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Performance evaluation of solar radiation equations for estimating reference evapotranspiration (*ETo*) in a humid tropical environment

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Abstract

Solar radiation (*Rs*) is an essential input for estimating reference crop evapotranspiration, *ETo*. An accurate estimate of *ETo* is the first step involved in determining water demand of field crops. The objective of this study was to assess the accuracy of fifteen empirical solar radiations (*Rs*) models and determine its effects on *ETo* estimates for three sites in humid tropical environment (Abakaliki, Nsukka, and Awka). Meteorological data from the archives of NASA (from 1983 to 2005) was used to derive empirical constants (calibration) for the different models at each location while data from 2006 to 2015 was used for validation. The results showed an overall improvement when comparing measured *Rs* with *Rs* determined using original constants and *Rs* using the new constants. After calibration, the Swartman–Ogunlade (R^2 = 0.97) and Chen 2 models (*RMSE* = 0.665 MJ·m^{-2}·day^{-1}) performed best while Chen 1 (R^2 = 0.66) and Bristow–Campbell models (*RMSE* = 1.58 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs* in Abakaliki. At the Nsukka station, Swartman–Ogunlade (R^2 = 0.96) and Adeala models (*RMSE* = 0.785 MJ·m^{-2}·day^{-1}) performed best while Hargreaves–Samani (R^2 = 0.64) and Chen 1 models (*RMSE* = 1.96 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs*. Chen 2 (R^2 = 0.98) and Swartman–Ogunlade models (*RMSE* = 0.43 MJ·m^{-2}·day^{-1}) performed best while Hargreaves–Samani (R^2 = 0.68) and Chen 1 models (*RMSE* = 1.64 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs* in Awka. For estimating *ETo*, Adeala (R^2 =0.98) and Swartman–Ogunlade models (*RMSE* = 0.064 MJ·m^{-2}·day^{-1}) performed best at the Awka station and Swartman–Ogunlade (R^2 = 0.98) and Chen 2 models (*RMSE* = 0.43 MJ·m^{-2}·day^{-1}) performed best at Abakaliki while Angstrom–Prescott–Page (R^2 = 0.96) and El-Sebaii models (*RMSE* = 0.0908 mm·day^{-1}) performed best at the Nsukka station.

Key words: *calibration, models, reference evapotranspiration, solar radiation, validation*

INTRODUCTION

Solar energy (radiation) is the primary source of energy on earth and a major driver of the hydrological cycle (evaporation, transpiration, evapotranspiration etc.), photosynthesis, photo voltaic cells, and solar energy systems. Evapotranspiration, *ET*, is an integrated process of evaporation and transpiration that describes water loss through the soil and plant's stomata openings in leaves and stem. The process of *ET* is simultaneous and combined, thus it is difficult to separate [ALLEN *et al.* 1998]. Determination of the crop evapotranspiration (*ETc*) is usually preceded by calculating the reference evapotranspiration [LÓPEZ-URREA *et al.* 2006]. The term "reference evapotranspiration (*ETo*) as defined by ALLEN *et al.* [1998] refers to evapotranspiration rate from a well-watered hypothetical grass surface of 0.12 m in crop height, albedo of 0.23 and surface resistance of 70 s m^{-1}". *ETo* is important in determining crop and irrigation water requirement of crops [ALLEN *et al.* 1998; VOZHEHOVA *et al.* 2018], ecological and climate change studies [NISTOR *et al.* 2017], hydrological modeling [SCHNEIDER *et al.* 2007], irrigation scheduling and irrigation design and implementation [SENTELHAS *et al.* 2010]. Solar radiation (*Rs*) is an important parameter in computing *ETo* together with other meteorological parameters like wind speed, temperature and relative humidity. Studies have shown strong correlation between solar radiation and *ETo* [DJAMAN *et al.* 2018; KOSA 2011; KOUDAHE *et al.* 2018; MARTEL *et al.* 2018]. This shows that solar radiation is a dominant factor controlling the evapotranspiration process in these regions. Despite its importance, *Rs* data are low when compared with precipitation or temperature data [THORNTON, RUNNING 1999]. Across the globe, temporal and spatial *Rs* data are scarce because measuring instruments (pyranometers) are costly, time consuming, and requires regular maintenance and calibration [LIU *et al.* 2009; WU *et al.* 2017]. Even measured *Rs* data are prone to inconsistencies caused by wind drift [WANG *et al.* 2015].

