Evaluation of FAO-56 Penman-Monteith and Temperature Based Models in Estimating Reference Evapotranspiration Using Complete and Limited Data, Application to Nigeria

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ABSTRACT

Accurate determination of reference evapotranspiration is very essential for precise computation of crop water use. Several models have been used in computing reference evapotranspiration and they require local calibration in order to validate their usage. Climatic data used in computing reference evapotranspiration (ET_o) for Abeokuta, Ijebu-Ode and Itoikin were obtained from Ogun-Osun River Basin and Rural Development Authourity, Abeokuta, Nigeria. For Abeokuta, complete climatic data were used in the computation of the ET_o while limited climatic data were used in computing ET_o for Ijebu-Ode and Itoikin using FAO-56 Penman-Monteith (FAO-56 PM), Jensen-Haise and Hargreaves models. In Abeokuta, the average coefficients of determination R^2 obtained when ET_o computed using Jensen-Haise and Hargreaves models were compared with FAO-56 PM model were 0.7914 and 0.5158 respectively. The average Root Mean Square Errors (RMSEs) obtained between Jensen-Haise, Hargreaves and FAO-56 PM models were 1.03 and 1.79 mmd^{-1} respectively. The index of agreement between pan evaporation and FAO-56 PM, Jensen-Haise and Hargreaves models were 0.56, 0.71 and 0.52 respectively. The average R^2 of the ET_o computed using R_s and temperature for FAO-56 PM and Jensen-Haise were 0.6784 and 0.8488 respectively. For Ijebu-Ode, the average R^2 when Jensen-Haise, Hargreaves were compared with FAO-56 PM model were 0.9908, 0.9907 respectively. The average RMSEs between FAO-56 PM, Jensen-Haise and Hargreaves were 2.51 and 0.87 mmd^{-1} respectively while the index of agreement between FAO-56 PM, Jensen-Haise and Hargreaves models were 0.49, 0.88 and 0.54 respectively. Similarly for Itoikin, the average R^2 obtained when Jensen-Haise and Hargreaves model were compared with FAO-56 PM were 0.9754 and 0.9557 respectively. The average RMSEs obtained between FAO-56 PM and Jensen-Haise and Hargreaves models were 2.50 and 0.89 mmd^{-1} respectively while the index of agreement between pan evaporation and FAO-56PM, Jensen-Haise and Hargreaves models were 0.28, 0.61 and 0.34 respectively. It is hereby recommended that beside FAO-56PM model, Jensen-Haise model is also recommended for the computation of ET_o in situations where only maximum and minimum temperatures are available in Ogun-Osun River basin.

Keywords: Reference evapotranspiration; Pan Evaporation; FAO-56 Penman-Monteith model; Jensen-Haise model; Hargreaves model; Complete and Limited data.

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 (Pereira, 2005). Dependency on rainfall for future crop production has become a major constraint for sustainable food production in the developing counties. Irrigated agriculture accounts for about 70% of the available fresh water globally Fischer, et al.,(2006). Sustainable food and fibre productions which are expected to cater for the teeming population will depend largely on judicious and conjunctive use of surface and underground water in order to attain the Millennium Development Goals (MDGs) of water for all by the year 2015 Smith, (2000).

The urgent need to develop a standard, precise and globally acceptable method of estimating reference evapotranspiration for accurate computation of crop water requirements has been stressed by many authours (Doorenbos and Pruit, 1975; Doorenbos and Kassam, 1979; Chiew et al., 1995; Allen et al., 1998; Xu and Singh, 2001; Dodds et al., 2005). Several models had been proposed by many authours and these include FAO-Penman, Penman, 1982-Kinberly-Penman, FAO-Corrected–Penman, Penman-Monteith, Blanney-Criddle, Priestley-Taylor, FAO-Radiation, Hargreaves, and FAO-Blanney Criddle (Allen et al., 1998; Dockter, 1999; Wang et al., 2003; DehghaniSaniji et al., 2004; Pereira and Pruitt, 2004; Dodds et al., 2005). Many of these models are subject to local calibration threby making them to have limited global acceptance. Due to the higher performance of FAO-56 Penman-Monteith (FAO-56 PM) model in different parts of the world when compared with other models, it has been accepted as the sole method of computing reference evapotranspiration from meteorological data (Jensen et al., 1990; Allen, et al., 1998; Hess, 1998; Ravelli and Rota, 1999; Zhao et al., 2005; Garcial et al., 2006; Gavila, et al, 2006).

In order to use FAO-56 PM model in computing daily evapotranspiration, specific meteorological data are required such as daily maximum and minimum air temperature, solar radiation, wind speed, and relative humidity. These data can be obtained directly from automatic weather stations which are now in use in different parts of the world. However, in Nigeria and other developing countries, these automatic weather stations are in most cases not available due to the high cost of acquiring and maintaining them. Similarly, in meteorological stations where analogue instruments are used, limited data are recorded due to obsolete or faulty equipment and lack of appropriate facilities. These hereby make it very difficult to estimate reference evapotranspiration. In most cases, only the maximum and minimum air temperature are available. In such situation, the procedure for estimating reference evapotranspiration outlined in Allen, et al., (1998) are used and has been found to produce accepted results Droogers and Allen, (2002). Hargreaves model has been recommended for the computation of reference evapotranspiration when only the maximum and minimum air temperature are available Allen et al., (1998). The result obtained from the use of Hargreaves model has been reported to produce satisfactory results in computing weekly or monthly reference evapotranspiration Hargreaves and Allen, (2003).

For effective planning and implementation of policies on irrigation projects, it is very necessary to determine reference evapotranspiration that is very essential in computing crop water use. The objectives of this study were to (i) evaluate the performances of three models namely: FAO-56 PM, Jensen-Haise and Hargreaves models in computing daily reference evapotranspiration in three locations in the South western part of Nigeria using complete and limited data; (ii) compare the relative performance of Jensen-Haise and Hargreaves models with FAO-56 PM model under complete and limited data set using statistical parameters; (iii) compare the computed reference evapotranspiration using the FAO-56 PM model under complete and limited data set and (iv) evaluate the use of Hargreaves model in computing reference evapotranspiration with only maximum and minimum air temperatures. The focus of this study was not to impose one model over the others however; it was to evaluate the use of temperature-based models in computing reference evapotranspiration using the available climatic data in the stated areas based on the procedures explained in Allen, et al., (1998).

2. MATERIALS AND METHODS

2.1 Determination of ET_o Using Complete Climatic Data Set

In order to evaluate the performances of three different models in estimating the reference evapotranspiration using complete and limited data in the South western part of Nigeria, climatic data were obtained from Ogun-Osun River Basin and Rural Development Authourity, Abeokuta, Nigeria. The geographic coordinates of the locations and periods considered are stated shown in Table 1. The three stations are located within Ogun-Osun River Basin in the South western part of Nigeria (see Fig 1). For Abeokuta, climatic data of 15years containing daily maximum and minimum air temperature, relative humidity, wind speed, sunshine duration and rainfall were used in this study. Abeokuta is located in sub-humid tropical region of Southwestern part of Nigeria. The mean daily temperature is about 28^{o}C (Orebiyi, et. al., 2008). There are different models for computing reference evapotranspiration and these models are generally classified according to the weather parameters that play the dominant role in the model. Generally these classifications include the temperature-based models such as Thornthwaite (1948); Blaney-Criddle (1950); Hargreaves and Samani (1982). The mass-transfer models which is based on vapour pressure or relative humidity include: Rohwer (1931) and Harbeck (1962)); the radiation models which is based on solar radiation, such as Priestly-Taylor (1972) and Makkink (1957)), and the combination models which is based on the energy balance and mass transfer principles and include the Penman (1948), modified Penman (Doorenbos and Puritt, 1977) and FAO-56 PM (Allen et al., 1998). Three models used in this study are FAO-56 PM, Hargreaves and Jensen-Haise models. Hargreaves and Jensen-Haise models were used in this study because they require lesser inputs which are available in most of the weather stations in Nigeria. The FAO-56 PM model has been universally accepted as the sole method for estimating reference evapotranspiration (Allen et.al, 1998). The ET_o for Abeokuta was computed with complete and limited data set using FAO-56 PM and the results were compared in order to evaluate the reliability of using limited data. The ET_o estimated using Hargreaves and Jensen-Haise models were compared with those computed using FAO-56 Penman-Monteith model as described in the procedures stated in Allen, at al., (1998) and statistical parameters such as coefficient of determination, Root Mean Square Error (RMSE) and index of agreement were used in determining the degree of fit of the models. The pan evaporation data in the three stations were compared with their respective reference evapotranspiration computed using the three stated models in order to determining the correlation between them.

2.2 The FAO-56 Penman-Monteith Equation and the Computation Procedures

The FAO-56 PM model uses an hypothetical green grass reference surface actively growing and is adequately watered with an assumed height of 0.12m having a surface resistance of 70s m^{-1} and an albedo of 0.23 (Allen et al., 1998). The FAO-56 PM model stated in (Allen et al., 1998) is given as:

Table1-Geographic locations, physical coefficients, variables observed, instruments and the period considered in the analysis in the study areas.

