Comparison of reference evapotranspiration models for the agro-ecological zones of Nigeria.

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Abstract. Irrigation practices are best done by estimating the crop water requirement in order to avoid over or under irrigation which may negatively affect crop yields. In this study, weather data (2004-2015) were collected and analyzed. The weather data include; minimum and maximum temperature (°C), relative humidity (%), wind speed (km/day), sunshine (hr/day) and radiation (MJ/m²/day). FAO Penman-Monteith model is a universal standard model used with other five evapotranspiration models such as; Priestley-Taylor model, Thornth-Waite model, Hargreaves model, ASCE-Penman Monteith model and Blaney-Criddle model to compute the mean monthly reference evapotranspiration (ET₀) for the six agro-ecological zones of Nigeria. Statistic regressions were performed to examine the relationship of the reference ET₀ estimates from the five models with the estimates by FAO Penman-Monteith model. The results of the analyses show that the mean monthly average ET₀ estimates by the FAO Penman-Monteith model, Priestley-Taylor model, Thornth-Waite model, Hargreaves model, ASCE-Penman Monteith model and Blaney-Criddle model across the six weather stations are; 6.48, 7.66, 14.14, 11.16, 5.57, and 3.70 mm/day, respectively. The best predictor is the ASCE-Penman Monteith model which correlated well with the FAO Penman-Monteith model while, the Priestley-Taylor model is the second-best model. Thornth-Waite model and Hargreaves model produced under-estimated ET values while, Blaney-Criddle model greatly over-estimated the FAO Penman-Monteith model. Therefore, this study is useful to the precise agricultural water management and regional water resources planning.

1. Introduction

The continuing growth of world population places new demands on water resources every day. Improved management and planning of water resources are needed to ensure proper use and distribution of water among competing users. Understanding the crop water requirement, use and consumption in irrigated agriculture is a prerequisite for better management and conservation of agricultural land [1]. Estimating crop water requirement by computing crop evapotranspiration is a widely used method [2]. The estimation of evapotranspiration and its components has been a key issue in hydrological studies and to enhance water use efficiency [3]. In practice, the estimation of ET₀ requires first calculating reference evapotranspiration (ET₀) and then applying the proper crop coefficient (Kc) to estimate actual crop evapotranspiration (ETa) [4]. The Kc is defined as the ratio of ET₀ to ET₀ and is used to scale the ET model to a specific crop. This
coefficient depends on several factors including crop type, stage of crop growth, canopy height and density. Consequently, different crops will have different \( K_c \) coefficients [5].

There are several models to calculate \( E_{To} \), but their performance in different environment is diverse, since all of them have some empirical background. The FAO Penman-Monteith model has been considered as a universal standard to estimate \( E_{To} \) for more than a decade [6]. This model accounts for aerodynamic as well as physiological parameters which requires several meteorological parameters such as net radiation, air temperature, vapour pressure deficit, relative humidity, sunshine, and wind speed [7]; [8].

The number of meteorological stations where reliable data for these parameters exist is an even smaller subset. This is especially true in developing countries where reliable collection of wind speed, humidity and radiation is limited [9]. However, the problem of over or under irrigation will be minimized if \( E_{To} \) is accurately estimated. Too much or too little water at the wrong stage of crop development can damage the crop and reduce yield.

It is in the light of the above that this study aimed at comparing reference evapotranspiration models with F.A.O Penman-Monteith model, using available climatic data for the agro-ecological zones of Nigeria.

2. Materials and Methods

2.1 Location of Study Area

Figure 1 is a map of Nigeria showing agro-ecological zones. The study area is located at the tropical zone of West Africa within Africa continent of the world, between latitudes 4°N and 14°N and longitudes 2°2'E and 14°30'E, and has a total area of 923,768 km². Approximately 13,000 km² of the land is covered by water (1.4%) and the remaining 98.6% of the land cover ranges from thick mangrove forests and dense rain forests in the south to a near-desert condition in the north-eastern corner of the country [10].
2.2 Data Collection
The weather data from 2004 to 2015 were collected from the Nigerian Meteorological Agency (NIMET), Abuja, Nigeria. The data include; minimum and maximum temperature (°C), relative humidity (%), wind speed (km/day), sunshine (hr./day) and radiation (MJ/m²/day). The twenty three weather stations considered in the study due to the availability of data include: {Sahel – Sokoto, Katsina and Jigawa}, {Sudan - Kano, Yobe and Borno}, {Northern Guinea – Adamawa, Kebbi and Niger}, {Southern Guinea – Kogi (2), Kwara and Benue}, {Forest - Enugu, Edo (2), Ekiti, Osun (2), Oyo and Ogun} and {Coastal – Lagos and Rivers}.

