

**TEMPORAL ANALYSIS OF FAO REFERENCE
EVAPOTRANSPIRATION (ET_0) AND EVALUATION
OF FOUR ET_0 MODELS FOR IITA NIGERIA
STATIONS**

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

This work is dedicated to the Lord, Who is merciful and gives grace and favour unto all mankind.



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I wish to express my sincere gratitude unto the Lord for the grace and privilege to complete this work. To Him is the glory forever.

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LIST OF SYMBOLS

SYMBOL	UNIT	DEFINITION
ET_o	mm of water day ⁻¹	Reference Evapotranspiration
ET_p	mm of water day ⁻¹	Potential Evapotranspiration
ET_a	mm of water day ⁻¹	Actual Evapotranspiration
ET_c	mm of water day ⁻¹	Crop Evapotranspiration
ET_m	mm of water day ⁻¹	Potential Evapotranspiration
E_{pan}	mm of water day ⁻¹	Pan Evaporation
K_p	-	Pan Coefficient
K_c	-	Crop Coefficient
λET	°C	Latent Heat Flux,
R	%	Relative humidity
R_n	MJ m ⁻² day ⁻¹	Net Radiation
R_s	MJ m ⁻² day ⁻¹	Extraterrestrial Radiation
G	MJ m ⁻² day ⁻¹	Soil Heat
H	-	Sensible Heat Flux
U_2	m s ⁻¹	Wind Speed at 2 m Height
U_z	m s ⁻¹	Wind Speed at height z
e_s	kPa	Saturation Vapour Pressure
e_a	kPa	Actual Vapour Pressure
Δ	kPa °C ⁻¹	Slope of Vapour Pressure Curve
γ	kPa °C ⁻¹	Psychrometric Constant
λ	MJ kg ⁻¹	Latent Heat of Vaporization
T	°C	Mean Daily Air Temperature
ρ_a	kg m ⁻³	Mean Air Density at Constant Pressure
c_p	MJ kg ⁻¹ °C ⁻¹	Specific Heat of the Air
r_a	s m ⁻¹	aerodynamic resistance
r_f	-	Ratio of Monthly Radiation To Annual Radiation
r_l	s m ⁻¹	Bulk Stomatal Resistance of Well-Illuminated Leaf
r_s	s m ⁻¹	(Bulk) Surface or Canopy Resistance
Z_m	M	Height of Wind Measurements
Z_h	M	Height of Humidity Measurements
D	M	Zero Plane Displacement Height
Z_{om}	M	Roughness Length Governing Momentum Transfer
Z_{oh}	M	Roughness Length Governing Transfer of Heat and Vapour
K	-	von Karman's constant (0.41)
α	-	Albedo (1.26)
R or r	-	Correlation coefficient
SEE	-	Standard Error of Estimates
MAE	-	Mean Absolute Error
MBE	-	Mean Bias Error
RMSE	-	Root Mean Square Error
S^2d	-	Measurement of the variability of the difference between the predicted and observed values
IWR	mm of water day ⁻¹	Irrigation Water Requirement

Abstract

Evapotranspiration (ET) rates have been reported to be decreasing in many parts of the world and this scenario had been attributed to the effect of climate change/variation. This study analyzed this phenomenon in the context of Nigeria and also carried out the performance evaluation of four ET models (Penman, Blaney-Morin-Nigeria (BMN), Hargreaves-Samani and Priestly-Taylor models). In addition, the study also re-examined the BMN model making use of the Sigma Plot software (based on the Levenberg – Marquardt algorithm) to generate modified versions of the BMN model that are applicable across the country and corrected some perceived shortcomings of the BMN.

Records of climatic variables (Solar radiation, Maximum and Minimum Temperature, Maximum and Minimum Relative Humidity and Wind speed) were collected from three International Institute of Tropical Agriculture (IITA) Stations in Ibadan, Kano and Onne. For Ibadan, a 36-year (1973 – 2008) record was obtained, for Kano, a 29-year (1980 - 2008) record was obtained and for Onne, a 31-year (1977 - 2006) record was obtained. Evapotranspiration rates for each of the stations were estimated using the FAO56-PM model. A non-parametric Mann-Kendal trend analysis was performed on the estimated ET rates and also the Aerodynamic and Radiative parts of these estimates to ascertain whether any or both the parts are major determinants in the trend of ET at the three stations.

The results obtained during the study showed that there was a significant decline in monthly and annual ET rates Ibadan ($P < 0.001$) over the 36 years considered, a not significant decline in monthly and annual ET rates in Kano over the past 29 years and a significant monthly and annual decline in ET rates for Onne ($P < 0.1$) over the past 31 years. The percentage annual decline for Ibadan, Kano and Onne are 4.05%, 0.54% and 1.87% respectively. Also BMN model was found out to be the best model that can be applied to estimate ET in each of these stations because it has a high correlation value with the values obtained from FAO56-PM model along with favourable statistic values and it requires a considerably less number of variables for its estimation. The re-calibrated BMN model also had a higher correlation values of 0.74, 0.79 and 0.75 for Ibadan, Onne and Kano respectively when compared with the FAO-56 model than the Original BMN model when compared with the FAO56-PM model with values of 0.7, 0.77 and 0.75 respectively for Ibadan, Onne and Kano.

CHAPTER ONE



GENERAL INTRODUCTION

Water being a major ingredient of life is becoming scarce in many parts of the world and also in Nigeria. Over the years, it is widely believed that any change in climate will have a significant impact on the availability of water. A lot of water is needed for agricultural practices and also for domestic purposes. In view of this, it is imperative to have the knowledge of the rate at which water is being returned to the atmosphere both from water bodies, reservoirs, and land surfaces and from plant bodies.

The rate at which water returns from the earth (also from vegetations) back to the atmosphere in the form of vapour is referred to as 'evapotranspiration'. Its knowledge helps in estimating irrigation requirements and carrying out its scheduling, estimate moisture loss from reservoirs and river basins.

Numerous methods can be used to estimate evapotranspiration and the method universally acceptable which has been standardized by the Food and Agriculture organization is the FAO – 56 Penman – Monteith method. In Nigeria, a model was developed by Duru (1984) called the Blaney-Morin-Nigeria model to estimate evapotranspiration and was widely judged to be most suitable to Nigeria's condition by the Nigerian Institute of Agricultural Engineers (NIAE).

Since the accuracy of estimated values of evapotranspiration is important for water resources planning and management, irrigation scheduling, control and agricultural productivity; in this study, the model designed for Nigeria is validated against the FAO – 56 PM model and is recalibrated to produce a more appropriate model that can be applied all

over the country. Also the trend of evapotranspiration over recent years across the country was analysed to determine its spatial distribution.

1.1 OBJECTIVES

The main focus of this study is to evaluate the performance of four ET models with respect to their applicability in Nigeria

Specific objectives are to:

- (i) perform temporal analysis of reference evapotranspiration estimated with FAO56-PM model for three agro-ecological stations;
- (ii) evaluate the performance of four evapotranspiration models with reference to FAO56-PM model (standard); and
- (iii) re-examine the Blaney-Morin-Nigeria model with a view to modifying it for improved performance.

1.2 JUSTIFICATION OF STUDY

In the execution of water related activities or development works, it is of great importance to take into consideration the impact which evapotranspiration will have on such leading to the need to have a dependable model of estimating evapotranspiration in Nigeria, have a knowledge on how evapotranspiration rate is temporally distributed across the country. Similar studies on ET distribution and trend in Changjiang catchment region of China by Xu et.al. (2006) has been carried out in recent times.

In Nigeria, some studies have been carried out on the development of ET models applicable in the country especially by Duru (1984). Since 1984 when Duru developed the Blaney-Morin-Nigeria model for estimating evapotranspiration, numerous researches have been carried out all over the world to improve the quality of results obtained from evapotranspiration models which led to the general adoption of the FAO Penman-Monteith combination equation developed by Allen et al. (1998).

In the development of the Blaney-Morin-Nigeria model for estimating ET by Duru (1984), there were some perceived shortcomings which may affect the reliability of its estimation in Nigeria. Some of the criticisms which this study is aimed at correcting include;

- The use of data from a single location in Nigeria for the development of the model;
- The use of a ten-year data for the model development;
- The choice of pan evapotranspiration estimates as the basis for reference (although this was acceptable at that time; and
- The application of manual iteration during its development which is prone to human error.

1.3 SCOPE OF STUDY

This research is focused on the proposition of a model for evaluating evapotranspiration by the evaluation of four different models and determining the trend of evapotranspiration across Nigeria over an average of twenty seven (27) years. The scope also includes the recalibration of the BMN for it to produce better results when applied.



CHAPTER TWO

LITERATURE REVIEW

DEVELOPMENT IN EVAPOTRANSPIRATION STUDIES

2.1 CONCEPT OF EVAPOTRANSPIRATION

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, removed and transported upwards into the atmosphere (Oguntunde, 1998). The driving force to remove water vapour from the evaporating surface is the difference between the water vapour pressure at the evaporating surface and that of the surrounding atmosphere. As evaporation proceeds, the surrounding air becomes gradually saturated and the process will slow down and might stop if wet air is not transferred to the atmosphere. The replacement of the saturated air with drier air depends greatly on wind speed and this in combination with solar radiation, air temperature, air humidity are parameters to consider when assessing the evaporation process.

Transpiration also is the vapourisation of liquid water contained in plant tissues and the vapour being removed to the atmosphere. The loss of the water is usually through the stomata of plants and it's affected by parameters influencing evaporation and the crop's characteristics.

Evapotranspiration is the combination of these two processes, there are about four sequential and distinct processes that takes place during evapotranspiration (Ayoade, 1988):

- (i) Movement of water within the soil towards the ground surface or zone of absorption around the root of plants;
- (ii) Transpiration;

- (iii) Vapourisation of water at the soil at plant surface of the stomata of leaves; and
- (iv) Removal and transport of the evaporated water, now in gaseous form, into the atmosphere.

The rate of evapotranspiration over any given surface is also dependent on the availability of moisture, if moisture is always available in sufficient quantities at the evapotranspiring surface, it will occur at the maximum rate possible.

The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_0 . The reference surface is a hypothetical grass reference crop with specific characteristics (Allen et al. 1998). This was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices. The FAO Penman-Monteith method is recommended as the sole method for determining ET_0 , (Allen et al. 1998). This method was selected because it takes into consideration the physical, physiological and aerodynamic properties of the location where it is used to estimate the ET_0 of grass which was a close approximation.



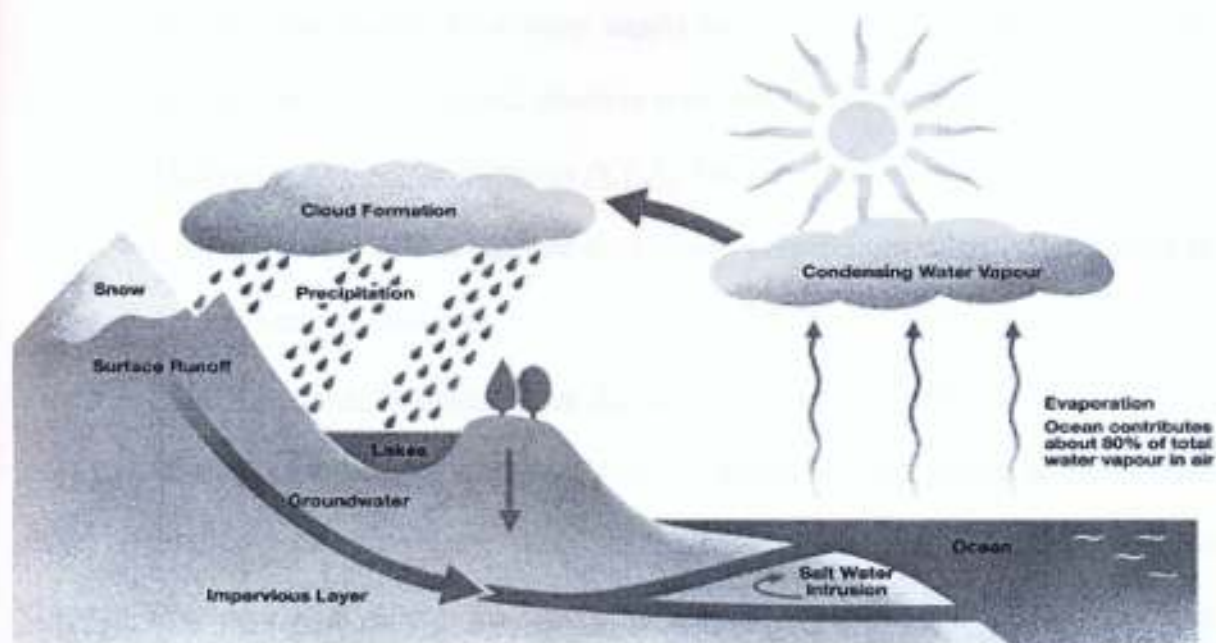


Figure 1: The Hydrologic Cycle.

2.2 DEFINITIONS OF EVAPOTRANSPIRATION

Evapotranspiration can be described as the combination of the return of water to the atmosphere from soil, water and plant surfaces (Evaporation) and through the opening of the leaves of plants (Transpiration) (Encarta dictionaries, 2008). Researchers and scientists have been making use of different terms to further clarify evapotranspiration, these includes Potential evapotranspiration, Actual evapotranspiration and Reference evapotranspiration.

- (i) **Potential Evapotranspiration (ET_p):** This term was defined by Penman (1948, 1956) as "the amount of water transpired in a given time by a short green crop, completely shading the ground, of uniform height with an unlimited supply of water" (Ward & Trimble, 2004) i.e. water is always available to the crop from the soil which does not really occur naturally.
- (ii) **Actual Evapotranspiration (ET_a):** This describes the process by which water evapotranspires from soil and plant bodies under natural conditions or prevailing

soil moisture content. Here water supply may be limited or not but ET_a depends among others on the climatic situation at the time of consideration.

- (iii) **Maximum Evapotranspiration (ET_m)**: This describes the evapotranspiration for a specified crop at a designated time where evapotranspiration is not limited by dry soil water conditions.
- (iv) **Reference Evapotranspiration (ET_0)**: Due to ambiguities associated with the definition of potential evapotranspiration, which was not related to any specific crop because many crops resemble the description given in its definition (Xu Chong-yu et al. 2006), the term reference evapotranspiration was introduced. It was defined by Allen et al. (1998) as “the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground”.
- (v) **Crop Evapotranspiration (ET_c)**: This is the evapotranspiration from a specific plant or crop grown under defined conditions including soil water, fertility and other cultural conditions.
- (vi) **Crop coefficient (K_c)**: Is a ratio used to relate crop evapotranspiration to reference evapotranspiration for a specific crop or plant at a specific time. It is dimensionless.

2.3 FACTORS AFFECTING EVAPOTRANSPIRATION RATE

Factors influencing the rate of evapotranspiration can be grouped into two categories (Oguntunde, 1998); climatological and non-climatological factors. The non-climatological factors include: surface characteristics (i.e. soil or water, vegetated or bare), the type of soil

and land management, moisture condition of the soil profile, the degree of plant cover and type.

Three major climatic factors affecting the rate of evapotranspiration (Ayoade, 1988) are:

- (i) The amount of energy available to vapourise water (which depends on air temperature, solar radiation and sunshine duration)
- (ii) Air humidity that indicates the capacity of the air to hold moisture; and
- (iii) Wind speed which helps to maintain the continuity of the evapotranspiration process.

Also, according to the FAO Irrigation and drainage paper 56, (Allen et al. 1998), weather parameters, crop characteristics, management and environmental aspects are factors affecting evaporation and transpiration.

2.3.1 Weather parameters

The principal weather parameters affecting evapotranspiration are radiation, air temperature, humidity and wind speed. Several procedures have been developed to assess the evaporation rate from these parameters.

