4	5.71	82.8	60.8	73.9	8.12
Solar Radiation	mm	16.2	11.7	13.7	1.25	22.3	14.2	17.1	2.01
Radiation ratio	mm/ mm	983	711	834	076	1040	731	859	092
	(x 10 ⁻⁴)								

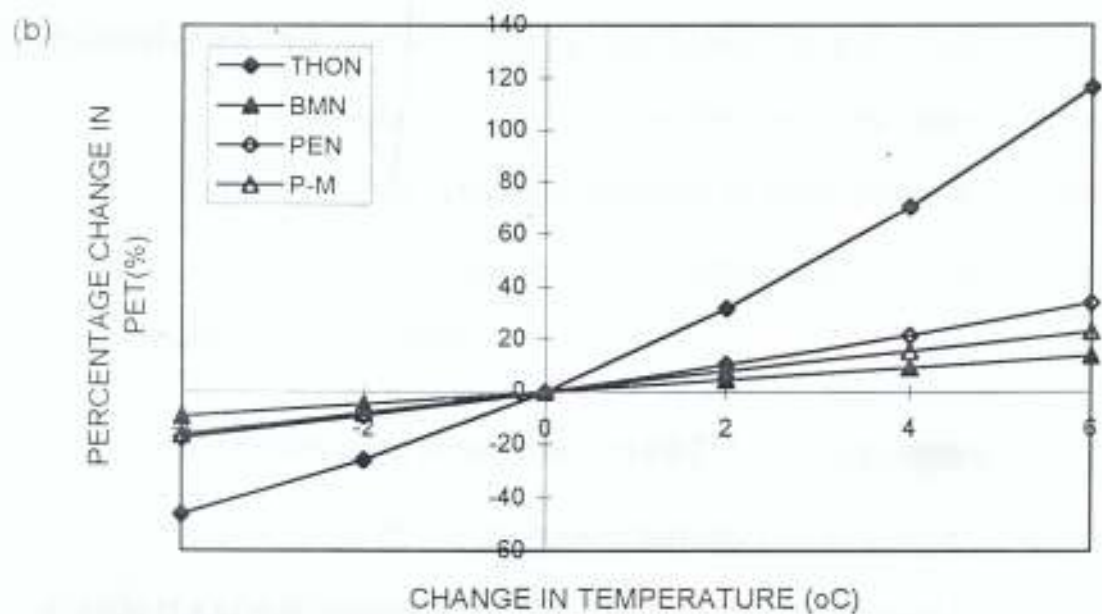
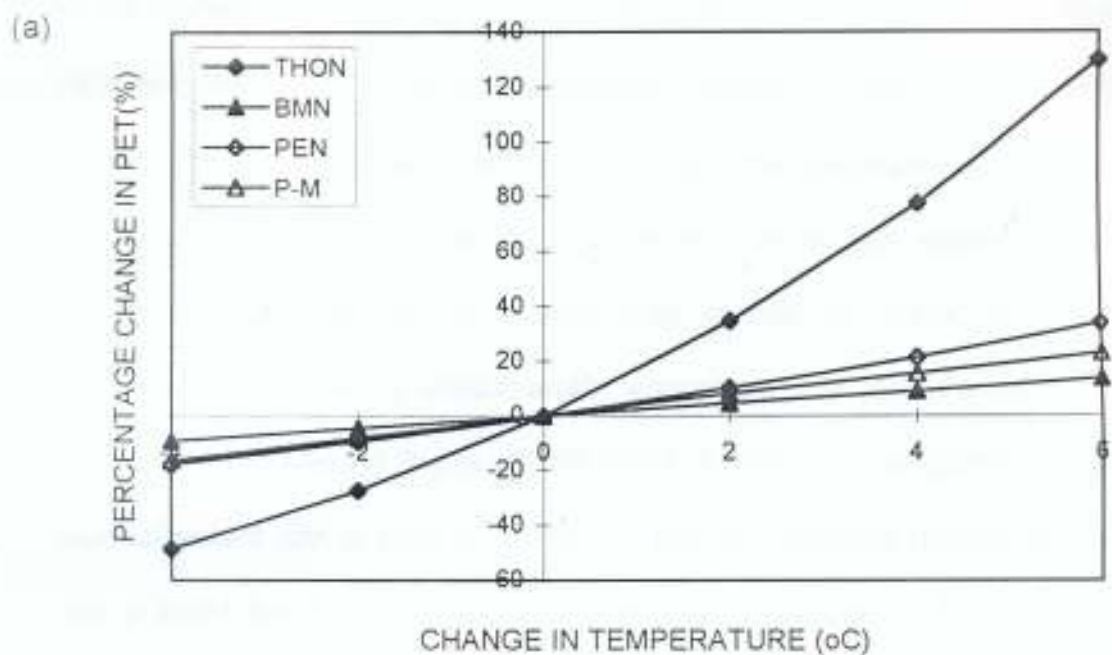


Figure 6: Effect of Change in Temperature on PET for the four models at (a) Onne, (b) Ibadan

followed by Penman-Monteith are in between the two. The relative sensitivity of all the models varied with location and time of the year. The responses of BMN, PEN and PM were linear and remarkably similar, in spite of their different structure and data requirements, over the range of temperature examined.

A non-linear response to temperature change was apparent with the THON formula: The rate of change was greater at higher temperatures, particularly during the dry season and/or warmer periods. It was evident that, for the four models used in this study, the effect of changes in temperature on PET was consistent with a clear-cut pattern in the two locations (Fig.6a, b). There was a slight trend towards increasing slope from Ibadan to Onne for all the equations. THON appeared to be the only outlier. At warmer location, Thornthwaite PET showed a response to temperature which was much greater than that of the other methods, leading us to believe that the values estimated by this method were unrealistically high. Hence, the use of the method should be avoided because it is not sufficiently sensitive in areas where temperature is relatively constant while other meteorological factors which promote evaporation vary considerably (Duru, 1984).

4.2.2 Effect Of Changes In Humidity On PET

The response of PET to changes in humidity was examined using a range of $\pm 30\%$ at increments of 10%. The results are presented in Figures 7a, b. Thornthwaite method is not sensitive to humidity. For the three other methods, the responses of PET to change in humidity was linear at Ibadan (Sub-humid locations) and non-linear at Onne

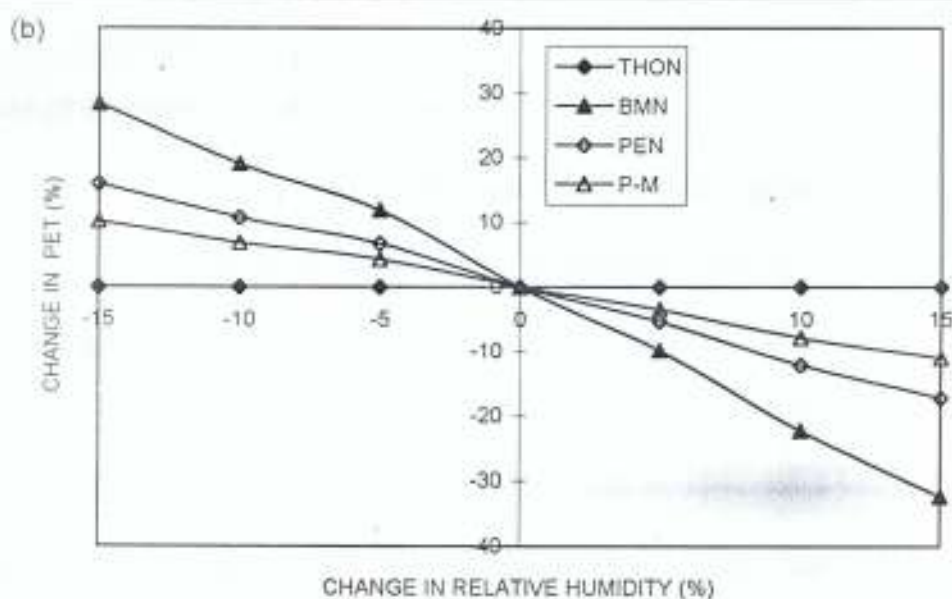
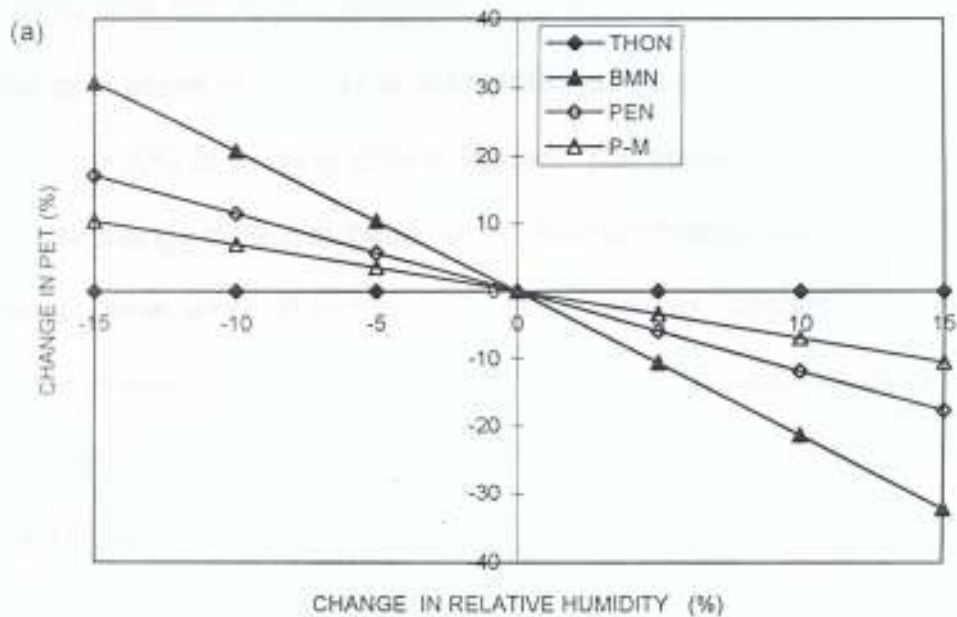