Parameters	Abeokuta	Ijebu-Ode	Itoikin
Latitude (N)	$7^0 10'$	$6^0 49'$	$3^0 45'$
Altitude (m)	62	300	129
Atmospheric Pressure (KPa)	100.58	97.80	99.79
Psychometric Constant (K Pa^0C^{-1})	0.0669	0.0650	0.0664
k_{rs} ($^0C^{-0.5}$)	0.1688	0.1628	0.1675
Temperature (^{0}C)	Maximum and Minimum Thermometer (1982-1994; 1999-2000); January-December	Maximum and Minimum Thermometer (1990-2005); January-December	Maximum and Minimum Thermometer (1984-2001); January-December
Relative Humidity (%)	Hygrometer (1982-1994; 1999-2000)	Hygrometer (1990-2005)	Hygrometer (1984-2001)
Wind speed (m/s)	Cup counter Anemometer at 10m (1982-1994; 1999-2000)	Cup counter Anemometer at 10m (1990-2005)	Cup counter Anemometer at 10m (1984-2001)
Sunshine Duration (hd^{-1})	Campbel-Stokes sunshine recorder (1982-1994; 1999-2000); January-December	Campbel-Stokes sunshine recorder (1990-2005); January-December	Campbel-Stokes sunshine recorder (1984-2001); January-December
Rainfall (mm)	Rainguage (1982-1994; 1999-2000); January-December	Rainguage (1990-2005); January-December	Rainguage (1984-2001); January-December

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

where,

ET_0 is Reference evapotranspiration (mmd^{-1});

R_n is Net radiation at the crop surface ($MJm^{-2}d^{-1}$);
G is Soil heat flux density ($MJm^{-2}d^{-1}$);
γ is Psychometric constant (KPa^0C^{-1});
T is the mean of the monthly maximum and minimum air temperatures (^oC),
u_2 is wind speed at 2 m height (ms^{-1});
e_s is saturated vapour pressure (KPa);
e_a is actual vapour pressure (KPa);
$e_s - e_a$ is saturated vapour pressure deficit ();
Δ is slope vapour pressure curve (KPa^0C^{-1}).

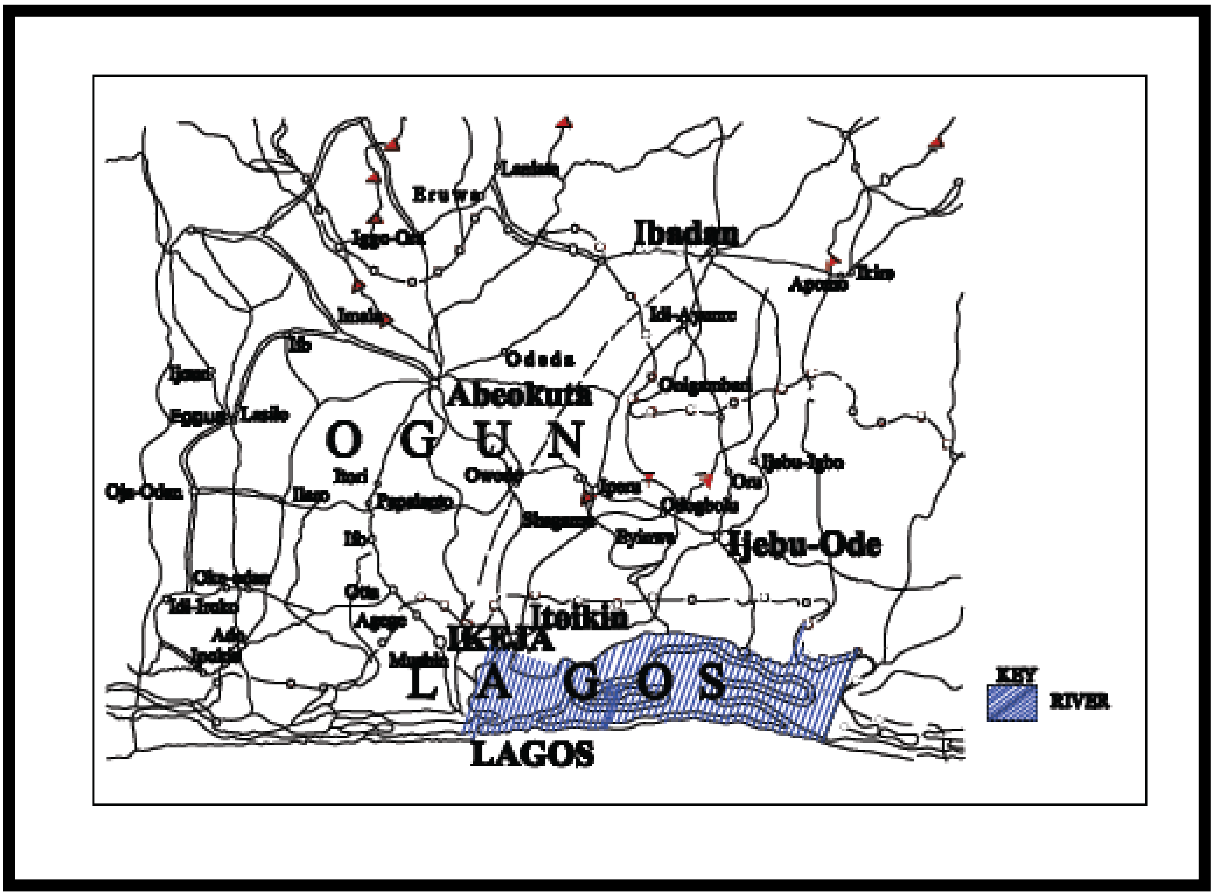


Figure 1: Locations of Abeokuta, Ijebu-Ode and Itoikin

The parameters in the FAO-56 PM model were determined using average monthly maximum and minimum air temperatures, sunshine duration, average relative humidity and wind speed. Measurements of these parameters were made at height 10 meter. However, the wind speeds were converted to the speed at height of 2m using Equation 19 (see Table 2). Other equations used in computing the ET_o are shown in Table 2. The atmospheric pressure for each location remains the same over the normal temperature range. Similarly, psychometric coefficient was also constant for each location (see Table 1). The solar radiation R_s was determined using Equation 14. The soil heat flux G ($MJm^{-2}d^{-1}$) was taken as zero for each day. The FAO-56 PM model procedure above was used in computing the reference evapotranspiration for Abeokuta.

2.3 Computation of ET_o using Limited Data set

For the other two locations, Ijebu-Ode and Itoikin where limited climatic data are available, maximum and minimum air temperatures were used in computing the ET_o (see Table 1). The procedures for computing reference evapotranspiration using limited data stated in Allen et al, (1998) were used and these procedures are as follow:

2.3.1 Solar radiation

In the absence solar radiation data, Allen et al., (1998) presented procedure for computing solar radiation using the difference between the maximum and minimum air temperatures. Solar radiation was determined using the Equation 20 (see Table 2) as stated by Allen et al., (1998). Allen, (1997) presented a method for estimating k_{rs} as a function of elevation and is presented as $k_{rs} = k_{ro}\left(P/P_o\right)$ where k_{rs} is the adjustment coefficient ($^0C^{-0.5}$) k_{ro} is an empirical coefficient equal to 0.17 for interior and 0.20 for coastal regions, P is the mean atmospheric pressure of the site (KPa), P_o the mean atmospheric pressure at sea level (101.3 KPa). k_{rs} was calibrated for each location as suggested by Popova et al., (2006) and the results are presented in Table 1.

2.3.2 Relative Humidity

Where data of relative humidity are not available, Allen et al, (1998) stated that the actual vapour pressure can be determined by assuming that the dew point temperature T_{dew} is close to the daily minimum air temperature $T_{\min}$ that is ($T_{dew} \approx T_{\min}$) which is usually experienced in reference weather station. Based on this, the actual vapour pressure was determined using Equation 6.

2.3.3 Wind speed

In a situation where the wind speed data are not available, Allen, et al, (1996) suggested that wind data from a nearby station can be imported and converted to default wind speed at 2m (u_2). Martinez-Cob and Tejero-Juste, (2004) stated that the value of $u_2 = 2\,ms^{-1}$ which is the average value in more than 2000 locations around the globe can be used where the wind data is totally not available. For Ijebu-Ode and Itoikin, the default value of $2\,ms^{-1}$ was used as wind speed.

2.4 Hargreaves model

In a situation where solar radiation, wind speed, relative humidity and other data are completely absent, reference evapotranspiration can also be estimated using the equation stated by Hargreaves and Samani (1982) and is given as:

$$ET_0 = 0.0023 \times (T_{mean} + 17.8) \times (T_{\max} - T_{\min})^{0.5} \times R_a \qquad (21)$$

where,

ET_o = reference evapotranspiration (mmd^{-1}),

$T_{mean} = (T_{\max} + T_{\min})/2$, average air temperature,

$T_{\max}$, $T_{\min}$, R_a are as previously defined R_a for the three locations.

For the three locations, Hargreaves model was also used in computing their daily reference evapotranspiration using the Equation (21).

2.5 Jensen Haise Model

Under situation of limited data, Jensen-Haise model is used in computing reference evapotranspiration as reported by James, (1988) and is given as:

$$ET_0 = C_T(T_{mean} - T_x) \times R_s \qquad (22)$$

where

ET_o is the reference evapotranspiration (mmd^{-1});

T_x and C_T are constants expressed as

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

$$T_x = -2.5 - 0.14 \times (e^o(T_{\max}) - e^0(T_{\min})) - \frac{h}{500}$$

where,

h is the altitude of location and R_s, $e^o(T_{\max})$, $e^o(T_{\min})$ are as previously defined.

The Hargreaves model was also used in computing the daily reference evapotranspiration for the three locations.