2.3.2 Crop Characteristics

The crop type, variety and development stage should be considered when assessing the evapotranspiration from crops grown in large, well-managed fields. Differences in resistance to transpiration, crop height, crop roughness, reflection, ground cover and crop rooting characteristics result in different evapotranspiration levels in different types of crops under identical environmental conditions.

2.3.3 Management and Environmental Conditions

Factors such as soil salinity, poor land fertility, and limited application of fertilizers, the presence of hard or impenetrable soil horizons, the absence of control of diseases and pests and poor soil management may limit the crop development and reduce the evapotranspiration. Other factors to be considered when assessing evapotranspiration are ground cover, plant density and the soil water content. When assessing the evapotranspiration rate, additional consideration should be given to the range of management practices that act on the climatic and crop factors affecting the evapotranspiration process. Cultivation practices and the type of irrigation method can alter the microclimate, affect the crop characteristics or affect the wetting of the soil and crop surface. Using windbreaks also reduces wind velocities and decreases the evapotranspiration rate of the field directly beyond the barrier. The use of mulches, especially when the crop is small, is another way of substantially reducing soil evaporation.

2.4 MEASUREMENT AND ESTIMATION OF EVAPOTRANSPIRATION

Evaporation can be measured using direct or indirect techniques; but carrying this out is usually not easy. Specific devices and the accuracy in the measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration, (Allen et al. 1998). Applied methods are often expensive and demanding in terms of accuracy of measurement and can only be best put into good use by well-trained research personnel. Although the methods are inappropriate for routine measurements, they remain important for the evaluation of ET estimates obtained by more indirect methods.

2.4.1 DIRECT MEASUREMENT

This method includes;

(i) **Energy Balance/Budget Approach:**

This method is based on the fact that for evapotranspiration of water from either the soil surface or through plant leaves (stomata) to take place, a lot of energy consumption through latent heat of vapourisation takes place. (Oguntunde, 1998). Using the energy budget equation which includes net radiation (R_n), soil heat (G) and sensible heat (H) fluxes, evapotranspiration can be estimated as its residual term (latent heat flux, λET) (Farahani, et al.). The equation can be written as:

$$R_n - G - \lambda ET - H = 0 \quad (1)$$

In its application, the equation is restricted to only the four stated components without taking into consideration other components like heat stored, released or used for plants metabolism. These are considered negligible (Allen et al. 1998).

(ii) **Soil Water Balance Approach:**

Evapotranspiration can also be determined by measuring the various components of the soil water balance. The method consists of assessing the incoming and outgoing water flux into the crop root zone over some time period.

$$ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW \quad (2)$$

Irrigation (I) and rainfall (P) add water to the root zone. Part of irrigation and rainfall might be lost by surface runoff (RO) and by deep percolation (DP) that will eventually recharge the water table. Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone or even

transferred horizontally by subsurface flow in (SF_{in}) or out of (SF_{out}) the root zone. In many situations, however, except under conditions with large slopes, SF_{in} and SF_{out} are minor and can be ignored. Soil evaporation and crop transpiration deplete water from the root zone. If all fluxes other than evapotranspiration (ET) can be assessed, the evapotranspiration can be deduced from the change in soil water content (ΔSW) over the time period. The soil water balance method can usually only give evapotranspiration estimates over long time periods of the order of week-long or ten-day periods.

(iii) **Use of Lysimeters:**

Weighing and non-weighing (drainage) lysimeters can be used to measure evapotranspiration depending on scale of measurements (Oguntunde, 1998). It operates on the basis of simple water balance equation. Crops are grown in isolated tanks filled with either disturbed or undisturbed soil. In precision weighing lysimeters, where the water loss is directly measured by the change of mass, evapotranspiration can be obtained with an accuracy of a few hundredths of a millimetre, and small time periods such as an hour can be considered. In non-weighing lysimeters the evapotranspiration for a given time period is determined by deducting the drainage water, collected at the bottom of the lysimeters, from the total water input. Daily measurements are taken and evapotranspiration is estimated using (Oguntunde, 1998):

$$ET_o = I - O \quad (3)$$

where

ET_o reference Evapotranspiration (mm),

I amount of water applied by irrigation and or rainfall (mm);

- O water output or runoff collected from lysimeter.

The storage term is assumed to be zero since the soil column is always saturated with moisture.

(iv) **Estimating from Pan Evaporation:**

Evaporation rate from a pan filled with water can be easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient:

$$ET_o = K_p E_{pan} \quad (4)$$

where

ET_o Reference evapotranspiration [mmday⁻¹],

K_p Pan coefficient,

E_{pan} Pan evaporation [mmday⁻¹].

Despite major differences in the loss of water from water surfaces in a shallow pan and from cropped surfaces, pan evaporimeters are still in use due to their simplicity. It is till commonly being used in America and Asia (Xu et al, 2006).

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

$$E_{pan} = r + 0.51(a-w) \quad (5)$$

where:

E_{pan} is pan evaporation 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.

(v) **Eddy Covariance Method:**

Another direct method of measuring evapotranspiration is with the eddy covariance technique in which fast fluctuations of vertical wind speed are correlated with fast fluctuations in atmospheric water vapour density. This directly estimates the transfer of water vapour (evapotranspiration) from the land (or canopy) surface to the atmosphere.

Many researchers prefer making use of this technique because it involves minimal theoretical assumptions (Farahani et al., 2007). It requires the use of sensors of vertical wind speed, temperature and humidity and the computation of the correlation between vertical air motion and climatic variables collected to deduce the flux using an ultrasonic Anemometer and an Infrared Gas Analyser. But a recent study has advised making use of this technique with caution to avoid errors because of its systemic under-estimation of surface fluxes especially at night (Shuttleworth, 2007).



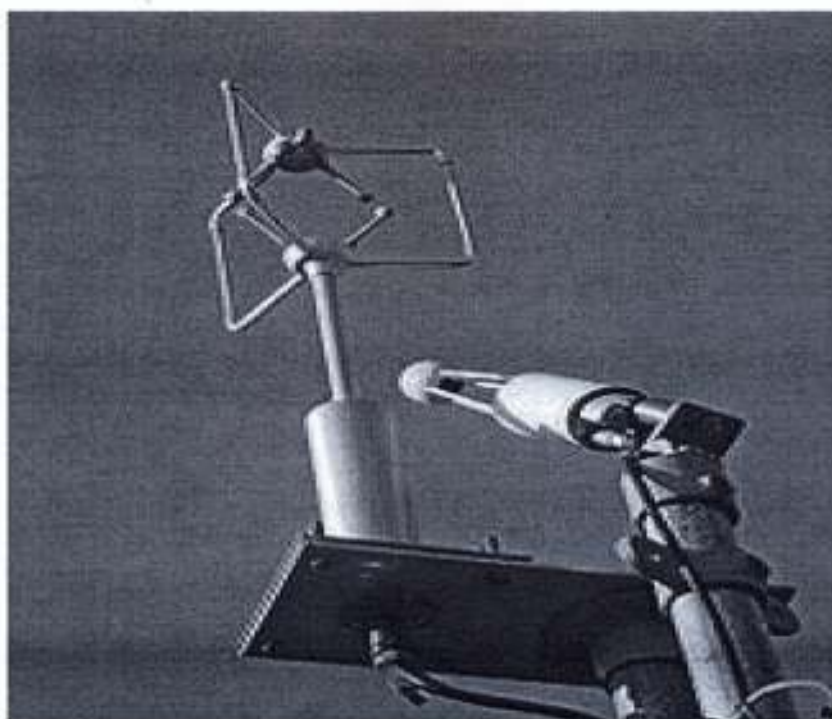


Figure 2: Eddy covariance system consisting of an ultrasonic anemometer and Infrared Gas Analyser (IRGA) – (Source: Wikipedia)

2.4.2 ESTIMATION FROM METEOROLOGICAL DATA

(i) Penman-Monteith Model

In 1948, Penman combined the energy balance with the mass transfer method and derived an equation to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed (Allen et al. 1998). The combination method was further developed by many researchers and extended to cropped surfaces by introducing resistance factors. According to Monteith(1965), Jensen(1966), Ostromecki(1965), Rijtema(1965) and Jackson et al.(1988), it is the most physically sound combination equation known at the time (Oguntunde, 1998).

These resistance factors are aerodynamic and surface. The surface resistance parameters are often combined into one parameter, the 'bulk' surface resistance parameter which operates in series with the aerodynamic resistance. The surface resistance, r_s , describes the resistance of vapour flow through stomata openings, total leaf area and soil surface. The aerodynamic resistance, r_a , describes the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces (Allen et al.1998).

Although these resistance factors cannot fully describe the complex exchange within a vegetation layer, good correlations can be obtained between measured and calculated evapotranspiration rates, especially for a uniform grass reference surface

(ii) **FAO 56 Penman-Monteith Model**

In 1990, a consultation experts and researchers was organized by FAO, in collaboration with the International Commission for Irrigation and Drainage and with the World Meteorological Organization, to review the FAO methodologies on crop water requirements and to advise on the revision and update of procedures.

The panel of experts then decided to adopt the Penman-Monteith approach as its basis giving the following definition

- That the reference crop is a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered.

The FAO Penman-Monteith model was then formed and this model overcame the shortcomings of previous models/methods giving more consistent values wherever they are applied across the world.

The reference evapotranspiration, ET_o , provides a standard to which: evapotranspiration at different periods of the year or in other regions can be compared and evapotranspiration of other crops can be related.

It should also be noted that to have a more consistent measurement, measurement of climatic data should be carried out at a height of 2m or converted to that height at the reference site. By using the FAO Penman-Monteith definition for ET_o , one may calculate crop coefficients at research sites by relating the measured crop evapotranspiration (ET_c) with the calculated ET_o , i.e., $K_c = ET_c/ET_o$ (Allen et al. 1998).

(iii) **Blaney-Morin Nigeria:**

According to Duru (1984), Blaney and Morin (1942) proposed a simple evaporation model shown below in S.I Unit form of measurement:

$$ET = p (0.45T + 8) (H - R^m)/100 \tag{6}$$

where

- ET Evapotranspiration (mm/day)
- p ratio of maximum sunshine hours to the annual maximum,
- $T \ \& \ R$ daily values of temperature and humidity
- $H \ \& \ m$ constants

This formula was later abandoned, and another model Blaney-criddle (1950) was adopted in its place. Having identified the weakness of the Blaney-Criddle model for Nigeria, Duru (1984) proposed a Nigeria based model on the original equation of Blaney and Morin (1942) and locally determined empirical constants H and m . He discovered that by replacing p

– the ratio of maximum possible hours of sunshine to the annual maximum with r_f – ratio of monthly radiation to annual radiation, the performance of the model was enhanced (Oguntunde, 1998).

(iv) **The Hargreaves-Samani Model:**

The Hargreaves (1975) working formula was modified in 1985 for grass conditions (Alexandris et al. 2008). It requires temperature (minimum and maximum and solar radiation for its measurements.

The mean air temperature in the Hargreaves equation is calculated as an average of T_{min} and T_{max} while R_a is computed from information about site (latitude) and the day of the year.

(v) **The Priestly – Taylor Model (Priestly and Taylor, 1972):**

This model constitutes a modification of Penman's equation; it's usually applied in areas of low moisture stress. Assumptions made in this model have been validated by a review of numerous studies which all conclude that in vegetated areas with very small water deficits; approximately 95% of evaporated demand is supplied by radiation (Stagnittii et al. 1989). Under these conditions, the mass transfer term in the penman combination equation approaches zero and radiation terms dominate (Alexandris et al. 2008). Due to this effect, Priestly – Taylor (1972) suggested the coefficient that was used to represent the aerodynamic term, this can be easily applied to most climates as pointed out by McAneney and Itier (1996).

Some other models that can be used to estimate evapotranspiration includes the adjusted Hargreaves method, Copais formula, the Makkink formula, the Turc method

(Alexandris et al., 2008) and the Thornthwaite approach. Below is a table of comparison of some of the methods of estimating evaporation based on the number of required parameters.

Parameters required by each model for the estimation of ET_0

Method	FAO-56 (Standard)	Penman – Monteith	Priestly- Taylor	Hargreaves- Samani	Blaney- Morin- Nigeria
Variables					
Temperature ($^{\circ}\text{C}$)	✓	✓	-	✓	✓
Humidity (%)	✓	✓	✓	-	✓
Wind speed (ms^{-1})	✓	✓	-	-	-
Solar Radiation ($\text{MJ m}^{-2} \text{day}^{-1}$)	✓	✓	✓	✓	-
Extra-terrestrial radiation ($\text{MJ m}^{-2} \text{day}^{-1}$)	✓	✓	✓	✓	✓
Sunshine Duration (hr)	-	-	✓	-	-
Saturated vapour pressure (kPa)	✓	✓	-	-	-
Crop Characteristics	✓	✓	-	-	-
No of parameters Req'd.	7	7	4	3	3

2.5 ESTIMATION OF EVAPOTRANSPIRATION IN A DATA SHORT ENVIRONMENT

In some instances where climatic data are not available in a region where evapotranspiration is to be measured, two methods of acquiring the data were proposed by Shih et al.

- (i) **Environmental Similarity:** An alternative Evapotranspiration estimation for an area is to adopt the available evapotranspiration data directly from other areas where crop and climatic conditions are similar. One of the approaches used to diagnose the similarity between two areas is the Koppen climate classification which is based on vegetation zones, temperature, rainfall and seasonal characteristics, (Critchfield, 1974). This alternative estimation is good for an area that has no reliable climatic data.
- (ii) **Climatic Data Generation:** Some mathematical models could be used to generate synthetic substitution for missing climatic data (Shih & Cheng, 1989). The

generated data are then used to estimate evapotranspiration employing the conventional methods. Based on this four techniques (Shih & Cheng, 1989) presented four methods for generating missing climatic data in Puerto Rico;

- a. **Regression Technique:** A stepwise technique is used to find the best correlation between the station with missing data and the stations without data missing.
- b. **Averaging Historical Data:** This method uses historical data available from the station to interpolate missing data for the same station. This method is recommended for implementation only when the regression technique is not applicable.
- c. **Regional Average:** This method which uses the data available from other stations to interpolate missing data for a single station can be implemented only under the following conditions: (1) No historical data are available from the station to be interpolated; and (2) The records are not long enough to establish a relationship through other methods.
- d. **Time Series Analysis Method:** This method uses the consecutive historical data available at a station to interpolate at missing data from the same station. It is particularly useful for generating a synthetic set of data for a time period that has no data available for implementing the other methods.

In recent times, based on the FAO Irrigation and drainage paper 56, (Allen et al. 1998), and the Modified Penman-Montieth reference evapotranspiration equation, a series of methods and procedures have also being suggested to generate missing climatological data, they include

- A. **Solar Radiation, R_s :** (Allen et al. 1998) suggest various methods to estimate R_s in the absence of local direct measurement (Popova et al. 2005):

- (i) From the observed duration of sunshine hours using the Angstrom Formula

$$R_s = [a_s + b_s \frac{n}{N}] R_a \quad (7)$$

- where R_s solar or shortwave radiation ($\text{MJm}^{-2}\text{day}^{-1}$),
 n actual duration of sunshine (hour),
 N maximum possible duration of sunshine or daylight hours (hour)
 n/N relative sunshine duration,
 R_a extraterrestrial radiation ($\text{MJ m}^{-2}\text{day}^{-1}$)
 A_s regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days ($n=0$)
 $a_s + b_s$ fraction of extraterrestrial radiation reaching the earth on clear days ($n=N$)

Extraterrestrial radiation R_a and daylight hours N are computed as a function of the day in the year and the latitude of the site (Allen et al. 1998) and the actual sunshine duration, n , is generally measured with a sunshine recorder, (Popova et al. 2005).

