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# A Comparison of Various Evapotranspiration Models for Estimating Reference Evapotranspiration in Sokoto, North Western, Nigeria

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### *Authors' contributions*

*This work was carried out in collaboration between both authors. The data for the work was sourced and analyzed by author DOA. Author DOA also designed the study, drafted and edited the manuscript. Author MII assisted in literature searches. Both authors read and approved the final manuscript.*

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## ABSTRACT

Evapotranspiration (ET) is an important component of the hydrological cycle and its accurate quantification is crucial for the design, operation and management of irrigation systems. Agricultural planning depending on evapotranspiration suffers due to inaccuracy in its estimation. The lack of meteorological data retrieved from ground stations required for accurate estimation of reference evapotranspiration ($ET_o$) led in the development of various models for estimating $ET_o$. This present study compares various universally accepted ET models for estimating $ET_o$, the six models considered in this study for estimating $ET_o$ for Sokoto, Nigeria (Latitude 13.02 °N, Longitude 05.25 °E and altitude 350.8 m above sea level) using measured meteorological parameters of monthly average daily global solar radiation, sunshine hour, wind speed, maximum and minimum temperatures and relative humidity covering a period of thirty one years (1980-2010) are Blaney-Morin-Nigeria, Priestly and Taylor, Makkink, Hargreaves and Samani, Abtew and the Jensen-Haise models using the FAO-56 Penman-Monteith model as a reference. Based on the FAO-56 Penman-Monteith model, the results showed that the lowest $ET_o$ ($4.6977\ mmday^{-1}$) occurred during the

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rainy season (August) while the highest $ET_o$ $(10.0600\,mmday^{-1})$ occurred during the dry season (March). The statistical indicators of Root Mean Square Error (RMSE), Mean Bias Error (MBE), Mean Absolute Error (MAE) and coefficient of correlation (r) were used for the comparison of the six ET models. The results indicates that the Blaney-Morin-Nigeria is the most appropriate model for estimating $ET_o$ for this particular study area, with lowest RMSE $(1.2147\,mmday^{-1})$, MBE $(-1.1581\,mmday^{-1})$, MAE $(1.1581\,mmday^{-1})$ and highest value of r $(0.9822)$. Based on the overall results, the Blaney-Morin-Nigeria model is recommended as an alternative to FAO-56 Penman-Monteith model for estimating $ET_o$ in Sokoto, North – Western, Nigeria when temperature and relative humidity data are available.

*Keywords: Reference evapotranspiration; FAO-56 PM model; blaney-morin-nigeria model; statistical indicators; Sokoto; Nigeria.*

## 1. INTRODUCTION

Water scarcity is a major challenge facing a lot of nations especially the third world countries in the present time. This can be attributed to climate change, increasing demand for freshwater by the competing users in different sectors and more importantly the environmentally induced problems such as desertification and overexploitation of the existing water resources [1]. Consequently, a careful control of the water used for irrigation is a key aspect to be considered in order for users to ensure a proper distribution of the available resources between residential, industrial and agricultural use [2].

ET is defined as the combination of two separate processes, in which water is lost on the one hand from the soil surface by evaporation (E) and on the other hand from the crop by transpiration (T) [3]. Reliable estimates of ET are essential to identify temporal variations on irrigation requirements, improve water resource allocation and evaluate the effect of land use and management changes on the water balance [4].

Appropriate management of irrigation through the knowledge and understanding of evapotranspiration is a veritable tool in preserving water resources both qualitatively and quantitatively [5]. Water is a limiting factor on crop growth (development), thus one major concern in modeling (evapotranspiration) is an accurate simulation of the soil water balance [5]. Farmers know that excess water in the soil will lead to decay of roots (and even crops) in the soil, while lack of water in the soil leads to weedering of planted crops. Therefore, all terms influencing the soil water balance has to be estimated accurately for water stress effects to be simulated properly [5]. Several studies have shown that careful irrigation management can considerably improve crops' water use efficiency without causing yield reduction [6,7].

Reference evapotranspiration ( $ET_o$ ) has been defined as "the rate of evapotranspiration from a hypothetical crop with an assumed crop height (0.12 m) and a fixed canopy resistance (70 s/m) and albedo (0.23) which would closely resemble evapotranspiration from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water" [3]. The knowledge of reference crop evapotranspiration ( $ET_o$ ) is routinely required for the estimation of crop water use in the planning, design and operation of irrigation and, soil and water conservation systems.

Direct measurement of evapotranspiration which often involve the use of lysimeter is usually not feasible in many field situations because it is expensive, difficult to maintain and time-consuming. The required instrumentation may also be lacking. Given the fact that the direct measurement of ET is a difficult task, the development of hydrometeorological models to estimate "reference ET" ( $ET_o$ ) resulted in important contributions for irrigation management at global, regional and local scales.

In 1998 the Penman–Monteith (PM) method reported by the Food and Agriculture Organization (FAO) of the United Nations recently adopted a standardized form of the Penman–Monteith equation (FAO – 56) which has been recognized as the standard method for most reliable and precise method to estimate $ET_o$ worldwide [8,9]. The FAO-56 PM equation has shown to be superior over other methods when comparing the daily $ET_o$ with lysimetric measurements for estimating $ET_o$ [8,9]. However, the full input data for a large number of climatic variables, such as mean maximum and minimum air temperatures, relative humidity, solar radiation, and wind speed limit the widespread use of the FAO-56 PM method [10,11]. Unfortunately, the climatic data in many developing regions cannot always meet the requirements of the FAO-56 PM method for calculating $ET_o$.