The FAO Penman–Monteith (FAO-PM) equation is the recommended method for estimating *ETo* [ALLEN *et al.* 1998]. Despite its accuracy and robustness, the FAO-PM method suffers constraint in application due to absence of weather data. The situation is worse in developing countries. In Nigeria, observation stations are poorly and sparsely distributed. Nigeria has about 40 sparsely distributed weather observations managed by NIMET (Nigerian Meteorological Agency) but only few measure *Rs* [ADARAMOLA 2012; OGOLO 2014]. To overcome this problem, empirical *Rs* models have been developed as alternative. Some of these models make use of readily available meteorological data like temperature to estimate *Rs*. A review of literature shows that there are so many empirical *Rs* equations developed for different regions in the world including Nigeria [ADARAMOLA 2012; AKPABIO *et al.* 2005; AKPABIO, ETUK 2003; BESHARAT *et al.* 2013; OKUNDAMIYA *et al.* 2016]. A major limitation of *Rs* models is that they are area specific. Thus, it is necessary to assess the performance of empirical *Rs* models before application in a location where it was not previously developed. Studies have shown that local calibration of empirical constants improved *Rs* estimate [DE MEDEIROS *et al.* 2017; ESTEVEZ *et al.* 2012; ZHANG *et al.* 2018]. For example, WU *et al.* [2017] calibrated the Angstrom–Prescott–Page *Rs* model across five stations in China. Some studies have further evaluated the impacts of different *Rs* models on *ETo* estimates [XU *et al.* 2008]. TABARI *et al.* [2016] calibrated twelve *Rs* models for estimating *ETo* under arid and semi-arid conditions in Iran. They found an improvement of estimates after calibration. Similarly, MOUSAVI *et al.* [2015] calibrated the Angstom–Prescott–Page *Rs* model for *ETo* estimate in Iran. ALADENOLA, MADRAMOOTOO [2014] studied nine *Rs* models for estimating *ETo* across Canada. Their results showed reduction of errors in *ETo* estimates with the new empirical constants.

However, there has not been any assessment of *Rs* and its effects on *ETo* estimate in Nigeria (south east) found in literature. The south eastern part of Nigeria is traditionally known to engage in agricultural activities, although in small holdings. The region is known for cultivation of cash and tree crops like oil palm, yam, kolanuts, cassava, vegetables, etc. So therefore, the objective of this study is to evaluate the performance of fifteen solar radiation models (Hargreaves–Samani, Bristow–Campbell, Swartman–Ogunlade, Chen 1, El-Sebaii, Almorox and Hontoria, Ogelman, Dogniaux and Lemoine, Glower and McCulloch model, Elagib and Mansell, Chen 2, Adeala, Hassan, Angstrom–Prescott–Page, and Ezekwe and Ezeifo) and determine its effects on *ETo* estimates in Abakaliki, Nsukka and Awka using the FAO-PM equation. The selected towns are within the south east agro-ecological zone of Nigeria particularly known for growing crops like Nsukka yellow pepper and Abakaliki rice. The results of this study will help in water resources management, planning and irrigation system design for the region.

METHODS

STUDY AREA

The study area falls within the south east geopolitical zone of Nigeria. Three major towns comprising of Nsukka (Enugu state), Abakaliki (Ebonyi) and Awka (Anambra state) were studied. The region is within the humid tropical region which is characterized by two seasons. The wet season usually starts from April to October and dry season runs from November to March. As characteristic of the dry season, water is limited, and evapotranspiration rates are 50% higher than during the wet season [GOBIN 2000]. Nsukka is native to the Nsukka hot yellow pepper (*Capsicum annuum L.*), commonly called 'ose nsukka' in local parlance and known for its unique flavor, quality and colour [ONWUBUYA *et al.* 2009]. The Abakaliki rice (*Oryza sativa*) is one of the characteristics Ebonyi state is known for. Historically, they are well known rice farmers growing different varieties of rice species. Anambra state also grow Abakaliki rice [EGBODION, AHAMDU 2015]. Dry season farming provides an economic advantage in the region because agricultural produce command high prices, hence more profit for the farmers. Thus, accurate estimates of *ETo* is therefore very important in the region for optimizing irrigation in order to have a guaranteed cropping season.

METEOROLOGICAL DATA

Daily weather data (solar radiation, minimum temperature, maximum temperature, relative humidity and wind speed) as summarized in Table 1, was obtained from the archives of NASA (National Aeronautics Space Administration) Prediction of Worldwide Energy Resource, POWER (https://power.larc.nasa.gov/) for a 32-year period (July 1983- December 2015). Similar studies [Adaramola 2012; Chineke 2008; Egeonu *et al.* 2015; Okundamiya *et al.* 2016] have adopted this method. The data was further checked for error, quality assessment, inconsistencies and missing data as recommended by World Meteorological Organization [WMO 1987] and Allen [1996]. NASA POWER datasets are from satellite observations that provides reliable time series solar and meteorology data in space and time, especially for areas where instruments are limited or not available [NASA 2016].

EMPIRICAL SOLAR RADIATION (*Rs*) MODELS

Empirical *Rs* models are broadly classified into sunshine-based, cloud-based, temperature-based, relative humidity-based, precipitation-based models and hybrid parameters-based models [Besharat *et al.* 2013; Nwokolo 2017]. This classification is based on the relationship between solar radiation and weather parameters. Fifteen solar radiation models were evaluated in this study. They include seven sunshine-based models (Almorox and Hontoria, Ogelman, Dogniaux and Lemoine, Glower and McCulloch, Elagib and Mansell, Angstrom–Prescott–Page, and Ezekwe and Ezeifo), four temperature-based models (Hargreaves–Samani, Bristow–Campbell, Hassan, and Chen 1), four hybrid models (Chen 2, El-Sebaii, Swartman-Ogunlade and Adeala).

