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Original Research Article

Seasonal Calibration of the Hargreaves Equation for Estimating Monthly Reference Evapotranspiration in a Data Sparse Region

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Abstract

Understanding and application of evapotranspiration is a prerequisite to the development and management of water resources, irrigation design, irrigation scheduling, agriculture, and agricultural crop productivity. Many macro-ecological and micro-meteorological analyses are based on the analyses of climatological data within which evapotranspiration estimates are of central importance. In this work, we present the results of the calibrated Hargreaves for the monthly reference evapotranspiration in a data sparse region and compared it with the original Hargreaves equation for the same site of study, and the FAO – 56PM. The results of the FAO – 56PM, and the Hargreaves and Hargreaves calibrated were; 5.19mm/d, 5.52mm/d and 4.25mm/d respectively. Summary statistics for analyses of mean monthly reference evapotranspiration estimated by the Hargreaves and Hargreaves calibrated against that estimated by the standard FAO – 56PM were; y = -0.0884x + 5.0739, y = -0.0788x + 4.0026 twice, and 4.0117, y = -0.0845x + 3.3977. Simple methods for estimating reference evapotranspiration requiring only temperature and day length of the year data are compared by reference to the result from the FAO – 56PM method. The calibrated equation is the Hargreaves that is tested for its degree of approximation of the Penman – Montieth method at the site of study for the period of 2000 – 2003. The calibrated value of 0.00188 correlated well with the accepted value of Eto in a humid – coastal region like Port Harcourt.

Keywords: Evapotranspiration, climate, Nigeria, Hargreaves, Penman – Montieth, humid region.

INTRODUCTION

Evapotranspiration Eto (potential or reference) is the amount of water taken up by a large surface vegetated by grass with a height between 8 and 15cm at an active growth, covering completely the soil surface and with no restriction of soil water supply. Evapotranspiration is limited only by the vertical energy balance, that is, by the conditions of local ambient. It is usually estimated by the empirical formulae developed and tested for several climatic conditions. Eto under this condition is termed *reference* if the goal is to determine the evapotranspiration of a crop that is under non – standard conditions (Andrè and Luiz, 2011). Evapotranspiration is recognized as a complex (and a component) of the hydrologic cycle (Dauda and Baiyeri, 2011). Thus, Eto is an indicative value of the atmospheric demand of a given site throughout a period of time (Andrè and Luiz, 2011).

Evapotranspiration is a complex quantity to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration (Okoro et al, 2008). However, solar radiation (and temperature) are an important input to many empirical equations that have been developed to estimated ET, obtaining accurate estimates of solar radiation is an important step in modeling the overall hydrological process of a given region (Okoro and Chineke, 2007). Many of these empirical models have been proposed in literature. Direct measurement of evapotranspiration requires special equipment and training (Chineke et al, 2008) and employsthe expertise of a professional. These measurements are generally time consuming, having several limitations and too expensive for a wide scale use (Chineke et al, 2008). These models developed ranges from simple to complex ones. Penman (1963 and 1965) introduced resistance terms into the well – known method of Penman (1948) and derived an equation for estimating evapotranspiration from surfaces with optimal or limited water supply (Okoro et al, 2008). This is referred to as Penman – Montieth model. This model has both the radiation term and the aerodynamic term (or advection term), and it has been adjudged as the most accurate method for estimating evapotranspiration virtually in every climate (arid and humid regions) (Chineke et al, 2008; Okoro et al., 2008). The Penman – Montieth equation model as recommended by the Food and Agricultural Organizationof the United Nations hereby referred to as FAO – 56PM is recommended when air temperature, relative humidity, wind speed and solar radiation data are available or can easily / readily be estimated. It can also be adjusted to the physical parameters of local weather station (Chineke et al., 2008). The FAO – 56PM is bulky and makes it difficult for use in a data sparse region. This led to the development of simple ET models like the Hargreaves and Samani, (1985),and Hargreaves,(2003). This simplest models / methods generally use the air temperature. (Chineke et al, 2008; Xu and Singh, 2000; Dauda and Baiyeri, 2011; Fotios and Andreas, 2001).However, many ET model approaches are between these extremes (Jensen et al., 1990). Determining Eto is an important tool in irrigation design, irrigation scheduling, water resources management, and hydrology and cropping systems modeling (Chineke et al, 2008). Thus, the objective of the work is to calibrate the Hargreaves equation for the estimation of monthly reference evapotranspiration in a data sparse region like Nigeria. The Hargreaves was calibrated using the estimated FAO – 56PM Eto model, and tested for its degree of approximating the Penman method at the study site of Port Harcourt Nigeria for the period of 2000 – 2003.