Several alternative methods such as those reported by [12] have been proposed to substitute for FAO-56 PM method based on considering the accuracy and conciseness with the PM method and lysimetric measurements. Since the accuracy of estimated values of $ET_o$ is important for water resources planning and management, irrigation scheduling, control and agricultural productivity; It has given rise to numerous researches that were carried out in different parts of the world to ascertain the best model which is suitable for application in such parts. Similar researches have been carried out in Japan [13], Bulgaria [14], Central Serbia [15], a region of Florida in the United States of America [16] a region in south western Nigeria [17] and recently in Tunisia - North Africa [12]. Among the methods used in estimating reference evapotranspiration is the method universally acceptable model. In Nigeria, a model was developed by [18] called the Blaney-Morin-Nigeria model to estimate reference evapotranspiration and was widely judged to be most suitable to Nigeria's condition by the Nigerian Institute of Agricultural Engineers (NIAE) [18]. Other models for estimating $ET_o$ include [19-25] to mention but a few.

This present study, evaluates and compares six evapotranspiration models for estimating reference evapotranspiration in Sokoto, Nigeria using FAO-56 PM method as standard. The purpose of this comparison is to ascertain which of the models is most appropriate to be considered as an alternative to FAO – 56 PM model for the estimation of $ET_o$ in the study area. The six models chosen covers the input parameters based on the available measured climatological data and each of them are in one way or the other found as an alternative as compared to the acceptable reference FAO-56 PM for estimating reference evapotranspiration in different part of the world as observed from different published studies. More so, some of the models incorporates the input parameters like station's altitude, net radiation, extraterrestrial radiation, soil heat flux and sunshine hour which are not found in the Blaney-Morin- Nigeria model that is widely judged to be the most suitable for estimating reference evapotranspiration to Nigeria's condition, hence, the motivation to search for other models for the study area under investigation.

## 2. STUDY AREA

Sokoto (Fig. 1), the capital of Sokoto state is a city located in the extreme northwest of Nigeria, near the confluence of the Sokoto River and the Rima River. Sokoto is in the dry Sahel surrounded by sandy savannah and isolated hills. Rainfall in Sokoto State as in other parts of Nigeria is dominantly controlled by the movement and pulsation of the ITD (Inter-Tropical Discontinuity) [26]. Similar to other extreme northern parts of the country, rainfall in Sokoto State is very erratic and unpredictable with irregular onsets and cessations which adversely affect the duration of the cropping seasons. The maximum daytime temperatures are generally under 40 °C (104.0 °F) most of the year, and the dryness makes the heat bearable. The warmest months are February to April, where daytime temperatures can exceed 45 °C (113.0 °F). The highest recorded temperature is 47.2 °C (117.0 °F). The rainy season is from June to October, during which showers are a daily occurrence. The showers rarely last long and are a far cry from the regular torrential showers known in many tropical regions. From late October to February, during the 'cold season', the climate is dominated by the harmattan wind blowing Sahara dust over the land. The dust dims the sunlight, thereby lowering temperatures significantly and also leading to the inconvenience of dust everywhere in the house. However, the weather in the state is always cold in the morning and hot in the afternoons, save in peak harmattan period. The topography of the state is dominated by the famous Hausa plain of northern Nigeria. As of 2006 it has a population of 427,760. Agriculture is the mainstay of the people [27].

## 3. METHODOLOGY

In Nigeria, we have over forty (40) weather observatories located at different stations which are controlled by the Nigerian Meteorological Agency. None of these stations measure evapotranspiration except in some few research institutes. The climatic data of measured monthly average daily global solar radiation, sunshine hour, wind speed, maximum and minimum temperatures and relative humidity covering a period of thirty one years (1980-2010) for Sokoto,

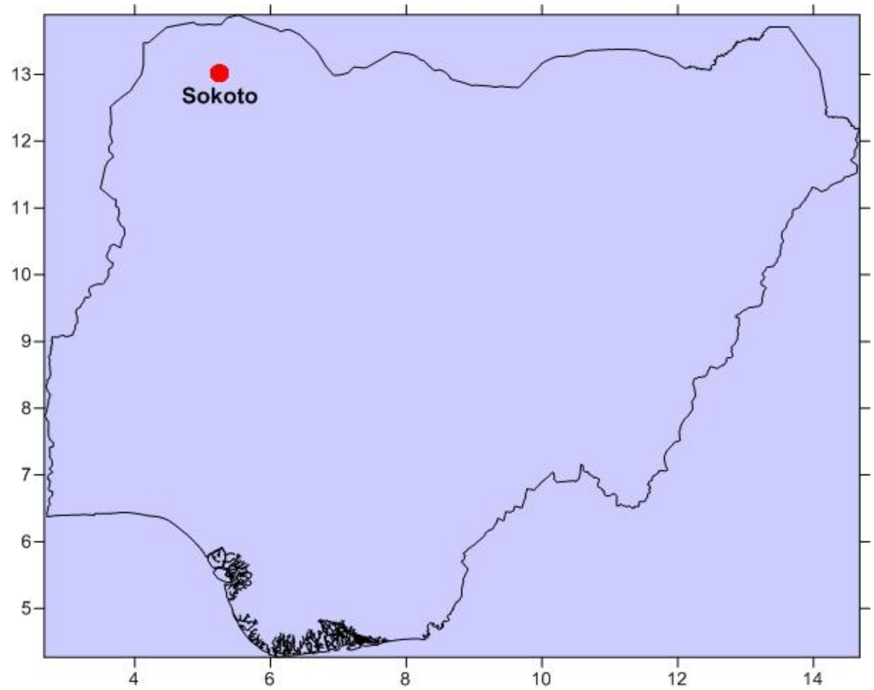


**Fig. 1. Map of Nigeria showing the study area**

North – Western, Nigeria used for this present study was obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos, Nigeria. The quality assurance of the meteorological measurements was determined by checking the overall consistency of the monthly average of the climatic parameters used in the study area.