2.8 Statistical Analysis

The three models described above were used in computing the daily reference evapotranspiration for their respective locations. Simple linear and polynomial regressions were used for all comparisons in order to determine the correlation of Jensen-Haise and Hargreaves models with FAO-56 PM model. Similarly, the ET_o computed with complete and limited climatic data using FAO-56PM for Abeokuta were also compared. The regression equation obtained can be used to compute the reference evapotranspiration when temperature is at the minimum that is, when there is no evapotranspiration as recommended by Jacovides and Kontoyiannis (1995). The Coefficients of determination R^2, Root Mean Square Error (RMSE), Analysis of Variance (ANOVA) at level of significance of $\alpha = 0.05$ and index of agreement (Alexandris and Kerkides, 2003; Cai et al., 2007) between the computed ET_o and pan evaporation were used in evaluating the performance of the models. The index of agreement and RMSE which is a measure of the total difference between the ET_o values computed using the FAO-56 PM, Hargreaves and Jensen-Haise models and are considered better indicator of model performance than the correlation statistics and was determined for Jensen-Haise and Hargreaves models in each year using the equation:

$$RMSE = \sqrt{\frac{1}{n}\sum\left(ET_{0_{FAO}} - ET_{0_{JHM/HGM}}\right)} \qquad (23)$$

where

RMSE is the root mean square (mmd^{-1});

n is the number of observations that is, months of the year;

Table 2 List of Equations and symbols used in determining ETo using FAO-56 PM Model

Eqn.	Expression	Quantity	Unit
2	$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26}$	Atmospheric pressure	KPa
3	$\gamma = \frac{c_p \times P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P$	Psychrometric constant	KPa°C^{-1}
4	$\Delta = \frac{4098\left[0.6108\exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$	Slope of the saturation vapour pressure curve	KPa°C^{-1}
5	$e_s = \frac{e^o(T_{\max}) + e^o(T_{\min})}{2}$	Mean of the saturation vapour pressure	KPa
6	$e^o(T) = 0.6108 \times 2.7183^{\left[\left(\frac{17.27T}{T+237.3}\right)\right]}$	Saturation vapour pressure at either maximum or minimum air temperatures.	KPa
7	$e_a = \frac{RH_{mean}}{100}\left[\frac{e^o(T_{T\max}) + e^o(T_{\min})}{2}\right]$	Actual vapour pressure	KPa
8	$e_s - e_a$	Vapour pressure deficit	KPa
9	$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\sin(\omega_s)]$	Ra is the extraterrestrial radiation	MJm^{-2}d^{-1}
10	$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right)$	Inverse relative distance Earth-Sun	Radian
11	$\delta = 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right)$	Solar declination	Radian
12	$\omega_s = \arccos[-\tan(\varphi)\tan(\delta)]$	Sun hour angle	Radian
13	$N = \frac{24}{\pi}\omega_s$	Possible daylight hour	hour
14	$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a$	Solar radiation	MJm^{-2} d^{-1}
15	$R_{so} = (0.75 + 2 \times 10^{-5}) R_a$	Clear sky solar radiation;	MJm^{-2} d^{-1}
16	$R_{ns} = (1 - \alpha) R_s$	Net shortwave radiation	MJm^{-2}d^{-1}
17	$R_{nl} = \sigma\left[\frac{T_{\max,}K^4 + T_{\min}K^4}{2}\right](0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$	Net outgoing longwave radiation	MJm^{-2}d^{-1}
18	$R_n = R_{ns} - R_{nl}$	Net radiation	MJm^{-2}d^{-1}
19	$u_2 = \frac{4.87}{\ln(67.8z - 5.42)} u_z$	Wind speed at height z(m)	ms^{-1}
20	$R_s = k_{rs}\sqrt{(T_{\max} - T_{\min})} R_a$	Solar radiation	MJm^{-2}d^{-1}

z is altitude, $T_{\max}$ and $T_{\min}$ are maximum and minimum air temperatures, T is mean air temperature, RH_{mean} is the mean of relative humidity, φ is latitude (rad), J is the day of year, σ is Stefan-Boltzmann constant (4.903 $\times$ 10^{-9} MJK^{-4}m^{-2}day^{-1}), α is albedo or canopy reflection coefficient (0.23), a_s and b_s are coefficients, u_z is the measurement height (m), k_{rs} is adjustment coefficient (0.16 to 0.19°C$^{-0.5}$).

$ET_{0_{FAO}}$ is the reference evapotranspiration computed using FAO 56 PM model (mmd^{-1});

$ET_{0_{JHM}}$ is the reference evapotranspiration computed using Jensen-Haise model;(mmd^{-1})

$ET_{0_{HGM}}$ is the reference evapotranspiration computed using Hargreaves model;

Similarly, the Willmott index of agreement between the computed ET_o using the three models and measured pan evaporation were determined and is expressed (Zhou and Zhou, 2009)as:

$$d = 1 - \frac{\sum_{i=1}^{n}(E_i - O_i)^2}{\sum_{i=1}^{n}\left[\left(\left|E_i - \overline{O}\right|\right) + \left(\left|O_i - \overline{O}\right|\right)\right]^2} \quad (24)$$

where,

E_i is computed ET_o using the three models (mmd^{-1});

O_i is observed pan evaporation (mmd^{-1});

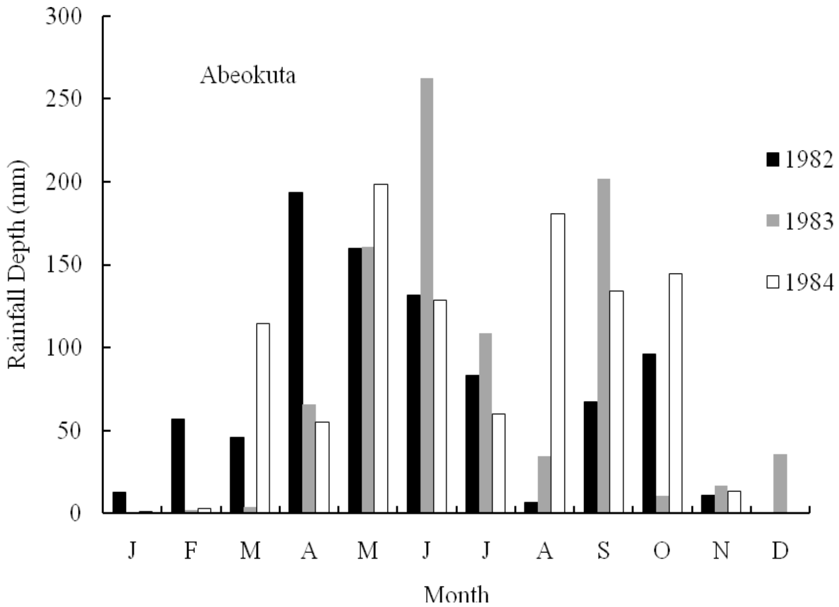
$\overline{O}$ is mean of the pan evaporation (mmd^{-1});

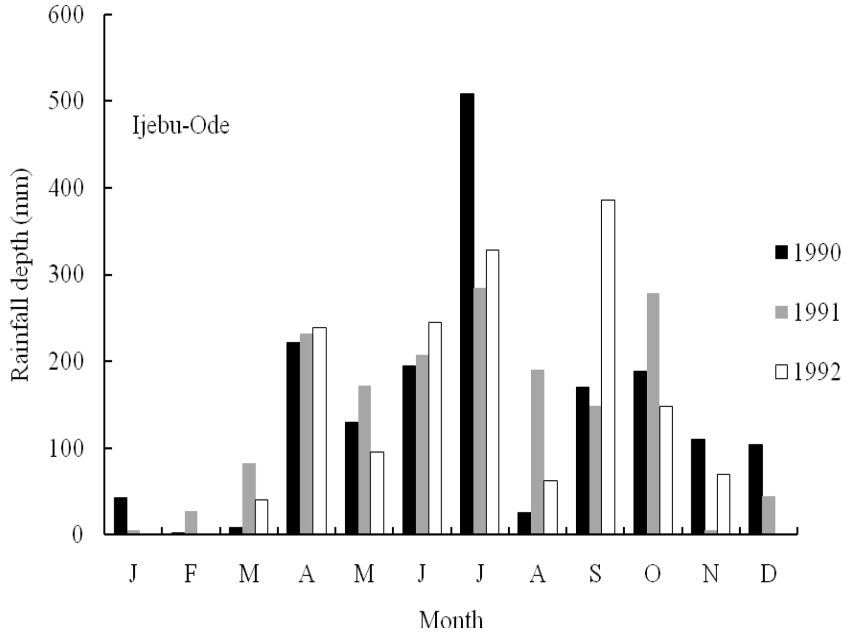
n is number of observations.

3. RESULTS AND DISCUSSION

3.1 Computation of ET_o Using Complete Meteorological Data

Figure 2 shows the rainfall distributions in Abeokuta, Ijebu-Ode and Itoikin stations respectively.