- (ii) Using the temperature difference method, based on the fact that differences between maximum and minimum temperatures are closely related to the existing daily solar radiation in a given location (Allen et al. 1998):

$$R_s = K_{Rs} \sqrt{T_{max} - T_{min}} R_a \quad (8)$$

- Where R_a extraterrestrial radiation ($\text{MJm}^{-2}\text{day}^{-1}$),

$T_{\max}$ maximum air temperature ($^{\circ}\text{C}$),

$T_{\min}$ minimum air temperature ($^{\circ}\text{C}$),

K_{Rs} adjustment coefficient ($0.16 - 0.19$) ($^{\circ}\text{C}^{-0.5}$)

The adjustment coefficient K_{Rs} is empirical and differs for 'interior' or 'coastal' regions: for 'interior' locations, where land mass dominates and air masses are not strongly influenced by a large water body, $K_{Rs} \approx 0.16$; for 'coastal' locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby body, $K_{Rs} \approx 0.19$. However, inherent to its empirical nature, there is some uncertainty relatively to this coefficient.

- (iii) Using R_s data observed in a nearby weather station. This method relies on the fact that for the same month and often for the same day, the variables affecting the incoming solar radiation, R_s and sunshine duration, n , are similar throughout a given region subject to the condition that the air masses governing rainfall and cloudiness are nearly identical within parts of the region; and the physiography of the region is almost homogenous. Where the north-south distance between weather stations within the same homogenous region exceeds 50 km, the R_s measurement should be adjusted using the ratio of the solar to extraterrestrial radiation as follows (Allen et.al 1998):

$$R_s = \frac{R_{s,\text{reg}}}{R_{a,\text{reg}}} R_a \quad (9)$$

where $R_{s,\text{reg}}$ solar radiation at the regional location ($\text{MJm}^{-2}\text{day}^{-1}$)

$R_{a,\text{reg}}$ extraterrestrial radiation at the regional location ($\text{MJm}^{-2}\text{day}^{-1}$).

This method was not tested.

- B. **Relative Humidity:** Where air humidity data are lacking, the actual vapour pressure, e_a , could be obtained by assuming that the dew point temperature, T_{dew} , is close to the daily minimum temperature, T_{min} , which is usually experienced at sunrise in reference weather stations. This statement implicitly assumes that at sunrise, when the air temperature is close to T_{min} , that the air is nearly saturated with water vapour and the relative humidity is nearly 100%. Then e_a is calculated by

$$e_a = e^o(T_{min}) = 0.611 \exp\left[\frac{17.27 T_{min}}{T_{min} + 237.3}\right] \quad (10)$$

T_{min} might be greater than T_{dew} in a non-reference weather station, as in a station located inside a town, where T_{min} may require correction (Allen, 1996 as cited in Allen et al., 1998). Allen et al. (1998) proposed that the estimate for e_a from T_{min} should be checked and that when the prediction by the above equation is validated for a region, it can be used for daily estimates of e_a .

- C. **Wind Speed:** Where no wind data are available, a procedure proposed by Allen et al. (1998), in addition to import data from a nearby station within the same homogenous region, is to use average wind speed data observed in a nearby location within the same homogenous region, preferably taking into consideration the seasonal variability of the wind. In fact, the impact of the wind speed on the reference evapotranspiration results is relatively small except for arid and windy areas (Popova et al. 2005). The 'average' wind speed estimates may be selected from information available for the regional climate, but should take seasonal changes into account. A value of 2 m/s can be used as a temporary estimate where

no wind data are available within the region. This value is the average over 2000 weather stations around the globe.

- D. **Using the Hargreaves (1985) method:** Estimation of reference evapotranspiration using the above method applies only the maximum and minimum temperatures with solar radiation measurements as stated in equation 10.

TREND IN EVAPOTRANSPIRATION MEASUREMENT AND MODELLING

Initial perceptions of evapotranspiration were that it was a simple atmosphere – surface exchange that is influenced by canopy cover. (Faharani et al., 2007). This led to the development of empirical formulae to estimate its value by some researchers like Thornthwaite (1948), Blaney and Criddle (1950) whose models were based on temperature, Christiansen (1968), based on pan evaporation, Jensen and Haise (1963); Hargreaves and Ghanani (1985) based on temperature and radiation.

During this period Penman (1948, 1963) made an important contribution by developing a combination model based on pure physics. The model consists of two terms, one accounting for energy required to maintain evaporation and the other term, atmospheric capacity to remove water vapour. A major contribution was then made to the Penman's model by Monteith (1965) when he stressed the importance of plants and canopy cover on evapotranspiration and thereby formulating the Penman-Monteith formula.

Further researches were thereafter carried out modifying already existing models to adapt them to a particular region or condition, e.g. Priestley and Taylor (1972) simplified the Penman's equation and fixed the aerodynamic term as a fraction (0.26) of the energy term in humid regions. Towards the turn of the century, a group of researchers in conjunction

with the FAO came up with a model referred to as the FAO 56 Penman-Monteith equation (Allen et al., 1998) which became universally accepted as the basis for the estimation of evapotranspiration.

Another significant progress which has really facilitated the estimation of evapotranspiration using models is the ability to acquire climatic variables such as air and soil temperature, humidity, solar radiation, wind speed and direction and rainfall using automated climate stations (Snyder et al., 1996)

In recent times, Sap Flow heat gauges are being used to measure transpiration and when it's used in combination with micrometeorological flux measurement, it is useful in the partitioning of evapotranspiration (Hutley et al., 2001). Also the estimation and partitioning of evapotranspiration has been carried out using stable isotopes technique because it helps to support conventional estimation methods by identifying the evaporation and transpiration contributions (Wang and Yakir, 2000)

Remote sensing technique of obtaining data using ground, aerial and satellite platforms are now being applied to estimate surface temperature, reflectance and vegetation indices and used with data from energy budget models to calculate heat and vapour fluxes (Farahani et al., 2007). This also creates opportunities for carrying out the mapping of evapotranspiration across large areas (Savige et al., 2005).

In a recent study in the conterminous United States carried out by Szilagyi (2001) using the Morton's WREVAP model (Morton et al. 1985) to analyse the trend of evaporation between 1961 – 1990, it was found out that evaporation significantly increased by 4% over the eastern part of the country which complements documented long term increases in temperature, rainfall and run-off values leading to increased activity of the hydrologic cycle in the conterminous United States. (Brutsaert and Parlange, 1998).

2.7 APPLICATION OF EVAPOTRANSPIRATION KNOWLEDGE

The knowledge of evapotranspiration cannot be ignored by Agricultural, Irrigation and Drainage Engineers because the concept of evapotranspiration crops up in most research and development activities carried out by them.

The increasing pressure on water resources requires a sound knowledge of where, when and how much water is used. This scenario makes evapotranspiration an important factor for evaluating water productivity and monitoring of irrigation performance (Mutiga et al. 2008).

Evapotranspiration is important in carrying out the following;

a) Estimation of Irrigation Requirements and its Scheduling

In carrying out irrigation, the knowledge of the crop water use (which can also be called evapotranspiration) among other things is necessary to adequately determine the volume of water required for each irrigation, the irrigation duration and irrigation period or frequency. The credible knowledge of evapotranspiration will help minimize water cost, optimize crop water use and eradicate run-off during irrigation.

b) Reservoir Design and Development

A reservoir is useful where the available flow in the stream is sometimes less than the flow required for water supply or irrigation, and water can be stored from a time when there is surplus, for example, from a wet season to a dry season when there is a deficit (Smout and Shaw, 1999). Reservoirs include dams, storage tanks, artificial ponds etc. To properly design and develop these structures (reservoirs) for effective and efficient delivery, the evapotranspiration requirement of the reservoir site is of utmost necessity.



c) **Crop modeling**

Changing climate has an effect on crop production, in view of this, researchers have come up with models to evaluate these effects and find ways to minimise its impact on crop production. Crop modelling performs a structured quantitative analysis that integrates the multiple effects of climate and CO₂, and the interactions with edaphic factors and management, on crop growth and yield (Paustian et al., 2000). Crop simulation model also helps to predict crop development and end grain yield.

d) **Agronomic studies**

With emphasis in production agriculture been placed on attaining the maximum yield possible, or obtaining the most economical yield, what is often not well understood is that yield is determined during the growing season when critical crop management decisions are being made on a daily basis. Final crop yield is often dependent on the quality and timeliness of the management decisions. Agronomic studies are carried out to determine the optimum plant population, sowing time, variety, fertility of soil; climatic conditions to achieve the best crop yield. Climatic conditions include temperature, humidity, rainfall which is the most important because it necessary for plant growth and production. To determine the optimum water requirement, the knowledge of evapotranspiration (crop water use) is necessary. This study can aid the farmer in making accurate and timely decisions and can greatly enhance production and profitability.

Other aspects where the knowledge of evapotranspiration is important are hydrological modeling, water resources planning and management

CHAPTER THREE

METHODOLOGY



3.1 The Study Area

The area considered under this study covers the whole of Nigeria with specific emphasis on three cities, Ibadan, Kano and Onne where IITA stations are located. It lies within latitudes $4^{\circ}\text{N} - 14^{\circ}\text{N}$ and Longitudes $2^{\circ}\text{E} - 15^{\circ}\text{E}$. The country has an estimated population of 138,283,380 people (2008 estimates, Source: Wikipedia) and a total land mass of $923,768\text{km}^2$ (the 32nd largest country in the world) with about 1.4% of this land mass covered by water.



Figure 3: Map showing Study Area, Ibadan, Kano and Onne(near Port Harcourt) within Nigeria

The southern region of the country is characterized by a coastline spanning from the south western to the south eastern part of the country which has the largest delta in Africa, the Niger delta. It has a tropical rainforest climate having an annual rainfall of between 60 – 80 inches (1524mm – 2032mm) with the most south region of the forest zone having salty water swamp popularly referred to as the mangrove swamp forest due to the presence of a large amount of mangrove in the area. Further north is the fresh water swamp and the rain forest. The relief of this region is typified by its hilly nature having rugged highlands in the west extending to the Benue Mountains in the east.

North of the tropical forest region of Nigeria is the Savannah Zone depicting the starting point of Northern Nigeria, characterized by an annual rainfall of between 20 – 60 inches (508mm – 1524mm). The savannah can be subdivided into three categories; the Guinea savannah having tall grasses and trees with a little moist climate; further north is the Sudan Savannah, a region of shorter grasses and more scattered, drought-resistant trees such as the baobab, tamarind, and acacia. In the furthest north of the country, the third category exists referred to as the Sahel savannah which has a near desert climate with annual rainfall usually below 20 inches. The relief of the northern region of Nigeria is a lowland with a relatively level topography spanning the Lake Chad basin to the Sokoto lowlands.

Special emphasis is placed on three location having distinct characteristics into which the climatic conditions of the country can be divided. They are:

- i. Onne (**4°45'0"N, 7°00'0"E**); near Port Harcourt having a humid climate characterized by swamps, heavy rainfall and mangrove forests. The region's soil is Thionic Fluvisol, having a mean annual rainfall of 2400mm, a unimodal rainfall pattern with annual maximum temperature ranging from 28-32°C, annual minimum temperature ranging from 21-23°C. It also has two distinct seasons; the lengthy and heavy rainy season and very short dry season. The rainy season spans

February to November while the dry season occurs in the remaining months although precipitation of about 20mm do occur during this period.

- ii. Ibadan ($7^{\circ}23'47''\text{N}$ $3^{\circ}55'0''\text{E}$); is also one of the locations. It has a sub-humid climate which is characterized by rain forests and slightly heavy rainfall. Its rainfall pattern is Bimodal with mean annual rainfall of 1250mm. The region's soil is majorly Ferric Luvisols, its seasons are wet which from March through October and dry running through November to February having annual maximum temperature ranging between $27-34^{\circ}\text{C}$ and annual minimum temperature ranging between $20-23^{\circ}\text{C}$.

Both regions mentioned above are characterized with light wind speeds. (Oguntunde, 1998).

- iii. The third location is Kano ($12^{\circ}00'0''\text{N}$ $8^{\circ}31'0''\text{E}$) which is situated in the northern region of the country. It has a semi-arid or savannah climate characterized with scattered trees and shrubs. The region has a high wind speed which carries large deposits of sand that are deposited in the area to replenish the soil removed by erosion. It has Ferric Latosol soils and the region has an annual mean rainfall of 748.1mm between 1988 and 2001. Its season can be divided into two, the wet/rainy season which occurs between May and September with temperature ranging between $24^{\circ}\text{C}-29^{\circ}\text{C}$ and the dry season between October and April with maximum temperature range between $28^{\circ}\text{C}-34^{\circ}\text{C}$ and minimum temperature range between $25^{\circ}\text{C}-27^{\circ}\text{C}$.

Other locations within the country were also covered under this study but their characteristics can be related to any of the three locations described above.

3.2 Description of models

Four methods of computing evapotranspiration making use of empirical formulae were compared with the FAO 56 Penman-Monteith formulae to determine which can be best applied to Nigeria. The methods are Penman-Monteith approach, Blaney-Morin-Nigeria model, Hargreaves-Samani model and Priestley-Taylor formula. The models were used to estimate ET for the three study locations and are described below:

(i) FAO 56 Penman-Monteith approach:

This method has been recommended as the sole method for the estimation of evapotranspiration certified by the FAO because it takes into consideration both physical and aerodynamic parameters. In calculating ET using this approach, the equation stated below was applied and the computation of all required data necessary for the calculation of ET was carried out using the laid out procedure given in Chapter 3 of the FAO paper 56 (Allen et al., 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (11)$$

where

ET_0	reference evapotranspiration [mm day^{-1}],
R_n	net radiation at the crop surface [$\text{MJ m}^{-2} \text{day}^{-1}$],
G	soil heat flux density [$\text{MJ m}^{-2} \text{day}^{-1}$],
T	mean daily air temperature at 2 m height [$^{\circ}\text{C}$],
u_2	wind speed at 2 m height [m s^{-1}],
e_s	saturation vapour pressure [kPa],
e_a	actual vapour pressure [kPa],

- $e_s - e_a$ saturation vapour pressure deficit [kPa],
 Δ slope vapour pressure curve [kPa °C⁻¹],
 γ psychrometric constant [kPa °C⁻¹].

(ii) **Penman-Monteith Approach:**

The method also required both physical and climatic parameters as well as vegetation characteristics. Parameters needed included information on humidity, radiation, wind speed, temperature, stomata resistance, vegetation height and Leaf Area Index (LAI). The equation applied for the Penman-Monteith approach is as stated below;

$$ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (12)$$

where R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapour pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapour pressure temperature relationship, γ is the psychrometric constant, and r_s and r_a are the (bulk) surface and aerodynamic resistances

And the procedure for the determination of the aerodynamic and bulk resistances were followed as outlined in Allen et al., (1998)

$$r_a = \frac{\ln \left[\frac{z_m - d}{z_{om}} \right] \ln \left[\frac{z_h - d}{z_{oh}} \right]}{k^2 u_z} \quad (13)$$

Where;

r_a = aerodynamic resistance [$s\ m^{-1}$]

z_m = height of wind measurements [m]

z_h = height of humidity measurements [m]

d = zero plane displacement height [m]

z_{om} = roughness length governing momentum transfer [m]

z_{oh} = roughness length governing transfer of heat and vapour [m]

k = von Karman's constant, 0.41 [-]

u_z = wind speed at height z [$m\ s^{-1}$]

The terms d and z_{om} can be derived as a function of crop height, h (h is the assumed crop height of 0.12m). $d = 0.67h$, $z_{om} = 0.123h$, also $z_{oh} = 0.1z_{om}$. Assuming $z_m = z_h = 2m$, $r_a = 228/u_2$ (Allen et al., 1998). u_2 is wind speed at 2m.