### 3.1 FAO-56 Penman- Monteith Method (FAO-56 PM)

The Penman-Monteith approach has been recommended as the sole method for the estimation of evapotranspiration by the United Nation Food and Agricultural Organization (FAO) and is widely used over the globe because it takes into consideration both physical and aerodynamic parameters. The Penman-Monteith equation is generally considered as the best method for the estimation of reference evapotranspiration in all climatic conditions. This has been confirmed by different researchers [28 - 33]. In line with this, FAO-56 PM method is often recommended as a standard procedure for accurate estimation of reference evapotranspiration, $ET_o$ where there is no measured lysimeter data on reference evapotranspiration. The evapotranspiration, ET values obtained from the derived equations were compared against this method. The $ET_o$ computed using the P-M model for the $ET_o$ estimation recommended by the FAO-56 paper [3] and standardized by the American Society of the civil Engineer-ASCE [34] is expressed as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{\bar{T}+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (1)$$

where $ET_o$ is the reference evapotranspiration $(mm day^{-1})$, $R_n$ is the net radiation at the crop surface $(MJm^{-2}day^{-1})$, $G$ is the soil heat flux $(MJm^{-2}day^{-1})$, $\bar{T}$ is the mean daily air temperature $(°C)$, $U_2$ is the wind speed at $2\,m$ height $(ms^{-1})$, $e_s$ is the saturated vapour pressure $(kPa)$, $e_a$ is the actual vapour pressure $(kPa)$, $e_s - e_a$ is the saturated vapour pressure deficit $(kPa)$, $\Delta$ is the slope of vapour pressure curve $(kPa)$ and $\gamma$ is the psychrometric constant $(kPa°C^{-1})$. According to [35] the soil heat flux can be ignored and assumed to be zero since it is small compared to $R_n$.

In this study, $R_n$, $\Delta$, $U_2$, $e_s$, $e_a$ and $\gamma$ were calculated as proposed by the FAO [3]. The mean saturated vapour pressure derived from air temperature is given by [3] as:

$$e_s = \frac{e(T_{max}) + e(T_{min})}{2} \qquad (2)$$

Where,

$$e_{(T_{min})} = 0.6108exp\left(\frac{17.27T_{min}}{T_{min}+273.3}\right) \quad (3)$$

$$e_{(T_{max})} = 0.6108exp\left(\frac{17.27T_{max}}{T_{max}+273.3}\right) \quad (4)$$

$T_{max}$ is the maximum daily air temperature, in ℃
$T_{min}$ is the minimum daily air temperature, in ℃

The actual vapour pressure derived from relative humidity was computed using the expression:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e_{(T_{max})}+e_{(T_{min})}}{2}\right] \quad (5)$$

The slope of the saturated vapour pressure curve was obtained using the following expression:

$$\Delta = 4098\left[\frac{0.6108exp\left(\frac{17.27\bar{T}}{\bar{T}+273.3}\right)}{(\bar{T}+273.3)^2}\right] \quad (6)$$

The atmospheric pressure $P$ is related to $Z$ by the expression:

$$P = 101.3\left(\frac{293-0.0056Z}{293}\right)^{5.26} \quad (7)$$

Where, $Z$ is the station elevation above sea level in meters.

The psychrometric constant, $\gamma$ is related to $P$ through the expression

$$\gamma = 0.665 \times 10^{-3}\, P \quad (8)$$

The net radiation, $R_n$ was computed using the expression

$$R_n = R_{ns} - R_{nl} \quad (9)$$

Where, $R_{ns}$ and $R_{nl}$ are the net shortwave and net longwave radiation in ( $MJm^{-2}day^{-1}$ ), calculated according to the FAO Irrigation and Drainage paper No 56 [3] as

$$R_{ns} = (1-a)R_s \quad (10)$$

where $a$ is the albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop (dimensionless), $R_s$ is the incoming solar radiation ($MJm^{-2}day^{-1}$)

$$R_{nl} = \left[\frac{T_{max,k}{}^4+T_{min,k}{}^4}{2}\right]\left(0.34-0.14\sqrt{e_a}\right)\left\{1.35\frac{R_s}{R_{so}}-0.35\right\} \quad (11)$$

Where, $\sigma$ is the Stefan-Boltzmann constant ($4.903 \times 10^{-9}\ MJK^{-4}m^{-2}day^{-1}$)

$T_{max,k}$ is the maximum absolute temperature during the 24-hour period ($K = ℃ + 273.16$)
$T_{min,k}$ is the minimum absolute temperature during the 24-hour period ($K = ℃ + 273.16$) , $R_s/R_{so}$ is the relative shortwave radiation (limited to $\leq 1.0$) and $R_{so}$ is the calculated clear-sky radiation ($MJm^{-2}day^{-1}$). $R_{so}$ was obtained using the following expression:

$$R_{so} = (a_s + b_s)R_a \quad (12)$$

$a_s + b_s$ is the fraction of extraterrestrial radiation reaching the earth on clear-sky days and $R_a$ is the extraterrestrial radiation ($MJm^{-2}day^{-1}$). The fraction of extraterrestrial radiation reaching the earth on clear-sky days was obtained using regression analysis with Minitab 16.0 Software based on the following expression:

$$R_s = \left[a_s + b_s\left(\frac{S}{S_0}\right)R_a\right] \quad (13)$$

Where, $S/S_0$ is the relative sunshine duration. $R_a$ was calculated according to the FAO Irrigation and Drainage paper No 56 [3]