Figure 7: Effect of Change in Relative Humidity on PET at (a) Onne, (b) Ibadan

(humid location) over the range considered. Blaney-Morin-Nigeria model was the most sensitive to changes in humidity at both locations. Response to a 15% change ranged from about 30% at Onne to 28% in Ibadan. The same 15% change caused between 16-18% change in PET at Ibadan when Penman method was used, and 10-11% change at Onne when Penman-Monteith method was compared. Apart from the fact that the slopes show a slight trend of increments from sub-humid to humid regions, the negativity of slopes were evident. This implies that the PET is inversely related to humidity and clearly explains while PET tends to decrease with increase in humidity. The result showed that the effect of humidity on PET cannot be overlooked or neglected particularly where this parameter varies widely as it is the case in the study area

4.3.3 Effect of Changes in Solar Radiation on PET

Two of the methods compared PEN and PM use solar radiation (SR) as an input while Blaney-Morin-Nigeria model uses the radiation ratio (r_f). Solar radiation was varied over a range of 10.0 mm and 18.0 mm of water at 10.0 mm, 12.0 mm, 15.0 mm, and 18 mm of water respectively. The radiation ratio was tested over a range of 0.04 - 0.10 at increments of 0.02.

Figures 8a,b and 9a, b show the change in PET in response to changes in solar radiation at both locations. The effect of solar radiation ratio on BMN is shown in Figures 10a, b. Both PEN and PM predicted the response of PET to SR in a curvi-linear manner. While the line graphs for PEN have a general upward curve over the range examined, there is a corresponding downward curve in PM line graphs. About 20% change in the variable caused an approximate change

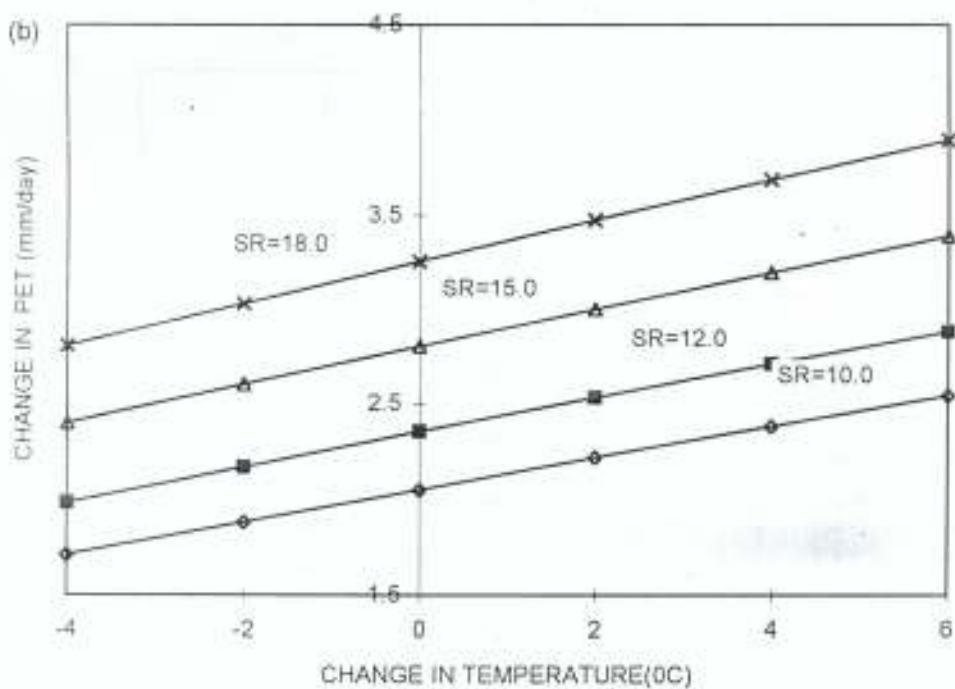
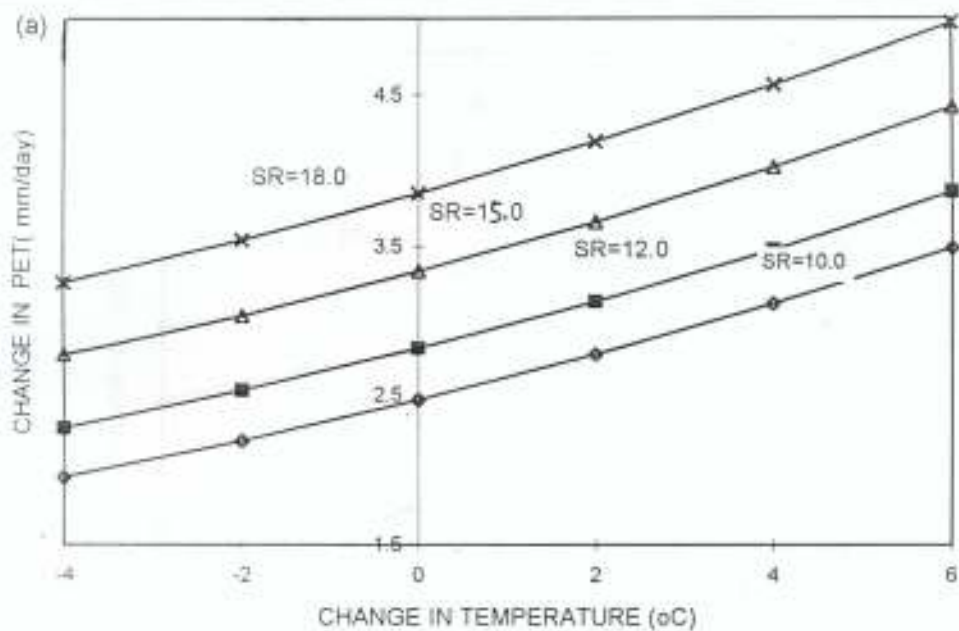


Figure 8: Effect of change in solar radiation (SR) on PET at Onne using (a) Penman model and (b) Penman-Monteith model

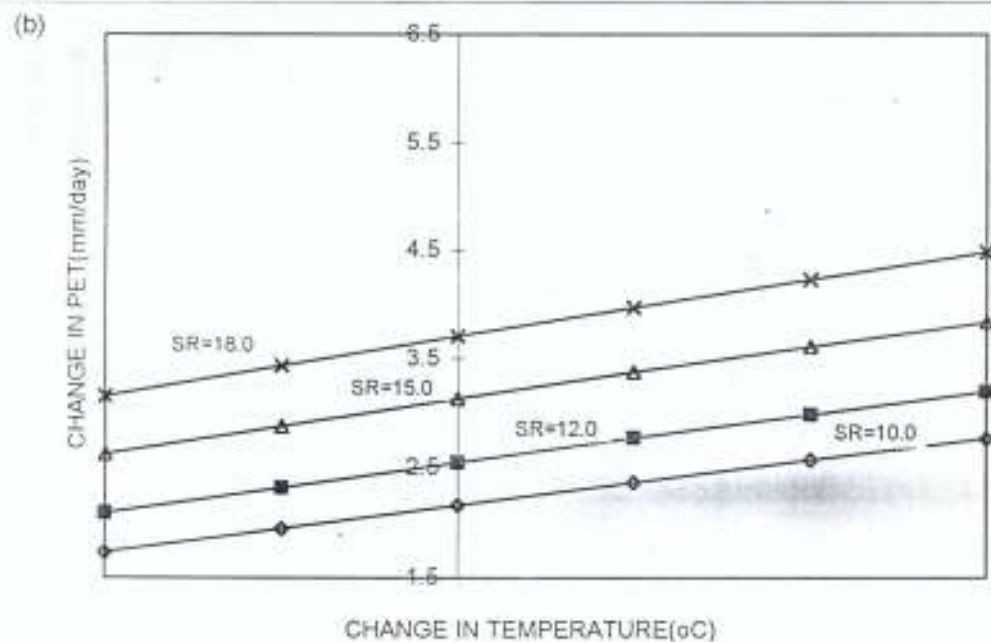
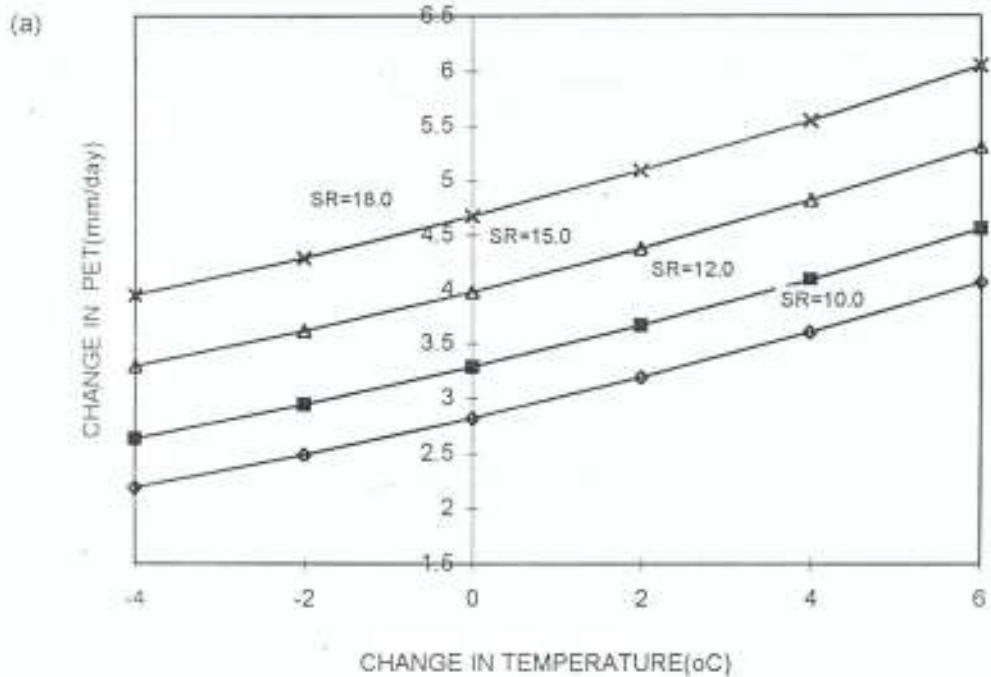