2.3 Evapotranspiration Models in the Study
2.3.1 Blaney-Criddle Model
The Blaney-Criddle model was first developed in 1942. It is an empirical equation and very simple to use. Blaney and Criddle in 1962 developed a simple mathematical model. Mean daily percentage (P) of annual day time hours for different latitudes is shown in Table 1.

| Latitude | North | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|----------|-------|-----|-----|-----|-----|-----|------|------|-----|------|-----|-----|-----|
| 40°      |       | 0.15| 0.20| 0.26| 0.32| 0.38| 0.41 | 0.40 | 0.34| 0.28 | 0.22| 0.17| 0.13|
| 55°      |       | 0.17| 0.21| 0.26| 0.32| 0.36| 0.39 | 0.38 | 0.33| 0.28 | 0.23| 0.18| 0.16|
| 50°      |       | 0.19| 0.23| 0.27| 0.31| 0.34| 0.36 | 0.35 | 0.32| 0.28 | 0.24| 0.20| 0.18|
| 45°      |       | 0.20| 0.23| 0.27| 0.30| 0.34| 0.35 | 0.34 | 0.32| 0.28 | 0.24| 0.21| 0.20|
| 40°      |       | 0.22| 0.24| 0.27| 0.30| 0.32| 0.34 | 0.33 | 0.31| 0.28 | 0.25| 0.22| 0.21|
| 35°      |       | 0.23| 0.25| 0.27| 0.29| 0.31| 0.32 | 0.32 | 0.30| 0.28 | 0.25| 0.23| 0.22|
| 30°      |       | 0.24| 0.25| 0.27| 0.29| 0.31| 0.32 | 0.31 | 0.30| 0.28 | 0.26| 0.24| 0.23|
| 25°      |       | 0.24| 0.26| 0.27| 0.29| 0.30| 0.31 | 0.31 | 0.29| 0.28 | 0.26| 0.25| 0.24|
| 20°      |       | 0.25| 0.26| 0.27| 0.28| 0.29| 0.30 | 0.30 | 0.29| 0.28 | 0.26| 0.25| 0.24|
| 15°      |       | 0.26| 0.26| 0.27| 0.28| 0.29| 0.29 | 0.29| 0.28| 0.27 | 0.27| 0.26| 0.25|
| 10°      |       | 0.26| 0.27| 0.27| 0.28| 0.28| 0.29 | 0.29| 0.28| 0.27 | 0.27| 0.26| 0.26|
| 5°       |       | 0.27| 0.27| 0.27| 0.28| 0.28| 0.28 | 0.28| 0.28| 0.27 | 0.27| 0.27| 0.27|
| 0°       |       | 0.27| 0.27| 0.27| 0.27| 0.27| 0.27 | 0.27| 0.27| 0.27 | 0.27| 0.27| 0.27|

Source: [11]

Although the model was originally developed to compute ET on a monthly basis, it can be modified to estimate daily values of ET with mean daily temperature. As temperature models tend to underestimate ET in arid regions while overestimating ET in humid regions, local calibration of the empirical coefficients is required to produce reliable estimates of ET [12]. The advantage of this model is the simplicity and disadvantage is that it underestimates ET grossly compared to the measured ET values [13].

2.3.2 Thornth-Waite Model. In 1948, Thornth-Waite and Penman both developed potential evapotranspiration model independently. The Thornth-Waite model is simpler than Penman’s model because the model requires less climatic data.

2.3.3 Hargreaves Model. Hargreaves in 1975 developed a model for estimating ET which doesn’t require wind speed data.
2.3.4 Priestley-Taylor Model. This model was developed by Priestley and Taylor in 1972 to compute reference crop evapotranspiration using the climatological data.

2.3.5 FAO Penman-Monteith (PM) Model. The FAO PM model is based on the Penman-Monteith model. The FAO PM method defines the reference crop as a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 m/s and an albedo of 0.23, closely resembling the evaporation of an extensive surface of green grass of uniform height, actively growing and adequately watered.