MATERIALS AND METHODS

The study area is located in the humid temperate region of the Southern Nigeria at 4.75^0N and 7.01^0E. The city lies within the mangrove coastal forest area of Nigeria. The data for the period of study was obtained from the branch of the Nigerian Meteorological Agency office based in Port Harcourt covering the period for 2000 to 2003 (4 years). The meteorological data collected are the maximum and minimum air temperatures (^{0}C), wind speed (m/s), maximum and minimum relative humidity (%) and rainfall. The average rainfall for the city is about 229.34mm per annum. The highest frequency of rainfall occurs within the middle of the year with onset rainfall in March and cessation in October the same year. Maximum rainfall occurs between June and September. The months of December to February the succeeding year is characterized by little or no rain. It is mostly the period of dry season and sometimes dominated by the Easterly dry wind from the Sahara desert. This period is occasioned by hammartan and occurs within dry season of the year succeeding the fiscal year (December to February).

Although, the FAO – 56PM requires a lot of meteorological parameters as input data for its estimation which is not available in many regions and climate, and meteorological stations. In this work, we used the mean temperature (^{0}C), wind speed (m/s) and relative humidity (%) data as our input parameters, the rest of the other meteorological and climate variables were estimated and applied.

ET Reference Methods

The universally accepted ET method as proposed by the Food and Agricultural Organisation (FAO) of the United Nations is the Penman – Montieth method. It is the standard to estimate, calibrate and evaluate the reference ET visually in every climate. This method has been applied by many researches (Gavilan et al, 2006; Rahimikhoob, 2008b; Fooladmand and Haghighat, 2007; NooriMohammadieh et al., 2009; Sabziparvar and Tabari, 2010; Chineke et al., 2008; Houshang et al, 2012) and the equation can be rewritten after Allen et al., (1998) as;

$$ET_{o,PM} = \frac{0.408\Delta(R_n - G) + \gamma \frac{37}{T+273} U_2\{e_s - e_a\}}{\Delta + \gamma\,[1 + 0.34U_2]} \quad \ldots\ldots\ldots\ldots\ldots 1$$

Where ETo is the reference evapotranspiration (mm/d);
Rn is the net radiation value at the crop surface (MJ/m^2/d);
G is the soil heat flux density (MJ/m^2/d);
T is the mean daily air temperature at a height of 2m (^{0}C);
U_2 is the wind speed at a height of 2m (m/s);
$e_s$is the saturation vapour pressure (KPa);
e_a is the actual vapour pressure (KPa);

$(e_s - e_a)$ is the pressure deficit (KPa);
Δ is the slope of the saturation vapour pressure – temperature curve (KPa/^{0}C);
γ is the Psichrometric constant (KPa/^{0}C).

The wind speed at 2m height was calculated using equation proposed by Allen et al, (1998) and referenced in Houshang et al., (2012) as;

$$U_2 = \frac{4.87u_z}{\ln(67.8 - 5.42)} \quad \ldots\ldots\ldots\ldots\ldots .2$$

Where U_2 is the average 24 – hour wind speed measured at a height of 2m and U_z is an average of 24 – hour wind speed measured at Z – height (m).
The solar radiation (Rs) was calculated using the Hargreaves method as;

$$Rs = K_{rs}(T_{max} - T_{min})^{0.5}Ra \quad \ldots\ldots\ldots\ldots\ldots\ldots .3$$

Where K_{RS} = 0.16 for humid region and 0.19 for coastal region.
Ra is the extraterrestrial radiation (MJ/m2/d);

Tmax, Tmin are the maximum and minimum air temperature (^{0}C) respectively;

The net long wave radiation was computed after ASCE, (2005) and Allen et al, (1998) as;

$$R_{nl} = \sigma\left[\frac{(T_{max} + 273)^4 - (T_{min} + 273)^4}{2}\right](0.34 - 0.14\sqrt{e_a})f_{cd} \quad \ldots\ldots 4$$

Where σ is the Stefan – Boltzman constant (4.903x10^{-9}MJ/m^2/d)
f_{cd} is the cloud function to account for impact of cloud temperature on R_{nl}

$$f_{cd} = a\frac{R_s}{R_{so}} + b \quad \ldots\ldots\ldots\ldots\ldots\ldots .4b$$

Where a = 1.35 and b = -0.35
The relation for clear sky solar radiation and net solar radiation used was proposed by Allen et al, (1998);

$$R_{so} = (0.75 + 2x10^{-5}z)Ra \quad \ldots\ldots\ldots\ldots\ldots\ldots .5$$
$$R_{ns} = (1 - \alpha)R_s \quad \ldots\ldots\ldots\ldots\ldots\ldots .6$$