Figure 9: Effect of solar radiation(SR) on PET at Ibadan using
 (a) Penman model (b) Penman -Monteith

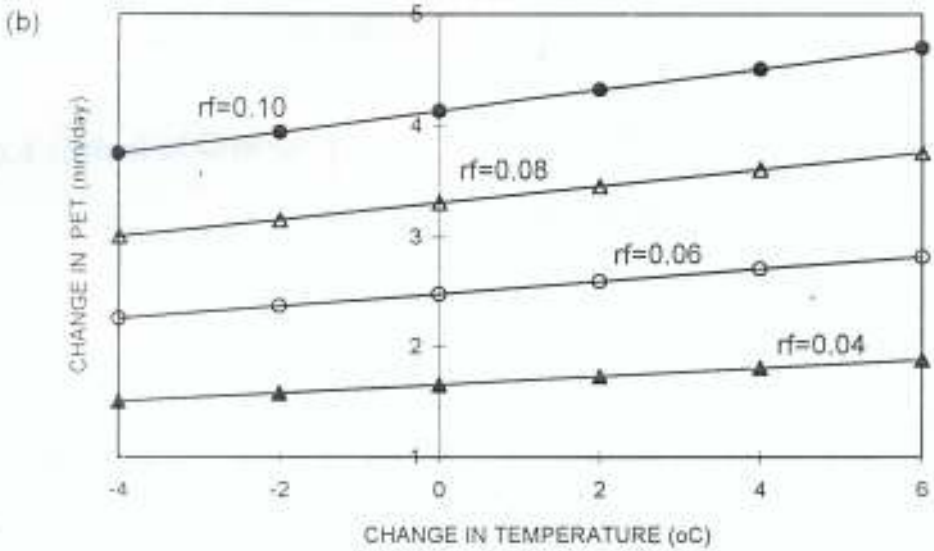
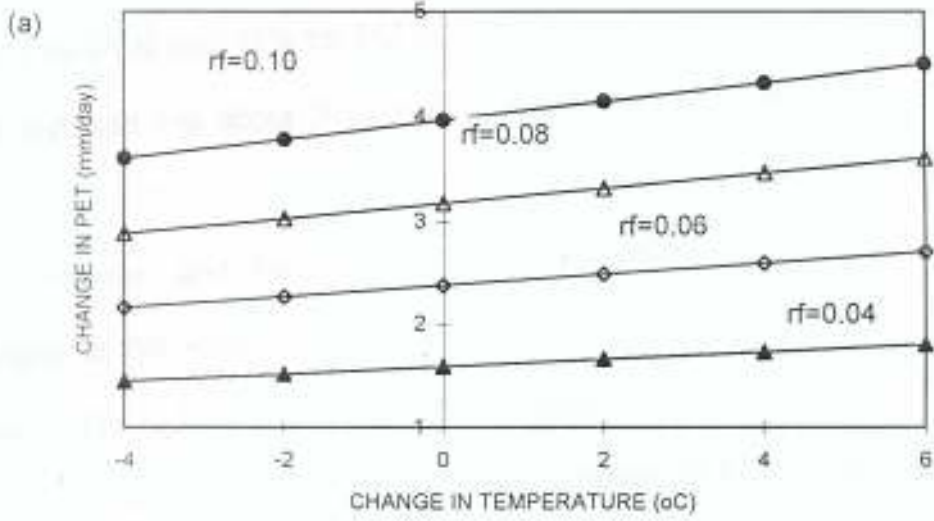


Figure 10 : Effect of radiation ratio(rf) on PET using BMN model at (a) Onne (b) Ibadan

of 15% for PEN and 12% for PM at Onne, and at Ibadan. The response of BMN revealed that about 20% change in radiation ratio caused about 20% response in PET.

Penman and Penman-Monteith had a more modest response to changes in SR, although the response varied somewhat by location and season. The fact that r_i is used in BMN instead of SR will in no way affect the conclusion as regards the impact of solar radiation on PET. This is because the r_i is a ratio of monthly SR to the annual SR and the relative magnitude of the corresponding r_i wholly depends on the individual value of monthly SR. Therefore, BMN was most influenced by solar radiation.

4.3.4 Effect of Change in Wind Speed (Windiness) on PET

A measure of windiness is an integral part of Penman and Penman-Monteith equations. The relative importance of this input was examined over a speed range of 2 km/hr. to 8 km/hr. The responses of each of the models at different locations are presented in Figures 11 a, b and 12 a, b. The sensitivity of the two models was very low. Although, it appeared PM is more sensitive to windiness than PEN, This occurred because wind speed is included in wind and aerodynamic resistance functions as against only wind function in PEN equation. There is generally, an increase in the predicted PET (however small) with corresponding increase in windiness. This is obvious in that as moisture laden air is moved away from a given environment, a vacuum is created, which must be refilled and hence more evaporation. The long-term windiness data of the study area revealed very low values, therefore, it may be

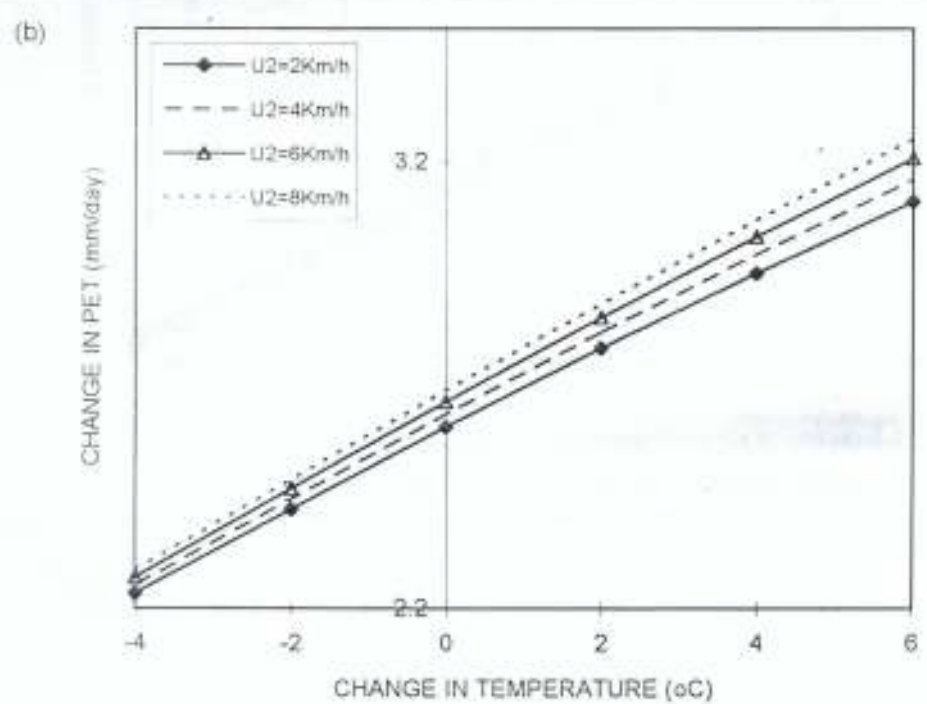
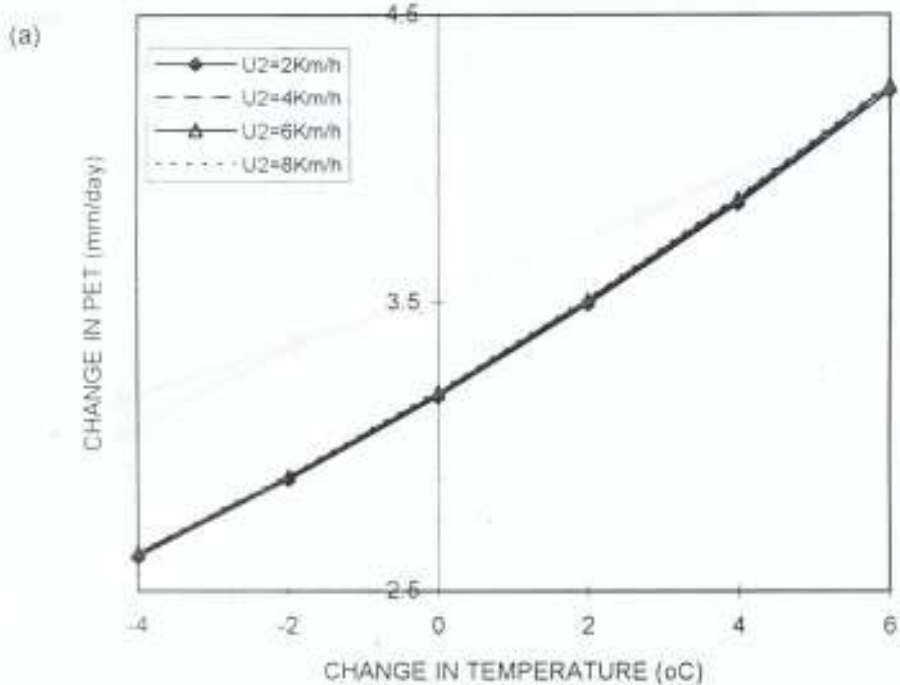