2.3.6 ASCE-EWRI Standardized Penman Monteith Evapotranspiration Model. The ASCE Standardized Reference Evapotranspiration Equation is based on the Penman-Monteith model, with some simplification and standardization on the aerodynamic and surface resistances. This model is applicable for both tall (Alfalfa) and short (grass) reference surfaces. A grass reference crop is defined as an extensive, uniform surface of dense, actively growing, cool-season grass with a height of 0.12 m, and not short of soil water; whereas a full cover alfalfa reference crop is defined as an extensive, uniform surface of dense, actively growing alfalfa with a height of 0.50 m, and not short of soil water [14], [15] Found a good correlation between the ASCE Standardized ET₀ equation results and the FAO 56 PM ET₀ results calculated on hourly time steps. However, the FAO 56 PM method estimated 5% to 8% lower ET₀ compared to the ASCE Standardized ET₀. According to [15] the results may be due to the higher surface resistance values during daytime periods in the FAO 56 PM equation.

2.4 Methodology

The daily weather data collected were summed and averaged to obtain the mean monthly values. Similarly, the mean daily values across the period of record were averaged to obtain the mean annual values. Six different ET models; two combination-based models (FAO Penman-Monteith and ASCE-Penman Monteith), two temperature-based models (Thornthwaite and Blaney-Criddle) and two radiation-based model (Priestley-Taylor and Hargreaves) were used to estimate mean monthly reference evapotranspiration (ET₀) for six agro-ecological zones of Nigeria. An Excel computer program was developed to calculate ET₀ for the six ET models on monthly basis, using the mean monthly weather data for the twenty three weather stations. Linear statistic regressions were performed to examine the relationship of the reference ET₀ estimates from the five ET models with the estimate by the standard FAO Penman-Monteith model for the six agro-ecological zones of Nigeria. The regression model is of the form:

\[ Y = MX + C \]  \hspace{1cm} (1)

Where,

\[ Y = \text{FAO Penman-Monteith monthly reference ET}_0 \]
\[ X = \text{Mean monthly reference ET}_0 \text{ estimated from each of the other two models, and} \]
\[ M \text{ and } C = \text{Slope and intercept, respectively.} \]

The values estimated from the mean monthly ET₀ for each of the five models were plotted against the mean monthly estimate by the standard FAO Penman-Monteith model. The deviations on the graph in the respect of FAO Penman-Monteith were adjusted. Parmele and McGuiness in 1974 recommended that the best model is the one with the lowest absolute deviation, C value closest to Zero, M value closest to 1.0, the smallest RMSE, and highest R². The mean monthly correction factors for the potential use of some models in the study area were also computed as the ratio of the monthly total FAO Penman-Monteith reference ET₀ to the monthly total for each model averaged over the record period.

3. Results and Discussion

3.1 Results and Comparison of ET models

The computed mean monthly reference evapotranspiration (ET₀) for each model in each zone are shown in tables 2, 3, 4, 5, 6 and 7. The FAO Penman-Monteith’s mean monthly ET₀ estimates ranged from
1.56 mm/day for Southern Guinea to 11.58 mm/day for Sudan. The mean monthly ET\textsubscript{o} estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 9.45 mm/day, 11.58 mm/day, 7.47 mm/day, 5.49 mm/day, 1.56 mm/day and 3.31 mm/day respectively. The Priestley-Taylor’s mean monthly ET\textsubscript{o} estimates ranged from 6.56 mm/day for Coastal to 8.82 mm/day for Sudan. The mean monthly ET\textsubscript{o} estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 7.98 mm/day, 8.82 mm/day, 7.97 mm/day, 7.52 mm/day, 7.13 mm/day and 6.56 mm/day respectively. Thornth-Waite’s mean monthly ET\textsubscript{o} estimates ranged from 13.89 mm/day for Coastal to 14.47 mm/day for Sudan. The mean monthly ET\textsubscript{o} estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 14.38 mm/day, 14.47 mm/day, 14.11 mm/day, 14.07 mm/day, 13.92 mm/day and 13.89 mm/day respectively.