Also,

$$r_s = \frac{r_i}{LAI_{active}} \quad (14)$$

where;

r_s = (bulk) surface resistance [$s\ m^{-1}$]

r_i = bulk stomatal resistance of the well-illuminated leaf [$s\ m^{-1}$]

LAI_{active} = leaf area index [m^2 (leaf area) m^{-2} (soil surface)]

(Note: $LAI_{active} = 0.5LAI$ and $LAI = 24 \cdot h$ and under a well watered condition, $r_i = 100\ s\ m^{-1}$, $r_s = 70\ s\ m^{-1}$).

- (iii) **Blaney-Morin-Nigeria Model (BMN)**: This method was applied following the steps laid down by Duru (1984) and it was easily carried out because of the few parameters needed to estimate ET using this model. The equation was given as;

$$ET = r_f (0.45T_a + 8) (520 - R^{1.31})/100 \quad (15)$$

where: r_f = ratio of monthly radiation to annual radiation

T_a = mean monthly temperature in °C

R = mean monthly relative humidity

- (iv) **Priestly-Taylor Model**: This model can be described by the following equation:

$$ET = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \frac{1}{\lambda} \quad (16)$$

where,

α 1.26

λ the latent heat of vaporization [2.45MJ kg⁻¹ @ 20°C]

Other parameters are as defined in equation above.

- (v) **Hargreaves-Samani Model**: The equation that was applied while using this model to estimate evapotranspiration was given as;

$$ET = 0.0023(T_{\max} - T_{\min})^{0.5} (T_m + 17.8)R_a \quad (17)$$

where

ET daily reference evaporation (mm.day⁻¹),

$T_{\max}$ daily maximum air temperature (°C)

$T_{\min}$ daily minimum air temperature (°C)

T_m mean daily air temperature (°C)

R_a extraterrestrial radiation (mm.day⁻¹)

The data requirements for each of the five models applied is as shown in Table 1.

3.3 Temporal Analysis Procedure

The non-parametric Mann – Kendall test was also applied to detect the significance of the trend in the observed evapotranspiration values and the Sen's non-parametric test was applied using a linear model to detect the magnitude of the trend. The procedures followed were outlined by Salmi, T. Et al. (2002).

The temporal trend of estimated values of ET over the study duration was carried out using an excel template, MAKESENS, the combination of both Mann-Kendall test for trend and Sen's slope estimates. The Mann-Kendall test statistic S according to Salmi et al. (2002) is given by

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (18)$$

where n is the length of the time series $x_1, \dots, x_n$, and $\text{sgn}()$ is a sign function, x_j and x_k are values in years j and k , respectively. The expected value of S equals zero for series without trend and the variance is computed as (Oguntunde et al. (2006)

The test statistic Z is then given as

$$\sigma^2(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (19)$$

Here q is the number of tied groups and t_p is the number of data values in p th group.

As a non-parametric test, no assumptions as to the underlying distribution of the data are necessary. The Z statistic is then used to test the null hypothesis, H_0 that the data is randomly ordered in time, against the alternative hypothesis, H_1 , where there is an increasing or decreasing monotonic trend. A positive (negative) value of Z indicates an upward (downward) monotone trend. H_0 is rejected at a particular level of significance if the absolute value of Z is greater than $Z_{\alpha/2}$, where $Z_{\alpha/2}$ is obtained from the standard normal cumulative

distribution tables. Hobbins et al. (2001) noted that the Mann-Kendall test is non-dimensional and does not quantify the scale or the magnitude of the trend but the direction of trend. In estimating the true slope of the trend, the Sen's nonparametric method was used. The Sen's method can be used in cases where the trend can be assumed to be linear.

3.4 Statistical Analysis

Five statistical models were used to test the efficiency of the models used for estimating evapotranspiration. They are;

- i. The Mean Bias Error (MBE)

$$MBE = N^{-1} \sum_{i=1}^N (Pi - Oi) \quad (20)$$

- ii. Measurement of the variability of the difference between the predicted and observed values;

$$S_d^2 = (N - 1)^{-1} \sum_{i=1}^N (Pi - Oi - MBE)^2 \quad (21)$$

- iii. The Mean Absolute Error (MAE); gives the mean difference between the observed and predicted values but more accurate for small or limited data.

$$MAE = N^{-1} \sum_{i=1}^N |Pi - Oi| \quad (22)$$

- iv. The Root Mean Square Error (RMSE); similar in operation with the Mean Absolute Error (MAE) but preferred for use with large data.

$$RMSE = [N^{-1} \sum_{i=1}^N (Pi - Oi)^2]^{0.5} \quad (23)$$

- v. The Coefficient of Correlation (r): Investigates the level of similarities between two sets of values.

$$r = \frac{\sum PO - \frac{\sum P \sum O}{N}}{\sqrt{(\sum P^2 - \frac{(\sum P)^2}{N})(\sum O^2 - \frac{(\sum O)^2}{N})}} \quad (24)$$

where O represents the observed evapotranspiration values (the FAO 56 model); P is the predicted values of evapotranspiration from the other models; the closer to zero the values of MBE, S²d, MAE and RMSE, the better performed the respective model, whereas the closer to unity (1) the value of 'r', the better the model.

3.5 Recalibration of Blaney-Morin-Nigeria Model

During the course of this study, modification of the existing Blaney-Morin-Nigeria model by Duru (1984) was carried out. This was done so as to generate a better model for evapotranspiration estimation that can be reliably applied at every region of the country bearing in mind, the minimal number of required variables needed for the model which can be easily obtained within the country and to also correct some shortcomings observed from the procedure applied by Duru in creating this model.

In the computation of the Duru (1984) model, climatic data used was obtained for only one station, that is Zaria and for a ten-year period. The station used as the basis for the computation of this model is located in the northern part of the country, a Sudan savannah region and from the illustration shown in the study area. It is clear that the climatic parameters that can be obtained in that region will differ significantly from that which can be obtained in other parts of the country, especially in the south. In trying to correct this anomaly, this study made use of data sourced from three stations scattered in different agro-ecologic zones across the country, these locations are Ibadan, a 36-year (1973 – 2008) data, Kano, a 29-year (1980 - 2008) data and Onne 31-year (1977 - 2007) data.

It was also discovered that pan evapotranspiration was used as the basis of comparison for the development of the Blaney-Morin-Nigeria model. This was acceptable at that time due to the level of research done at that time. But in recent times, a more reliable model has been developed as a universal basis for comparison or evaluating evapotranspiration, thereby putting into question the accuracy of the BMN (1984). According to the FAO Irrigation and drainage paper 56, (Allen et al. 1998), the widely accepted model for the estimation of evapotranspiration all over the world is the FAO56 Penman-Monteith mode. This model was applied to this study. Also a constant pan coefficient of 0.7 was used for the development of the BMN (1984) model which if the varying climatic conditions across the country were considered will not be very accurate because different pan coefficients will exist for different regions in the country.

A trial and error method was applied by manually increasing suggested values of m which was prone to error whereas in this study, an algorithm developed by Levenberg – Marquardt was applied to give more accurate values of the parameters H and m thereby minimizing any possible errors. The Levenberg-Marquardt algorithm is an iterative technique that locates the minimum of a multivariate function that is expressed as the sum of squares of non-linear real-valued functions (Lourakis, 2005). It has become a standard technique for non-linear least-squares problems, widely adopted in a broad spectrum of disciplines.

In applying the above algorithm, the equation 6 was used with all the necessary parameters supplied and the needed parameters, i.e. H and m were obtained using the procedure described below;

The obtained data from the three study locations were divided into two parts at each location. This was done by sorting them into one part containing two-third of the data and the remaining third forming the one-third part. The data for each location was arranged according to their years and the first two years were selected to form part of the two-third data and the

third year as part of the one-third data. This was repeated successively until the sorting was completed. The two-third parts from each station were then harmonized (pooled together) to form the data representing all stations. The 4 two-third data parts were then used to generate 4 new Blaney-Morin-Nigeria models, one each peculiar to the three stations while the fourth can be generally applied to any of the stations to obtain a reliable result likewise across the country. These models were then validated using the remaining one-third part data at each station by using the equations to estimate evapotranspiration values and the values estimated by their application were also compared to the values obtained from the FAO 56 model using the five statistical parameters stated in section 3.4.

The arguments above agrees with the issues raised by Idike, (2008) in his paper titled Blaney-Morin-Nigeria Evapotranspiration Model, A Technical Note where he also found faults with the procedures applied by Duru in the development of the Blaney-Morin-Nigeria model.

CHAPTER FOUR

RESULTS AND DISCUSSION



4.1 Temporal Trends in Evapotranspiration

The Non-Parametric Mann-Kendall and Sen's test was applied to test the trend i.e. the increase or decline in evapotranspiration of the values estimated from the FAO 56 model. The ET_0 values estimated were separated into two components; they are the Aerodynamic term and the Radiative term. The test was also applied to these terms to help ascertain the direction of trend for either of the two that contributes majorly to the direction of the trend for estimated ET_0 Values. This trend was determined for each station, Ibadan, Kano and Onne. The results of the analysis for each station are shown below:

4.1.1 Evapotranspiration Trends for Ibadan

The summary of the temporal analysis for Ibadan is given in Table 2. Monthly values of ET_0 declined between the ranges of 1.51% in January to 3.8% in July. These reductions were significant at $P < 0.01$ in all the months except for January. The annual ET_0 declined significantly ($P < 0.001$) at 4.05% over the 36 years. For the radiative term, monthly values declined significantly ($P < 0.01$) between the ranges of 2.66% in March to 4.42% in February and its annual value significantly ($P < 0.001$) reduced by 4.45%. The aerodynamic term declined in every month except for January (0.42%) and December (0.67%) which increased, insignificantly. The decline was between 0.23% in February and 3.12% in August, which were significant at $P < 0.1$ in the months that showed a decrease in their aerodynamic term.

except for the months of February, March, April, June and November. The aerodynamic term decreased at 0.72% over the 36 years but it was not significant.

Table 2: Non-parametric Mann-Kendall and Sen's test summary statistics for Ibadan

Month	Rad Term (mmday ⁻¹)			Aero Term (mmday ⁻¹)			Evapotranspiration (mmday ⁻¹)		
	%Change/ yr	Sig.	Slope (/yr)	%Change /yr	Sig.	Slope (/yr)	%Change/ yr	Sig.	Slope (/yr)
JAN	-3.582	***	-0.014	0.422		0.004	-1.512		-0.012
FEB	-4.427	***	-0.021	-0.232		-0.002	-3.092	**	-0.023
MAR	-2.656	**	-0.014	-0.558		-0.003	-2.901	**	-0.022
APR	-3.637	***	-0.019	-0.586		-0.002	-3.337	***	-0.021
MAY	-3.392	***	-0.013	-1.784	∞	-0.003	-3.337	***	-0.017
JUN	-3.582	***	-0.015	-1.539		-0.004	-3.310	***	-0.019
JUL	-2.983	**	-0.015	-2.574	*	-0.006	-3.800	***	-0.022
AUG	-2.738	**	-0.015	-3.119	**	-0.008	-3.555	***	-0.022
SEP	-3.446	***	-0.016	-1.975	*	-0.005	-3.392	***	-0.021
OCT	-3.528	***	-0.016	-2.111	*	-0.005	-3.664	***	-0.022
NOV	-3.855	***	-0.017	-0.368		-0.001	-3.092	**	-0.018
DEC	-3.610	***	-0.012	0.667		0.002	-3.228	**	-0.012
ANNUAL	-4.454	***	-0.015	-0.722		-0.002	-4.045	***	-0.020

*** significant at 0.001, **significant at 0.01, * significant at 0.05, ∞ significant at 0.1

Rad Term: radiative part of evapotranspiration;

Aero Term: aerodynamic part of evapotranspiration

The annual time series of ET_o , the radiative and aerodynamic terms for the station are also shown in figure below. These figures further explain the trend of ET_o and its component parts over the years under consideration;

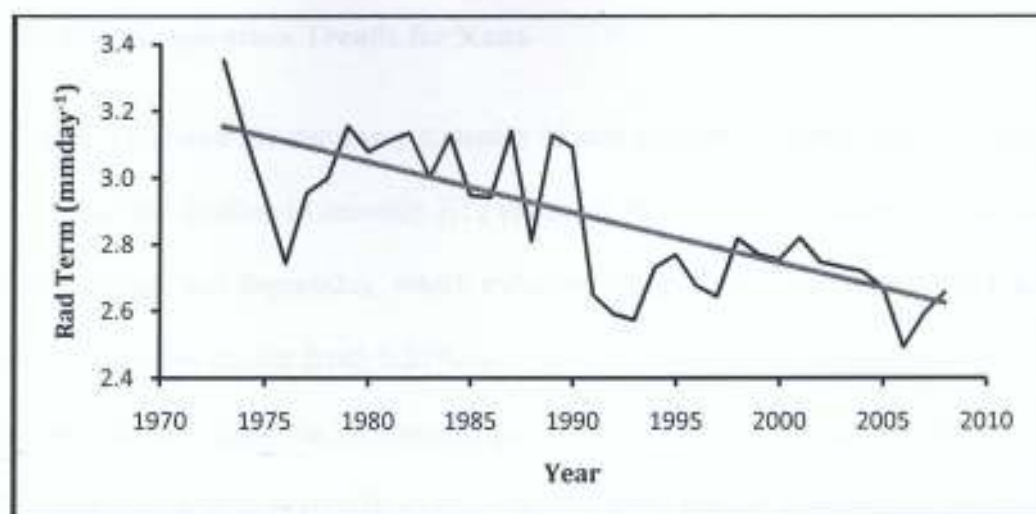


Figure 4 (a): Annual trend of radiation term of evapotranspiration for Ibadan

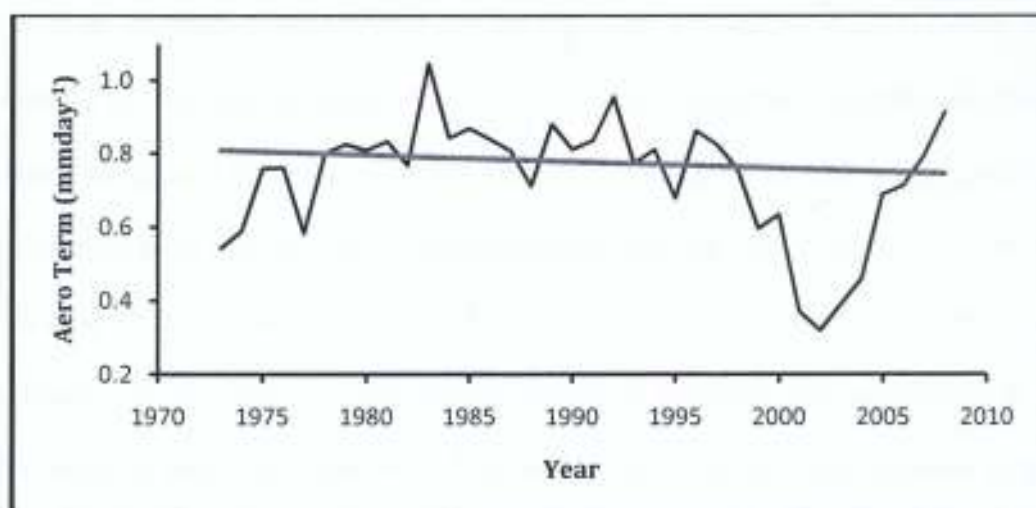


Figure 4 (b): Annual trend of Aerodynamic term of evapotranspiration for Ibadan

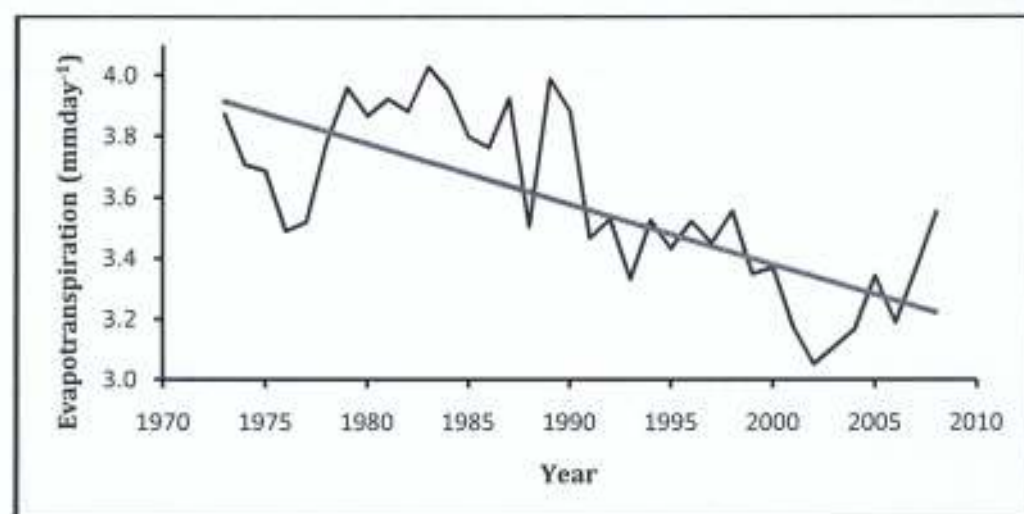


Figure 4 (c): Annual Evapotranspiration trend for Ibadan (1973 – 2008)