Figure 11: Effect of wind speed(U_2) on PET at Onne using (a) Penman model (b) Penman-Monteith model

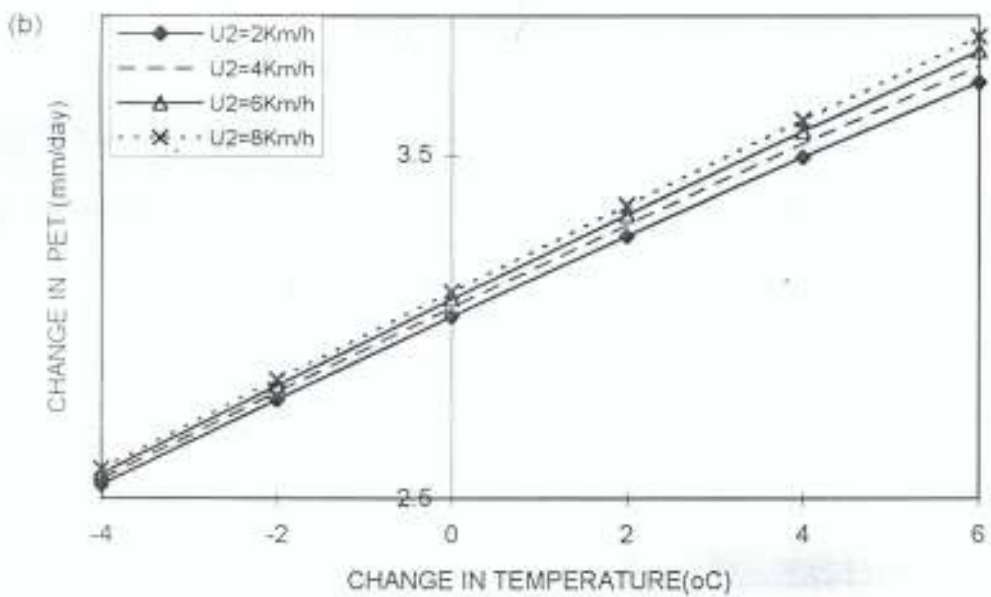
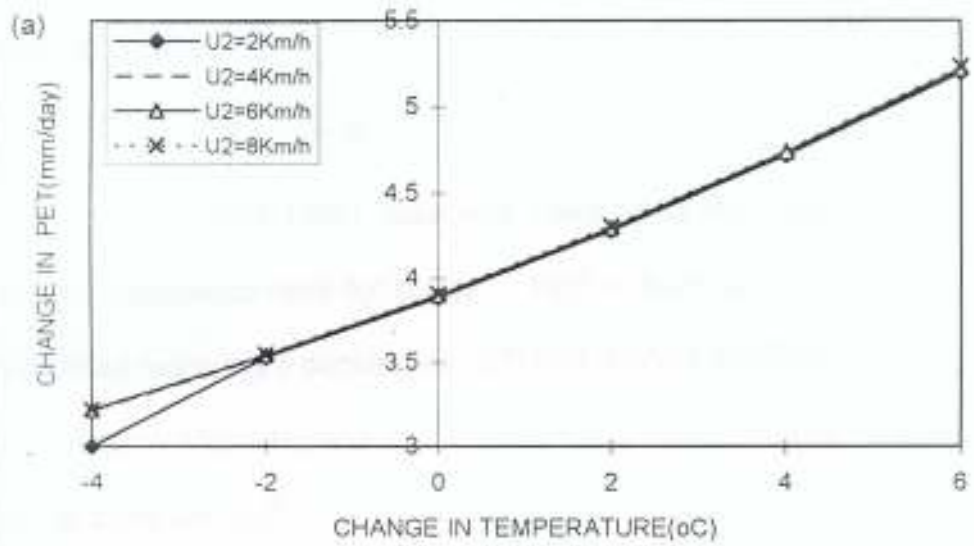


Figure 12: Effect of wind speed (U_2) on PET at Ibadan using
 (a) Penman model (b) Penman-Monteith model

said without significant loss of accuracy, that the effect of windiness on PET is negligible in southern Nigeria.

4.3 Model Fitting And Testing

The ten years (1985-1995) data was used to fit the relationship in equation(36) but expressed here for clarity: $PET = Epan / (p - q \cdot RH)$. The resulting simplified models are denoted as : STHON, SBMN, SPEN and SPM for Thornthwaite, Blaney-Morin-Nigeria model, Penman and Penman-Monteith respectively. A computer software Microcal-Origin version 2.75 was used in fitting the models. Table 14 shows the summary of the fitted parameters (p and q), chi-square for the simplified models as well as the correlation coefficients between the previous and the simplified formulas curves of best fit were forced accordingly to the relationship. They are shown in figures 13 a,b,c & d. The ' p ' parameter varied from 1.11 ± 0.11 to 1.50 ± 0.13 while the ' q ' ranged between 0.38 ± 0.15 and 0.89 ± 0.20 for the four simplified models.

The four simplified models were tested using two years independent data at both locations which are 1995-1996 data sets. The coefficient of correlation ranged between 0.83 and 0.91. The graphs of simplified models against the previous ones are presented in figures 14 to 17. Simplified Thornthwaite has the highest R at both sites, 0.91 in Onne and 0.89 in Ibadan. This comparably high performance may be attributed to the fact that humidity, a very important input parameter for PET estimation not included in the actual THON was in a way incorporated in the STHON. As shown in appendices III and IV, Simplified formulas generally predicted lower PET values compared to their previous

estimates, although they were still overestimated when compared with Epan values

Table 12: Summary of the fitted parameters (p and q) and coefficient of correlation between the simplified and the actual equations.

Simplified Equations	Fitted Parameters		Chi Square (χ^2)	Coefficient of Correlation (R)	
	p	q		Onne	Ibadan
STHON	1.41±0.15	0.89±0.20	0.01141	0.91	0.89
SBMN	1.11±0.11	0.38±0.15	0.00801	0.87	0.86
SPEN	1.14±0.11	0.50±0.15	0.00893	0.90	0.83
SPM	1.50±0.13	0.68±0.18	0.00893	0.86	0.89

Where:

STHON - simplified Thornthwaite, SBMN- simplified Blaney-Morin-Nigeria model, SPEN- simplified Penman and SPM- simplified Penman-Monteith.
p and q are the fitted parameters and R - coefficient of correlation.