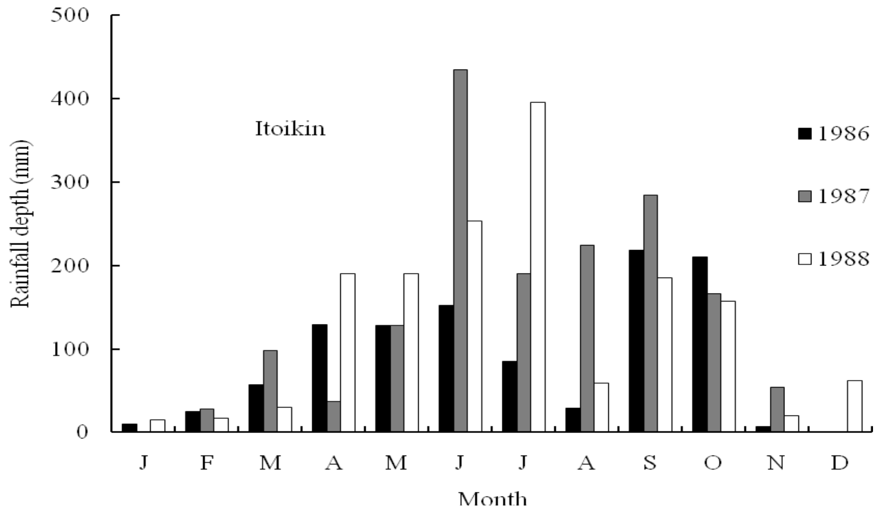


Figure 2 Rainfall patterns in Abeokuta, Ijebu-Ode and Itoikin respectively.

Figure 3 shows the ET_o computed for Abeokuta using the three models from 1982 to 1984 respectively. In 1982, the reference evapotranspiration computed using FAO-56 PM, Hargreaves and Jensen-Haise models were 4.16, 5.16 and 3.41 mm/day respectively in January when rainfall depth was 3.4mm (see Fig. 2). The ET_o computed in August using the FAO-56PM, Hargreaves and Jensen-Haise models were 2.27, 3.42 and 0.80 mmd^{-1} respectively when rainfall depth was 8mm (see Fig. 2). Similarly, the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models in December were 3.66, 4.79 and 2.55 mmd^{-1} respectively when there was no rainfall. The Hargreaves model overestimated the ET_o while Jensen-Haise model underestimated it when compared with those computed using the FAO-56 PM. The Root Mean Square Error (RMSE) of 1.41 and 0.98 mmd^{-1} were obtained (see Table 2) for Jensen-Haise and Hargreaves models respectively when compared with the FAO-56 PM. The coefficient of determination R^2 of 0.9430 and 0.8640 were

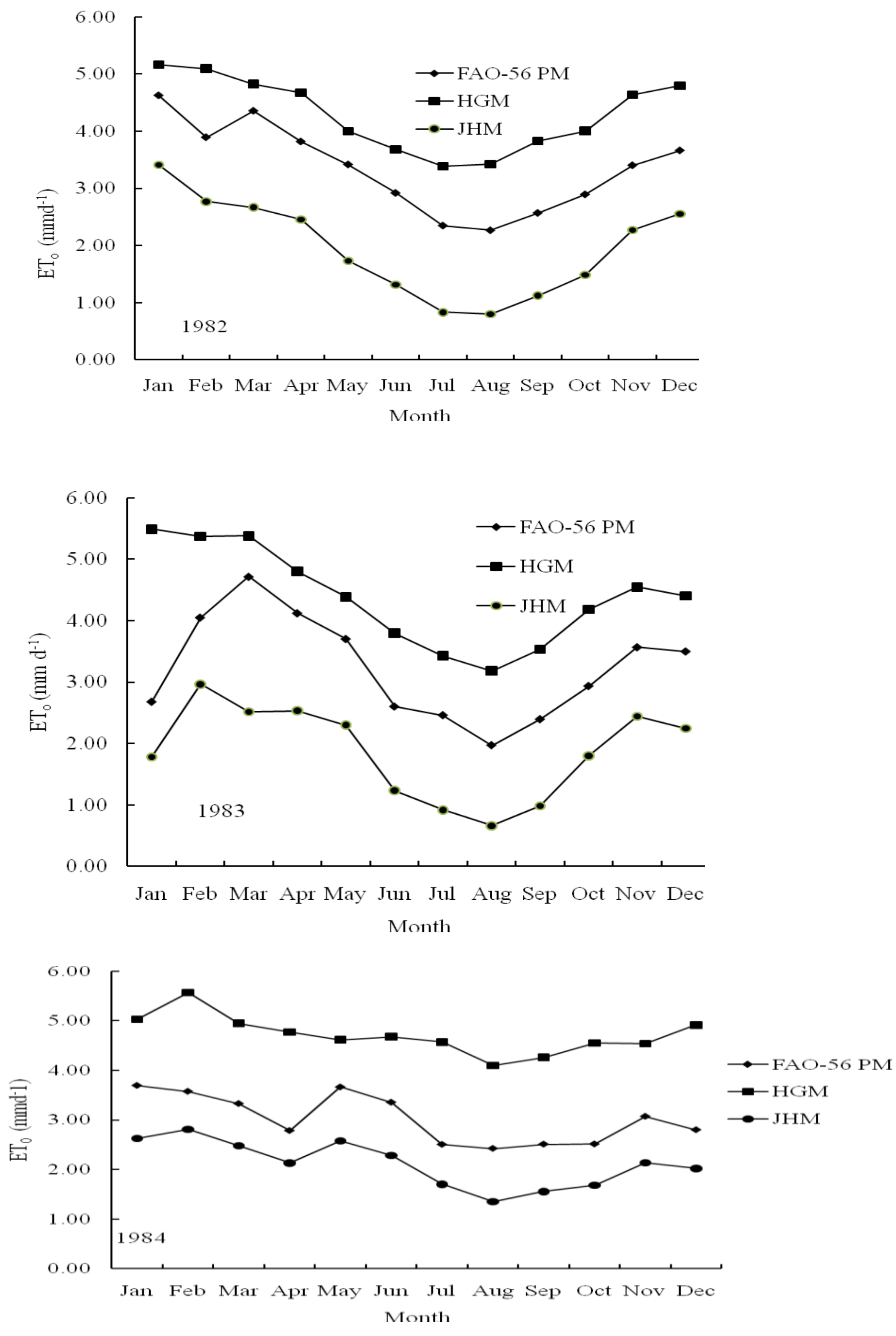


Figure 3-Computed reference evapotraspiration in Abeokuta using FAO-56 PM, Jensen-Haise and Hargreaves model in 1982, 1983 and 1984 respectively

obtained when ET_o computed using Jensen-Haise and Hargreaves models were plotted against those of FAO-56 PM model (See Table 3). The computed ET_o for each day of the months using the three models were significantly different at $P<0.05$ and this is similar to the result obtained in Tanzania (Igbadun et al, 2006). Figure 4 contains the correlation between the computed ET_o values and the pan evaporation measured at the Abeokuta station.

Coefficients of determination R^2 of 0.7982, 0.9025 and 0.9240 were obtained when for FAO-56 PM, Jensen-Haise and Hargreaves model respectively were plotted against the pan evaporation data (see Fig. 4) in 1982. Index of agreement between ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were 0.84, 0.78 and 0.67 respectively (Table 3). The R^2 between the ET_o computed using R_s and temperature were 0.8660 and 0.9653 for FAO-56 PM and Jense-Haise models respectively (see Table 3).

In 1983, the computed ET_o using FAO-56 PM, Hargreaves and Jensen-Haise Models in January were 2.68, 5.49 and 1.78 mmd^{-1} respectively when there was no rainfall. In August the ET_o computed using FAO-56 PM, Hargreaves and Jensen-Haise models were 1.96, 3.18 and 0.66 mmd^{-1} respectively (see Fig. 3) when the average monthly rainfall depth was 38.3 mm (See Fig. 2). In December, the ET_o computed were 3.50, 4.40 and 2.25 mmd^{-1} for FAO-56 PM, Hargreaves and Jensen-Haise models respectively with average monthly rainfall depth of 27.5mm. The coefficients of determination R^2 of 0.8451 and 0.5695 were obtained when ET_o obtained using Jensen-Haise and Hargreaves models respectively were plotted against those computed using FAO-56 PM model. The ET_o computed using the three models were significantly different at $p<0.05$ (see Table 3). The RMSE obtained between Jensen-Haise and Hargreaves models and FAO-56 PM model were 1.40 and 1.27 mmd^{-1} respectively. Coefficient of determination R^2 of 0.8674, 0.9117 and 0.8674 were obtained when ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models respectively were plotted against the measured pan evaporation (see Fig.4). The degree of agreement between ET_o computed using FAO-56 PM model, Jensen-Haise and Hargreaves models were 0.48, 0.52 and 0.33 respectively (See Table 3).

In 1984, the ET_o computed using FAO-56 PM, Hargreaves and Jensen-Haise models were 3.69, 5.03, 2.63 mmd^{-1} respectively in January (See Fig. 3). In August the ET_o were 2.42, 4.10 and 1.35 mmd^{-1} for FAO-56PM, Hargreaves and Jensen-Haise models respectively while in December, they were 2.80, 4.91and 2.02 mmd^{-1} for FAO PM, Hargreaves and Jensen-Haise models respectively. The coefficients of determination R^2 of 0.9112 and 0.4485 were obtained when the ET_o computed using Jensen-Haise and Hargreaves model were plotted against those obtained using FAO-56 PM model (see Table 3). The RMSE obtained were 1.73 and 0.91 mmd^{-1} for Jensen Haise and Hargreaves models respectively when compared with FAO-56 PM model. Coefficients of determination R^2 of 0.4485, 0.6149 and 0.8368 were obtained when the ET_o computed using the FAO-56PM, Jensen-Haise and Hargreaves models were compared with pan evaporation (See Fig. 4). The index of agreement between ET_o computed using FAO-56 PM model, Jensen-Haise, Hargreaves models and pan evaporation were 0.67, 0.99 and 0.55 respectively (See Table 3). The ET_o computed using the three models were significantly different at $p<0.05$.