4.1.2 Evapotranspiration Trends for Kano

Table 3 showed the summary statistics of non-parametric trend test for Kano. There is a non-significant decline in monthly ET_0 values in all the months except for the months of May, June, August and September, which indicates a non-significant increase in ET_0 values. The reduction values ranges from 0.21% in February to 0.99% in March and April over the 29 years considered, while the increase ranges from 0.24% in September to 0.77 % in June. The ET_0 rate declined non-significantly at 0.54% over the 29 years. The analysis of the radiative term portrayed an increase in all the months except for December that showed a decrease (non-significant with value of 0.17% over 29 years). The increase was not significant in all the months except for the months of September, October and November which were significant ($P<0.05$) over the range 0.17% in April to 2.68% in September. The annual radiative term also showed a non-significant increase with a value of 0.47% over 29 years. In case of the aerodynamic term, the analysis gave a decrease in its value in all the months except for the month of May which showed an increase (non-significant) at the rate of 0.39% over 29 years and February, which indicated no change. The decrease in the other months were non-significant except for the months of August and September ($P<0.1$) and the decline value ranges from 0.28% in January to 1.78% in August. Its annual value depicted a non-significant decline rate of 1.14% over the 29 years.

Table 3: Non-parametric Mann-Kendall and Sen's test summary statistics for Kano

Month	Rad Term (mmday ⁻¹)			Aeroterm (mmday ⁻¹)			Evapotranspiration (mmday ⁻¹)		
	%Change /yr	Sig.	Slope (/yr)	%Change /yr	Sig.	Slope (/yr)	%Change /yr	Sig.	Slope (/yr)
JAN	0.506		0.003	-0.281		-0.007	-0.319		-0.011
FEB	0.882		0.007	0.000		-0.001	-0.206		-0.010
MAR	1.144		0.010	-1.219		-0.031	-0.994		-0.053
APR	0.169		0.003	-0.957		-0.036	-0.994		-0.033
MAY	1.069		0.017	0.394		0.011	0.544		0.025
JUN	1.144		0.015	-0.506		-0.006	0.769		0.016
JUL	0.469		0.005	-1.107		-0.009	-0.356		-0.004
AUG	1.257		0.011	-1.782	∞	-0.010	0.506		0.004
SEP	2.682	**	0.026	-1.707	∞	-0.020	0.244		0.002
OCT	2.082	*	0.025	-1.219		-0.042	-0.469		-0.013
NOV	2.045	*	0.014	-0.844		-0.020	-0.431		-0.012
DEC	-0.169		-0.001	-0.506		-0.012	-0.506		-0.006
ANNUAL	0.469		0.003	-1.144		-0.021	-0.544		-0.011

**significant at 0.01, * significant at 0.05, ∞ significant at 0.1

Rad Term: radiative part of evapotranspiration;

Aero Term: aerodynamic part of evapotranspiration

The annual time series of ET₀, the radiative and aerodynamic terms for the station are also shown in figure below. These figures further explain the trend of ET₀ and its component parts over the years under consideration;

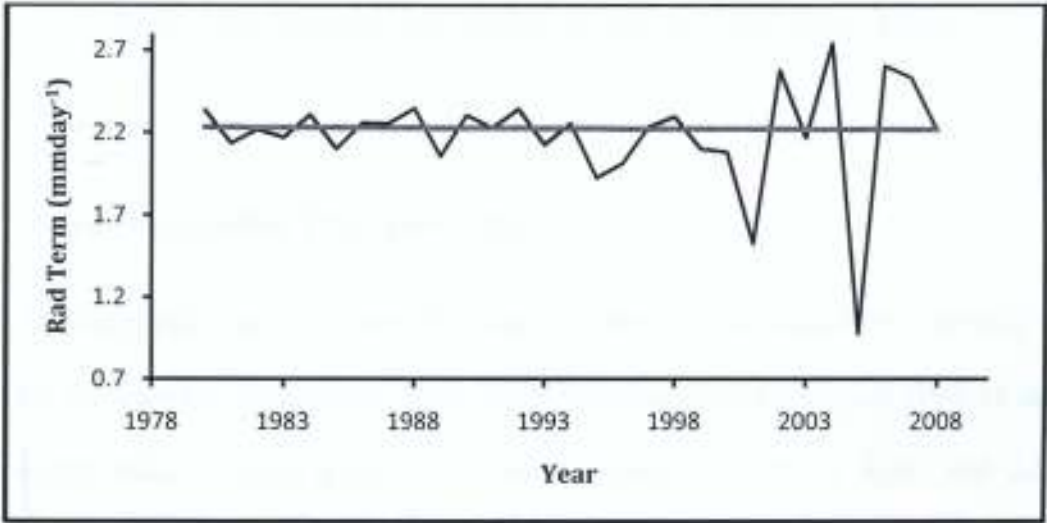


Figure 5 (a): Annual trend of radiation term of evapotranspiration for Kano

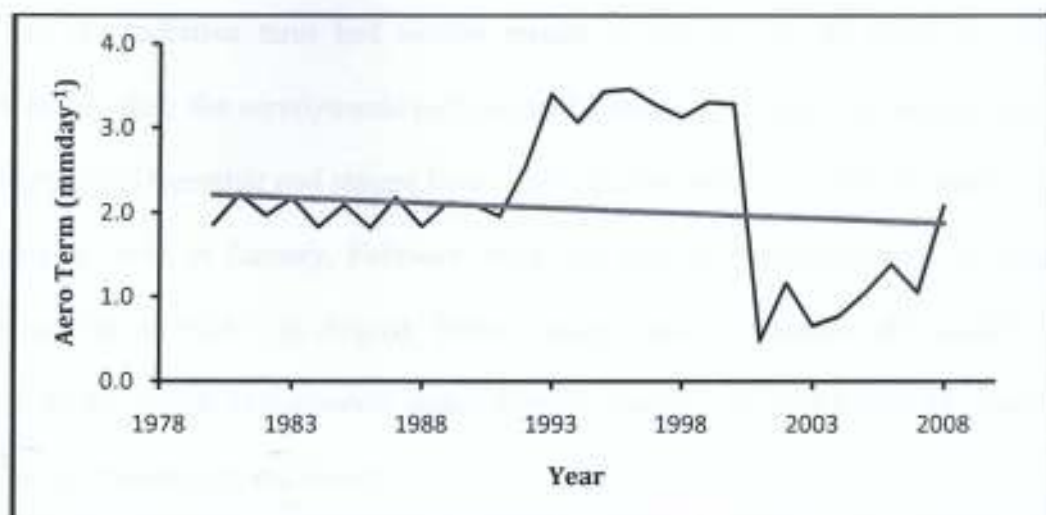


Figure 5 (b): Annual trend of Aerodynamic term of evapotranspiration for Kano

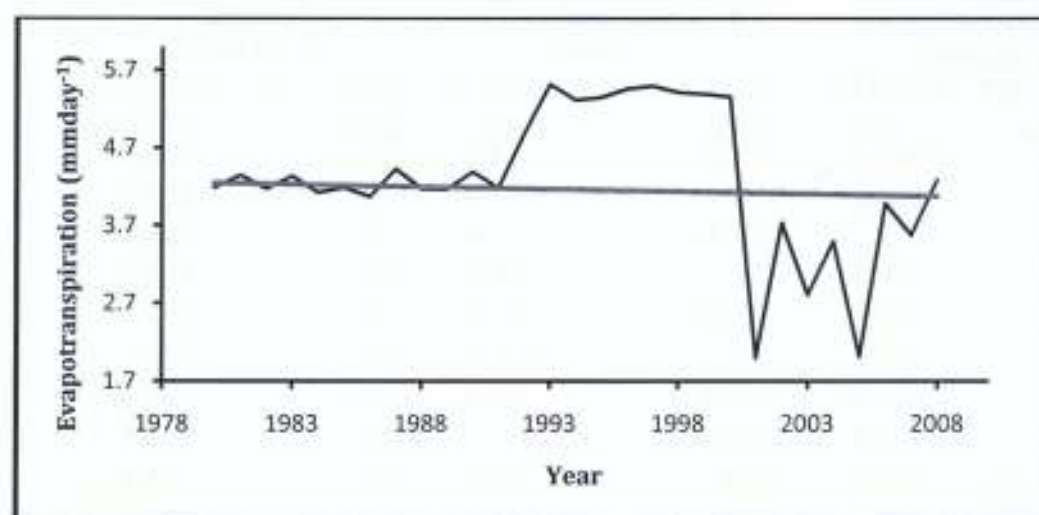


Figure 5 (c): Annual Evapotranspiration trend for Kano (1980 – 2008)

4.1.3 Evapotranspiration Trends for Onne

At Onne, the analysis of the ET_o values showed a non-significant monthly decline except for the months of February, June and September with significant ($P < 0.1$) decrease. The monthly value reduced over the range of between 0.37% in April and 2.45% in September. Annual ET_o value decreased at the rate of 1.87% over the 31 years (1989 – 2006). This reduction is significant ($P < 0.1$), as shown in Table 4. Also from the table, it could be

seen that the radiative term had similar results to that of ET_0 in terms of values and significances while the aerodynamic term showed a decrease in value for March, April, June, and October to December and ranged from 0.02% in December to 0.99% in April. Aero term increased in trend in January, February, May and July to September with its range from 0.14% in May to 0.65% in August. These changes were not statistically significant. The analysis of the annual aerodynamic terms showed change in its trend over 31 years but this was also not statistically significant.

Table 4: Non-parametric Mann-Kendall and Sen's test summary statistics for Onne

Month	Rad term (mmday ⁻¹)			Aero Term (mmday ⁻¹)			Evapotranspiration (mmday ⁻¹)		
	%Change /yr	Sig.	Slope (/yr)	%Change /yr	Sig.	Slope (/yr)	%Change /yr	Sig.	Slope (/yr)
JAN	-1.360		-0.007	0.306		0.0018	-1.360		-0.007
FEB	-1.972	*	-0.009	0.544		0.0030	-1.972	*	-0.009
MAR	-1.428		-0.006	-0.544		-0.0032	-1.428		-0.006
APR	-0.374		-0.002	-0.986		-0.0039	-0.374		-0.002
MAY	-1.190		-0.006	0.136		0.0003	-1.190		-0.006
JUN	-1.768	∞	-0.010	-0.204		-0.0006	-1.768	∞	-0.010
JUL	-0.680		-0.008	0.238		0.0005	-0.680		-0.008
AUG	-1.564		-0.007	0.646		0.0004	-1.564		-0.007
SEP	-2.447	*	-0.013	0.238		0.0002	-2.447	*	-0.013
OCT	-0.986		-0.005	-0.442		-0.0008	-0.986		-0.005
NOV	-1.360		-0.006	-0.102		-0.0004	-1.360		-0.006
DEC	-1.462		-0.009	-0.017		-0.0001	-1.462		-0.009
ANNUAL	-1.870	∞	-0.008	0.000		0.0000	-1.870	∞	-0.008

* significant at 0.05, ∞ significant at 0.1

Rad Term: radiative part of evapotranspiration;

Aero Term: aerodynamic part of evapotranspiration

The annual time series of ET_0 , the radiative and aerodynamic terms for the station are also shown in figure below. These figures further explain the trend of ET_0 and its component parts over the years under consideration;

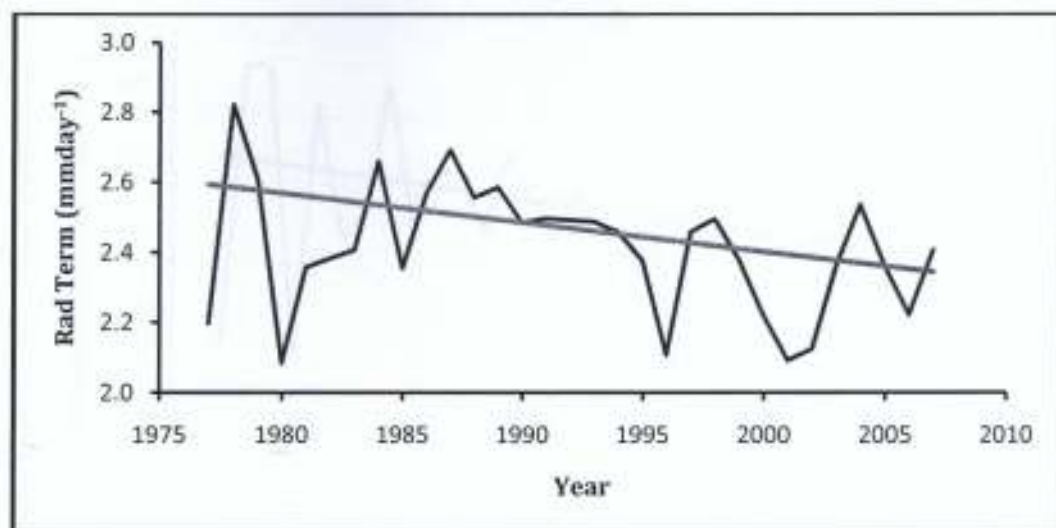


Figure 6 (a): Annual trend of radiation term of evapotranspiration for Onne

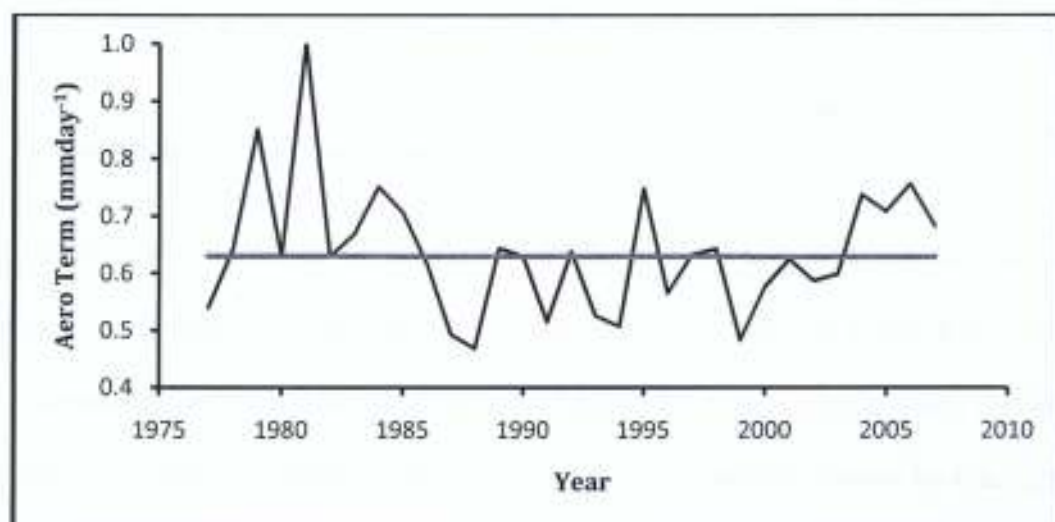


Figure 6 (b): Annual trend of Aerodynamic term of evapotranspiration for Onne

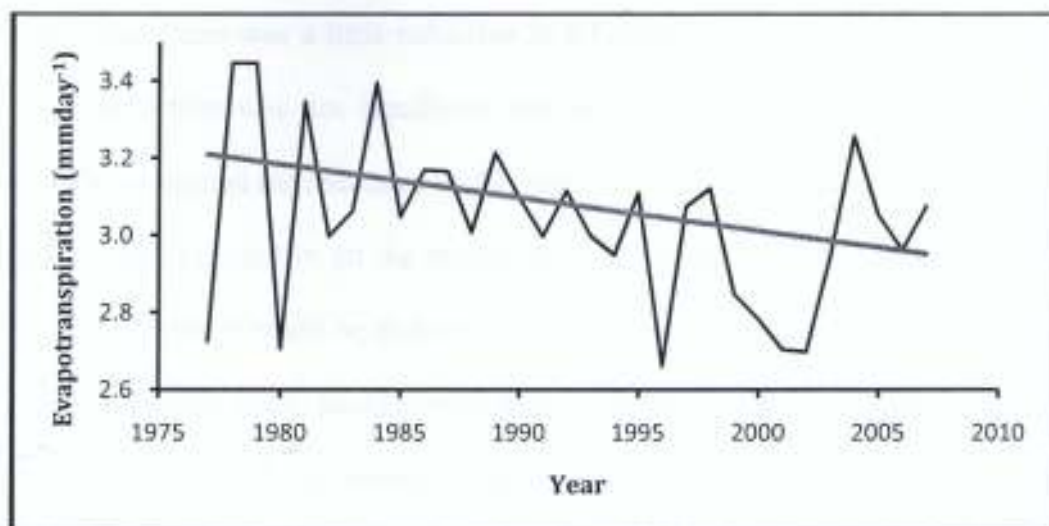


Figure 6 (c): Annual Evapotranspiration trend for Onne (1977 – 2006)