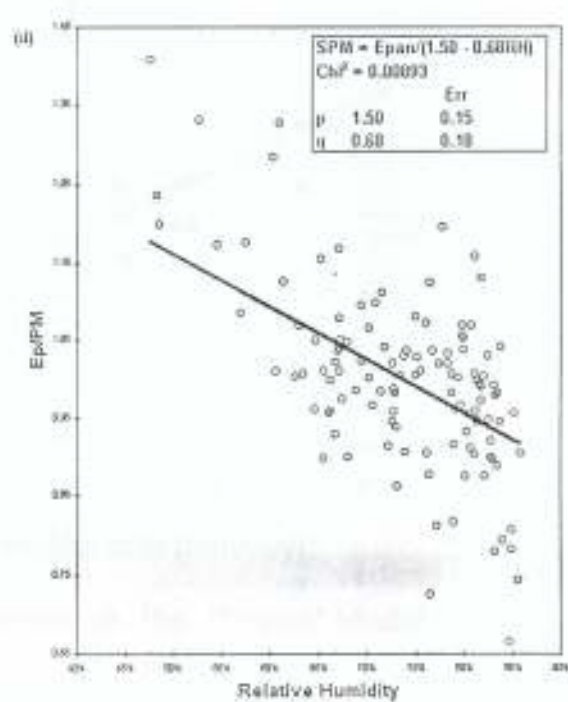
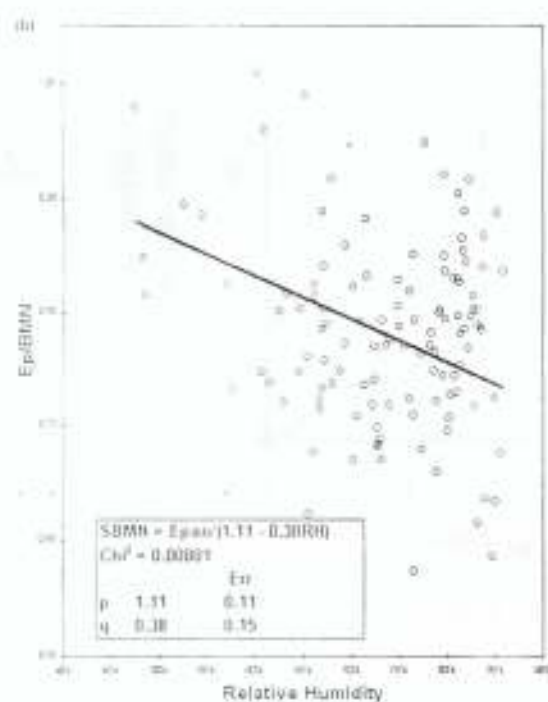
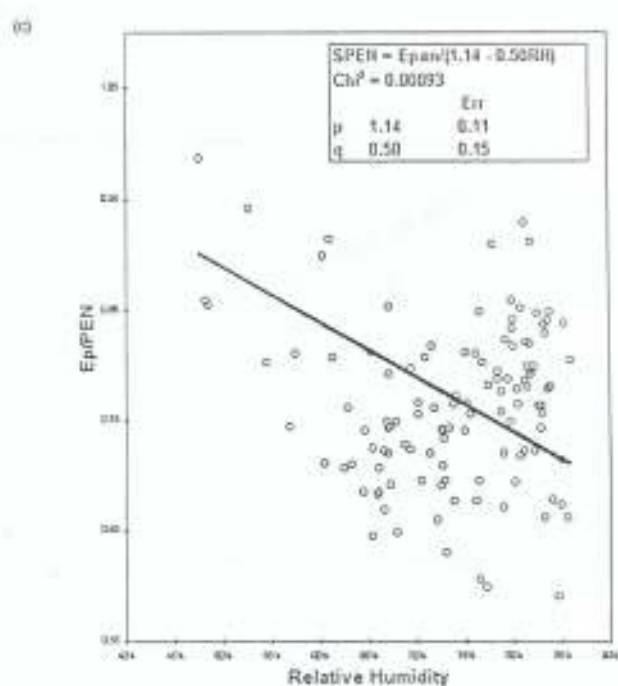
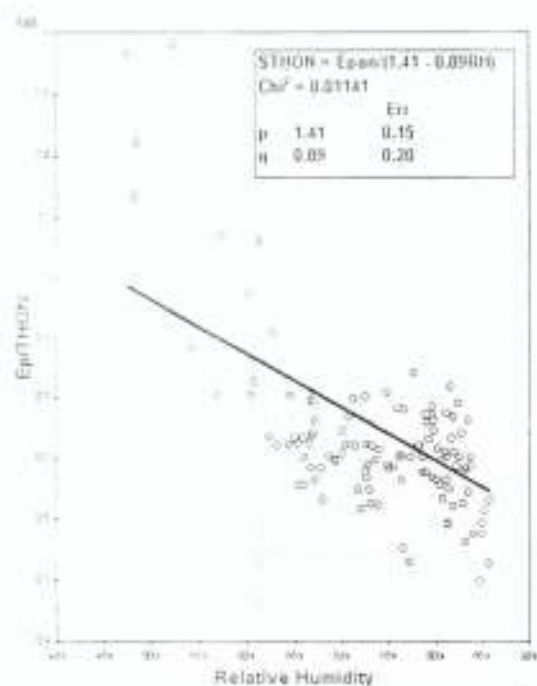


Fig. 13 Ratio of Epan and PET against Relative Humidity using models (a) Thornthwaite (THON) (b) Blaney - Morin - Nigeria (BMM) (c) Penman (PEN) (d) Penman - Monteith (PM)

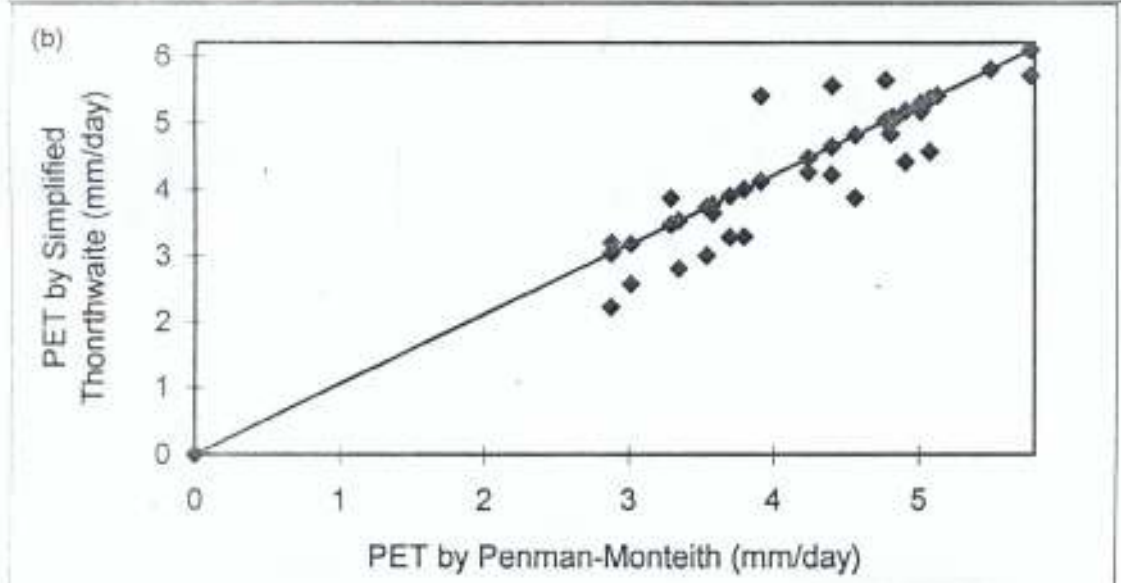
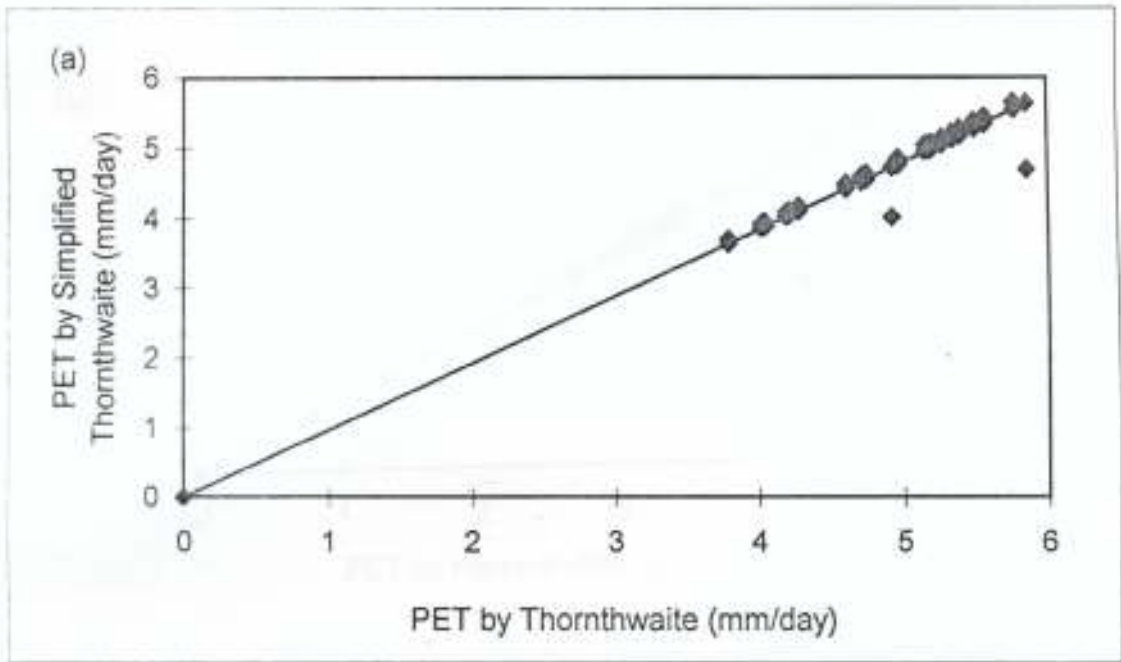


FIG.14 : Simplified Thornthwaite vs. the Original Model at (a) Onne and (b) Ibadan