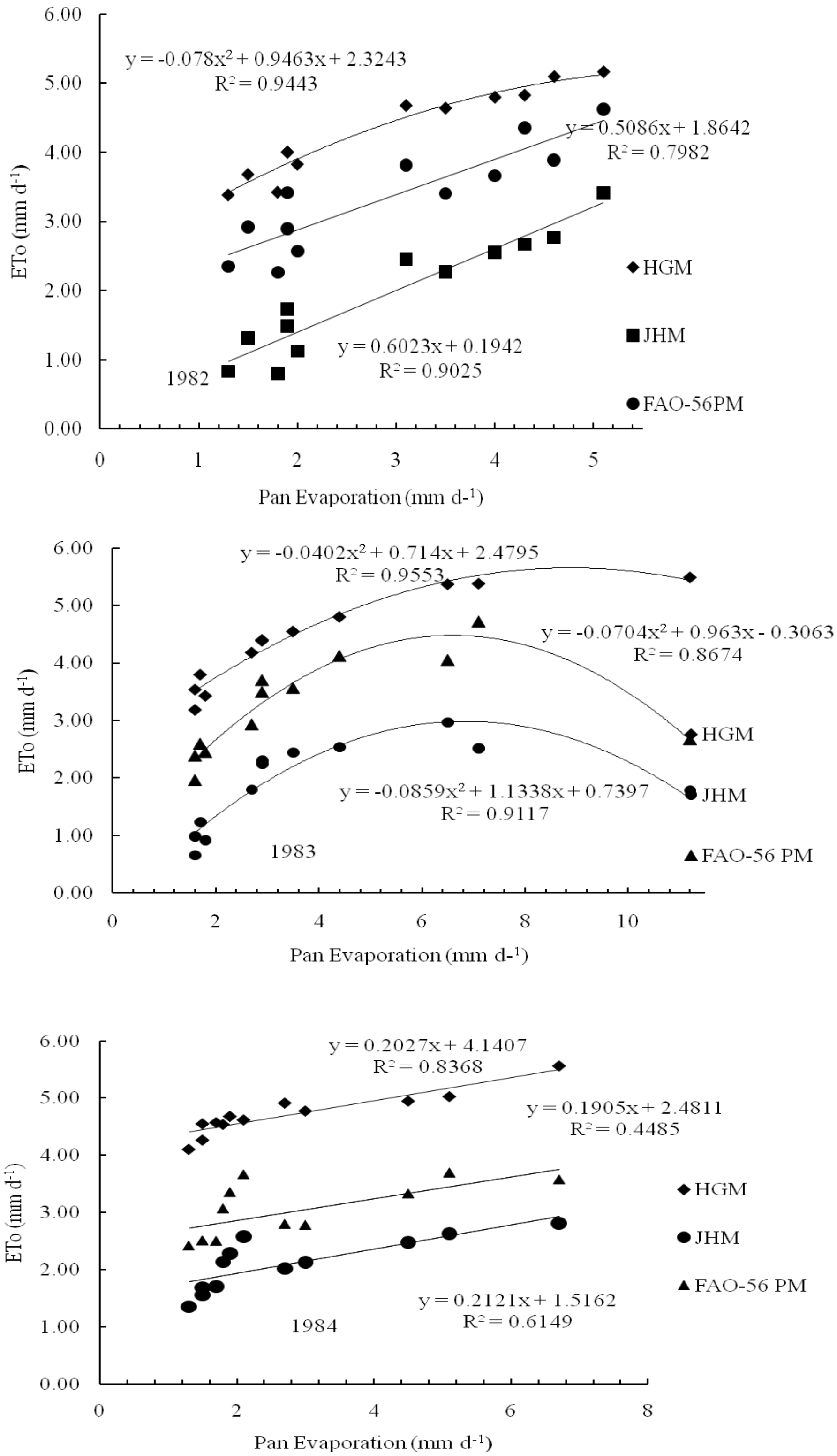


Figure 4 Correlation between FAO-56 PM, Jensen-Haise, Hargreaves and pan evaporation data in Abeokuta in 1982, 1983 and 1984 respectively.

3.2 Computation of ET_o Using Limited Meteorological Data

Limited meteorological data namely daily maximum and minimum air temperatures were used in computing the daily reference evapotranspiration using the three models for Ijebu-Ode and Itoikin. Figure 5 shows the ET_o computed using the three models in the years 1990, 1991 and 1992 respectively. The ET_o computed in 1990 for January using the FAO-56 PM, Jensen-Haise and Hargreaves models were 5.28, 2.72 and 4.37 mmd^{-1} respectively when the rainfall depth was 42.7mm (see Fig. 2). In July, the computed ET_o were 3.27, 0.97 and 3.05mm/day respectively when average monthly rainfall depth was 508.4mm. However in December, the ET_o computed using the three models were 4.90, 2.35 and 4.15 mmd^{-1} when average monthly rainfall depth was 103.6 mm (see Fig.2). The coefficient of determination

Table 3: Coefficients of determination R^2, Root Mean Square Error (RMSE) and degree of agreement between the ET_o computed using the three models and pan evaporation for Abeokuta.

Year	Coefficient of determination R^2		RMSE (mmd^{-1})		Index of agreement between ET_o Models and Pan Evaporation			R^2 between ET_o computed using R_s and Temp.	
	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM	JHM	HGM	FAO-56 PM	JHM
1982	0.9430	0.8640	1.41	0.98	0.84	0.78	0.67	0.8860	0.9653
1983	0.8451	0.5695	1.40	1.27	0.48	0.52	0.33	0.7100	0.7816
1984	0.9112	0.4485	1.73	0.91	0.67	0.99	0.55	0.5616	0.6859
1985	0.9095	0.7828	1.14	1.58	0.53	0.99	0.44	0.8009	0.8947
1986	0.4759	0.6955	1.98	0.40	0.48	0.72	0.70	0.7391	0.8569
1987	0.8876	0.8227	1.05	0.85	0.42	0.57	0.35	0.8625	0.9861
1988	0.7260	0.2364	0.56	2.35	0.68	0.74	0.40	0.5684	0.9034
1989	0.7250	0.3835	0.36	2.78	0.50	0.36	0.52	0.5465	0.8552
1990	0.7293	0.5860	0.44	2.64	0.52	0.76	0.50	0.5617	0.9124
1991	0.9549	0.7284	0.49	2.20	0.65	0.71	0.36	0.8953	0.9026
1992	0.8434	0.4664	0.47	2.73	0.61	0.76	0.52	0.7491	0.8428
1993	0.8555	0.2131	0.70	1.94	0.52	0.70	0.71	0.5074	0.6276
1994	0.6266	0.4500	2.58	1.42	0.61	0.86	0.85	0.7677	0.9566
1999	0.7963	0.6534	0.56	2.17	0.52	0.46	0.43	0.5795	0.6456
2000	0.6419	0.3811	0.60	2.61	0.39	0.75	0.51	0.4405	0.9149
Average	**0.7914**	**0.5521**	**1.03**	**1.79**	**0.56**	**0.71**	**0.52**	**0.6784**	**0.8488**

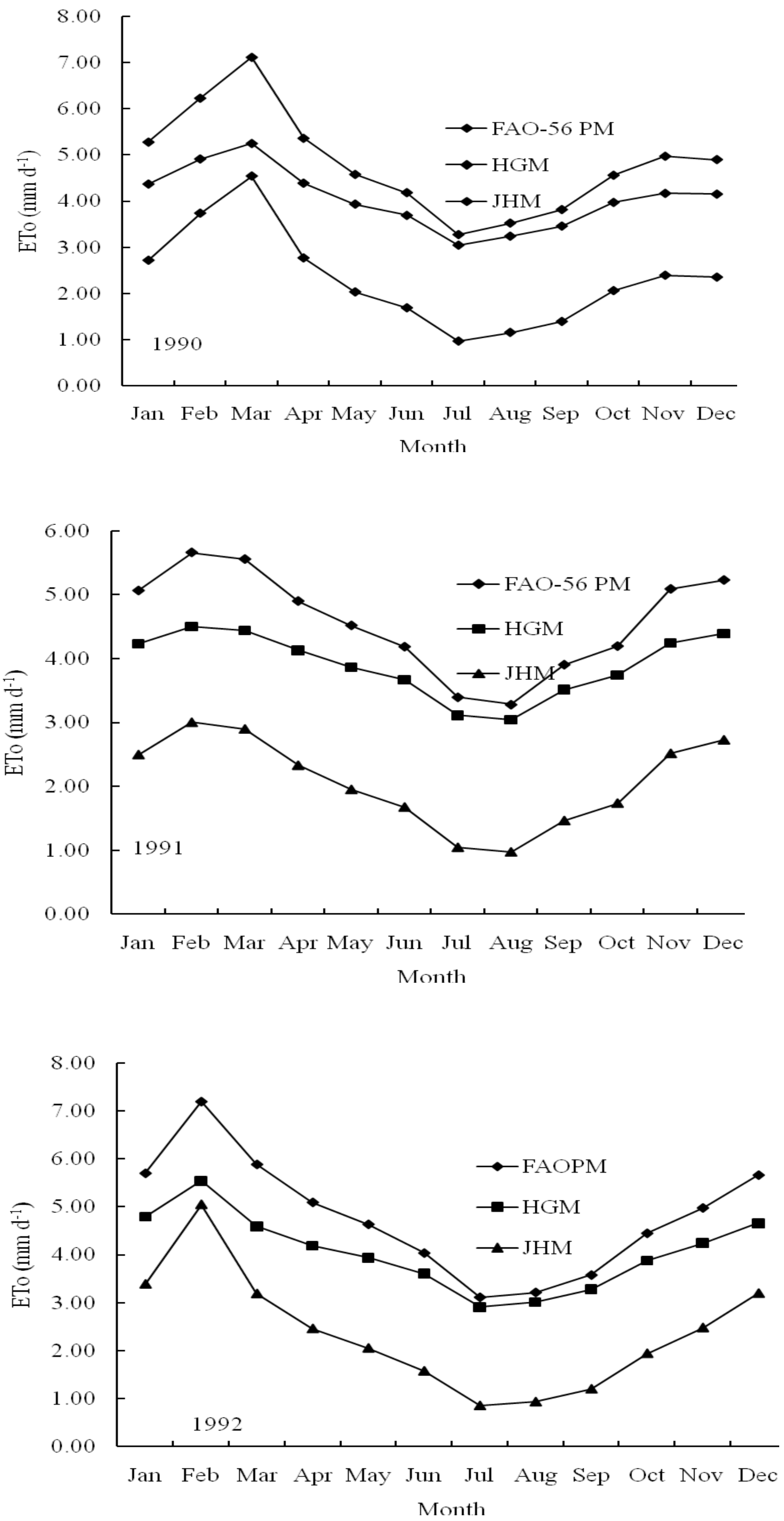


Figure 5 Computed reference evapotraspiration in Ijebu-Ode using the three models in 1990, 1991 and 1992 respectively