Table 2: Reference evapotranspiration (ET\textsubscript{o} mm/day) using FAO Penman-Monteith model

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|-------|--------|
| 2004 | 11.45 | 11.22 | 7.18            | 6.98            | 2.69  | 4.19   |
| 2005 | 15.67 | 13.61 | 8.87            | 9.02            | 3.08  | 4.54   |
| 2006 | 20.73 | 20.45 | 9.78            | 10.84           | 2.52  | 4.52   |
| 2007 | 15.94 | 23.62 | 9.76            | 6.32            | 1.87  | 4.29   |
| 2008 | 9.66  | 16.07 | 7.30            | 4.49            | 1.17  | 3.34   |
| 2009 | 4.22  | 10.15 | 5.52            | 3.67            | 0.01  | 2.79   |
| 2010 | 4.19  | 4.93  | 13.42           | 3.28            | 0.17  | 2.13   |
| 2011 | 3.35  | 2.53  | 4.43            | 3.45            | 1.22  | 2.30   |
| 2012 | 3.56  | 3.13  | 4.31            | 3.46            | 1.05  | 2.31   |
| 2013 | 5.56  | 9.28  | 4.94            | 3.69            | 0.98  | 2.73   |
| 2014 | 8.90  | 13.26 | 7.50            | 4.84            | 1.38  | 3.17   |
| 2015 | 10.22 | 10.75 | 6.64            | 5.85            | 2.63  | 3.44   |
| Mean | 9.45  | 11.58 | 7.47            | 5.49            | 1.56  | 3.31   |

Table 3: Reference evapotranspiration (ET\textsubscript{o} mm/day) using Priestley Taylor model

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|-------|--------|
| 2004 | 8.10  | 7.90  | 8.09            | 7.58            | 7.12  | 6.93   |
| 2005 | 8.89  | 9.01  | 8.88            | 8.45            | 8.14  | 7.84   |
| 2006 | 8.94  | 9.48  | 8.93            | 8.15            | 8.28  | 7.26   |
| 2007 | 8.46  | 9.37  | 8.45            | 8.28            | 8.26  | 7.30   |
| 2008 | 8.33  | 9.56  | 8.32            | 8.02            | 7.49  | 7.04   |
| 2009 | 7.56  | 9.61  | 7.55            | 7.10            | 6.35  | 5.90   |
| 2010 | 7.00  | 8.36  | 6.99            | 6.42            | 5.75  | 5.46   |
| 2011 | 6.72  | 7.79  | 6.71            | 6.22            | 5.99  | 5.63   |
| 2012 | 7.32  | 8.78  | 7.31            | 6.66            | 6.19  | 5.53   |
| 2013 | 7.96  | 9.41  | 7.95            | 7.54            | 7.09  | 6.29   |
| 2014 | 8.43  | 8.68  | 8.42            | 7.96            | 7.59  | 6.63   |
| 2015 | 8.07  | 7.96  | 8.06            | 7.80            | 7.34  | 6.91   |
| Mean | 7.98  | 8.82  | 7.97            | 7.52            | 7.13  | 6.56   |
Table 4: Reference evapotranspiration (ET₀ mm/day) using Thornth-Waite model

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|--------|---------|
| 2004 | 13.51 | 13.26 | 13.71           | 13.94           | 14.07  | 13.91   |
| 2005 | 14.37 | 13.82 | 14.48           | 14.56           | 14.43  | 14.29   |
| 2006 | 15.58 | 15.13 | 14.93           | 14.71           | 14.45  | 14.27   |
| 2007 | 16.26 | 16.26 | 14.66           | 14.93           | 14.27  | 14.19   |
| 2008 | 15.11 | 15.87 | 14.38           | 14.14           | 13.99  | 14.02   |
| 2009 | 14.41 | 14.95 | 13.96           | 13.84           | 13.56  | 13.76   |
| 2010 | 14.02 | 14.29 | 13.78           | 13.65           | 13.46  | 13.53   |
| 2011 | 13.81 | 13.82 | 13.78           | 13.66           | 13.41  | 13.55   |
| 2012 | 13.87 | 14.13 | 13.78           | 13.72           | 13.53  | 13.62   |
| 2013 | 14.21 | 14.78 | 13.96           | 13.90           | 13.78  | 13.75   |
| 2014 | 13.91 | 14.13 | 14.17           | 14.00           | 14.04  | 13.90   |
| 2015 | 13.48 | 13.26 | 13.71           | 13.81           | 14.02  | 13.84   |
| Mean | 14.38 | 14.47 | 14.11           | 14.07           | 13.92  | 13.89   |