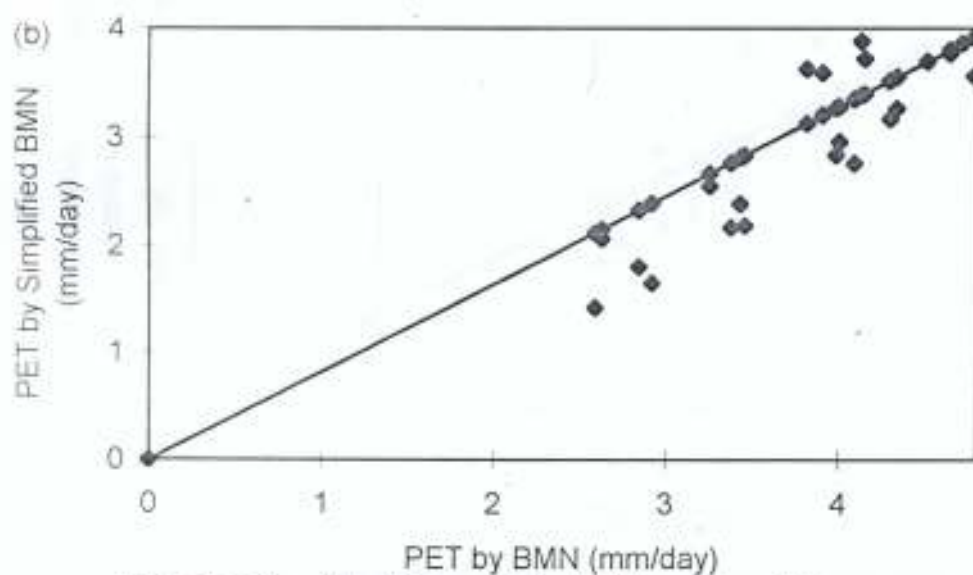
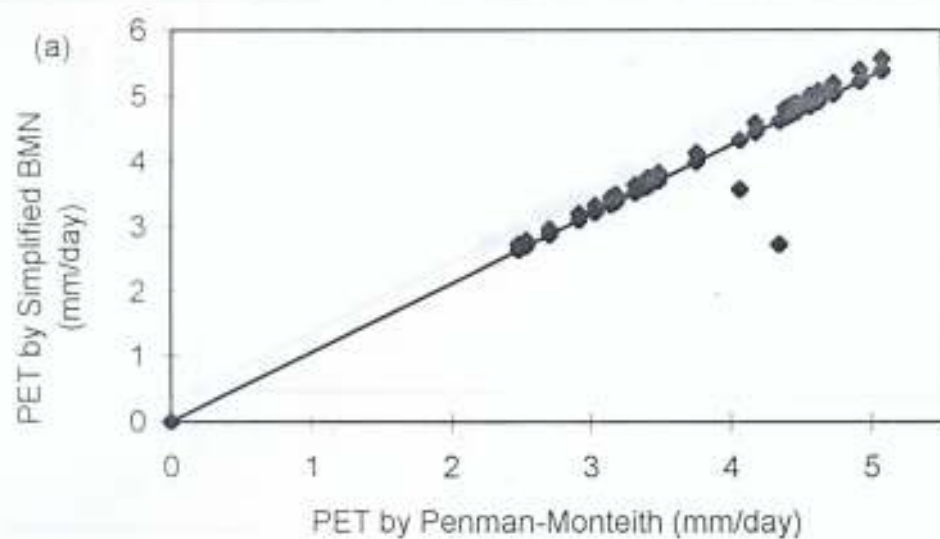


FIG.15 Simplified Blaney-Morin-Nigeria model versus the Original Model at (a) Onne and (b) Ibadan

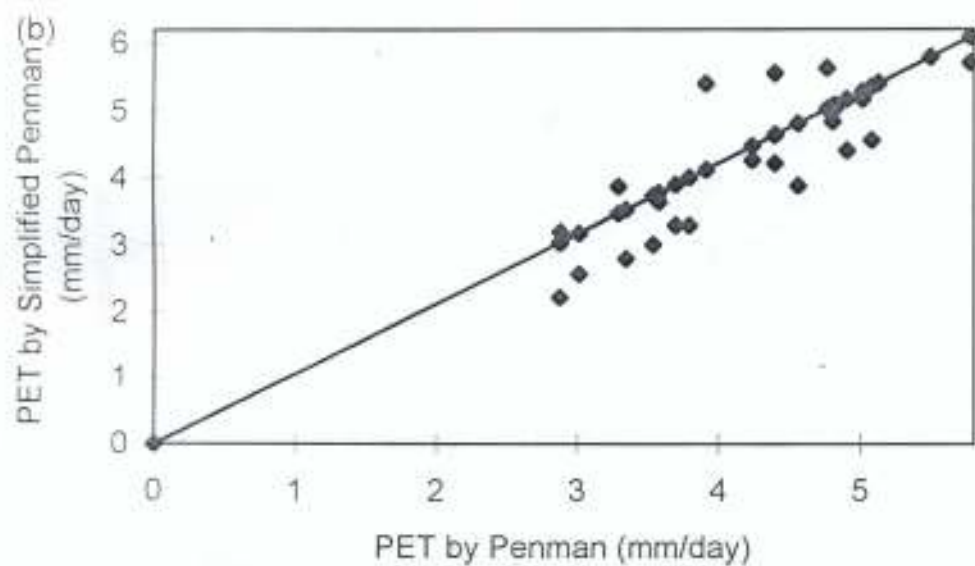
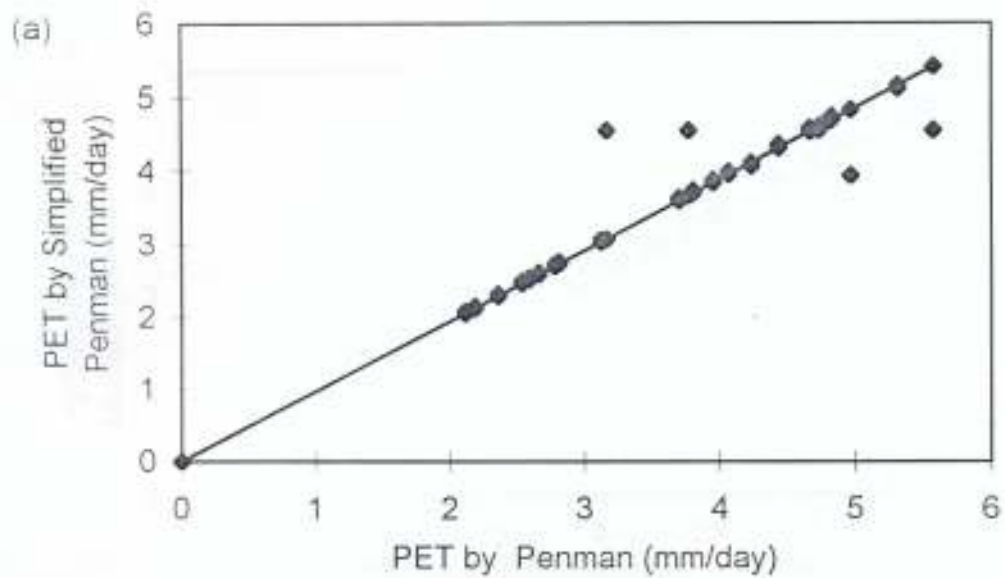


FIG.16 : Simplified Penman Equation against the Original Model at (a) Onne and (b) Ibadan

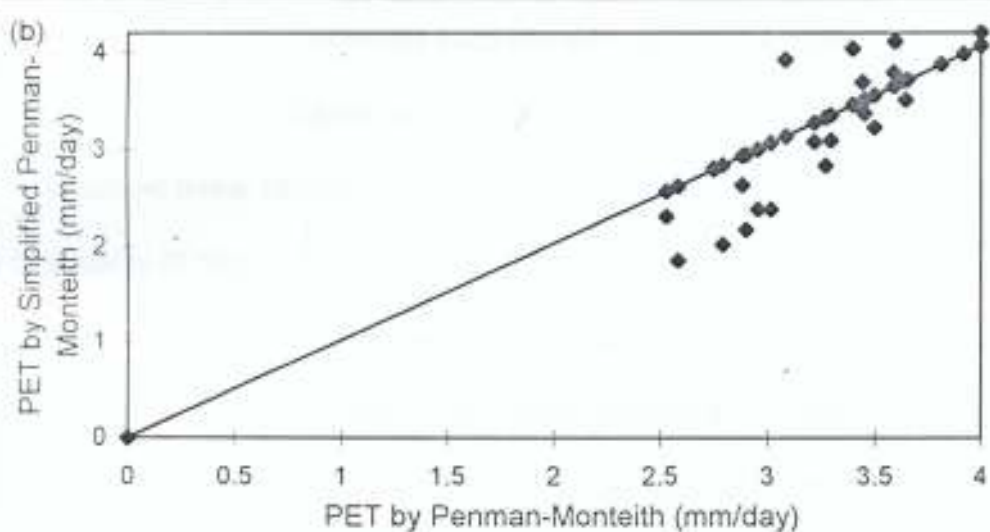
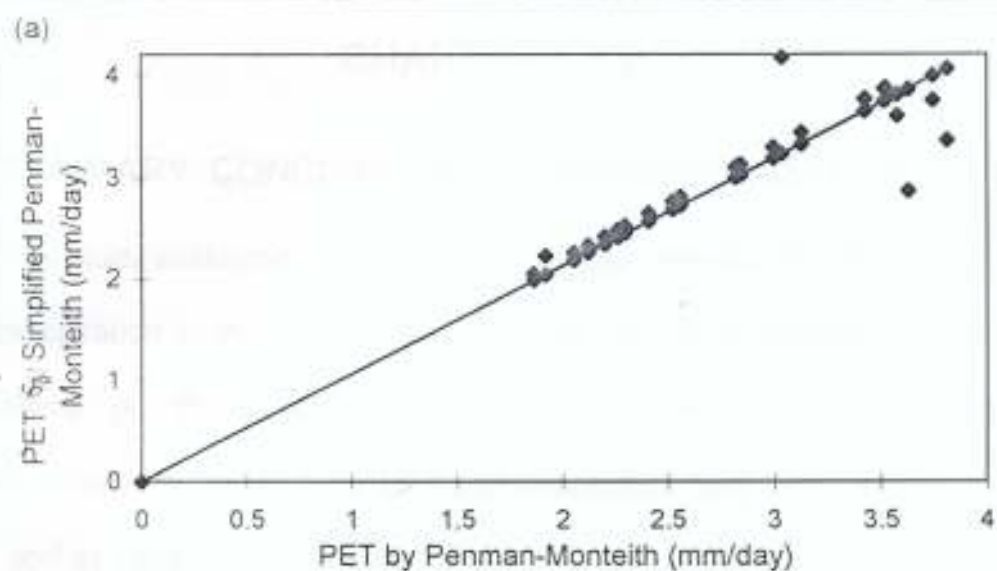


Figure.17: Simplified Penman-Monteith Equation against the original Model at (a) Onne and (b) Ibadan

CHAPTER FIVE

5.0 SUMMARY, CONCLUSION AND RECOMMENDATION

This study evaluated the performance of four methods of estimating potential evapotranspiration in the humid and sub-humid regions of Nigeria, Namely : (i.) Thornthwaite, (ii.) Blaney-Morin-Nigeria model, (iii.) Penman, and (iv) Penman-Monteith formulae. The crude class A pan evaporation was used as the observed values, and as basis for comparison.