4.1.4 Discussion on Observed Trends

A general decline in ET_0 values over the periods and stations considered were observed. This decline was significant for Ibadan at 0.001 levels, for Onne at 0.1, except for Kano with an insignificant decrease. These findings agree with a similar study carried out in China which showed a decreasing trend of ET_0 which was largely caused by the decrease in solar radiation followed by the decrease in wind speed (Xu et al., 2006).

At Ibadan, it was observed from the component parts of ET_0 that there was a significant decrease in the values of the radiative term and an insignificant decrease in the aerodynamic term. It can be concluded that the reduction in the values of the radiative term which is majorly derived from solar radiation is the major contributor to the decline in ET_0 for Ibadan. This agrees with a similar research carried out in China which showed that the widespread decline of pan evaporation was as a result of decreasing solar irradiance (Liu et al., 2004). Previous studies showed that evapotranspiration and pan evaporation have similar regional distribution patterns (Xu et al., 2006).

At Kano, there was a little reduction in ET_0 rate over the period considered for this study. This reduction was not significant and in this case, there was an increase in the radiative term as against the reduction in this term observed in Ibadan. On the other hand, the aerodynamic term reduced in all the months and the annual average which agreed with the reduction in ET_0 rate. It could be deduced from the result that the major cause of the decline in ET_0 trend for Kano is the aerodynamic term of the ET_0 which was mainly influenced by reduction in wind speed. It also showed from the increase in the radiative term that the effect of climate change is more pronounced in this part of the country in the aspect of increasing temperature, reduction in cloud cover, leading to increase solar radiation.

This decrease in ET_0 with an observed increase in solar radiation contradicts results obtained for similar researches carried out in some parts of the world. For example in Canada, ET_0 showed an increasing trend which was as a result of increase in air temperature and solar radiation (Fernandez et al., 2007).

In Onne, the ET_0 rate showed a decline in its trend, and from the results obtained from the analysis, the annual aerodynamic term had no change over the period considered and it could be seen that the decline in ET_0 rates was mainly influenced by the decline in the radiative component of ET_0 and this was significant at 0.1.

4.2 Performance Evaluation of Selected ET_0 Models

Evapotranspiration values were estimated from the data obtained from three IITA stations, Ibadan (1977 – 2008), Kano (1980 – 2008) and Onne (1977 – 2006) using the FAO 56, Penman, Blaney-Morin-Nigeria, Hargreaves-Samani and Priestly Taylor models. The models were thereafter compared making use of five statistical parameters (stated in 3.3) with FAO 56 serving as the basis of comparison (observed values) and values obtained from the

other models serving as the predicted values. The results of the comparison are presented as follows.

4.2.1 ET_0 Models Evaluation at Ibadan

Table 5: Summary of evaluation statistics of four evapotranspiration models at Ibadan

Statistical Parameters	MODELS			
	Penman-Monteith	BMN	Hargreaves-Samani	Priestly Taylor
MBE	0.018 (1)	0.338 (2)	0.695 (3)	3.418 (4)
S^2d	0.002 (1)	0.264 (3)	0.231 (2)	0.598 (4)
MAE	0.041 (1)	0.470 (2)	0.739 (3)	3.418 (4)
RMSE	0.048 (1)	0.470 (2)	0.502 (3)	3.199 (4)
R	0.997 (1)	0.706 (3)	0.672 (4)	0.725 (2)
Average Rank	(1)	(2)	(3)	(4)

Rank Value is given in parenthesis ranging from 1 – 4 with the rating of the model increasing as rank value decreases. (MBE - Mean Bias Error; S^2d - Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and r - Correlation Coefficient)

In Ibadan, the BMN model produced the second best estimate for ET_0 which is mainly because the model was specifically developed to be applied in Nigeria. This was closely followed by the Hargreaves-Samani model which was a modification of the Hargreaves model developed for grass conditions (Alexandris et al., 2008). The characteristic vegetation of Ibadan is that of forests which extensively cover large parts of the region and this vegetative cover allows for the little reliability of the Hargreaves-Samani model in Ibadan. The Priestly-Taylor Model gave the least reliable estimates for this region.

4.2.2 ET_o Models Evaluation at Kano

Table 6: Summary of evaluation statistics of four evapotranspiration models at Kano

Statistical Parameters	MODELS			
	Penman-Monteith	BMN	Hargreaves-Samani	Priestly Taylor
MBE	0.025 (1)	1.191 (3)	3.085 (4)	1.318 (2)
S ² d	0.022 (1)	1.563 (2)	2.956 (4)	2.771 (3)
MAE	0.107 (1)	0.879 (2)	1.206 (3)	1.334 (4)
RMSE	0.151 (1)	1.726 (2)	3.531 (4)	2.121 (3)
R	0.996 (1)	0.636 (2)	0.456 (3)	0.066 (4)
Average Rank	(1)	(2)	(4)	(3)

Rank Value is given in parenthesis ranging from 1 – 4 with the rating of the model increasing as rank value decreases. (MBE - Mean Bias Error; S²d- Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and r - Correlation Coefficient)

For Kano, the BMN model produced the next reliable ET_o estimates after the Penman model. Contrary to the result obtained for Ibadan, the model which gave the third best ET_o estimates was the Priestly-Taylor model; a model dominated by radiation (Alexandris et al., 2008). From the trend results obtained for this station, it could be deduced that the most significant part of the ET_o estimated is the Radiative Term making this model to be more reliable in these regions than the Hargreaves-Samani model.

4.2.3 ET_o Models Evaluation at Onne

Table 7: Summary of evaluation statistics of four evapotranspiration models at Onne

Statistical Parameters	MODELS			
	Penman-Monteith	BMN	Hargreaves-Samani	Priestly Taylor
MBE	0.016 (1)	0.728 (2)	3.421 (4)	0.748 (3)
S ² d	0.007 (1)	0.230 (3)	0.571 (4)	0.168 (2)
MAE	0.047 (1)	0.734 (2)	3.425 (4)	0.775 (3)
RMSE	0.085 (1)	0.871 (2)	3.503 (4)	0.852 (3)
R	0.989 (1)	0.723 (2)	0.709 (3)	0.686 (4)
Average Rank	(1)	(2)	(4)	(3)

Rank Value is given in parenthesis ranging from 1 – 4 with the rating of the model increasing as rank value decreases. (MBE - Mean Bias Error; S²d- Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and r - Correlation Coefficient)

For Kano and Onne, the BMN model produced the next reliable ET_0 estimates after the Penman model. Similar to the result obtained for Kano, the model which gave the third best ET_0 estimates was the Priestly-Taylor model; a model dominated by radiation (Alexandris et al., 2008). From the trend results obtained for this location, it could be deduced that the most significant part of the ET_0 estimated is the Radiative Term making this model to be more reliable in these regions than the Hargreaves-Samani model.

From the results shown above, it could be seen that the model with the nearest estimate of ET_0 (having a rank of 1 in the stations considered for this study) to the FAO56 model is the Penman model. This is as a result of the FAO 56 model being a modification of the Penman model.

Although in these locations, the most reliable model for the estimation of ET_0 in is the Penman-Monteith Model, the optimal model that can be selected for the estimation of ET_0 is the BMN model because it requires lesser data requirement (three (3) variables) than the Penman-Monteith Model which requires seven (7) variables for its estimation.

4.3 Re-examination of the BMN Model

Duru (1984) model was nationally acclaimed by the Nigerian Institute of Agricultural Engineers (NIAE) as the most suitable for Nigeria's condition and that was why the name Blaney-Morin Nigeria was given to the model. However as stated earlier, certain shortcomings were identified:

- a) Low volume of data used: Being an empirical formula, its accuracy would depend on the volume of data used in the development of the model, the larger the volume of data used, the better the accuracy of the model;
- b) Equating pan evaporation to be equivalent to reference evapotranspiration; and

c) Limited Computational Analysis: The application of manual iteration for its development.

Hence, there was need owing to the above to re-examine the BMN model taking into consideration the noted shortcomings.

4.3.1 Modification of the BMN Model

The recalibration was carried out using the Sigma Plot software (based on the Levenberg – Marquardt algorithm) and a new model was generated, one for each study agro-ecological zone. A generalized model for all zones was also parameterized using pooled data from all the zones. The summary of generated parameters for all the new models are shown below; (Original Blaney-Morin-Nigeria model is expressed as $ET_o = r_f (0.45T + 8) (H - R^m)/100$, H and m are empirical values of 520 and 1.31 respectively and other terms as previously defined in equation 3);

Table 8: Generated parameters for the New Blaney-Morin-Nigeria Models

STATION	H	m	R	SEE	P
IBADAN	386 ± 9	1.19±0.012	0.769	0.403	<0.0001
ONNE	346 ± 9	1.18 ± 0.013	0.731	0.391	<0.0001
KANO	395 ± 7	1.18 ± 0.019	0.656	1.049	<0.0001
COMBINED	403 ± 4	1.22 ± 0.005	0.839	0.709	<0.0001

r – Coefficient of Correlation, *SEE* – Standard Error of Estimate, *P* – Probability Level

The modified BMN equations are of the form;

BMN Ibadan:- $ET_o = r_f (0.45T + 8) (386 - R^{1.19})/100$ (25)

BMN Onne: - $ET_o = r_f (0.45T + 8) (346 - R^{1.18})/100$ (26)

BMN Kano: - $ET_o = r_f (0.45T + 8) (395 - R^{1.18})/100$ (27)

$$\text{Combined BMN: - } ET_0 = r_f (0.45T + 8) (403 - R^{1.22})/100 \quad (28)$$

The validation of the above equations (25 – 27) was thereafter carried out, making use of the one-third part of the data separated from the obtained data from each station. In the case of the Modified BMN (All Station), the data from the three stations was pooled together and separated into a two-third part (2/3 for calibration) and a one-third part which was used for the validation of equation 28. The five (5) statistical parameters earlier used were also applied in this case.

The results obtained from the validation as described by the statistical parameters showed that the estimated values of ET compared favourably with the ET_0 values estimated from the FAO56 model (see Table 9 below). Results obtained from the modified BMN models for each station had high correlations with those obtained from the FAO 56 model at the stations. The general BMN model (All Station) was also applied for the estimation of ET_0 at the individual stations and when the results obtained were compared to the estimates realized from the FAO 56 model for the respective stations, the comparison showed a great deal of correlation although a little less than when the models modified for each stations were used and the resulting statistic parameters obtained were favourable implying that the modified model can be reliably applied in any of the stations used or in any part of the country to obtain useful ET_0 estimates.

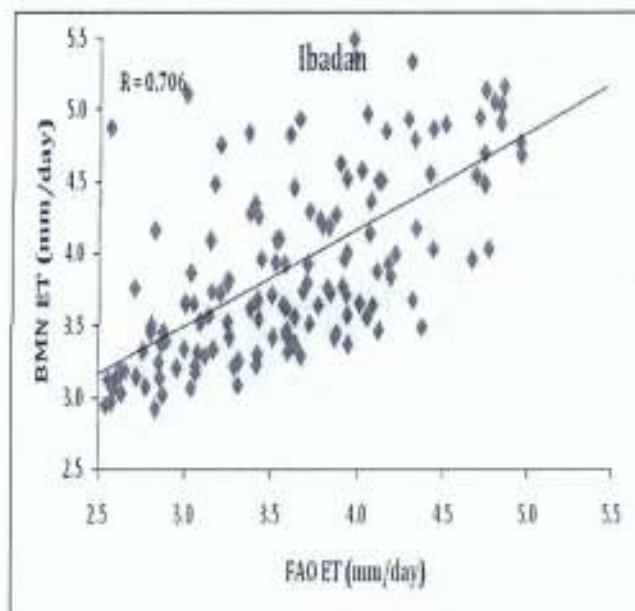
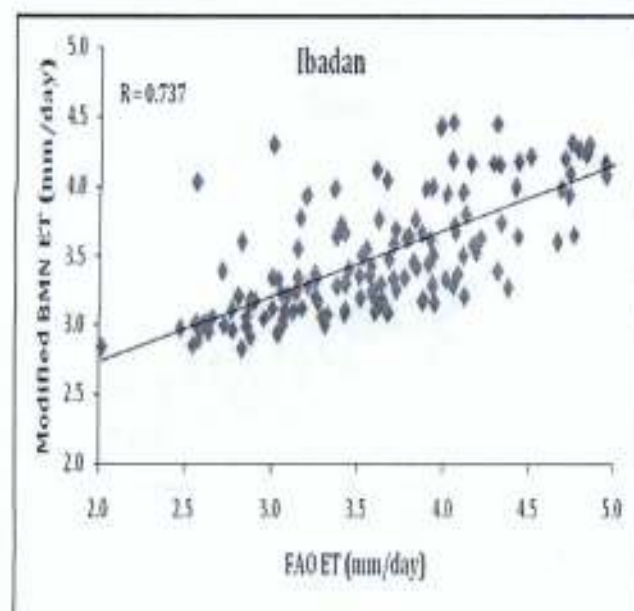
These comparisons were also shown graphically in Figure 5 where the points are more closely distributed along the trend-line on the graphs for the modified BMN models than the Original BMN model which implies that the ET_0 estimates from the modified BMN models are less deviated from themselves than estimates from the original BMN model.