- **Model 1: Hargreaves-Samani model [**Hargreaves, Samani 1985]. It relates solar radiation, difference between the maximum and minimum air temperature and extra-terrestrial radiation. The Hargreaves–Samani equation is given as:

  $$R_s = a(\Delta T)^{0.5} R_a$$

  Hargreaves and Samani [1985] determined a = 0.16 for inland region, a = 0.19 for coastal region
- **Model 2: Bristow-Campbell model** [Bristow, Campbell 1984]. It is given as:

  $$R_s = a[1 - \exp(-b\Delta T)^C]\, R_a$$

  where: a = 0.7, b = 0.004, c = 2.4.
- **Model 3: Swartman-Ogunlade model** [Swartman, Ogunlade 1967]. It is given as:

  $$R_s = \left[a + b\left(\frac{n}{N}\right) + cRH\right] \cdot 0.485 \cdot 0.0864$$

  where: a = 464, b = 265, c = 248.
- **Model 4: Chen 1 model** [Chen *et al.* 2004]. It is expressed as:

  $$R_s = [a(\Delta T)^{0.5} + b]R_a$$

  where: a = 0.28, b = –0.15
- **Model 5: El-Sebaii model** [El-Sebaii *et al.* 2009]. It is expressed as:

  $$R_s = [a + bT + cRH]R_a$$

  where: a = –1.62, b = 2.24, c = 0.332.
- **Model 6: Almorox and Hontoria model** [Almorox, Hontoria 2004]. This model for estimating *Rs* is given as:

  $$R_s = \left[a + b\exp\left(\frac{n}{N}\right)\right] R_a$$

  where: a = –0.0271, b = 0.3096.
- **Model 7: Ogelman model** [Ogelman *et al.* 1984]. *Rs* model is given as:

  $$R_s = \left[a + b\left(\frac{n}{N}\right) + c\left(\frac{n}{N}\right)^2\right] R_a$$

  where: a = 0.195, b = 0.676, c = 0.142.
- **Model 8: Dogniaux and Lemoine model** [Dogniaux, Lemoine 1983]. It is expressed as:

  $$R_s = \left[a + \left[\mathrm{b}\left(\frac{n}{N}\right) - c\right]\varphi + d\left(\frac{n}{N}\right)\right] R_a$$

  where: a = 0.37022, b = 0.00506, c = 0.00313, d = 0.32029.
- **Model 9: Glower and McCulloch model** [Glower, McCulloch 1958]. It is expressed as:

  $R_s = \left[a\cos\varphi + b\left(\frac{n}{N}\right)\right] \cdot R_a$ where a = 0.29, b = 0.52
- **Model 10: Elagib and Mansell model** [Elagib, Mansell 2000]. It is expressed as:

  $$R_s = \left[a\exp[b\left(\frac{n}{N}\right)]\right] R_a$$

  Togrul and Togrul [2002] calibrated the Elagib and Mansell model as a = 0.3396 and b= 0.8985
- **Model 11: Chen 2 model** [Chen *et al.* 2004]. *Rs* model is expressed as:

  $$R_s = \left[a\ln(\Delta T) + b\left(\frac{n}{N}\right)^c + d\right] R_a$$

  where: a = 0.04, b = 0.48, c = 0.83, d = 0.11
- **Model 12: Adeala model** [Adeala *et al.* 2015]. *Rs* model is given as:

  $$R_s = \left[a + b\left(\frac{n}{N}\right) - cRH + dT + eU_2\right] R_a$$

  where a = 0.96518, b = 1.0928, c = –0.00364, d = 0.04022, e = 0.1293 according to Adeala *et al.* [2015].
- **Model 13: Hassan model** [Hassan *et al.* 2016]. *Rs* model is expressed as:

  $$R_s = [(a + bT)(\Delta T)^c]R_a$$

  where: a = –0.05614, b = 0.0101, c = 0.4908.
- **Model 14: Angstrom-Prescott-Page model** [Angstrom 1924; Prescott 1940; Page 1961]. It is one of the oldest *Rs* model and is expressed as:

  $$R_s = \left[a + b\log\left(\frac{n}{N}\right)\right] R_a$$

  where: a = 0.46, b = 0.16 according to Ayodele and Ogunjuyigbe [2016].

- **Model 15: Ezekwe and Ezeifo model** [Ezekwe, Ezeifo 1981]. *Rs* model is expressed as:

$$R_s = \left[a + b\left(\frac{n}{N}\right)\right] R_a$$

where: $a = 0.28$ and $b = 0.18$.

Extraterrestrial radiation, R_a, is expressed as:

$$R_a = \frac{24 \cdot 60 \cdot G_{sc} \cdot d_r}{\pi}\left[\omega_s \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\omega_s\right]$$

where: d_r is the relative distance between the earth and the sun, ω_s is the sunset hour angle in radians, φ is latitude, δ is solar declination angle

$$d_r = 1 + 0.033\cos\frac{2\pi J}{365},$$

$$\omega_s = \arccos(-\tan\varphi \tan\delta), \delta = 0.4093\sin(\frac{2\pi}{365}J - 1.39)$$

where: J = Julian day number.

Day light hours, N is determined as:

$$\mathrm{N} = \frac{24\omega_s}{\pi}$$

where: R_s is solar radiation (MJ·m^{-2}·day^{-1}), R_a is extraterrestrial radiation (MJ·m^{-2}·day^{-1}), n is sunshine hours, N is day light hours, $T_{\min}$ and $T_{\max}$ minimum and maximum temperature respectively, *RH* is relative humidity (%), *P* is precipitation (mm), T_{ave} is average temperature (°C), ΔT is difference between minimum and maximum temperature, φ is latitude, *a*, *b*, *c*, *d*, *e* are regression coefficients.