Table 5: Reference evapotranspiration (ET₀ mm/day) using Hargreaves model

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|--------|---------|
| 2004 | 11.61 | 10.51 | 11.35           | 10.70           | 10.21  | 9.87    |
| 2005 | 13.73 | 12.38 | 12.81           | 12.30           | 11.80  | 11.30   |
| 2006 | 14.72 | 14.10 | 13.23           | 12.02           | 12.00  | 10.54   |
| 2007 | 14.54 | 14.77 | 12.38           | 12.35           | 11.83  | 10.53   |
| 2008 | 14.11 | 14.77 | 11.10           | 11.42           | 10.63  | 10.07   |
| 2009 | 12.60 | 14.14 | 10.69           | 10.02           | 8.90   | 8.47    |
| 2010 | 11.27 | 11.95 | 9.85            | 9.03            | 8.09   | 7.78    |
| 2011 | 10.49 | 10.86 | 9.50            | 8.80            | 8.35   | 8.00    |
| 2012 | 11.34 | 12.35 | 10.25           | 9.38            | 8.68   | 7.92    |
| 2013 | 13.04 | 13.73 | 11.20           | 10.62           | 9.97   | 8.95    |
| 2014 | 12.87 | 12.23 | 11.96           | 11.23           | 10.80  | 9.48    |
| 2015 | 11.75 | 10.58 | 11.12           | 10.87           | 10.46  | 9.79    |
| Mean | 12.67 | 12.70 | 11.34           | 10.73           | 10.14  | 9.39    |
The Hargreaves’s mean monthly ET₀ estimates ranged from 8.00 mm/day for Coastal to 14.77 mm/day for Sudan. The mean monthly ET₀ estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 12.67 mm/day, 12.70 mm/day, 11.34 mm/day, 10.73 mm/day, 10.14 mm/day and 9.39 mm/day respectively. The Blaney-Criddle’s mean monthly ET₀ estimates ranged from 5.20 mm/day for Sudan to 6.32 mm/day for Sahel. The mean monthly ET₀ estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 5.66 mm/day, 5.69 mm/day, 5.56 mm/day, 5.55 mm/day, 5.49 mm/day and 5.48 mm/day respectively. The ASCE-Penman Monteith’s mean monthly ET₀ estimates ranged from 0.08 mm/day for Southern Guinea to 11.94 mm/day for Sahel. The mean monthly ET₀ estimates

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|--------|---------|
| 2004 | 5.32  | 5.20  | 5.40            | 5.50            | 5.55   | 5.49    |
| 2005 | 5.67  | 5.45  | 5.71            | 5.74            | 5.69   | 5.64    |
| 2006 | 6.10  | 5.96  | 5.88            | 5.80            | 5.70   | 5.63    |
| 2007 | 6.32  | 6.32  | 5.78            | 5.88            | 5.63   | 5.60    |
| 2008 | 5.94  | 6.20  | 5.68            | 5.58            | 5.52   | 5.53    |
| 2009 | 5.69  | 5.89  | 5.51            | 5.46            | 5.34   | 5.43    |
| 2010 | 5.53  | 5.64  | 5.43            | 5.38            | 5.30   | 5.33    |
| 2011 | 5.45  | 5.45  | 5.43            | 5.38            | 5.27   | 5.33    |
| 2012 | 5.47  | 5.58  | 5.43            | 5.41            | 5.33   | 5.36    |
| 2013 | 5.61  | 5.82  | 5.51            | 5.48            | 5.43   | 5.42    |
| 2014 | 5.49  | 5.58  | 5.59            | 5.53            | 5.54   | 5.48    |
| 2015 | 5.30  | 5.20  | 5.40            | 5.45            | 5.53   | 5.46    |
| Mean | 5.66  | 5.69  | 5.56            | 5.55            | 5.49   | 5.48    |