The wind speed data obtained from the meteorological station was converted to 2 m as required for agrometeorology [3] according to the following expression:

$$U_2 = U_z\frac{4.87}{ln(67.8Z-5.42)} \quad (14)$$

Where, $U_z$ is the measured wind speed at Z m above ground surface ($ms^{-1}$)

### 3.2 Blaney- Morin- Nigeria Model (BMNM)

The Blaney-Morin-Nigeria (BMN) model was developed for the estimation of reference evapotranspiration in Nigeria by [18]. This method was applied following the steps laid down by [18]. The model equation is given by:

$$ET_0 = \frac{rf(0.45T_{mean}+8)(520-R^{1.31})}{100} \quad (15)$$

Where, $rf$ is the ratio of monthly radiation to annual radiation, $T_{mean}$ is the mean monthly temperature in ℃ and $R$ is the mean monthly relative humidity, 520 and 1.31 are the model constants given by [18]. $ET_0$ is as previously defined.

### 3.3 Priestly and Taylor Model (PTM)

The [25] method is a simplified method requiring only solar radiation and temperature weather parameters for the estimation of evapotranspiration. This is based on the fact that radiation is the major source of energy and thus a potential factor as compared to other weather parameters for evapotranspiration estimation. According to them about two-third radiation components contributes to the evolution of evapotranspiration. The model estimation is done using the equation:

$$ET_0 = \alpha \frac{\Delta}{\Delta+\gamma}(R_n - G)\frac{1}{\lambda} \quad (16)$$

Where, $\alpha$ is an empirically determined dimensionless correction given as $\alpha = 1.26$ and $\lambda$ is latent heat of vaporization $(2.45\ MJkg^{-1}@20°\mathrm{C})$, $\Delta$, $\gamma$, $R_n$, $ET_0$ and $G$ are as previously defined.

### 3.4 Makkink Model (MAKM)

[24] Model, according to [36] the model was developed from a study conducted over a grassed surface under a cool climatic condition of Netherlands. The model is a simplified method of the Priestly and Taylor model as also requires the radiation and temperature parameters for evapotranspiration estimation. However, the major difference in the input variable is that Makkink utilizes solar radiation while Priestly and Taylor used net radiation. Though, there is relationship between the two radiation components. The model equation for Makkink is expressed as

$$ET_0 = 0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\left(\frac{R_S}{\lambda} - 0.12\right) \quad (17)$$

Where, $ET_0$ , $\Delta$ , $\gamma$ , $R_s$ and $\lambda$ are as previously defined.

### 3.5 Hargreaves and Samani Model (HSM)

The Hargreaves method was developed by [22], using eight years of daily lysimeter data from Davis, California, and tested in different locations such as Australia, Haiti and Bangladesh. Since then, the method has been successfully applied worldwide e.g. [37]. The Hargreaves equation requires only daily mean, maximum and minimum air temperature and extraterrestrial radiation. This implies that, in a situation where solar radiation, wind speed and relative humidity data are not measured, reference evapotranspiration can be estimated using temperature data according to the model equation stated by [22] as:

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}R_a \quad (18)$$

Where, $T_{mean}$ is the mean air temperature given as

$T_{mean} = \frac{T_{max}+T_{min}}{2}$ as previously employed.

Where, $ET_0$, $R_a$, $T_{max}$ and $T_{min}$ are as previously defined.

### 3.6 Abtew Model (ABTM)

[19] Utilized a simple empirical equation for the estimation of reference evapotranspiration as a function of solar radiation used as the only weather parameter. The model equation is given as:

$$ET_0 = \frac{0.53R_S}{\lambda} \quad (19)$$

Abtew model was cross validated by comparing the estimates to four years of Bowen-Ratio ET measurement at nine sites in the Everglades of South Florida [19] and the results revealed a very good correlation of ET estimated by Abtew model and that obtained by Bowen-Ratio over a wetland. The terms $ET_0$, $R_s$ and $\lambda$ in the equation are as previously defined.

### 3.7 Jensen-Haise Model (JHM)

[23] Evaluated 3,000 observations of Evapotranspiration (ET) as determined by soil sampling procedures over a 35 year period in western USA. From their study, Jensen-Haise developed the following linear relationship for ET model used in computing reference evapotranspiration as reported by [38], the model equation is given by

$$ET_0 = C_T(T_{mean} - T_x)R_s \quad (20)$$

$C_T$ and $T_x$ are constants expressed as

$$C_T = \frac{1}{\left[\left(45 - \frac{h}{137}\right) + \left(\frac{365}{e_{(T_{max})} - e_{(T_{min})}}\right)\right]}$$ and

$$T_x = -2.5 - 0.14\left[e_{(T_{max})} - e_{(T_{min})}\right] - \frac{h}{500}$$

Where, $h$ is the altitude of the location, $e_{(T_{max})}$, $e_{(T_{min})}$, $T_{mean}$ and $R_s$ are as previously defined.

### 3.8 Statistical Analysis

The six models used in this study were used in computing the reference evapotranspiration ($ET_0$) for the location under study. The statistical test of Mean Bias Error (MBE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and coefficient of correlation (r) were used to compare the efficiency of the models, according to the following equations.