Thus, net radiation is given as Allen et al, (1998);

$$R_n = R_{ns} - R_{nl} \quad \ldots\ldots\ldots\ldots\ldots\ldots .7$$

The Hargreaves ET model equation is written after Hargreaves and Samani, (1985) as;

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}Ra \quad \ldots\ldots\ldots\ldots\ldots 8$$

Where T_{mean}, T_{max} and T_{min} are the mean, maximum and minimum air temperatures (^{0}C) respectively. Ra is the extraterrestrial radiation (MJ/m^2/d).

Calibration

To calibrate the Hargreaves ET model equation using the monthly data, the Penman – Montieth method was applied as follows after Houshang et al, (2012);

$$ET_{o-pm} = \lambda x ET_{o-Har} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 9$$

Where λ is the slope of the correlation of the ET by Hargreaves and Penman. Thus, the Hargreaves equation model for the city and for each month of the year was corrected after Houshang et al, (2012) as;

$$C = \lambda x 0.0023 \quad \ldots\ldots\ldots\ldots\ldots\ldots .10$$

Statistical Analysis

The estimated ETos of the Hargreaves (HG) and Penman (PM) models were compared using simple statistical analysis method. They include; root mean square error (RMSE), mean bias error (MBE), mean percentage error (MPE) and the ratio (R) of the average estimations HG to PM (Houshang et al, 2012; Augustine and Nnabuchi, 2010).

I. $$RMSE = \left[\frac{\sum_{i=1}^{n}(X_{HG} - X_{PM})^2}{n}\right]^{1/2} \quad \ldots\ldots\ldots\ldots\ldots .11$$

II. $$MBE = \left[\frac{\sum_{i=1}^{n}(X_{HG} - X_{PM})}{n}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots 12$$

III. $$MPE = \left[\frac{\sum\left(\frac{X_{HG} - X_{PM}}{X_{HG}} X \frac{100}{1}\right)}{n}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .13$$

Where X_{HG}, X_{PM} and n are the evaporation values estimated by the Hargreaves and Penman – Montieth models and data number respectively.

RESULTS AND DISCUSSION

The monthly ETo values of Port Harcourt city of Nigeria were carried out by the FAO – 56PM and the Hargreaves methods and the results compared. Table 1, shows the monthly values of the root mean square error (RMSE)of the HG – PM ETo estimation. A comparison shows that the lowest monthly RMSE index occurred in February 2002 with a record value of 0.096 while the highest RMSE value for the same year is 0.497 in September. In 2001, the lowest value occurred in the month of February recording 0.363 while its highest value index is 0.629 in

Table 1. Monthly values of the RMSE

Months	2000	2001	2002	2003
January	0.25254193	0.4625365	0.1313925	0.546497
February	0.09629594	0.3625751	0.498897	0.54756
March	0.47242688	0.6289057	0.5182342	0.495504
April	0.44773019	0.5486337	0.5506414	0.536639
May	0.40963432	0.5510121	0.522638	0.462177
June	0.33953763	0.5232768	0.3671371	0.310604
July	0.3736369	0.4240409	0.3897317	0.499169
August	0.44650841	0.4975431	0.4655312	0.512696
September	0.49674643	0.5310284	0.4803379	0.385318
October	0.29401861	0.3531474	0.2879914	0.452591
November	0.28503593	0.4292992	0.3131646	0.174066
December	0.38157232	0.3960098	0.3773217	0.083793

Table 2. Monthly values of the MBE

Months	2000	2001	2002	2003
January	0.072902576	0.133522797	0.037929744	0.1577602
February	0.027798245	0.104666424	0.144019173	0.158066948
March	0.136377893	0.181549447	0.149601339	0.143039584
April	0.129248572	0.158376897	0.158956487	0.15491446
May	0.118251243	0.159063491	0.150872609	0.133419083
June	0.098016071	0.151057013	0.105983352	0.089663716
July	0.107859683	0.122410066	0.112505847	0.144097547
August	0.128895875	0.143628319	0.134387274	0.148002629
September	0.143398343	0.153294697	0.138661597	0.111231626
October	0.084875862	0.101944875	0.083135945	0.130651824
November	0.082282786	0.123927998	0.090402819	0.05024859
December	0.110150442	0.114318172	0.108923394	0.024189044

the month of March. The years 2002 and 2003 recorded their least values of RMSE in January and November, of 0.131 and 0.174 respectively. Highest valuesof RMSE are 0.551 and 0.548 in the months of March and February respectively. There is a discrepancy in the signature of the ETo recordings calculated by both the Hargreaves and Penman – Montieth. That is a situation whereby warm periods records low ETo, while cold periods records higher ETo. This may be attributed to regional global warming Edebeatu et al, (2010).