| Year | Sahel | Sudan | Northern Guinea | Southern Guinea | Forest | Coastal |
|------|-------|-------|-----------------|-----------------|--------|---------|
| 2004 | 6.50  | 6.45  | 4.01            | 3.96            | 1.50   | 2.34    |
| 2005 | 8.97  | 7.86  | 4.97            | 5.15            | 1.73   | 2.55    |
| 2006 | 11.97 | 11.94 | 5.51            | 6.20            | 1.41   | 2.53    |
| 2007 | 9.24  | 13.89 | 5.49            | 3.62            | 1.04   | 2.41    |
| 2008 | 5.55  | 9.43  | 4.09            | 2.55            | 0.65   | 1.87    |
| 2009 | 2.40  | 5.91  | 3.07            | 2.08            | 0.36   | 1.55    |
| 2010 | 2.38  | 2.85  | 7.52            | 1.85            | 0.08   | 1.18    |
| 2011 | 1.90  | 1.45  | 2.46            | 1.95            | 0.67   | 1.28    |
| 2012 | 2.01  | 1.80  | 2.39            | 1.96            | 0.58   | 1.28    |
| 2013 | 3.16  | 5.40  | 2.74            | 2.09            | 0.54   | 1.52    |
| 2014 | 5.06  | 7.68  | 4.19            | 2.74            | 0.76   | 1.77    |
| 2015 | 5.80  | 6.18  | 3.70            | 2.31            | 1.47   | 1.91    |
| Mean | 5.41  | 6.74  | 4.38            | 3.12            | 0.90   | 1.85    |

The Hargreaves’s mean monthly ET₀ estimates ranged from 8.00 mm/day for Coastal to 14.77 mm/day for Sudan. The mean monthly ET₀ estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 12.67 mm/day, 12.70 mm/day, 11.34 mm/day, 10.73 mm/day, 10.14 mm/day and 9.39 mm/day respectively. The Blaney-Criddle’s mean monthly ET₀ estimates ranged from 5.20 mm/day for Sudan to 6.32 mm/day for Sahel. The mean monthly ET₀ estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 5.66 mm/day, 5.69 mm/day, 5.56 mm/day, 5.55 mm/day, 5.49 mm/day and 5.48 mm/day respectively. The ASCE-Penman Monteith’s mean monthly ET₀ estimates ranged from 0.08 mm/day for Southern Guinea to 11.94 mm/day for Sahel. The mean monthly ET₀
estimates for Sahel, Sudan, Northern Guinea, Southern Guinea, Forest and Coastal are; 5.41 mm/day, 6.74 mm/day, 4.18 mm/day, 3.12 mm/day, 0.90 mm/day and 1.85 mm/day respectively. The computed mean monthly ET$_o$ for the six ET models across the six agro-ecological zones are shown in table 8.

Table 8: Mean monthly ET$_o$ (mm/day) for the six ET models across the six agro-ecological zones

| Agro-Ecological Zones   | FAO Penman-Monteith | Thornth-Waite | Priestley-Taylor | Hargreaves | Blaney-Criddle | ASCE-Penman Monteith |
|-------------------------|--------------------|---------------|------------------|------------|---------------|----------------------|
| Sahel                   | 9.45               | 14.38         | 7.98             | 12.67      | 5.66          | 5.41                 |
| Sudan                   | 11.58              | 14.47         | 8.82             | 12.70      | 5.69          | 6.74                 |
| Northern Guinea         | 7.47               | 14.11         | 7.97             | 11.34      | 5.56          | 4.18                 |
| Southern Guinea         | 5.49               | 14.07         | 7.52             | 10.73      | 5.55          | 3.12                 |
| Forest                  | 1.56               | 13.92         | 7.13             | 10.14      | 5.49          | 0.90                 |
| Coastal                 | 3.31               | 13.89         | 6.56             | 9.39       | 5.48          | 1.85                 |

The mean monthly average ET$_o$ estimates by FAO Penman-Monteith model, Thornth-Waite model, Priestley-Taylor model, Hargreaves model, Blaney-Criddle model and ASCE-Penman Monteith model are; 6.48, 14.14, 7.66, 11.16, 5.57 and 3.70 respectively. The mean monthly ET$_o$ values for each year average over given years of record as estimated by six ET models are plotted against the mean monthly ET$_o$ estimated by FAO Penman-Monteith model. The relationship between mean monthly ET$_o$ estimates for each of model against the FAO Penman Monteith ET$_o$ and the coefficient of determination ($R^2$) are as shown in Figure 2, 3, 4, 5 and 6 respectively, using the linear regression equations.

Figure 2: Mean monthly FAO Penman-Monteith’s ET$_o$ against Priestley-Taylor’s ET$_o$
Figure 3: Mean monthly FAO Penman-Monteith’s ET₀ against Thornthwaite’s ET₀

Figure 4: Mean monthly FAO Penman-Monteith’s ET₀ against Blaney-Criddle’s ET₀
Figure 5: Mean monthly FAO Penman-Monteith’s ET₀ against Hargreaves’s ET₀.