#### 3.8.1 Root mean square error (RMSE)

Root Mean Square Error measures the average difference. RMSE involves the square of the difference and therefore becomes sensitive to extreme values [39]. The smaller the value of the RMSE the better is the model performance. The magnitudes of RMSE values are useful to identify model performance but not of under or overestimation by individual model [40]. The optimum value for RMSE is zero or 0.0 ≤ RMSE [41]. The RMSE is represented by equation as:

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}\left(ET_{0_{est}} - ET_{0_{FAO}}\right)^2\right]^{\frac{1}{2}} \qquad (21)$$

#### 3.8.2 Mean bias error (MBE)

The mean bias error is a good measure of model bias and is simply the average of all differences in the set. It provides general biasness but not of the average error that could be expected [39]. The positive MBE value indicates overestimation and negative value indicates the underestimation. The absolute value is indicator of model performance. The optimal value for MBE is zero and the biasness lies between - ∞ to + ∞ (- ∞ < bias ≤ + ∞) [42]. The MBE is given as:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}\left(ET_{0_{est}} - ET_{0_{FAO}}\right) \qquad (22)$$

#### 3.8.3 Mean absolute error (MAE)

The MAE is an absolute value of the MBE. Thus, in this case, all the values of MBE become positive. The MAE is given by the expression.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|ET_{0_{est}} - ET_{0_{FAO}}\right| \qquad (23)$$

#### 3.8.4 Coefficient of correlation (r)

The quantity r, called the coefficient of correlation (or briefly correlation coefficient), is given by the expression:

$$r = \frac{\sum ET_{0_{est}}ET_{0_{FAO}} - \frac{\sum ET_{0_{est}}\sum ET_{0_{FAO}}}{n}}{\sqrt{\left(\sum ET_{0_{est}}{}^2 - \frac{\left(\sum ET_{0_{est}}\right)^2}{n}\right)\left(\sum ET_{0_{FAO}}{}^2 - \frac{\left(\sum ET_{0_{FAO}}\right)^2}{n}\right)}} \qquad (24)$$

The value of r varies between -1 and +1. The + and – signs are used for positive linear correlation and negative linear correlation, respectively. The r is a dimensionless quantity. The computed value of r measures the degree of the relationship relative to the type of equation that is actually assumed. Thus, the r measures the goodness of fit between the equation actually assumed and the data. High correlation coefficient, r, implies (near 1 or -1). In general, values of r close to unity are desirable.

From equation (21) to (24) $ET_{0_{FAO}}$ represents the observed/measured evapotranspiration ($ET_0$) values (the FAO-56 PM model); $ET_{0_{est}}$ is the estimated/predicted values of evapotranspiration ($ET_0$) obtained from other models (the Blaney-Morin- Nigeria, Priestly and Taylor, Makkink, Hargreaves and Samani, Abtew and Jensen-Haise Models), $n$ is the number of observation, Σ is the summation sign. In this study, coefficient of correlation (r) was also verified using scatter plots as well.

## 4. RESULTS AND DISCUSSION

The relative short wave radiation obtained in this study ranged between 0.5743 – 0.7712 which is consistent to that reported by [3] that relative short wave radiation should be limited to $\leq 1.0$. The fraction of extraterrestrial radiation reaching the earth on clear-sky days obtained through regression analysis for the study area is 0.8820.

Table 1 shows the climate data used for the study area over the period under investigation. All the terms used have been previously defined. The wind speed, U, was before the conversion to 2 m height.

Fig. 2 shows the variation of evapotranspiration with month for the study area during the study period. It was observed that the highest value of evapotranspiration was obtained during the dry season in the month of March as 10.0600 mmday$^{-1}$ while the lowest during the rainy season in the month of August as 4.6977 mmday$^{-1}$. The high value is attributed to the fact that evapotranspiration is high during the hot dry

**Table 1. Climate data for Sokoto during the period (1980 – 2010)**

| Month | $T_{min}$(°C) | $T_{max}$(°C) | U($ms^{-1}$) | RH (%) | Rs/Ra | S/So |
|---|---|---|---|---|---|---|
| Jan | 17.5452 | 31.7226 | 8.8194 | 19.5806 | 0.6630 | 0.7103 |
| Feb | 19.1194 | 34.5613 | 8.7032 | 16.3548 | 0.6636 | 0.7195 |
| Mar | 23.6032 | 38.2129 | 7.5226 | 18.4516 | 0.6394 | 0.6362 |
| Apr | 26.4645 | 40.5452 | 7.8452 | 31.3871 | 0.6066 | 0.6189 |
| May | 26.9484 | 39.3290 | 8.5581 | 50.3226 | 0.5771 | 0.6084 |
| Jun | 25.3774 | 36.2613 | 8.8581 | 60.9355 | 0.5565 | 0.6179 |
| Jul | 23.6097 | 32.7452 | 7.7710 | 72.8387 | 0.5106 | 0.5852 |
| Aug | 23.0129 | 31.5355 | 6.0258 | 77.6452 | 0.5075 | 0.5405 |
| Sep | 23.0645 | 33.0968 | 5.6548 | 71.1613 | 0.5817 | 0.6590 |
| Oct | 23.4032 | 36.4258 | 6.2097 | 48.0968 | 0.6450 | 0.7226 |
| Nov | 20.3161 | 35.5355 | 7.6290 | 24.5484 | 0.6815 | 0.7679 |
| Dec | 17.0903 | 32.0903 | 8.0000 | 25.0645 | 0.6628 | 0.7226 |