FAO-PM EVAPOTRANSPIRATION EQUATION, *ETo*

As stated earlier, the FAO-PM equation is the standard equation for determining reference crop evapotranspiration and was used for estimating *ETo* in this study. It is expressed as

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}[e_s - e_a]u_2}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)}$$

Where: *ETo* is the reference crop evapotranspiration (mm·day^{-1}); R_n is the net radiation (MJ·m^{-2}·day^{-1}); G is the soil heat flux (MJ·m^{-2}·day^{-1}); T is the average daily air temperature at a height of 2 m (°C); u_2 is the wind speed at a height of 2 m (m·s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); $e_s - e_a$ is the vapour pressure deficit (kPa); Δ is the slope of the saturation vapour pressure-temperature curve (kPa·°C^{-1}); and γ is the psychrometric constant (kPa·°C^{-1}).

STATISTICAL ANALYSIS

Goodness of fit was assessed by qualitative and statistical test. Qualitative assessment involves a graphical plot of empirical versus measured data to show trend. Statistical tests such as coefficient of determination (R^2), root mean square error (*RMSE*), mean bias error (*MBE*), mean absolute error (*MAE*) and mean percent error (*MPE*) were also used for assessment.

R^2 is used to express relationship between observed and predicted values. R^2 ranges from 0 to 1. An $R^2 = 1$ represents an optimal model. Generally, $R^2 > 0.5$ is acceptable [Moriasi *et al.* 2007]. It is given as:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \overline{O})(P_i - \overline{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \overline{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \overline{P})^2}}\right)^2$$

RMSE is a measure of how dispersed prediction errors are on the regression line. Lower *RMSE* values is an indication of high model performance. It is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}}$$

MBE is used to indicate over prediction or under prediction of a model. It is given as:

$$MBE = \frac{\sum_i^n (O_i - P_i)}{n}100$$

$$MAE = \frac{\sum_i^n |O_i - P_i|}{n}100$$

$$MPE = \frac{1}{n}\sum_{1=n}^{n}\left(\frac{O_i - P_i}{O_i}\right)100$$

Where: O_i is observed data, P_i is the predicted data by empirical model, $\overline{O_i}$ is the mean of observed measured data, n is the total number of observed data points. Low values of *MBE*, *MAE* and *MPE* are indications of good model performance [Djaman *et al.* 2018; Moriasi *et al.* 2007; Ndulue *et al.* 2018].

The meteorological data were further checked for error, quality assessment, inconsistencies and missing data were excluded as recommended by WMO [1987] and Allen [1996]. After excluding missing data, total number of observations, *n* were subjected to analysis. With this, monthly averages for the 32 years was determined.

RESULTS AND DISCUSSIONS

CLIMATIC ANALYSIS

The climatic condition of the study area is summarized in Table 1. Peak solar radiation was observed between December to February while lowest solar radiation was between June to August across all the three sites. This corresponds to dry and wet season in the region. Mean monthly

Table 1. Mean monthly meteorological parameters (1983–2015)

Parameter	Values for the station		
	Nsukka	Abakaliki	Awka
$T_{\max}$ (°C)	29.4±1.5	28.5±1.7	27.9±1.4
$T_{\min}$ (°C)	22.3±1.6	21.9±0.81	21.5±0.76
R_s (MJ·m^{-2}·day^{-2})	18.3±2.5	18.2±2.1	17.7±2.2
u_2 (m·s^{-1})	1.8±0.32	1.5±0.17	1.6±0.18
RH (%)	79.1±9.1	81.4±11.0	81.4±9
Latitude (°N)	6.843	6.323	6.222
Longitude (°E)	7.373	8.112	7.082
Number of observations, *n*	11,676	11,606	11,675

Explanations: $T_{\min}$ = minimum temperature, $T_{\max}$ = maximum temperature, R_s = solar radiation, u_2 = the wind speed at a height of 2 m, *RH* = relative humidity.
Source: own elaboration.

highest solar radiation in Nsukka, Abakaliki and Awka are 21.86, 20.49 and 20.05 MJ·m^{-2}·day^{-1} while mean monthly lowest solar radiation are 14.56, 14.1 and 13.32 MJ·m^{-2}·day^{-1} for Nsukka, Abakaliki and Awka respectively.