Figure 6: Mean monthly FAO Penman-Monteith’s ET₀ against ASCE-Penman Monteith’s ET₀.

The intercept and the slope of each regression line are also shown for comparing the measured and the estimated values. Summary statistics for regression of monthly ET₀ estimated by each of the five ET models against that estimated by the standard FAO Penman-Monteith model for the total period of observation (N = 4,380 days) are presented in Table 9. With regards to regression equations, ASCE-Penman Monteith model resulted in a slope (M) slightly more than unity (1.7209) and an intercept (C) close to zero (0.1133), given the best predicted values. The second-best values were those obtained by the Priestley-Taylor model (M = 0.1890) and (C = 6.4404). The Thornth-Waite model produced the greatest underestimates (by as much as 16%), while the Hargreaves model yielded the least underestimated values (7%). Hence, the Blaney-Criddle model over-estimated by as much as 24%, given the worst estimates among all the tested models.

Table 9: Summary Statistics for Regression of mean annual ET₀ estimated by five ET models against that estimated by FAO Penman-Monteith model (N = 4380 days)
A correlation coefficient (R²) is used to reflect how the estimated ETo best matches with the FAO Penman-Monteith model estimation. Root mean square error (RMSE) and Absolute average deviation (ADD) also represent the deviation of estimated ET₀ from the FAO Penman-Monteith model estimation, and it does so in a more comprehensive manner [16]. It revealed that the most acceptable model of computing ET₀ is ASCE-Penman Monteith model (R² = 0.9992 %) which requires many parameters viz. monthly radiation, mean temperature, wind speed and vapour pressure data. RMSE and ADD values ranged from -5.43 to 0.92 mm/day and from 0.025 to 1.740 mm/day respectively, for all the five models. The ASCE-Penman Monteith model showed its superiority over the other models studied with a smallest RMSE value of -5.43 mm/day and the Blaney-Criddle model was the one that demonstrated the worst performance with RMSE of 0.92 mm/day. Similarly, the ASCE-Penman Monteith model showed the best performance over the other models with the lowest ADD value of 0.025 mm/day and Blaney-Criddle model was the least effective model with ADD value of 1.740 mm/day.

The mean monthly correction factors that can be used for adjusting the Blaney-Criddle, Hargreaves and Thornth-Waite model for their potential use at each agro-ecological zone are shown in Table 10.

Table 10: Mean monthly correction factors for Blaney-Criddle, Hargreaves and Thornth-Waite model

| Agro-Ecological Zones | Blaney-Criddle | Hargreaves | Thornth-Waite |
|-----------------------|----------------|------------|--------------|
| Sahel                 | 1.126          | 0.267      | 0.068        |
| Sudan                 | 1.153          | 0.341      | 0.210        |
| Northern Guinea       | 0.151          | 0.334      | 1.146        |
| Southern Guinea       | 0.117          | 1.026      | 0.164        |
| Forest                | 0.225          | 0.191      | 1.420        |
| Coastal               | 0.142          | 0.273      | 0.260        |

4. Conclusions and Recommendations

4.1 Conclusions
The FAO Penman-Monteith model is well established as the accurate and robust model to estimate ET₀. The mean monthly average ET₀ estimates by the FAO Penman-Monteith model for twenty three weather stations ranged from 2.58 mm/day for South-West to 15.03 mm/day for North-West. Similarly, the mean monthly average ET₀ estimates by the FAO Penman-Monteith, Priestley-Taylor, Thornth-Waite, Hargreaves, ASCE-Penman Monteith and Blaney-Criddle model are found to be 6.48, 14.14, 7.66, 11.16, 5.57 and 3.70 respectively. The results show considerable variability among the models, in addition, the relationship among models depends on location. The best predictor is the ASCE-Penman Monteith model which correlated well with the FAO Penman-Monteith model while, the Priestley-Taylor model remains the second-best model. Thornth-Waite and Hargreaves model produced the underestimated values while, Blaney-Criddle model greatly overestimated the FAO Penman-Monteith model.

4.2 Recommendations
The following recommendations were drawn from this study:
(i) In the absence of radiation, vapour pressure and sunshine data which may not allow the use of FAO Penman-Monteith model for estimating crop water requirement in Nigeria, the Priestley-Taylor, Hargreaves and Blaney-Criddle model with the developed correction factors can be used.

(ii) Twenty to thirty years of weather data is recommended for accurate estimation of ET₀.

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