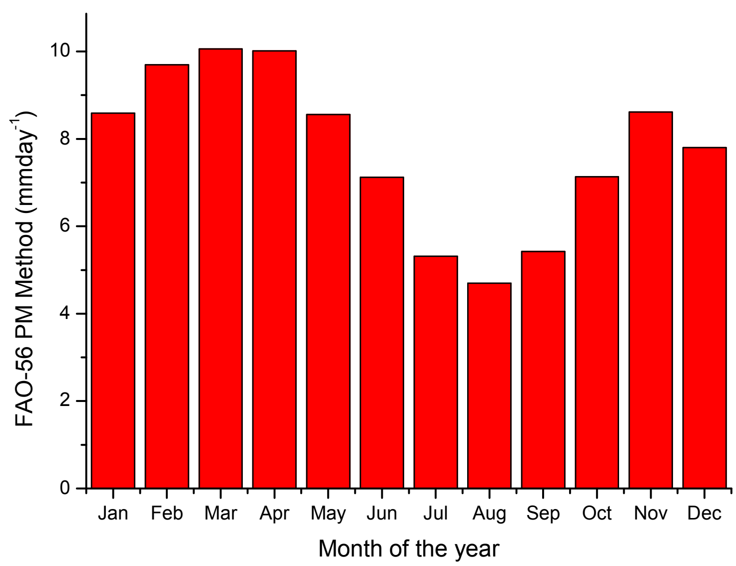


**Fig. 2. Monthly values of $ET_o$ for FAO-56 method in sokoto during the period (1980-2010)**

weather or clear skies condition as a result of the dryness of air and amount of energy available for evaporation. Solar radiation is one of the weather parameters that contributes huge amounts of energy to vegetation in desert and therefore a meteorological parameter with the greatest impact on ET on most days; During this period wind may also serve to accelerate evaporation by enhancing turbulent transfer of water vapour from moist vegetation to the dry atmosphere. In this situation, the wind is constantly replacing the moist air located within and just above the plant canopy with dry air from above; thus, the solar radiation and wind speed plays a crucial role in ET rate. On the other hand, during the rainy season or under humid weather conditions, the high humidity of the air and presence of clouds lowers the rate of evapotranspiration, this is in line with observations made by [42] on monitoring of evapotranspiration in major districts of Haryana using Penman Monteith method as reported by [43]. It was observed from the figure that the $ET_o$ decreases during the months of July, August and September which comprised the peak monsoon season with high relative humidity, low wind speed and lower temperature; this is in line with similar observation carried out by [44] as reported by [45].

Fig. 3 shows the monthly averages values of $ET_o$ estimates, using as baseline the period from 1980-2010. A critical examination of the figure shows that the Blaney-Morin-Nigeria, Priestly and Taylor, Makkink, Abtew and the Jensen-Haise models underestimates the FAO-56 Penman-Monteith model except in the month of

August and September where the Priestly and Taylor model overestimates the FAO-56 Penman-Monteith model. The pattern of the curve depicted by Blaney-Morin-Nigeria model estimates closely follow the pattern obtained using the reference FAO-56 Penman-Monteith model during almost the entire year, In contrast, the pattern obtained by the other ET models show remarkable differences in comparison with the reference FAO-56 Penman-Monteith model during the study period. In particular, a large overestimation was observed for the Hargreaves and Samani model in comparison with the other models including the reference FAO-56 Penman-Monteith model.

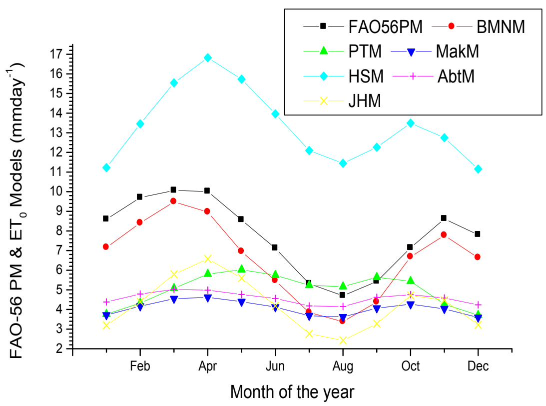


**Fig. 3. Comparison between estimated $ET_o$ by FAO-56 PM and evaluated models in Sokoto during the period (1980-2010)**

Considering the six evaluated ET models, the highest value of ET was recorded in the month of March and the lowest in the month of August for Blaney-Morin-Nigeria model. The highest value of ET was recorded in the month of May and the lowest in the month of December for Priestly and Taylor model. The highest value of ET was recorded in the month of April and the lowest in the month of December for Makkink model. The highest value of ET was recorded in the month of April and the lowest in the month of December for Hargreaves and Samani model. The highest value of ET was recorded in the month of March and the lowest in the month of August for Abtew model. The highest value of ET was recorded in the month of April and the lowest in the month of August for Jensen-Haise model. Fig. 3 reviewed that none of the evaluated models shows similar result with the reference FAO-56 Penman-Monteith model. In general, the difference in the evaluated $ET_o$ values is as a result of the different climatological variables used in each of the ET models, similar differences in results were observed in literatures e.g. [45–49].

Based on the computed values for $ET_o$, it was observed that the Blaney-Morin-Nigeria and the Abtew models are in line with the reference FAO-56 Penman-Monteith model as they both have their highest and lowest values of ET in the months of March and August respectively. However, the Blaney-Morin-Nigeria model for estimating $ET_o$ compares favourably well with the reference FAO-56 Penman-Monteith model as compared with the other evaluated model in the study area.