R^2 of 0.9964 and 0.9895 were obtained when ET_o computed using Jensen-Haise and Hargreaves models respectively were plotted against those computed using FAO-56 PM model (see Fig. 9). The RMSE obtained between Jensen-Haise and Hargreaves model when compared with FAO-56 PM model were 2.50 and 0.89 mmd^{-1} (see Table 4) respectively. FAO-56 PM, Jensen-Haise and Hargreaves models had index of agreement of 0.58, 0.97 and 0.62 respectively when compared with pan evaporation. Figure 6 shows the correlation between the measured pan evaporation and the ET_o computed using the three stated models. The R^2 obtained when ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were plotted against evaporation were 0.9041, 0.9240 and 0.8717 respectively.

In 1991, the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves model were 5.06, 2.50 and 4.24 mmd^{-1} respectively in January (see Fig. 6) with average monthly rainfall depth of 5mm (see Fig.2). In August, the ET_o computed using FAO-56PM, Jensen-Haise and Hargreaves models were 3.28, 0.97 and 3.04 mmd^{-1} respectively with an average monthly rainfall of 190.3mm (see Fig. 2). However, in December, the ET_o computed using the FAO-56 PM, Jensen-Haise and Hargreaves models were 5.23, 2.73 and 4.39 mmd^{-1} respectively (see Fig.5) when the average monthly rainfall depth was 44.2mm (see Fig.2). The coefficient of determination R^2 obtained when ET_o computed using the FAO-56 PM, and Jensen-Haise and Hargreaves models were compared were 0.9966 and 0.9885 (see Table 4). The R^2 obtained when FAO-56 PM, Jensen-Haise and Hargreaves models were plotted against pan evaporation were 0.8701, 0.8842 and 0.8445 respectively (See Fig. 6). The RMSE between FAO-56 PM, Jensen-Haise and Hargreaves models were 2.52 and 0.73 mmd^{-1} respectively (See Table 4).The computed index of agreement between pan evaporation and ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were of 0.40, 0.96 and 0.37respectively.

Similarly in 1992, the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were 5.70, 3.39 and 4.79 mmd^{-1} (see Fig. 6) respectively when there was no rainfall (see Fig. 2). In July FAO-56 PM model had the highest ET_o of 3.11 mmd^{-1} while the computed ET_o for Jensen-Haise and Hargreaves models were 0.85 and 2.91 mmd^{-1} respectively with an average monthly rainfall of 327.7mm (see Fig. 2). In December, the computed ET_o for FAO-56 PM rose to 5.66mmd^{-1} while 3.19 and 4.65 mmd^{-1} respectively were computed for Jensen-Haise and Hargreaves models with no monthly rainfall. The R^2 obtained when the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves model were plotted against pan evaporation were 0.7474, 0.7870 and 0.7718 respectively. The R^2 values for other years under investigation are shown in Table 4. The ET_o computed using each model were significantly different ($p<0.05$). The index of agreement between FAO-56 PM, Jensen-Haise and Hargreaves models and pan evaporation were 0.610, 0.9233 and 0.66 respectively.

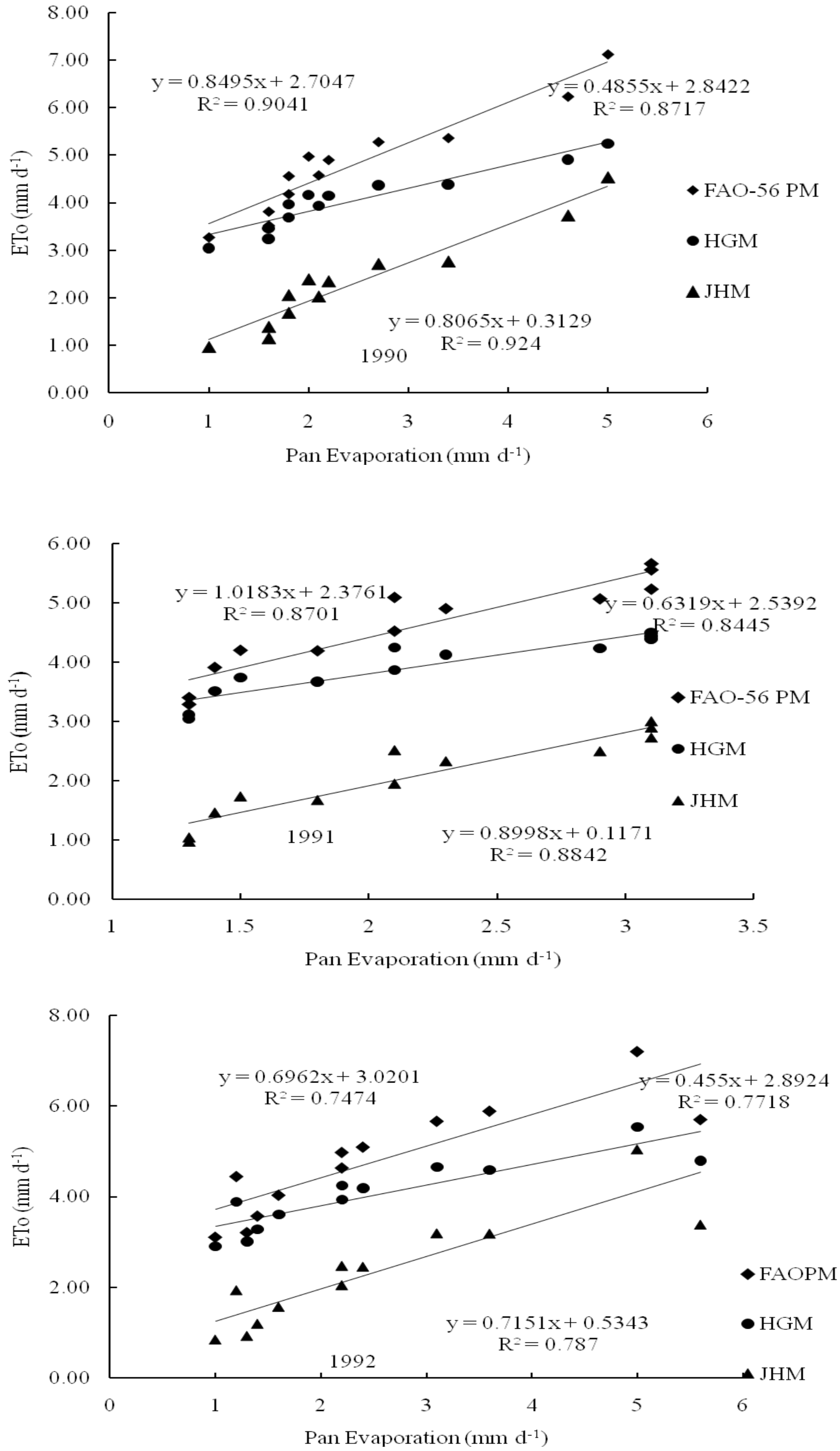


Figure 6-Correlation between ET_o computed using FAO-56 Penman-Monteith model and Jensen-Haise and Hargreaves models for Ijebu-Ode in 1990, 1991 and 1992.