The mean bias errors (MBE) of the study site for the months are shown in Table 2. A comparison of the results showed only positive values, an indication of overestimation Houshang et al, (2012), as predicted by the HG – PM methods. Table 2 of the MBE showed that the minimum values were recorded in the months of February, November, October and June 2000 with a value index of 0.028, 0.082, 0.085 and 0.098 respectively. Maximum values of MBE were recorded in the months of September and March as 0.143 and 0.136 respectively. In 2001, maximum values occurred from the months of March to June having 0.182, 0.158, 0.159 and 0.151, and in September at 0.153. The minimum overestimated values of MBE index were recorded in the months of October with 0.101 and in February with 0.105. The year 2002 recorded minimum values in January with 0.038 and in October with 0.083 respectively. Maximum values are seen in the months of April and May with index values of 0.159 and 0.151 respectively. The year 2003 showed that the HG – PM methods of maximum positive values were recorded in the months of January, February and April with index values of 0.158, 0.158 and 0.155, while minimum positive values occurred in the months of December, November and June at 0.024, 0.050 and 0.0896 respectively.

Table 3 is the mean percentage error (MPE) of the ETo estimated by the HG and PM methods for the meteorological station from 2000 – 2003. The minimum MPE are in the months of February at 0.503 in 2000, 2.034 in February 2001, 0.776 in January 2001 and 0.530 in December 2003.The maximum ETo_{-HG} and ETo_{-PM} values stood at 3.574mm/d in September 2000, 4.057mm/d in August 2001, 3.634mm/d in September 2002 and 3.847mm/d in August 2003 again.

Table 4 presents the annual values of the RMSE, MBE and MPE for the meteorological station of study. Maximum RMSE was recorded in 2001 with index value of 5.708, while minimumvalue occurred in 2003 with a

Table 3. Monthly values of MPE

Months	2000	2001	2002	2003
January	1.528501629	2.610545282	0.776180836	3.254097132
February	0.503331485	2.033938534	2.677927981	3.066944639
March	2.474580768	3.465329132	3.080953108	2.786594634
April	2.798603546	3.092340933	3.289948232	3.150772195
May	2.532682585	3.286459606	3.252288541	2.935723864
June	2.429462102	3.535404371	2.731364287	2.401152358
July	2.868121665	3.202863732	3.016613116	3.547218419
August	3.473118147	4.057405603	3.690744683	3.847486329
September	3.573792535	3.901824442	3.633746045	2.901133815
October	2.019780469	2.460722339	2.098102484	2.969112004
November	1.887280528	2.875338738	2.054993896	1.129608865
December	2.287199805	2.552454726	2.327106365	0.529542039

Table 4. Annual values RMSE, MBE, MPE and R for the study site

Annual	2000	2001	2002	2003
RMSE	4.295685499	5.708008755	4.90301869	1.445285252
MBE	1.240057589	1.647760196	1.41537958	1.445285252
MPE	2.296922648	3.05388035	2.6857238	2.7019559
R	1.380511328	1.578446358	1.475550546	1.479803731

Table 5. Monthly values of C for calibrated HG model

Months	2000	2001	2002	2003
January	0.001878	0.001579	0.0020858	0.001402
February	0.002161	0.001739	0.0015609	0.001454
March	0.001617	0.001344	0.0014497	0.001531
April	0.001528	0.001447	0.001392	0.00143
May	0.001601	0.001393	0.0014024	0.00149
June	0.001629	0.001324	0.0015461	0.001637
July	0.001508	0.001416	0.0014674	0.001321
August	0.001341	0.00118	0.0012814	0.001238
September	0.001314	0.001223	0.0012971	0.001499
October	0.001743	0.001621	0.0017209	0.001481
November	0.001779	0.001506	0.0017328	0.001988
December	0.001669	0.001596	0.0016577	0.002154

value of 1.445. MBE of the ETo_{-HG} and ETo_{-PM} recorded minimum value in 2000 with a value of 1.24 and maximum of 1.648 in 2001 respectively. Maximum MPE was predicted in 2001 with a value of 3.054 and minimum in 2000 with a value of 2.702 in 2003. Jabloun and Sahli, (2008) and Houshang et al, (2012) evaluated the Hargreaves equation and compared with the FAO – PM. They literature reported that the results of the ETo estimates compared the ETo – HG with ETo – PM estimates with different locations in Tunisia showed an overestimate at the inland sites and an under estimate at coastal locations by the HG equation, and in Provinces of Iran respectively. Table 5 presents C, the coefficients were lower than 0.0023 for the entire period of study. The corrected coefficient gave a more standard estimate of the Hargreaves reference evapotranspiration value than the Hargreaves coefficient of 0.0023. The values of C has nearly the same values with the FAO – 56PM except in February 2000. Figs 5a – 8a show the estimates of the ETo_{-HG} and ETo_{-PM}.The corrected HGs are shown in figs 5b – 8b alongside with the uncorrected Hargreaves model.