SOLAR RADIATION (*Rs*) MODEL PERFORMANCE WITH ORIGINAL *RS* EMPIRICAL CONSTANTS

Statistical tests between measured solar radiation and the different empirical solar radiation using their original constants is summarized in Table 2. As shown, R^2 ranged from 0.39 to 0.90, 0.23 to 0.88 and 0.14 to 0.76 for Abakaliki, Nsukka, and Awka stations respectively. Across all three sites, *RMSE* ranged from 1.23 to 12.48 MJ·m^{-2}·day^{-1}, *MBE* ranged from –10.62 to 11.32 MJ·m^{-2}·day^{-1}, *MAE* ranged from 1.017 to 11.32 MJ·m^{-2}·day^{-1} while *MPE* ranged from –59.9 to 68.78%. Also, Elagib and Mansell model performed best with least *RMSE* (1.23 MJ·m^{-2}·day^{-1}), *MBE* (–0.17 MJ·m^{-2}·day^{-1}), *MAE* (1.02 MJ·m^{-2}·day^{-1}) and *MPE* (–0.27%) while the worst performance was by Hassan model with (R^2 = 0.39, *RMSE* = 5.69 MJ·m^{-2}·day^{-1}, *MBE* = 4.91 MJ·m^{-2}·day^{-1}, *MAE* = 4.918 MJ·m^{-2}·day^{-1} and *MPE* = 29.1%) for Abakaliki station. The Swartman–Ogunlade model performed best with an R^2 of 0.88, *RMSE* of 1.95 MJ·m^{-2}·day^{-1}, *MBE* of –1.47 MJ·m^{-2}·day^{-1}, *MAE* of 1.72 MJ·m^{-2}·day^{-1} and *MPE* of –7.22% while the worst performance was by El-Sebaii model with *RMSE* of 11.38 MJ·m^{-2}·day^{-1}, *MBE* of 9.71 MJ·m^{-2}·day^{-1}, *MAE* of 9.71 MJ·m^{-2}·day^{-1} and *MPE* of 58.7% for Nsukka station. Also, for Awka station, Elagib and Mansell model performed best with the least *RMSE* of 1.374 MJ·m^{-2}·day^{-1}, *MBE* of –0.074 MJ·m^{-2}·day^{-1}, *MAE* of 1.08 MJ·m^{-2}·day^{-1} and *MPE* 0.452% while the worst performance was by El-Sebaii (*RMSE* of 12.48 MJ·m^{-2}·day^{-1}) and Hassan models (R^2 = 0.14). From the *MBE* values, it was observed that the Bristow–Campbell model underestimated *Rs* by 10.63, 7.64 and 10.15 MJ·m^{-2}·day^{-1} for Abakaliki, Nsukka and Awka stations respectively. Similarly, El-Sebaii overestimated *Rs* across the stations by 10.04, 9.72 and 11.31 MJ·m^{-2}·day^{-1} for Abakaliki, Nsukka and Awka stations respectively. The poor performance of Hassan and Bristow–Campbell models is likely because they require single parameter (temperature) as the only model input to predict *Rs*. This is also in line with OKUNDAMIYA *et al.* [2016] who that reported that hybrid-model perform better than single based parameter. Despite being a hybrid model, the El-Sebaii model did not yield satisfactory results. This is because the El-Sebaii model was developed using weather data of Saudi Arabia, which is very different from the climate of the study area.

Overall, model performance was poor for most models and was improved by determination of location specific constants for each of the empirical solar radiation model.

DETERMINATION OF EMPIRICAL *Rs* CONSTANTS

The data was divided into two groups. The first subdata (1983–2005) was used for determining regression coefficients while the second sub-data set (2006–2015) was used for validation of the calibrated equations. This was done by the principle of least squares method. Least square method minimizes the sum of squared deviations (residuals) from the regression line. Applying this method, new regression coefficients were derived for the different solar radiation models. Statistical test for each model is shown in Table 3. For example, the derived coefficient for the Hargreaves–Samani model was found to be 0.1939, 0.1989 and 0.1921 for Nsukka, Abakaliki and Awka respectively

Table 2. Statistical analysis of measured solar radiation and solar radiation using original constants

Parameter	Model														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Nsukka															
R^2	0.621	0.66	0.888	0.60	0.691	0.679	0.713	0.231	0.634	0.598	0.788	0.687	0.263	0.321	0.72
RMSE	2.89	8.175	1.956	4.49	11.388	1.8	1.814	2.361	2.222	2.031	2.462	1.898	6.063	4.43	3.454
MBE	–2.416	–7.691	–1.477	4.116	9.717	–0.086	–0.603	0.634	1.284	0.718	–1.883	–1.264	4.882	–3.601	3.072
MAE	2.652	7.691	1.725	4.116	9.717	1.454	1.467	1.991	1.826	1.689	2.115	1.554	5.18	3.803	3.099
MPE	–12.414	–43.752	–7.226	23.204	58.79	0.936	–2.041	5.346	8.574	5.5	–9.275	–6.351	30.01	–18.028	18.331
Abakaliki															
R^2	0.640	0.659	0.895	0.64	0.553	0.772	0.801	0.586	0.807	0.745	0.908	0.734	0.397	0.498	0.798
RMSE	4.022	10.994	2.383	2.337	11.718	1.539	1.97	1.542	3.338	1.23	3.181	2.157	5.695	4.336	2.017
MBE	–3.864	–10.627	–2.274	1.55	10.042	–1.032	–1.71	0.017	–3.184	–0.171	–3.089	–1.669	4.918	–3.906	1.773
MAE	3.864	10.627	2.274	1.717	10.262	1.098	1.71	1.349	3.184	1.017	3.089	1.868	4.918	3.906	1.815
MPE	–20.997	–59.889	–12.387	8.328	59.384	–5.13	–9.12	1.041	–17.246	–0.275	–16.816	–9.288	29.105	–20.502	10.088
Awka															
R^2	0.633	0.665	0.759	0.662	0.533	0.494	0.533	0.346	0.538	0.466	0.631	0.598	0.14	0.571	0.527
RMSE	3.37	10.324	2.488	2.673	12.483	1.64	2.089	1.648	3.41	1.374	3.162	1.939	6.459	1.571	1.931
MBE	–3.112	–10.149	–2.323	2.348	11.319	–0.982	–1.768	0.313	–3.206	–0.074	–3.007	–1.482	5.863	1.325	1.596
MAE	3.112	10.149	2.323	2.348	11.319	1.147	1.768	1.432	3.206	1.085	3.007	1.608	5.863	1.325	1.741
MPE	–17.124	–58.839	–12.901	13.753	68.785	–4.852	–9.657	2.916	–17.869	0.452	–16.794	–8.213	35.712	7.353	9.627