The fitted regression lines obtained in the regression analysis using the reference FAO-56 PM model and the evaluated models are shown on Figs. (4–9). The Blaney-Morin-Nigeria model achieved the best fit resulting in correlation coefficient of 0.9882 showing a high positive correlation between the Blaney-Morin-Nigeria and the FAO-56 PM models, followed by the Jensen-Haise model with correlation coefficient of 0.7794. On the other hand, the worst correlation is observed for Priestly and Taylor model (-0.2141) which is a low negative correlation. The values of correlation coefficient obtained for the evaluated models agrees perfectly with that obtained through equation (24) shown on Table 2.

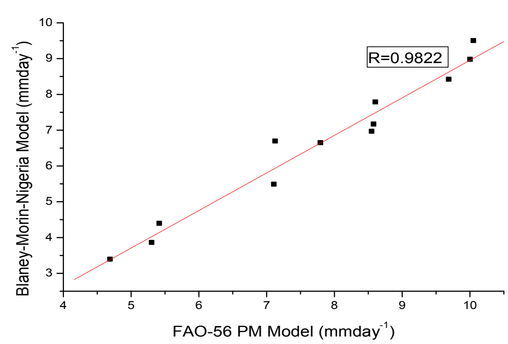


**Fig. 4. Fitted regression line of BMNM with reference FAO-56 PM model**

**Table 2. Statistical comparison between ET by FAO-56 PM and other empirical models**

| Models | RMSE | MBE | MAE | R |
|---|---|---|---|---|
| BMN | 1.2147 | -1.1581 | 1.1581 | 0.9822 |
| PTM | 3.4367 | -2.7354 | 2.7354 | -0.2141 |
| MAK | 4.0083 | -3.6834 | 3.6834 | 0.6332 |
| HSM | 5.7949 | 5.5773 | 5.5773 | 0.6133 |
| Abt M | 3.5394 | -3.1672 | 3.1672 | 0.7280 |
| JHM | 3.7077 | -3.5342 | 3.5342 | 0.7794 |

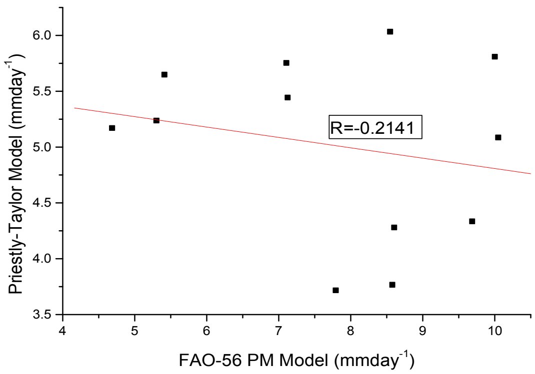


**Fig. 5. Fitted regression line of PTM with reference FAO-56 PM mode**

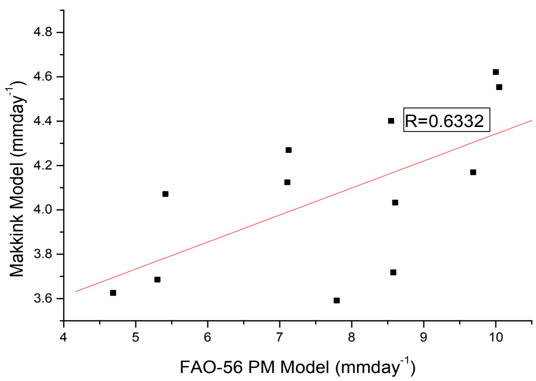


**Fig. 6. Fitted regression line of MakM with reference FAO-56 PM model**

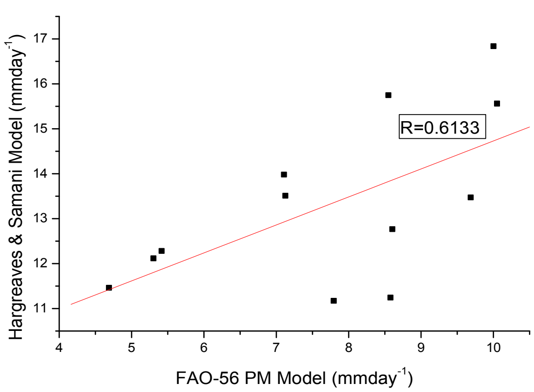


**Fig. 7. Fitted regression line of HSM with reference FAO-56 PM model**

Table 2 shows the different statistical indicators of RMSE, MBE, MAE and r which were carried out to test the performance of the selected models with the reference FAO-56 PM model and the results evaluated were used for ranking to ascertain the best model for the study area. The RMSE values ranged from 1.2147 mmday$^{-1}$ with the Blaney-Morin-Nigeria model to 5.7949 mmday$^{-1}$ with the Hargreaves and Samani model. Based on the RMSE value the Blaney-Morin-Nigeria model (1.2147 mmday$^{-1}$) performed best followed by the Priestly and Taylor model (3.4367 mmday$^{-1}$) and the worst is Hargreaves and Samani model (5.7949 mmday$^{-1}$). The MBE values ranged from -1.1581 mmday$^{-1}$ with the Blaney-Morin-Nigeria model to 5.5773 mmday$^{-1}$ with the Hargreaves and Samani model. The biasness which was indicated by Mean Bias Error (MBE) represents overestimation when it is positive and underestimation when it was negative. Based on the MBE values the Blaney-Morin-Nigeria model (-1.1581 mmday$^{-1}$) performed best followed by the Priestly and Taylor model (-2.7354 mmday$^{-1}$) and the worst is the Hargreaves and Samani model (5.5773 mmday$^{-1}$), all the models indicates underestimation except the Hargreaves and Samani model which shows overestimation in the reference FAO-56 PM throughout the year during the study period as indicated in the MBE analysis. Based on the coefficient of correlation (r) the Blaney-Morin-Nigeria model performed best with correlation coefficient of 0.9882 followed by the Jensen-Haise model with correlation coefficient of 0.7794 and the worst correlation is observed for Priestly and Taylor model (-0.2141). The overall results indicate that the Blaney-Morin-Nigeria model performed best in terms of RMSE, MBE, MAE and r.