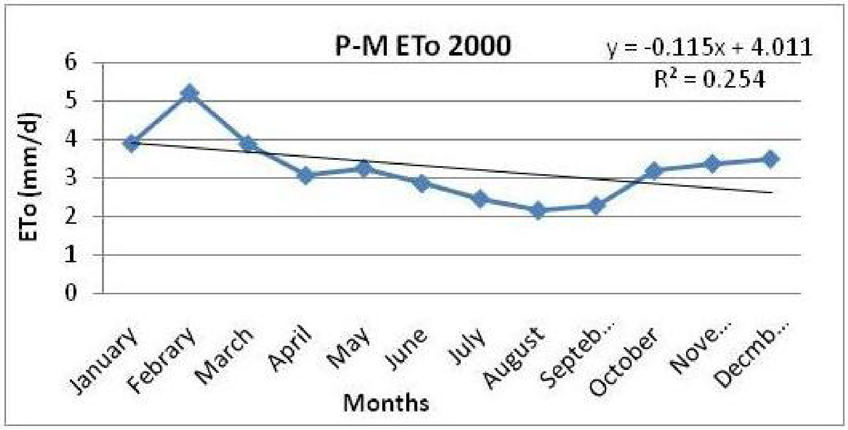

Figure 1. ETo P-M distribution for the year 2000

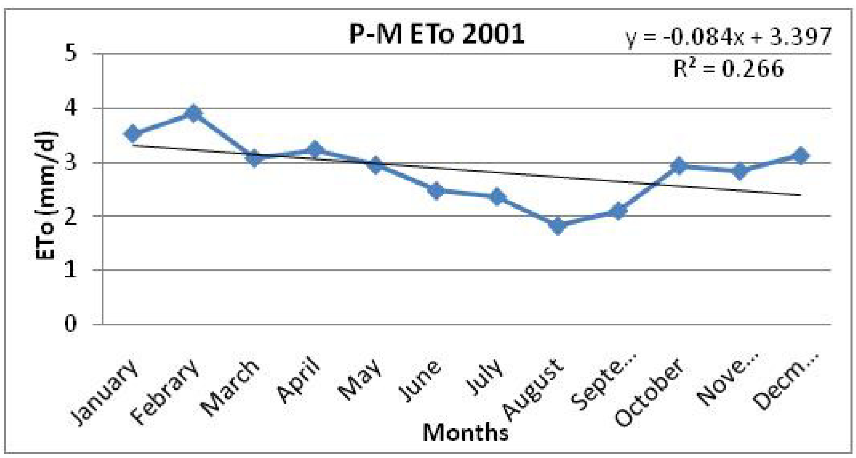

Figure 2. ETo P-M distribution for the year 2001

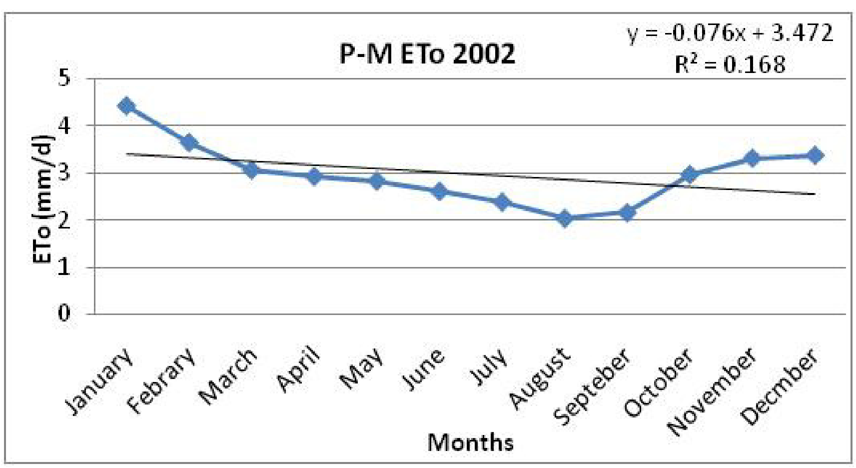

Figure 3. ETo P-M distribution for the year 20002

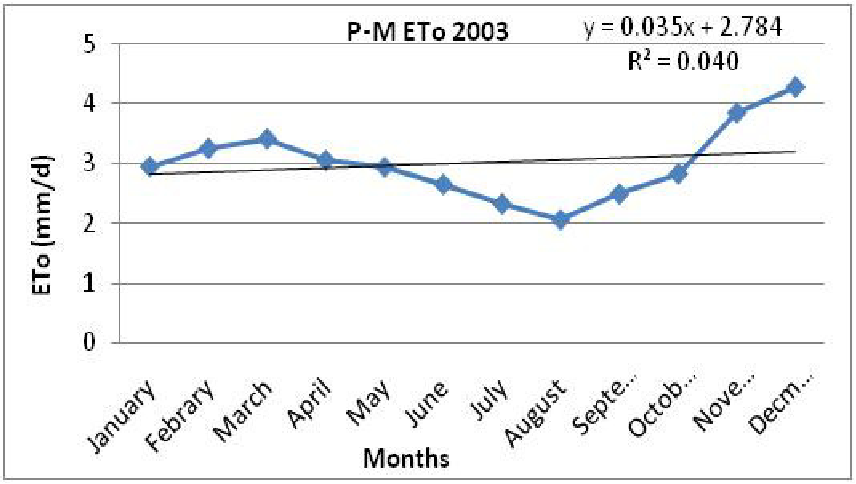

Figure 4. ETo P-M distribution for the year 2003

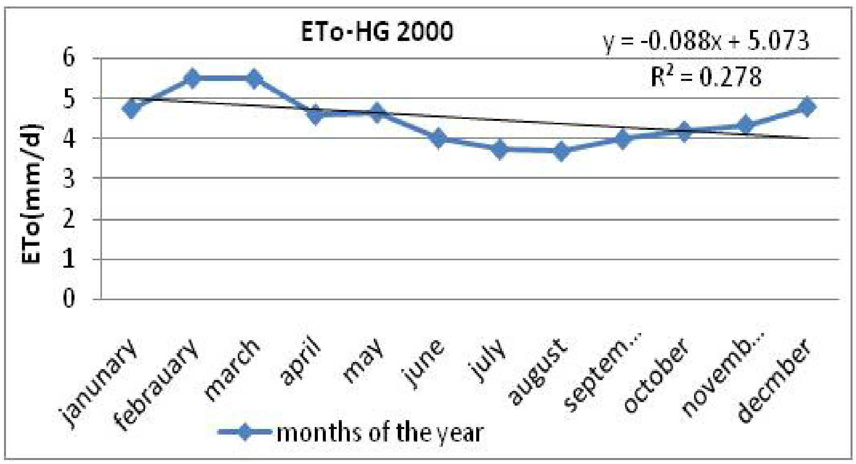

Figure 5a. ETo H-G distribution for the year 2000