Table 9: Summary of Statistical parameters for validation of the New Blaney-Morin-Nigeria models

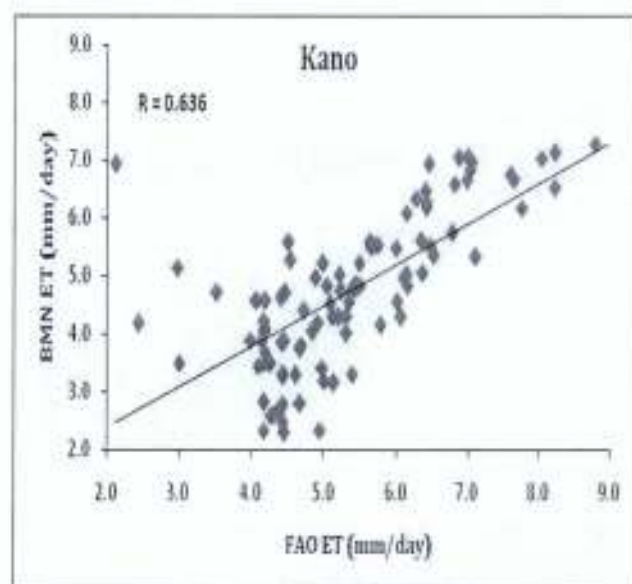
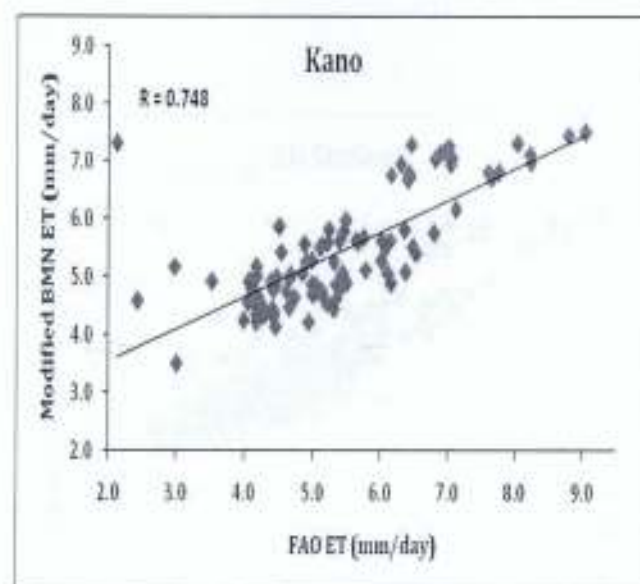
STATION	MBE	S ² d	MAE	RMSE	R
IBADAN	0.003 (0.338)	0.208 (0.264)	0.369 (0.470)	0.454 (0.470)	0.737 (0.706)
ONNE	0.081 (0.728)	0.097 (0.230)	0.264 (0.734)	0.320 (0.871)	0.785 (0.723)
KANO	0.510 (1.191)	4.509 (1.563)	1.014 (0.879)	1.851 (1.726)	0.748 (0.636)
COMBINED	0.130	1.108	0.552	1.055	0.877

MBE - Mean Bias Error; S²d- Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and r - Correlation Coefficient (The values in parenthesis are the corresponding values of comparison when ET_o was evaluated with the All Station Model at each location)

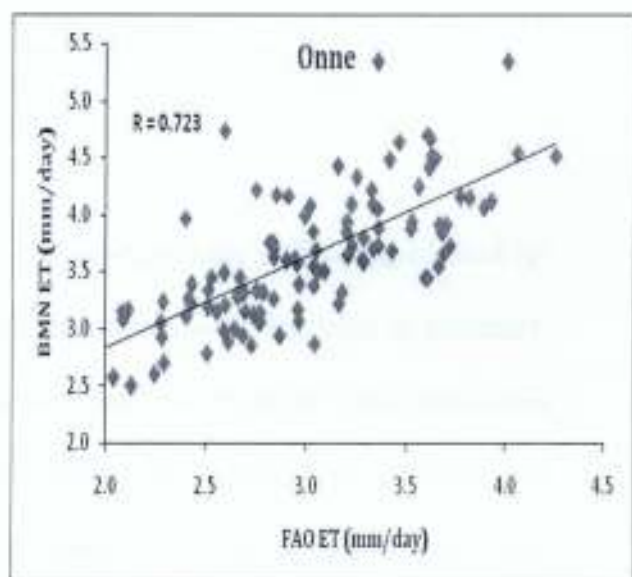
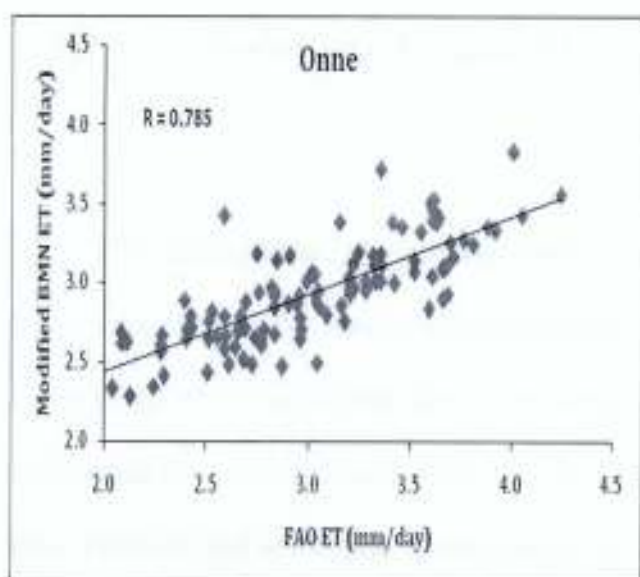
(a)



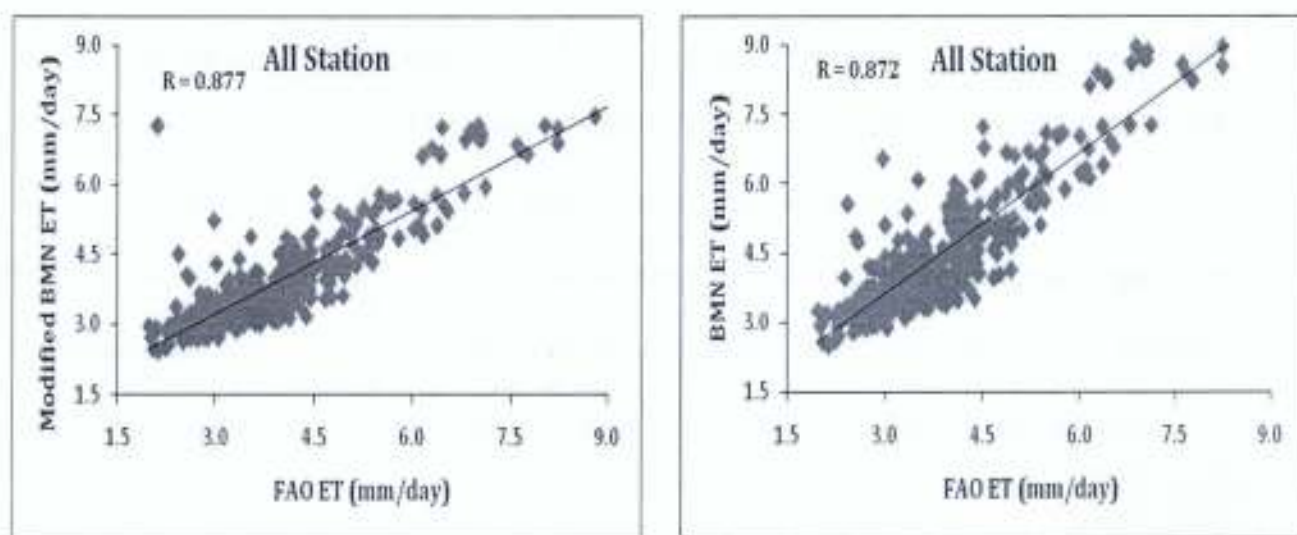
(b)



(c)



(d)



R – Coefficient of correlation

Figure 7(a-d): Plot of Modified and Original BMN ET values against the FAO 56 ET values

(a – Ibadan BMN, b – Kano BMN, c – Onne BMN, d – General BMN).

The results above showed that there were some shortcomings in the method used for the development of the Blaney-Morin-Nigeria model which this work has tried to eliminate. The original BMN model was developed using data from only one location (Zaria) while this study made use of three locations to have more spread across the country so as to incorporate more climatic and ecological characteristics that are familiar to these locations. This work also made use of climatic data for over a period of 30 years as against the 10year data used for the development of the original model. This gave rise to the new recalibrated models that provided more accurate results at their specific location as compared to results obtained from the application of the original BMN model to estimate ET_o in these locations. These comparisons are shown in Table 10 and Figure 8-10.

Other shortcomings which were identified in the development of the original BMN model which this study also corrected include the use of the ET_0 values estimated from the FAO 56 Penman-Monteith model which is globally accepted as the model for ET_0 estimation as the basis for the model recalibration in place of pan evaporation that was used for the development of the Original BMN model, although it was acceptable at the time the model was developed. The old Model also employed the use of manual iteration technique to generate the model constants while the recalibrated model applied a non-linear regression technique (the sigma-plot software based on the Levenberg-Marquardt algorithm) to generate the model constants which is prone to little or no error as in the case of manual iteration.

Table 10: Comparison of Statistical parameters for the New BMN model and the Old BMN model at the stations

STATION	MBE		S^2d		MAE		RMSE		r	
	New	Old	New	Old	New	Old	New	Old	New	Old
IBADAN	0.003	0.338	0.208	0.264	0.369	0.470	0.454	0.470	0.737	0.706
ONNE	0.081	0.728	0.097	0.230	0.264	0.734	0.320	0.871	0.785	0.723
KANO	0.510	1.191	4.509	1.563	1.014	0.879	1.851	1.726	0.748	0.636
ALL	0.130		1.108		0.552		1.055		0.877	

MBE - Mean Bias Error; S^2d - Measurement of the variability of the difference between the predicted and observed values; MAE - Mean Absolute Error; RMSE - Root Mean square error and R - Correlation Coefficient. The closer to zero the values of MBE, S^2d , MAE and RMSE, the better performed the respective model, whereas the closer to unity (1) the value of 'r', the better the model.

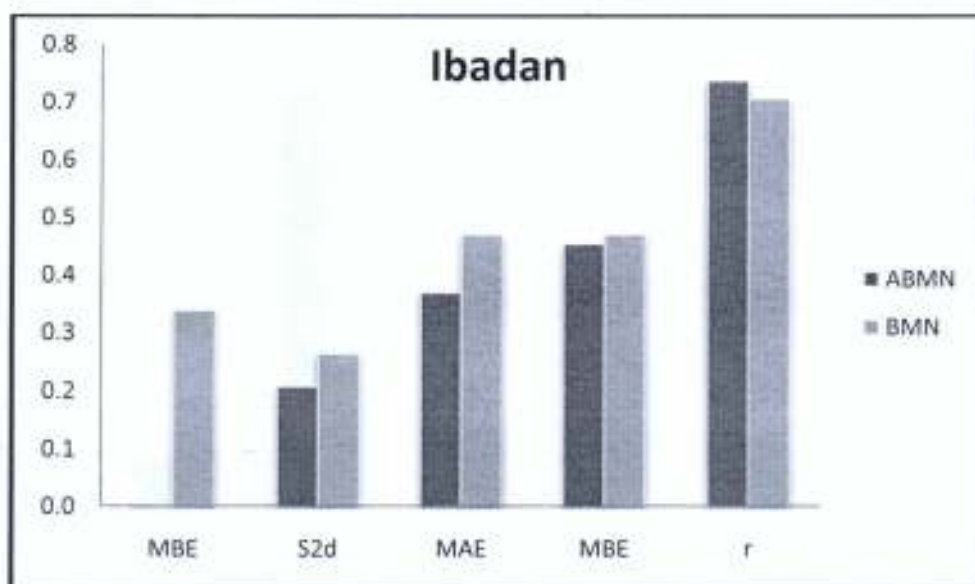


Figure 8: Statistical parameters for the BMN models for Ibadan (ABMN is Modified Blaney-Morin-Nigeria. The closer to zero the values of MBE, S^2d , MAE and RMSE, the better performed the respective model, whereas the closer to unity (1) the value of 'r', the better the model)

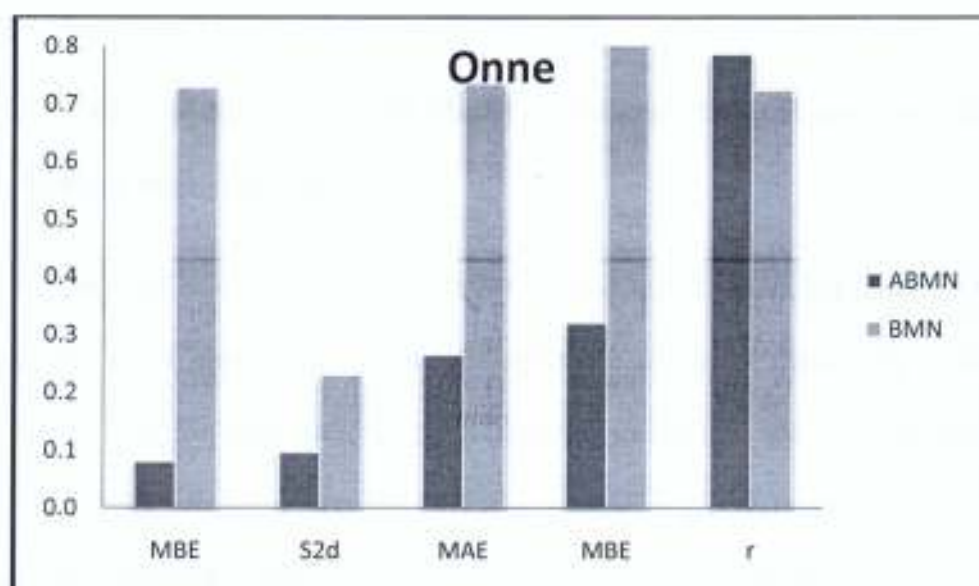


Figure 9: Statistical parameters for the BMN models for Onne (ABMN is Modified Blaney-Morin-Nigeria. The closer to zero the values of MBE, S^2d , MAE and RMSE, the better performed the respective model, whereas the closer to unity (1) the value of 'r', the better the model)

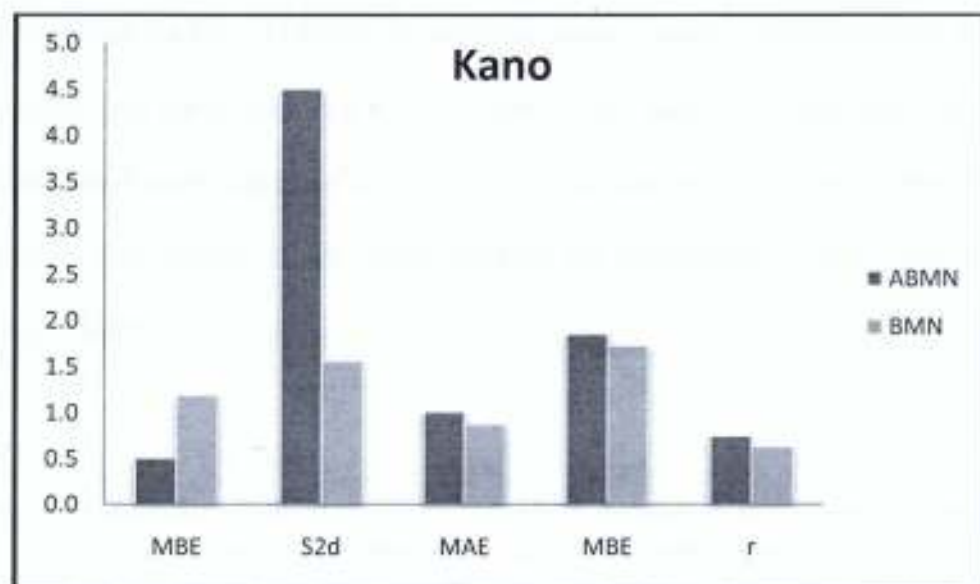


Figure 10: Statistical parameters for the BMN models for Kano (*ABMN is Modified Blaney-Morin-Nigeria*. The closer to zero the values of MBE, S^2d , MAE and RMSE, the better performed the respective model, whereas the closer to unity (1) the value of 'r', the better the model)

4.4 Application of Modified BMN Model to Estimate Crop Evapotranspiration and Irrigation Water Requirement

The modified Blaney Morin Nigeria Model was tested for its applicability by using it to estimate the mean monthly crop evapotranspiration (ET_c) for maize ($K_c = 1.2$, Source: Allen et al. 1998) at the three stations considered for this study. The result showed that the original BMN model over-predicted the ET_c for maize in all the locations used to a larger extent than the modified model for each of these places (see figure 8). This implies that the volume of water needed for irrigation will be higher when the original BMN model is used to estimate ET_c in any of these places than if the modified models are used. For Ibadan, the location specific and generalized model showed similar estimation of ET_c and to some extent under-estimates ET_c than the FAO-56 model. In Kano, both the location specific model and generalized model also have similar prediction pattern but the location specific pattern gives

a better estimation for ET_c . At Onne, the location specific model under-estimates ET_c in some of the months and over-estimates ET_c in some of the months in the year. Although the generalized model over-estimates ET_c in Onne, its estimation is still lower than estimations obtained from the original BMN model, making the generalized model more suitable for application in Onne.