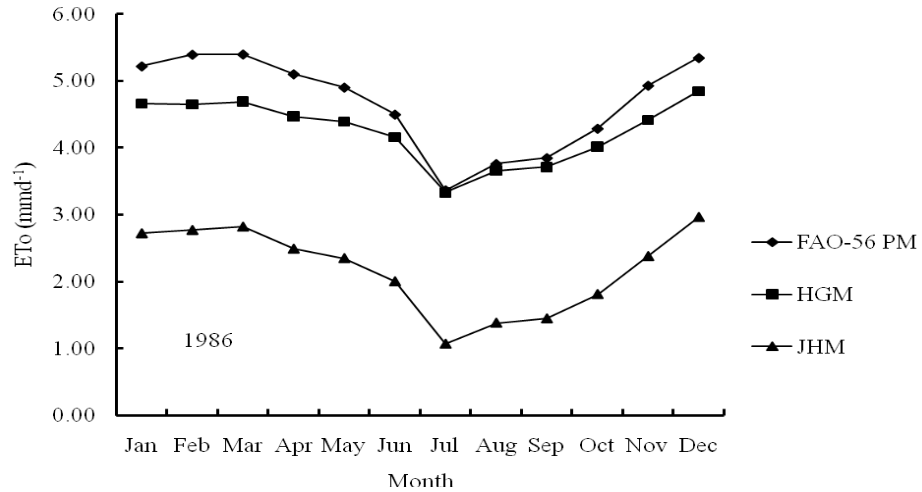
Table 4-Coefficients of determination R^2, Root Mean Square Error (RMSE) and level of degree of agreement between ET_o models and pan evaporation for Ijebu-Ode

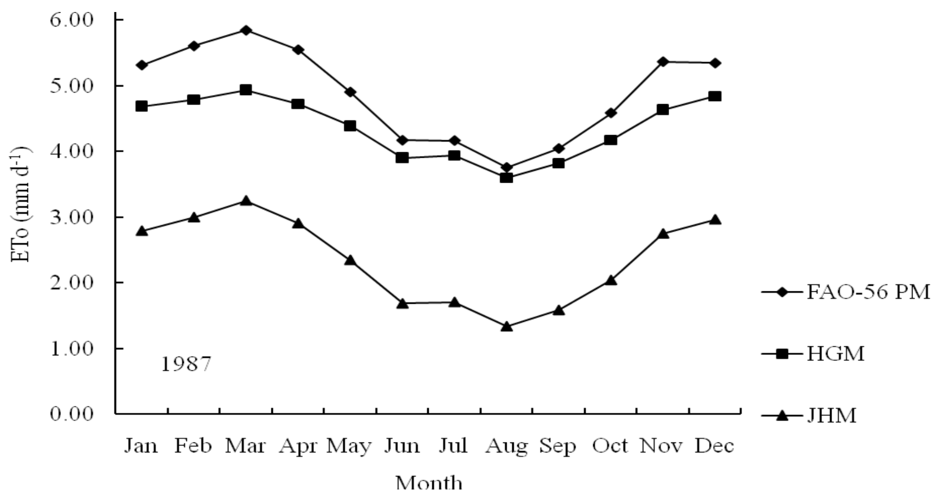
Year	**Coefficient of Determination R^2**		**RMSE (mmd^{-1})**		**Index of agreement between ET_o Models and Pan Evaporation**		
	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM	JHM	HGM
1990	0.9970	0.9895	2.45	0.52	0.64	0.89	0.62
1991	0.9966	0.9885	2.44	0.36	0.45	0.96	0.37
1992	0.9841	0.9887	2.40	0.49	0.66	0.85	0.66
1993	0.9813	0.9925	2.38	0.45	0.62	0.76	0.62
1994	0.9925	0.9927	2.45	0.45	0.45	0.88	0.48
1995	0.9939	0.9932	2.46	0.50	0.55	0.99	0.57
1996	0.9978	0.9972	2.45	0.38	0.42	0.98	0.44
1997	0.9923	0.9967	2.45	0.46	0.64	0.93	0.61
1998	0.9941	0.9810	2.53	0.70	0.64	0.98	0.66
1999	0.9970	0.9920	2.48	0.44	0.39	0.95	0.40
2000	0.9936	0.9934	2.51	0.62	0.68	0.88	0.66
2001	0.9960	0.9947	2.49	0.94	0.60	0.89	0.59
2002	0.9914	0.9877	2.48	0.54	0.41	0.95	0.44
2003	0.9965	0.9897	2.47	0.49	0.44	0.41	0.49
2004	0.9980	0.9912	2.50	0.55	0.52	0.65	0.53
2005	0.9870	0.9916	2.48	0.38	0.42	0.88	0.44
Average	**0.9931**	**0.9913**	**2.46**	**0.52**	**0.53**	**0.86**	**0.54**

Limited meteorological data namely the daily maximum and minimum air temperature were also used in computing ET_o for Itoikin. Figure 7 shows the ET_o computed for Itoikin using the three models. In 1986, the computed ET_o using FAO-56 PM, Jensen-Haise and Hargreaves models were 5.22, 2.72 and 4.66 mmd^{-1} respectively in January when there the average monthly rainfall depth was 9.9mm. In August the ET_o were 3.76, 1.38 and 3.66 mmd^{-1} using FAO-56 PM, Jensen-Haise and Hargreaves models respectively when the average monthly rainfall was 29.3mm. However in December, when there was no rainfall, the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were 5.35, 2.96 and 4.84 mmd^{-1}. Using FAO-56 PM, Jensen-Haise and Hargreaves models, R^2 of 0.7829, 0.8091 and 0.7651 respectively were obtained when ET_o computed were plotted against pan evaporation (see Fig 8). Table 5 contains the R^2, RMSE and significance of the Jensen-Haise and Hargreaves models when compared with the FAO-56 PM model using limited data. The index of agreement between pan evaporation and FAO-56 PM, Jensen-Haise and Hargreaves models were 0.34, 0.93 and 0.37 respectively.

In 1987, the ET_o computed in January using FAO-56PM, Jensen-Haise and Hargreaves models were 5.32, 2.79 and 4.69 mmd^{-1} in January when there was no rainfall (see Fig.2). In August, the ET_o using FAO-56 PM, Jensen-Haise and Hargreaves model were 3.75, 1.34 and 3.60 mmd^{-1} when the rainfall depth was 244.2mm. In December however, when there was no rainfall, the ET_o computed using FAO-56PM, Jensen-Haise and Hargreaves models were

5.35, 2.96 and 4.84mmd^{-1} respectively. Coefficient of determination R^2 of 0.9074, 0.9282 and 0.9248 were obtained when ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models respectively were plotted against pan evaporation (see Fig. 8). The index of agreement between pan evaporation and FAO-56 PM, Jensen-Haise and Hargreaves models were 0.37, 0.95 and 0.41 respectively. Both Hargreaves and Jensen-Haise models underestimated the ET_o when compared with FAO-56 PM model. Similarly, in 1988, the ET_o in January using FAO-56 PM, Jensen-Haise and Hargreaves models were 5.53, 3.07 and 4.88 mmd^{-1} respectively when the average monthly rainfall was 14.7mm (see Fig.2). In August, the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were 3.86, 1.46 and 3.73 mmd^{-1} respectively when the average monthly rainfall was 59.5mm (see Fig 2). However, the ET_o computed in December were 5.07, 3.66 and 5.01 mmd^{-1} using the FAO-56 PM, Jensen-Haise and Hargreaves model respectively with average monthly rainfall depth of 62.2 mm. Coefficient of determination R^2 of 0.5716, 0.5149 and 0.5033 were obtained when the ET_o computed using FAO-56 PM, Jensen-Haise and Hargreaves models were plotted against pan evaporation (see Fig.8). The pan evaporation, FAO-56 PM, Jensen-Haise and Hargreaves models had degree of agreement of 0.33, 0.82 and 0.36 respectively.





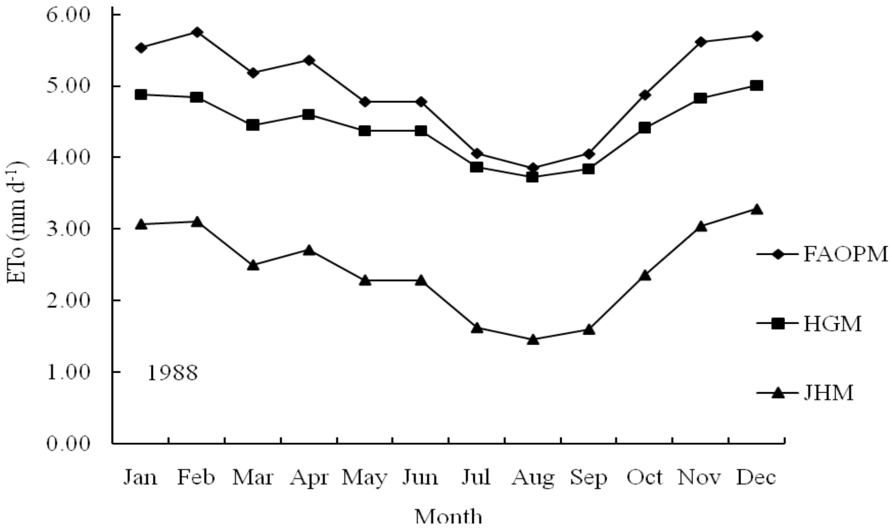
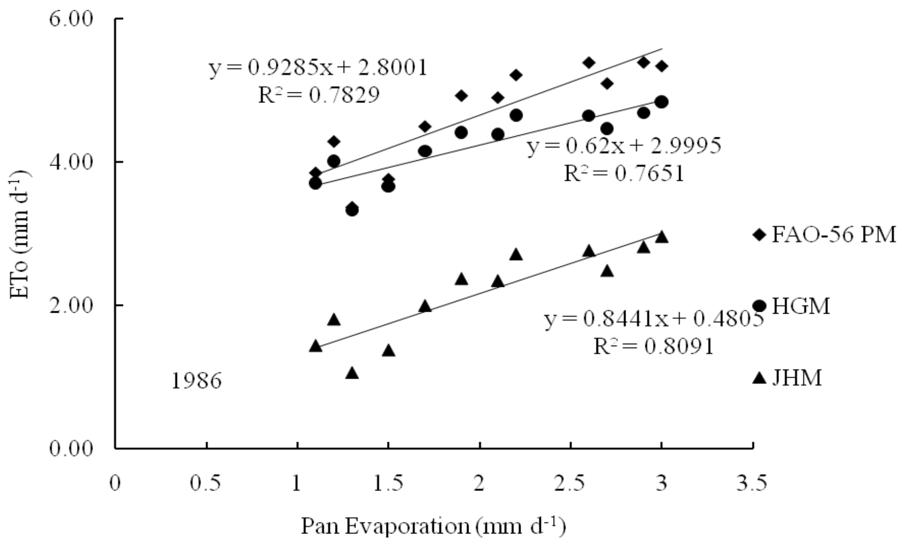
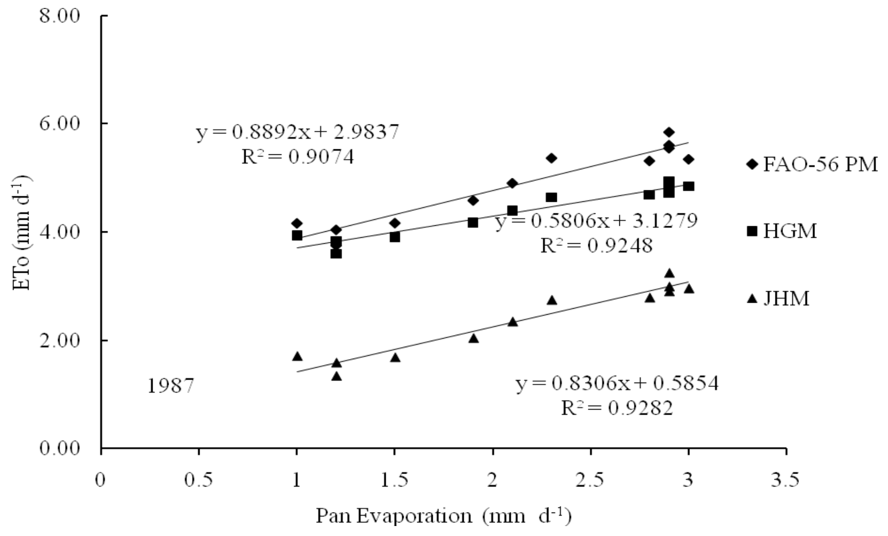