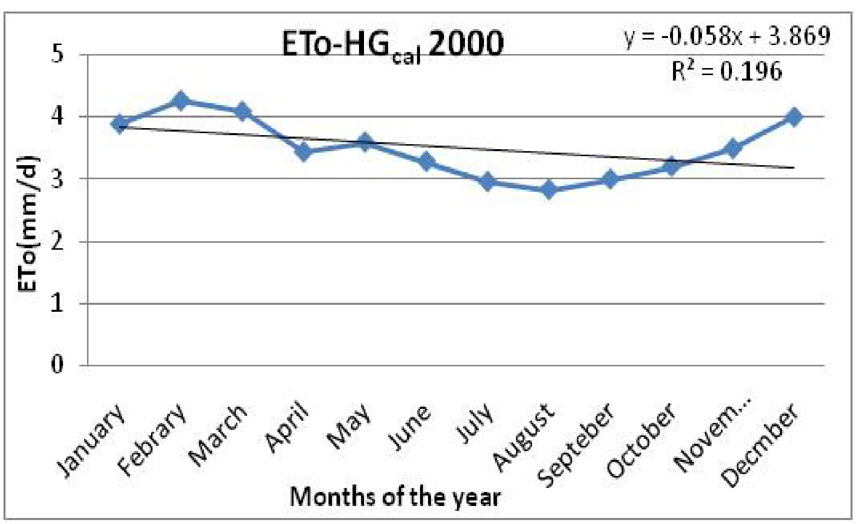

Figure 5b. ETo H-G distribution for the year 2000

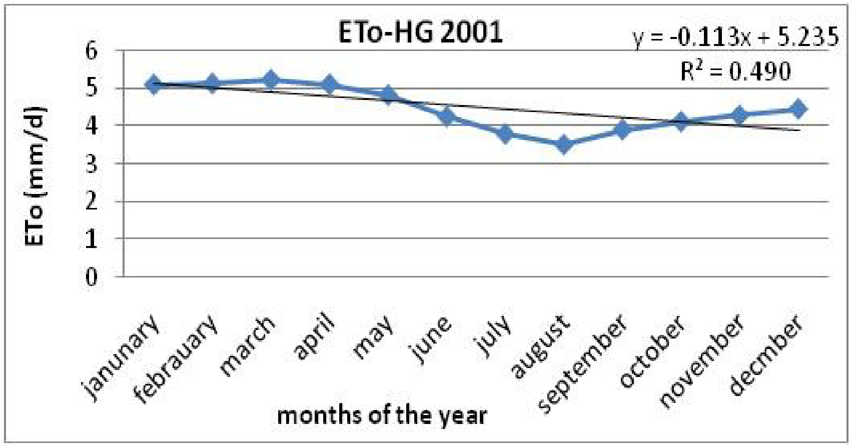

Figure 6a. ETo H-G distribution for the year 2001

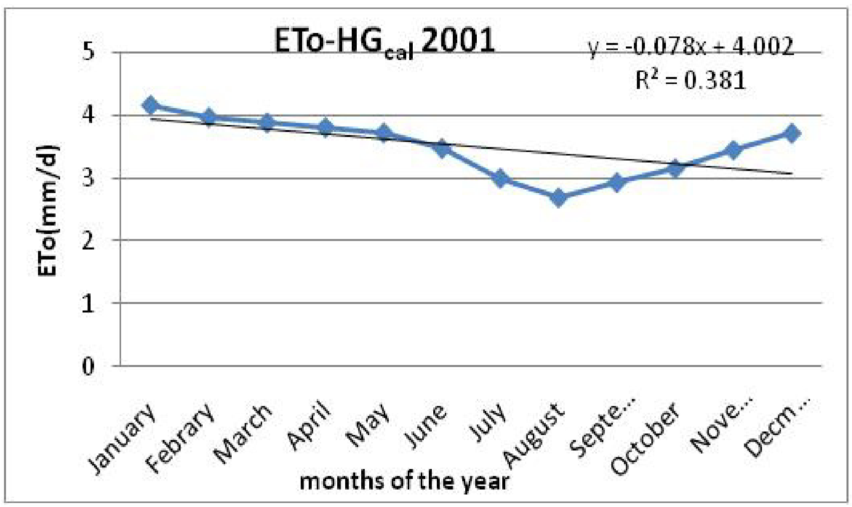

Figure 6b. ETo H-G distribution for the year 2001

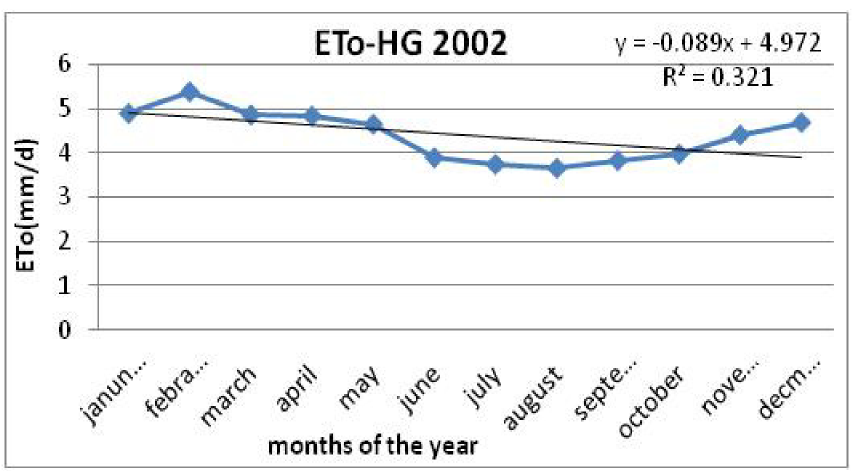

Figure 7a. ETo H-G distribution for the year 2002

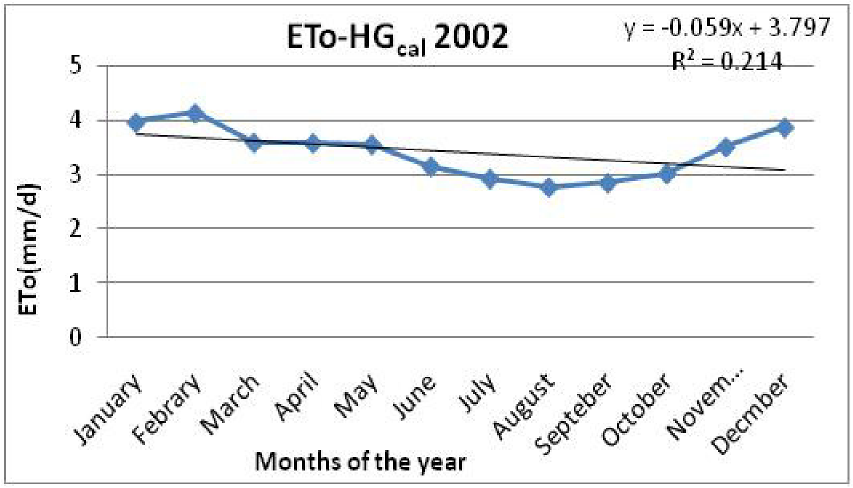