Explanations: models: 1 = Hargreaves Samani, 2 = Bristow–Campbell, 3 = Swartman–Ogunlade, 4 = Chen1, 5 = El-Sebaii, 6 = Almorox and Hontoria, 7 = Ogelman, 8 = Dogniaux and Lemoine, 9 = McC-Glower and McCulloch, 10 = Elagib and Mansell and Mansell, 11 = Chen2, 12 = Adeala *et al.*, 13 = Hassan, 14 = Angstrom-Prescott-Page, 15 = Ezekwe and Ezeifo; R^2 = determination coefficient, *RMSE* = root mean square error, *MBE* = mean bias error, *MAE* = mean absolute error, *MPE* = mean percent error.
Source: own elaboration.

Table 3. Statistical analysis of measured solar radiation and solar radiation using new regression constants

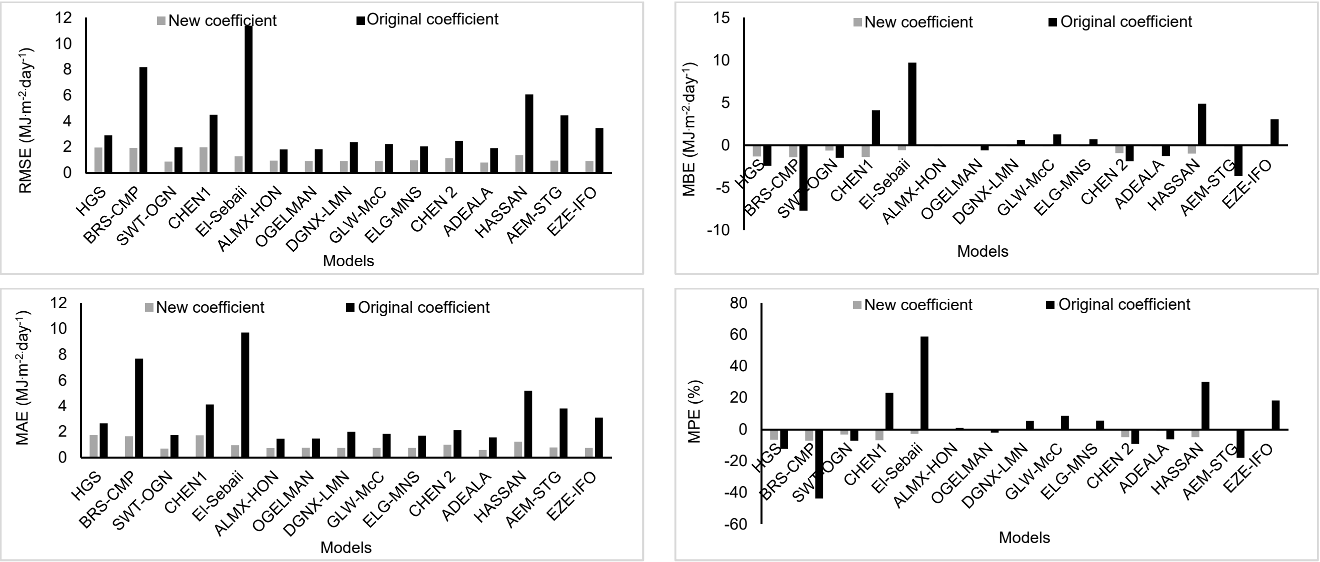
Model	*a*	*b*	*c*	*d*	*e*	R^2	*RMSE*	*MBE*	*MAE*	*MPE* (%)
							(MJ·m^{-2}·day^{-1})			
Nsukka										
1	0.19370					0.64	1.545	–0.761	1.371	–3.497
2	0.74390	–0.04360	0.26650			0.79	1.403	–0.403	1.256	–1.425
3	0.68730	0.45950	–0.00475			0.97	0.848	–0.574	0.719	–2.816
4	0.19967	–0.01538				0.65	1.580	–0.545	1.448	–2.069
5	0.84470	0.76886	0.03213			0.83	0.954	0.287	0.760	1.837
6	–0.17341	0.41810				0.89	0.749	–0.058	0.589	–0.103
7	0.11998	0.98137	–0.35660			0.89	0.756	–0.057	0.588	–0.088
8	0.14959	0.64575	0.32340	0.58370		0.89	0.745	–0.060	0.591	–0.128
9	0.18960	0.66090				0.89	0.745	–0.060	0.591	–0.128
10	0.26310	1.34230				0.89	0.754	–0.057	0.590	–0.092
11	0.16640	0.33500	1.27100	0.05130		0.96	0.665	–0.316	0.595	–1.422
12	0.96518	1.09280	–0.00364	0.04022	0.12930	0.96	0.715	–0.251	0.619	–0.991
13	–0.05614	0.01010	0.49080			0.67	1.345	–0.067	1.085	0.450
14	0.72110	0.65619				0.87	0.797	–0.065	0.650	–0.162
15	0.18822	0.66092				0.89	0.745	–0.060	0.591	–0.128
Abakaliki										
1	0.19890					0.72	1.940	–1.325	1.723	–6.644
2	0.67410	0.74186	0.30730			0.68	1.919	–1.407	1.645	–7.263
3	0.51548	0.45682	–0.00260			0.96	0.855	–0.625	0.679	–3.231
4	0.15671	–0.10970				0.73	1.960	–1.370	1.720	–6.931
5	–0.22470	0.51676	0.02022			0.76	1.265	–0.579	0.940	–2.836
6	–0.16490	0.43270				0.84	0.934	–0.132	0.723	–0.445
7	0.30371	0.23277	0.51168			0.85	0.905	–0.137	0.746	–0.529
8	0.18107	0.64490	0.34095	0.57797		0.84	0.910	–0.134	0.732	–0.489
9	0.22340	0.65501				0.84	0.910	–0.134	0.732	–0.489
10	0.28095	1.33646				0.83	0.949	–0.129	0.727	–0.399
11	0.13047	2.73670	0.05591	–2.34090		0.94	1.124	–0.930	0.977	–4.999
12	0.46659	0.47634	–0.00250	–0.00030	0.01758	0.92	0.785	–0.138	0.564	–0.960
13	–0.02980	0.01271	0.30300			0.86	1.367	–0.975	1.213	–4.968
14	0.72760	0.59057				0.84	0.929	–0.140	0.773	–0.554
15	0.22180	0.65500				0.84	0.910	–0.134	0.732	–0.489
Awka										
1	0.19210					0.68	1.617	–0.969	1.464	–4.747
2	0.77290	0.61263	0.25459			0.72	1.599	–1.080	1.370	–5.570
3	0.54754	0.50465	–0.00320			0.98	0.433	–0.134	0.336	–0.564
4	0.20970	0.04588				0.69	1.645	–1.068	1.437	–5.415
5	–0.36780	0.55141	0.02496			0.84	1.031	0.430	0.889	2.551
6	–0.21800	0.47297				0.89	1.005	0.679	0.867	3.948
7	0.16980	0.91887	–0.27650			0.88	0.994	0.612	0.826	3.611
8	0.16932	0.65194	0.33598	0.62517		0.89	0.993	0.642	0.832	3.760
9	0.21096	0.70304				0.89	0.993	0.642	0.832	3.760
10	0.27360	1.43843				0.90	1.012	0.691	0.883	4.022
11	0.17465	4.37890	0.03430	–4.07510		0.98	0.528	–0.349	0.431	–1.848
12	0.29694	0.45062	–0.0029	–0.01020	–0.00650	0.97	0.516	–0.258	0.404	–1.281
13	–0.06360	0.01110	0.42514			0.79	1.414	–0.927	1.197	–4.694
14	0.73886	0.60382				0.85	1.027	0.553	0.851	3.350
15	0.20945	0.70304				0.89	0.993	0.642	0.832	3.760