Figure 7- ET_o computed using FAO 56 Penman-Monteith model and Jensen-Haise and Hargreaves models in 1984, 1985 and 1986 respectively for Itoikin.





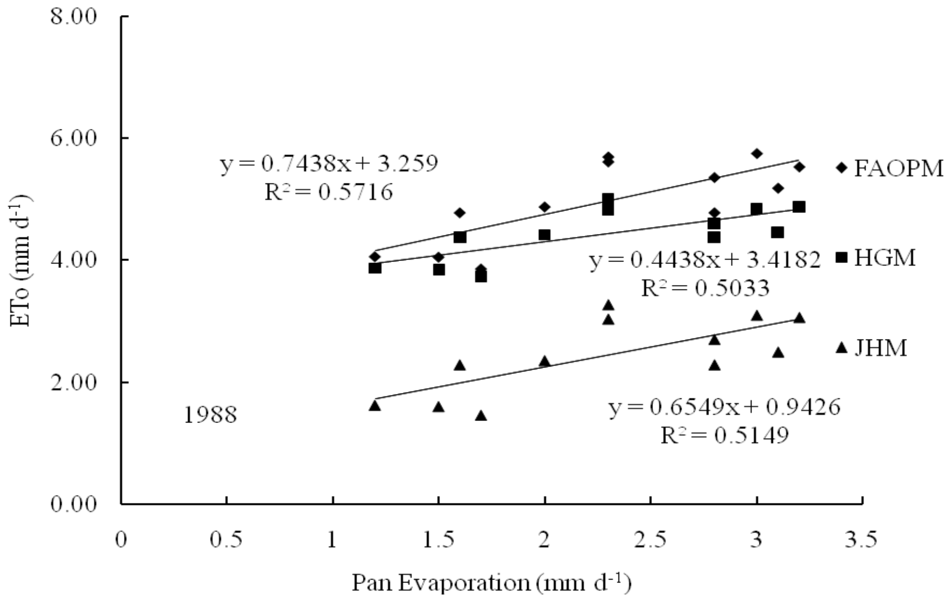


Figure 8-Correlation between ET_o computed using FAO-56 Penman-Monteith model and Jensen-Haise and Hargreaves models for Itoikin in 1986, 1987 and 1988 respectively.

Table 5: Coefficients of determination R^2, Root Mean Square Error (RMSE) and level of Significance of the three models for Itoikin

Year	**Coefficient of Determination R^2**		**RMSE (mmd^{-1})**		**Index agreement between ET_o Models and Pan Evaporation**		
	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM and JHM	FAO-56 PM and HGM	FAO-56 PM	JHM	HGM
1984	0.8790	0.7862	2.47	0.55	0.34	0.56	0.35
1985	0.9874	0.9908	2.52	0.43	0.39	0.65	0.42
1986	0.9884	0.9841	2.53	0.48	0.34	0.93	0.37
1987	0.9907	0.9799	2.53	0.58	0.37	0.95	0.41
1988	0.9832	0.9723	2.52	0.59	0.33	0.82	0.36
1989	0.9602	0.9510	2.47	0.59	0.35	0.88	0.40
1990	0.9885	0.9884	2.50	0.49	0.29	0.63	0.32
1991	0.9897	0.9852	2.52	0.49	0.29	0.87	0.32
1992	0.9952	0.9917	2.51	0.68	0.29	0.73	0.32
1993	0.9671	0.9183	2.47	0.73	0.34	0.56	0.38
1994	0.9654	0.9557	2.47	0.58	0.26	0.25	0.31
1995	0.9943	0.9794	2.55	0.90	0.24	0.58	0.29
1997	0.9865	0.9684	2.50	0.72	0.38	0.74	0.41
1998	0.9760	0.9403	2.50	0.50	0.25	0.44	0.37
1999	0.9929	0.9811	2.43	0.73	0.15	0.42	0.18
2001	0.9680	0.9064	2.51	0.63	0.17	0.24	0.19
Average	**0.9758**	**0.9550**	**2.50**	**0.60**	**0.30**	**0.64**	**0.34**

Although Jensen-Haise model had higher R^2 when plotted against FAO-56 PM model, the RMSE between the FAO-56 PM model was considerably lower than those of FAO-56 PM and Jensen-Haise models. The ET_o computed were significantly different having ($p<0.05$) in the years under investigation.

4. Conclusion

Meteorological data of three stations Abeokuta, Ijebu-Ode and Itoikin obtained from Nigerian Meteorological Station (NIMET) were analysed using three models namely, FAO-56 PM, Jensen-Haise and Hargreaves models. The ET_o computed using Jensen-Haise and Hargreaves models were compared with those computed using FAO-56 PM model in order to determine their performance under situations of complete and limited data. Also the ET_o computed using the three models were compared with the pan evaporation data obtained from each location. When complete data were used in the computation, Hargreaves model overestimated ET_o while Jensen-Haise model underestimated. However, under limited data set, both Jensen-Haise and Hargreaves model underestimated ET_o. Jensen-Haise and Hargreaves models underestimated ET_o under limited data input for Ijebu-Ode when compared with those computed using FAO-56 PM model and this compares favourably with similar analysis done in Tunisia (Jabloun and Sahli, 2008). In the absence of solar radiation data, the procedures for estimating R_s from monthly maximum and minimum temperatures produced accurate estimates of ET_o in the three stations over the stated years. Similarly, the computation of e_a using the procedures outlined in Allen et al., 1998 that is, when $T_w \approx T_{dew}$ is a good alternative when relative humidity is doubtful of completely absent.

Good correlations were observed when Jensen-Haise and Hargreaves models were compared with FAO-56 PM models for Abeokuta. The average R^2 values between FAO-56PM and Jensen-Haise and Hargreaves models were 0.7914 and 0.55218 respectively. The lowest average RMSE of 1.03mmd^{-1} was obtained between FAO-56 PM and Jensen-Haise models. Similarly, the highest index of agreement of 0.71 was obtained when the ET_o computed using Jensen-Haise model were compared the pan evaporation data. The average R^2 obtained for ET_o computed using complete and limited data for FAO-56 PM and Jensen-Haise models were 0.6784 and 0.8488 respectively. In the absence of data on solar radiation, the alternative means of using minimum and maximum air temperatures in computing ET_o yielded very good result as observed in the average R^2 values of 0.9931 and 0.9913 when Jensen-Haise and Hargreaves models were compared with FAO-56 PM models respectively for for Ijebu-Ode with k_{rs} of 0.16. Jensen-Haise model had the highest average index of agreement of 0.88 but for Hargreaves model it was 0.87. For Itoikin, the average R^2 obtained for Jensen-Haise and Hargreaves models when compared with FAO-56 PM model were 0.9758 and 0.9550 respectively with k_{rs} of 0.17. The highest index of agreement of 0.64 was obtained between ET_o computed using Jensen-Haise model and pan evaporation while RMSE of 0.60 was obtained between FAO-56 PM and Hargreaves model. It is evident that the climatic data fitted well into the models and the computed ET_o using the three models compared favourably with the pan evaporation data at each station. The ET_o computed with complete and limited data set compared well. It is hereby recommended that in the absence of complete climatic data, ET_o should be computed using temperature data in Ogun-Osun basin. Similarly k_{rs} of 0.16 and 0.17 are hereby recommended for Ijebu-ode and Itoikin stations respectively. Automatic weather recording equipment should be installed in the meteorological stations in order to enhance data acquisition. However, similar analysis should be carried out using climatic data from other parts of Nigeria in order to validate the performances of the models.

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