Meteorological data collected from the IITA data-base were used. Annual, monthly and decadal PET values were computed and regressed with the observed values. The simple linear regression equations formed ($Y = a + bx$) were subjected to the test of equality of regression equations. To investigate the relative importance and the effect of each of the input parameters required by each estimation method, sensitivity analysis was carried out. The results showed that humidity varied widely over the study area. A simple equation relating the estimated PET values and the class A pan evaporation (Epan) and the relative humidity in decimals has been proposed. The resulting relationship correlated well with observed values. They present an improvement over the original formulae. For instance, the coefficient of correlation increased from $R = 0.68$ to 0.91 in Onne and from 0.72 to 0.89 in Ibadan with the Thornthwaite formula.

The following conclusions and recommendations are drawn from the results of this study:

1. Blaney-Morin-Nigeria model was found to present the best result in terms of the number of input requirements , the ease of computation and the degree of correlation with pan value.
2. Penman-Monteith method yielded the best estimate of the total annual potential evapotranspiration (PET). All other methods over-predicted the annual PET by at least 20% in the study area.
3. There exists a monthly bimodal evapotranspiration pattern in the study area between January and December. These occurred around January /March September/ November of the year.
4. The decreasing order of accuracy for monthly PET is $PM > BMN > PEN > THON$, over the years of record used (1985 - 1994) , i.e. Penman-Monteith formula evaluated potential evapotranspiration to the best accuracy while Thornthwaite to the least accuracy
5. Contrary to the general reports of under-prediction levelled against Thornthwaite formula, the study revealed a consistently high over-prediction due to humid tropical nature of the sites.
6. On equality of linear regression equations, formed by regressing each of the models with the observed pan evaporation, the slope and intercept of Penman-Monteith, Penman and Blaney-Morin-Nigeria model were not statistically similar at 0.001 level of significance but the coefficients of correlation were similar. This indicated that the three methods would give comparable result of potential evapotranspiration estimates.

7. Thornthwaite and, to a lesser degree, Blaney-Morin-Nigeria model are most sensitive to temperature. The sensitivity analysis showed a spatial temperature dimension, for example, contrary to expectation Thornthwaite formula predicted a highly non-linear response to temperature change.

8. BMN is the most sensitive to humidity and radiation, these response varied with respect to locations. BMN responds directly to change in radiation. A 50% change in the parameter produced about the same change in the PET.

9. Thornthwaite model could be greatly improved by incorporating a relative humidity term as shown in the fitted model.

10. The simplified models could be adequately used to predict PET in the study area, provided the class A pan evaporation and relative humidity data are available.

It is highly recommended that the work be continued. Installation of lysimeters to measure actual field potential evapotranspiration (PET) should be pursued in Universities and research centres situated in major ecological zones, Measured data from the research centres should be used to locally calibrate some of these empirical methods on location basis. The use of Blaney-Morin-Nigeria model(BMN) is highly encouraged for its simplicity and accuracy as compared with the seemingly most accurate PM with a very complex structure in data short environment. Thornthwaite should be avoided for its unrealistic estimates and response to temperature, except improved upon or adjusted with suitable coefficient. Error analysis by the application of partial derivatives (which is outside the scope of this study) is also recommended to be carried out so as to compliment the sensitivity analysis and enhance better accuracy. It is suggested that, the Federal Ministry of Water

Resources in conjunction with the Nigerian Society of Engineers (NSE); come up with a workable plan for the management of Nigerian Water Resources by proper monitoring of this very important process-EVAPOTRANSPIRATION. This could be approached by setting up of a committee of professionals who will parallel the work Jensen et al is doing for United States (USA), which was began in the early 70's. The report of this study will therefore be of value to such a committee



REFERENCES

- Allen, R. G., Jensen, M. E, Wright, J. L. and Burman, R. D. 1989. Operational estimates of Reference Evapotranspiration Agron. J. 81: 650-662.
- Allen, R. G, Smith, M. Perrier, A, and Pereira, L. S 1994: An Update for the definition of reference evapotranspiration ICID Bulletin. 43(2) : 1-34.
- Amatya, D. M., Skaggs, R. W and Gregory, J. D 1995: Comparison of methods for estimating REF-ET. J. irri and Drain Engrg. 121: (6), 427 - 435.
- Ayoade, O. A. 1988. Tropical Hydrology and Water Resources . Macmillan pub., London, 10-25.
- Baldy, Ch. M. 1978: Utilisation d'une relation simple entre le bac classe A et la formulae de 4 Penman pour l'estimation de l'ETP en zone soudano-shahelienne. Ann - agron. 29(5), 439 - 452.
- Blaney, H. F. and Criddle, W. D, 1949: "Consumptive use of Water in the Irrigated Areas of the Upper Colorado River Basin," US Dept. Agr. Soil Conserv. Serv. 49 pp.
- Blaney, H. F and Criddle, W. D 1950: Determining water Requirements in Irrigated Areas: from Climatological and Irrigation data. USDA soil conserv. serv. Tech. paper 96: 48pp.
- Blaney, H. F. and Morrin, K. V. 1942: "Evaporation and Consumptive use of water Empirical formulas" Am. Geophys. Union Trans, Pp. 76 - 83.
- Bosen, J. F. 1960: A formula for approximation of saturation vapour pressure over water. Monthly weather Rev. 88: 275 - 276.

- Brutsaert, W. H. 1982: Evaporation into the Atmosphere: Theory, History and Applications: D Reidel Pub. Dordrecht, 299pp.
- Campbell, G. S and Norman, J. M. (1990) Estimation of plant water status from canopy temperature. An analysis of inverse problem: In Applications of Remote sensing in Agriculture Steven M. D and J. A. Clark (eds) 225 -271.
- Choisnel, E, De Villele, O. and Lacroze, F. 1992: Une Approche Uniformisee du calcul de le'vapotranspiration Potentielle r l'ensemble des pays de la communatte' Europeenne. Commission des Communautes Europeenes, Luxemburg, EUR14223, 178P.
- Doorenbos. J and Pruitt, W. P 1977: Guidelines for Predicting Crop Water Requirements FAO Irri. and Drain Paper 24, 144 pp.
- Duru, J.O. 1984: Blaney-Morin-Nigeria evapotranspiration model, J. Hydrol, 70: 71 - 83.
- FAO, 1986 Early Agrometeorological crop yield Assessment. FAO plant production and protection paper 73. 114-149pp
- FAO, 1990. "Report on the expert committee consultation on revision of FAO methodologies for water requirements" , Land and water development division, Rome , Italy
- Itier, B,1996, "Measurement and Estimation of Evapotranspiration" In: "Sustainability of Irrigated Agriculture" L. S Pereira, Feddes ,J. R. Gilley and B. Lesaffre (eds) NATO Workshop VIMEIRO (part.) 171-192.
- Jackson, R. D, William, P. K. and Choudhovey, B. J. (1988): A Re-examination of the crop water stress Index, J. Irrig. Sci. 9: 309 - 317

- Jagtab, S. S. and Alabi, R. T. 1997a. Reliability of Daily, Weekly, and Monthly Grass Evapotranspiration Using Hourly Estimates by Penman Method in three Agroecological zones of West Africa. *Met. J.* 2(1) : 59-68.
- Jagtab, S. S. and Alabi, R. T. 1997b. Evaluation of Evapotranspiration by Adjusted Penman Formula with class A pan at Humid and Sub-Humid Regions of Nigeria and Republic of Benin using Long-term data . *Proceeding of Sustain Africa*, 3: 5-12.
- Jensen, M. E and Haise, H. R., 1963: "Estimating Evapotranspiration from solar radiation" *J. Irrig. and Drain Div. Am. Soc. Civil. Engr.* 89: 15 - 41.
- Jensen, M. E 1981: Design and operation of farm irrigation systems. ASAE Monograph No. 3 Michigan, USA.
- Jensen, M. E, 1966. "Empirical methods of Estimating or Predicting evapotranspiration using Radiation". *Proc Conf. on Evapotranspiration, Am. Soc. of Agric. Engr. Chicago, Dec., PP 57 - 69.*
- Jensen, M. E, 1973. *Consumptive use of water and Irrigation Water Requirements. A report of the Technical Committee on Irrigation and Water Requirements of the Irrigation and Drainage Division of American Society of Civil Engineer.* 214p
- Jensen, M. E, Burman, R. D and Allen, R. G (1990). "Evaporation and irrigation water requirements". *ASCE Manual and Rep. on Engrg. Pract. No 70, ASCE, New York, N.Y.*
- Kleinbaum, D. G. and Kupper, L. L. 1978: *Applied Regression Analysis and other Multivariable Methods.* Duxbury Press; Massachusetts. 556pp.