Explanations: a, b, c, d, e = new empirical constants, the others as in Table 1.
Source: own elaboration.

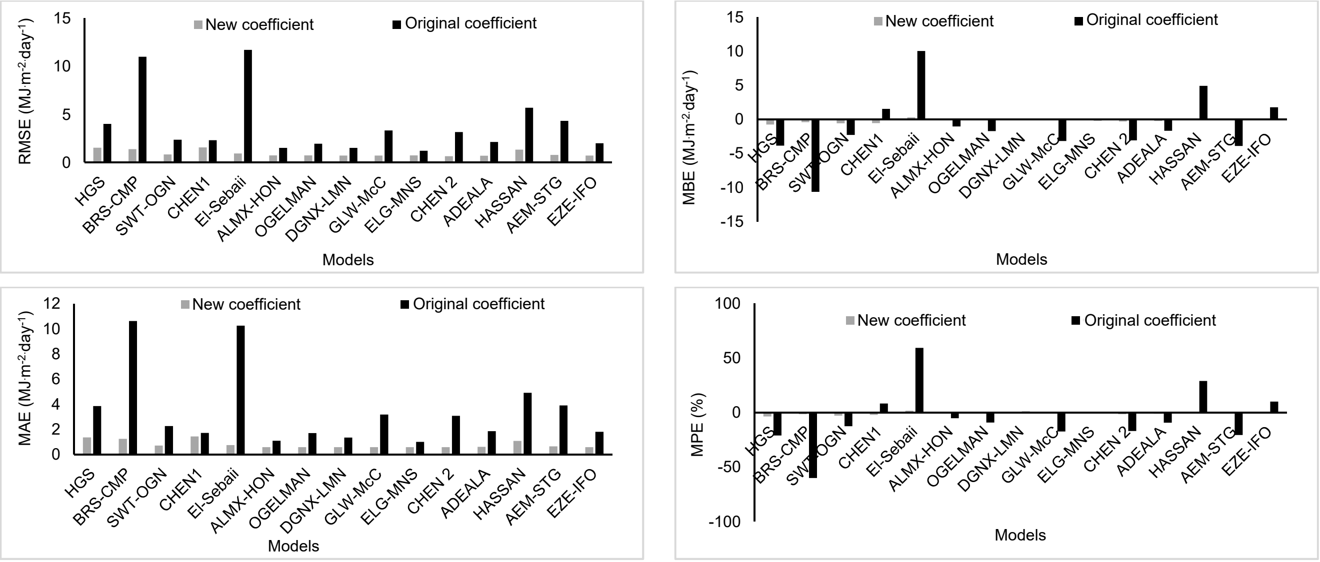
which is 21.19, 24.3 and 20% higher than the recommended 0.16. The result agrees closely with the reported coefficient of 0.1945 by ADARAMOLA [2012] for Akure. In contrast, ADEBOYE *et al.* [2009] reported a constant of 0.16–0.17 for Abeokuta, Ijebu-Ode and Itoikin in South-West Nigeria. The derived coefficients for other *Rs* models are summarized in Table 3. The statistical tests also showed a significantly improvements of each of the *Rs* models (Fig. 1).