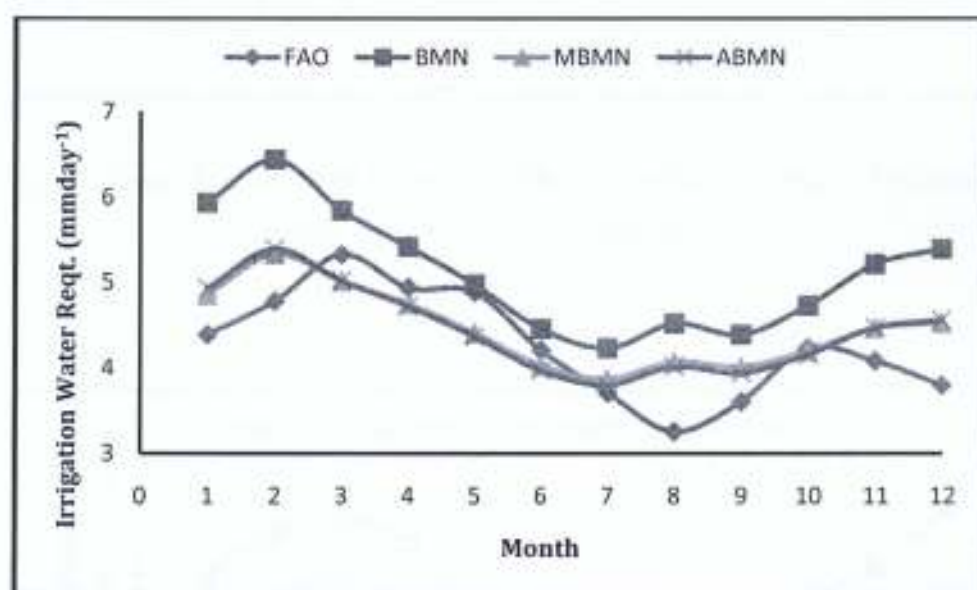


Figure 11(a): Mean Monthly Crop Evapotranspiration for Ibadan [MBMN-Location specific model, ABMN – Generalized model]

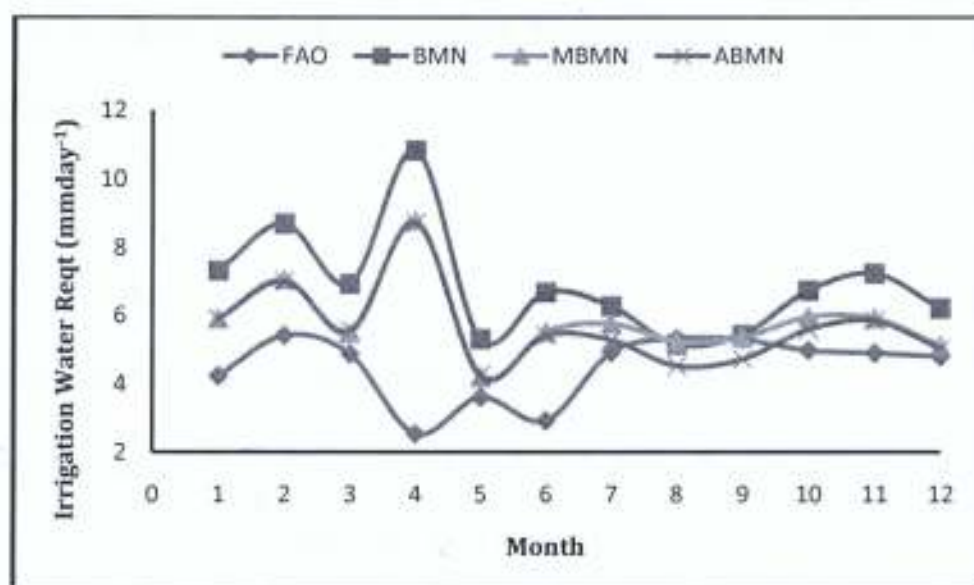


Figure 11(b): Mean Monthly Crop Evapotranspiration for Kano [MBMN-Location specific model, ABMN – Generalized model]

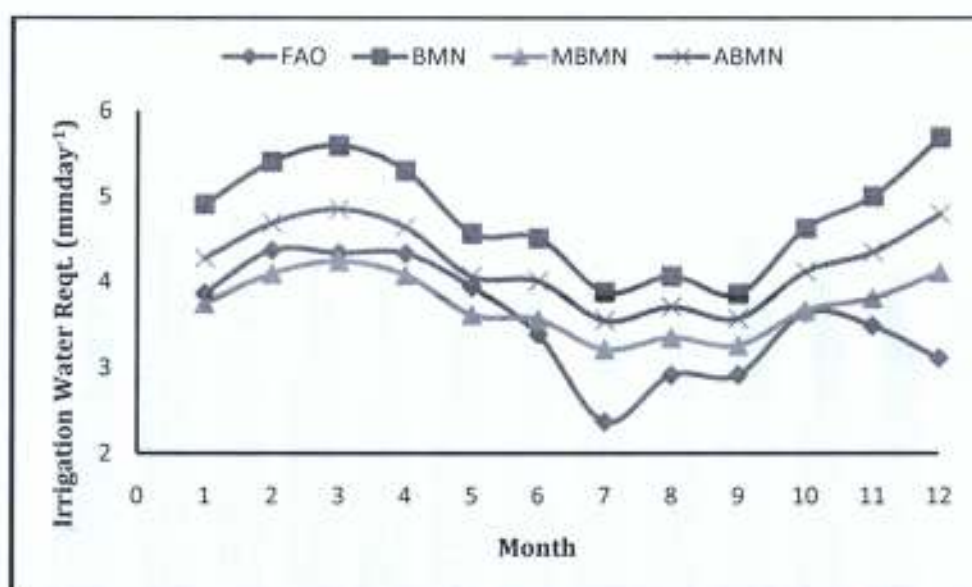


Figure 11(c): Mean Monthly Crop Evapotranspiration for Onne [MBMN-Location specific model, ABMN – Generalized model]

In the estimation of the irrigation water requirement for maize, a scenario was created with Akure used as a case study. Climatic data for Akure was used to estimate ET values for

FAO-56, BMN and the Modified BMN models. The estimation was carried out based on the following information

Crop:	Maize;
Crop coefficient (K_c):	1.2;
Useful Precipitation:	It was assumed to be zero, i.e. $P = 0$;
Irrigation type/Factor:	Sprinkler System/0.7, Flood System/0.5 (Source: Jacobs and Satti, S.R., 2001)

The results are illustrated in figures 12 and 13. In the two irrigation systems considered, the observed outcome was similar to previous findings, with the original BMN over-estimating the values obtained and the modified version predicting values closer to estimates obtained from the FAO-56 model.

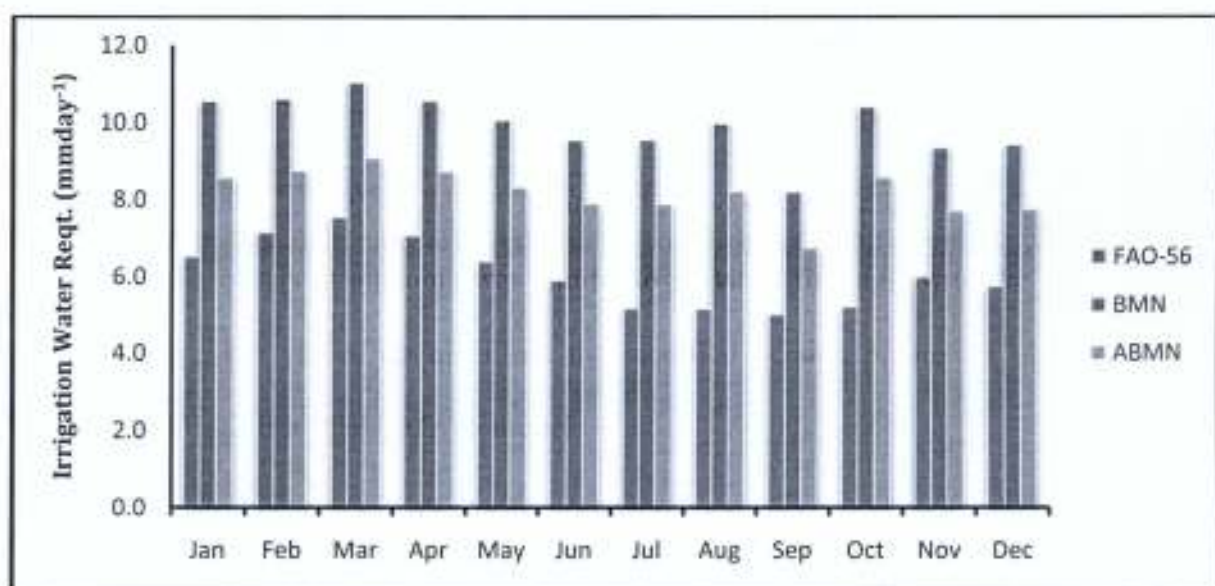


Figure 12: Mean Monthly Irrigation Water Requirement for Maize (Akure) Using Sprinkler System

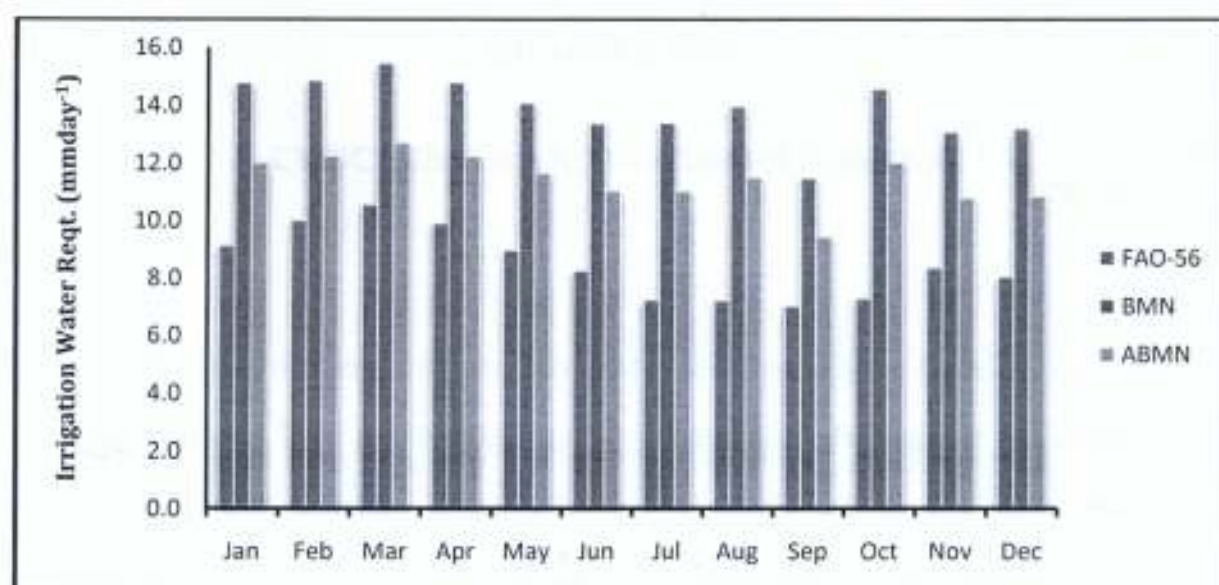


Figure 13: Mean Monthly Irrigation Water Requirement for Maize (Akure) Using Flooding System

Generally, the modified BMN model(s) performed better than the original BMN model when applied for use in the three stations considered for this study, the test location (Akure) and from the study it was deduced that the generalized all station model (Equation 28) can be applied anywhere in the country to estimate ET_o reliably.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION



This study determined the temporal trend of evapotranspiration for three IITA stations located in Ibadan, Kano and Onne in Nigeria, evaluated the performance of four models for estimating evapotranspiration in these stations. The models are Penman model, Blaney-Morin-Nigeria model, Priestly-Taylor model and the Hargreaves-Samani model with FAO 56 Penman-Monteith model used as the observed values and the basis for comparison with the other models. The Blaney-Morin-Nigeria model was also recalibrated for better performance in these stations and across the country.

Climatic data used for this study was sourced from these IITA stations, with the Mann-Kendall test for trend and Sen's slope estimates and Sigma Plot software (based on the Levenberg – Marquardt algorithm) were used to determine the direction of trend for ET and re-calibrate the BMN model respectively for the stations. 5 statistic parameters were also used to evaluate the performance of the above named models.

5.1 CONCLUSION

The overall results obtained from this work indicate that the ET rate is decreasing across the country. This decline was found in the three stations with Ibadan exhibiting the largest decline followed by Onne and Kano in that order. The study also went further to determine the factors responsible for the direction of these trends and for Ibadan and Onne, it

was shown that the declines in Ibadan and Onne occurred majorly due to the reduction in solar radiation while in Kano, it was caused by reducing aerodynamic parameters.

The Penman model ranked first with best performance in the three stations and this was obviously because it served as the basis of development for the FAO 56 Penman-Monteith model, the Blaney-Morin-Nigeria model ranked second best in the stations followed by the Priestly-Taylor model and the Hargreaves-Samani model which showed the weakest performance in Kano and Onne. In Ibadan, the Hargreaves-Samani model was the third best with the Priestly-Taylor model exhibiting the weakest performance.

Although the Penman model can be adjudged to be the most reliable model for estimating ET in the three stations based on the result obtained from this comparison but it might cost more in its application due to the number of variable it will require for its ET estimation (7) as against the number of variables needed by the Blaney-Morin-Nigeria model (3) which also showed a good performance when compared to the FAO 56 Penman-Monteith model across the three stations. It can therefore be concluded that the best model that should be employed when estimating ET across Nigeria is the Blaney-Morin-Nigeria model based on its simplicity and costs implication.

The recalibration of the Blaney-Morin-Nigeria model resulted in the generation of a new form of the model that provides a more reliable estimation of ET across the country. Also new models were generated for each study location that can provide better ET estimates in these regions.

5.2 RECOMMENDATION

It is highly recommended that this work be continued by evaluating the performance of other models for ET estimation in Nigeria to find out whether there are still some models that can be favourably applied in the country or that can be modified to suit the ecological and climatic conditions of the region.

Researches should also be carried out to generate modified Blaney-Morin-Nigeria models for most regions or major cities in the country so as to have models that are location specific and that provide better ET estimates for such places. Also more meteorological stations should be set up to provide reliable data source for researchers, developers, scientists and engineers across the country.



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