Figure 7b. ETo H-G distribution for the year 2002

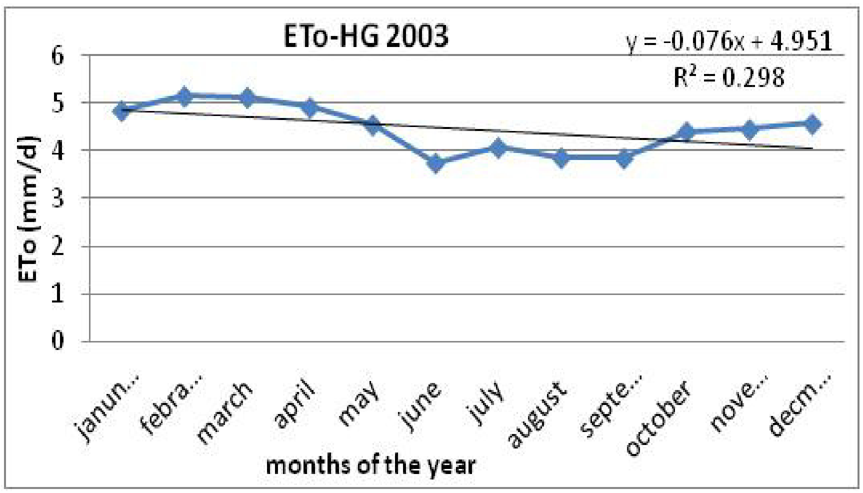

Figure 8a. ETo H-G distribution for the year 2003

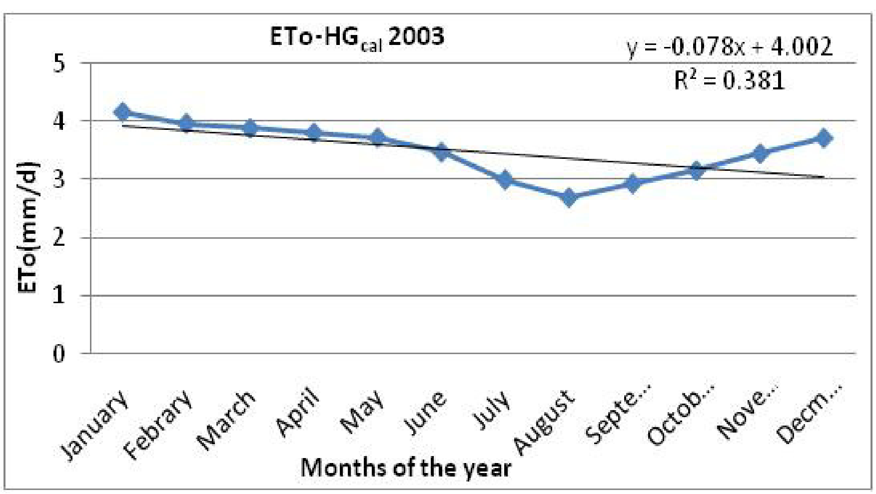

Figure 8b. ETo H-G distribution for the year 2003

CONCLUSION

The seasonal calibration of the Hargreaves equation for the estimation of monthly reference evapotranspiration has been carried out in the city of Port Harcourt, which lies within the mangroves geographical rainforest humid zone of Nigeria, 4.750N and 7.010E. The result of the analysis shows that the calibrated Hargreaves equation proves a better model for the estimation of reference evapotranspiration in the humid zones of Nigeria and indeed maybe extended to other humid regions, since the Hargreaves equation model would either overestimate or underestimate in these regions.

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