- List, R. J. (1971) Smithsonian meteorological tables, 6th rev. ed. Smithsonian Institution Press P. 527.
- McKenney, M. S and Roseberg, N. J., 1993: Sensitivity of some potential evapotranspiration estimation methods to climate change. *Agric Jer. Meteorol.* 64: 81 - 110.
- Mohammed, F. S (1978). "Evaluation of methods for predicting, potential evapotranspiration in humid regions" Ms thesis, North Carolina State University, Raleigh, N.C.
- Monteith, J. L. 1965: Evaporation and environment. In: The state and movement of water in living organisms, 19th Symposium, the Soc. for Expt. Biol. Swansea, Cambridge University Press. Pp. 205 - 234.
- Ostromecki, 1965: "Remarks on Methods of computation of water requirements of field and Grass land, U. S Dept. Int. T. T. 67 - 56052, 23pp.
- Parmele, L. H., and McGuinness, J. L., 1974. "Comparisons of measured and estimated daily potential evapotranspiration in a humid region, 22:239-251"
- Penman, H. L. 1948: Natural Evaporation from open water, Bare soil and Grass Proc. Roy. Soc. London, Ser. A 193: 120 - 145.
- Penman, H. L., 1963. Vegetation and Hydrology, Tech. Comm. No.53 Commonwealth Bureau of soils. Harpenden, England. 125pp
- Rijtema, P. F 1965: An analysis of Actual Evapotranspiration. Thesis, Agric Res Report 659, Pudoc, Wageningen, 107pp.

- Seguin, B. 1975: Etude comparee des methodes d'estimation d'ETP en climate'diterranein du sud de la France (region d'Avignon). Ann. Agron 26: 671 - 691.
- Shih, S. F., and Cheng, Ke. S. 1991. Evapotranspiration Estimation for data - Short Environment. J. Irrig. And Drain. Engrg., ASCE, 117(1) 107-122.
- Smajstrala, A. G., Clark, G. A and Shih, S. F. (1984): "Comparison of potential evapotranspiration calculation methods in a humid region" Paper No. 842010, , Am. Soc. Agric, Engrs (ASAE) St. Joseph, Mich.
- Smith, M. Allen, R. G, Monteith, J. L, Perrier, A; Santos Pereira, L. and Segeren, A 1991: Report on the Expert consultation on procedures for revision of FAO guidelines for prediction of crop water requirements. Land and water Dev. Div., FAO, Rome, 54p.
- Svehlik, Z.J. 1982: " Irrigation water Requirements." in: short course on irrigation and drainage practices. Kaduna, Nigeria. 2.1 - 2.11.
- Thornthwaite, C. W, and Holzman, B.,1939. "The Determination of Evaporation from Land and Water Surface ," Monthly Rev., 67: 4-11
- Thornthwaite, C. W., 1944. Report of the Committee on Transpiration and Evaporation , Trans. Am. Geophys. Union , vol. 25, 687pp.
- Thornthwaite, C. W, 1948. An approach Toward a Rational classification of climate. Geograph Rev. 38, 55.
- Thom, A. S and Oliver, H. R (1977): On Penman's equation for estimating regional evaporation. Q. J. Meteorol, Soc. 103: 345 - 357.
- Von Barel, C. H. M, 1966. "Potential Evaporation the combination concept and its experimental verification." Water Resources Res., 2(3) 455-467

Weiss, R. L. 1983. A quantitative approach to the Pruitt and Doorenboes 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: 193 - 201.

APPENDICES

APPENDIX 1: Comparing two straight lines

There are three basic questions to be considered when making a comparison of two straight-line regression equations. These are:

- 1) Are the two slopes the same or different (regardless of whether or not the intercepts are different)?
- 2) Are the two intercepts the same or different (regardless of whether or not the slopes are different)?
- 3) Are the correlation coefficients the same or different (regardless of whether or not the slopes or intercepts are different)?

One of the approaches that can be used to answer the three questions given above is to fit separately the two regression equations as:

$$Y_1 = a_1 + b_1X \dots\dots\dots 38$$

$$Y_2 = a_2 + b_2X \dots\dots\dots 39$$

(i) **Comparing the Slopes - Test for the parallelism**

From 38 and 39 the appropriate null hypothesis for a comparison of slopes is given by

$$H_0 : b_1 = b_2$$

Any of the three alternative hypothesis can be used:

$$H_a \begin{cases} b_1 > b_2 \text{ (One sided)} \\ b_1 < b_2 \text{ (One sided)} \\ b_1 \neq b_2 \text{ (Two sided)} \end{cases}$$

Z test was used (for $n > 25$) and is given as

$$Z = \frac{b_1 - b_2}{\sqrt{S_1^2 + S_2^2}} \dots\dots\dots 40$$

S_1^2 = estimates the variance of the estimated slope b_1 for the first equation

Appendix I continued

S_2^2 = estimates the variance of the estimated slope b_2 for the second equation

The appropriate critical regions are thus given by

$$|Z| \geq Z_{1-\alpha/2} \text{ for } H_A: b_1 \neq b_2$$

where $Z_{1-\alpha/2}$ stands for the upper $100(1-\alpha)\%$ point of the standard normal distribution.

(ii) Comparing two Intercepts

The null hypothesis is given by

$$H_0: a_1 = a_2$$

Z test was also used as in test of parallelism

(iii) Comparing two Correlation Coefficients

The null hypothesis is given by

$$H_0: R_1 = R_2$$

Where R_1 and R_2 denote the correlation coefficients for both equations.

To test this it is necessary to use Fisher's Z transformation. Given by

$$z_1 = \frac{1}{2} \log_e \frac{1 + R_1}{1 - R_1} \dots\dots\dots 41$$

$$z_2 = \frac{1}{2} \log_e \frac{1 + R_2}{1 - R_2} \dots\dots\dots 42$$

The test is equivalent to

$H_0^* : z_1 = z_2$, while the test statistic is given by

$$Z = \frac{z_1 - z_2}{\sqrt{1/n_1 - 3 + 1/n_2 - 3}}$$

The null hypothesis is given

$$|Z| \geq Z_{1-\alpha/2}$$

APPENDIX II: Standard normal cumulative probabilities

Z	$p(Z < z)$	Z	$P(Z < z)$
-4.265	0.00001	0.000	0.50
-3.891	0.00005	0.126	0.55
-3.719	0.0001	0.253	0.60
-3.291	0.0005	0.385	0.65
-3.090	0.001	0.524	0.70
-2.576	0.005	0.674	0.75
-2.326	0.01	0.842	0.80
-2.054	-0.02	1.036	0.85
-1.960	-0.025	1.282	0.90
-1.881	0.03	1.341	0.91
-1.751	0.04	1.405	0.92
-1.645	0.05	1.476	0.93
-1.555	0.06	1.555	0.94
-1.476	0.07	1.645	0.95
-1.405	0.08	1.751	0.96
-1.341	0.09	1.881	0.97
-1.282	0.10	1.960	0.975
-1.036	0.15	2.054	0.98
-0.842	0.20	2.326	0.99
-0.674	0.25	2.576	0.995
-0.524	0.30	3.090	0.999
-0.385	0.35	3.291	0.9995
-0.253	0.40	3.719	0.9999
-0.126	0.45	3.891	0.99995
0.000	0.50	4.265	0.99999

Source : Kleinbaum and Kupper (1978)

YEAR	THON	STHON	BMN	SBMN	PEN	SPEN	PM	SPM
1995	3.99	4.06	4.79	3.56	5.08	4.57	3.45	3.74
	5.76	5.19	4.72	4.26	5.77	5.71	4.00	4.20
	5.31	5.38	4.14	3.88	4.77	5.64	3.60	4.11
	5.29	4.67	4.34	3.26	4.80	4.84	3.65	3.52
	4.72	4.16	3.99	2.84	4.24	4.27	3.30	3.10
	4.41	3.59	3.44	2.39	3.58	3.65	2.89	2.65
	3.78	2.57	2.92	1.65	3.01	2.57	2.59	1.86
	3.93	2.22	2.59	1.42	2.88	2.22	2.54	1.60
	4.02	2.96	3.07	1.97	3.54	3.01	2.90	2.18
	3.97	3.23	3.38	2.17	3.70	3.29	2.96	2.39
	3.97	3.99	4.01	2.96	4.40	4.23	3.22	3.09
	4.65	3.63	4.09	2.76	4.56	3.89	3.27	2.84
1996	5.70	4.71	3.91	3.59	4.82	5.05	3.44	3.69
	6.59	6.43	4.30	5.00	5.50	6.94	3.92	5.09
	6.38	6.27	4.52	4.70	5.13	6.67	3.81	4.88
	5.96	6.38	4.34	4.45	4.82	6.60	3.65	4.81
	5.56	5.39	4.15	3.72	4.40	5.56	3.40	4.04
	5.35	5.23	3.82	3.63	3.91	5.40	3.09	3.93
	4.49	3.80	3.26	2.55	3.29	3.88	2.75	2.81
	4.04	3.19	2.63	2.07	2.88	3.20	2.53	2.32
	4.17	2.79	2.85	1.80	3.35	2.80	2.80	2.03
	4.58	3.21	3.46	2.19	3.79	3.30	3.02	2.39
	5.17	4.76	4.64	3.77	5.01	5.17	3.59	3.80
	5.93	4.10	4.30	3.17	4.91	4.42	3.50	3.24