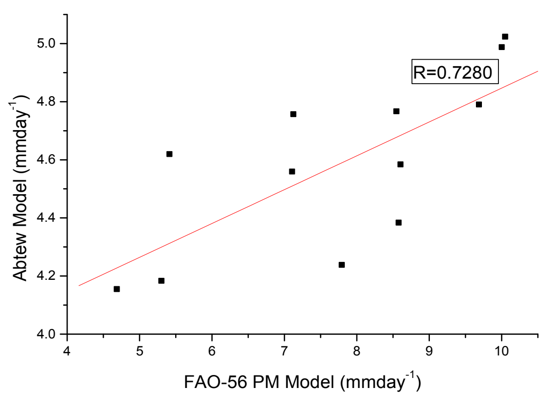


**Fig. 8. Fitted regression line of AbtM with reference FAO-56 PM model**

The low values of RMSE, MAE and high value of r obtained by Blaney-Morin-Nigeria model in this present study are consistent with results obtained in previous published studies. For instance, in a study carried out in Enugu, Nigeria.

**Table 3. Ranking of evaluated models as per statistical indicators for estimating $ET_0$**

| Statistical indicators | Models | | | | | |
|---|---|---|---|---|---|---|
| | BMNM | PTM | MakM | HSM | AbtM | JHM |
| RMSE | 1.00 | 2.00 | 5.00 | 6.00 | 3.00 | 4.00 |
| MBE | 1.00 | 2.00 | 5.00 | 6.00 | 3.00 | 4.00 |
| r | 1.00 | 2.00 | 4.00 | 5.00 | 3.00 | 2.00 |
| Total | 3.00 | 10.00 | 14.00 | 17.00 | 9.00 | 10.00 |
| Rank | 1.00 | 3.00 | 5.00 | 6.00 | 2.00 | 3.00 |

[50] Achieved RMSE, MAE and r of 0.3641 $mmday^{-1}$, 0.133 $mmday^{-1}$ and 0.82. In another study carried out in Ibadan, Kano and Onne, Nigeria. [29] found RMSE, MAE and r as (0.470 $mmday^{-1}$, 0.470 $mmday^{-1}$ and 0.706), (1.726 $mmday^{-1}$, 0.879 $mmday^{-1}$ and 0.636) and (0.871 $mmday^{-1}$, 0.734 $mmday^{-1}$ and 0.723). In all these studies, the RMSE, MAE and r were ranked first, except for Ibadan and Onne where r is ranked second. However, the Blaney-Morin-Nigeria model was reported as most accurate for estimating $ET_o$ in those study areas.

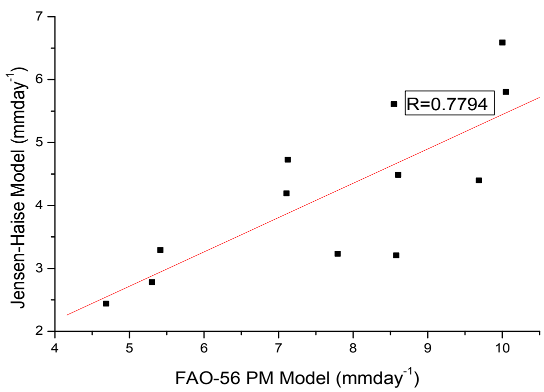


**Fig. 9. Fitted regression line of JHM with reference FAO-56 PM model**

The ranking of the selected models (Table 3) was done based on the statistical indicators of RMSE, MBE and r. The MAE was not considered since it is an absolute value of the MBE. The total ranks acquired by the different models were in the range of 3.00 to 17.00. Based on the total ranks acquired, the Blaney-Morin-Nigeria model was found suitable for estimating $ET_0$ followed by the Abtew model. The Priestly and Taylor and the Jensen-Haise models was ranked 3$^{rd}$, Makkink model, 5$^{th}$ and the Hargreaves and Samani, 6$^{th}$. Thus, the Blaney-Morin-Nigeria model was judge the best ET model for estimating $ET_0$ in the study area.

## 5. CONCLUSION

In this present study, six different evapotranspiration models were compared to evaluate the reference evapotranspiration for Sokoto, North Werstern, Nigeria using the FAO-56 PM model as standard. The Blaney-Morin-Nigeria model was found to achieve the best results in the fitted regression lines and in the analysis of errors when compared with other models considered in the study area. The results are consistent with previous published studies in literatures, such as, [47,50]. Based on these research results, we can safely conclude that, it is feasible to assert that the Blaney-Morin-Nigeria model is considered the most appropriate alternative to FAO-56 PM method for estimating $ET_0$ in Sokoto, North Western, Nigeria. Therefore, it is believed that this research on evapotranspiration information, if properly utilized, can provide accurate estimates of daily water usage and thus can assist irrigation managers in Sokoto and those with similar climatic information with the important decisions of when to apply water and how much water to apply for the design, operation and management of irrigation systems. However, there are other models not evaluated in this present study. These models are therefore a line to be explored.


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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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