In general, R^2 ranged from 0.64 to 0.96, 0.68 to 0.96 and 0.68 to 0.98 for Nsukka, Abakaliki and Awka respectively. Similarly, *RMSE* ranged from 0.79 to 1.58, 0.85 to 1.96 and 0.43 to 1.64 MJ·m^{-2}·day^{-1} for Nsukka, Abakaliki and Awka respectively. The Swartman–Ogunlade (R^2 = 0.96) and Adeala models (*RMSE* = 0.785 MJ·m^{-2}·day^{-1}) performed best while Chen 1 (R^2 = 0.73) and Bristow–Campbell (*RMSE* = 1.91 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs* in Abakaliki. At the Nsukka station, Swart-

a) Nsukka



b) Abakaliki



c) Awka

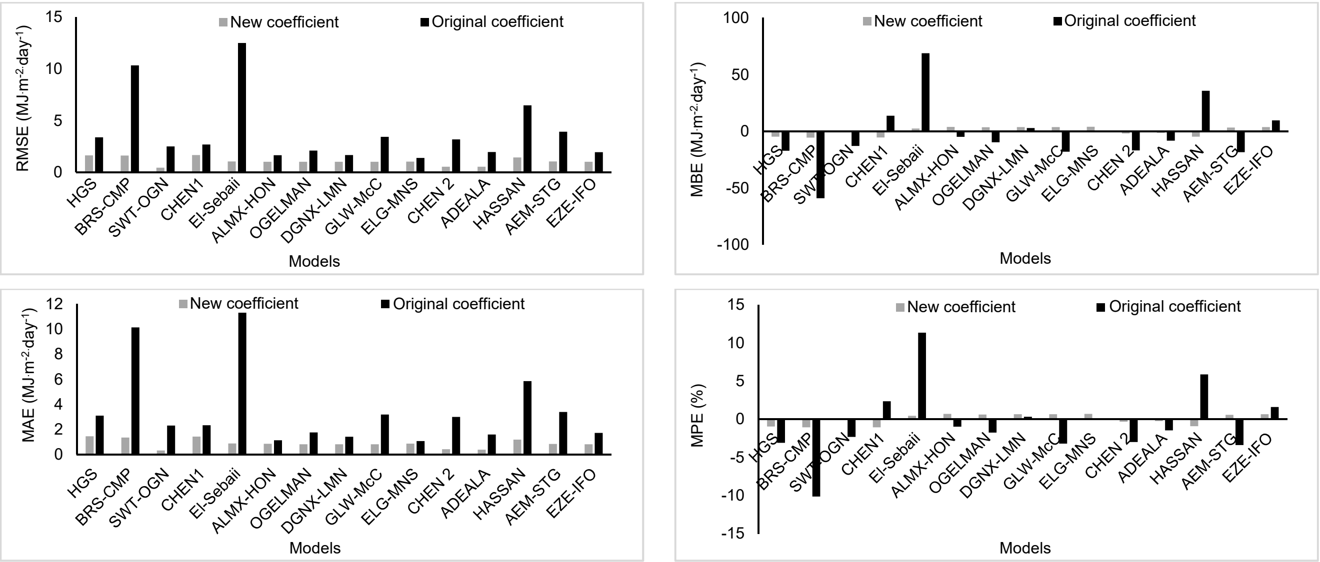


Fig. 1. Comparison of statistical tests for *Rs* estimated using the original constants and the original and new constants for stations: a) Nsukka, b) Abakaliki, c) Awka; models numbers as in Table 1; source: own study

man–Ogunlade (R^2 =0.97) and Adeala (*RMSE* = 0.715 MJ·m^{-2}·day^{-1}) models performed best while Hargreaves–Samani (R^2 = 0.64) and Chen 1 (*RMSE* = 1.58 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs*. Chen 2 (R^2 = 0.98) and Swartman–Ogunlade models (*RMSE* = 0.43 MJ·m^{-2}·day^{-1}) performed best while Hargreaves-Samani (R^2 = 0.68) and Chen 1 (*RMSE* = 1.64 MJ·m^{-2}·day^{-1}) performed least in estimating *Rs* in Awka. Based on the *MBE* values, all models underestimated *Rs* ranging from –1.407 to –0.129 MJ·m^{-2}·day^{-1} at the Abakaliki station. Similarly, all the models underestimated *Rs* except El-Sebaii model (*MBE* = 0.287 MJ·m^{-2}·day^{-1}) for the Nsukka station. For the Awka station, most models overestimated *Rs* except Hargreaves–Samani, Bristow–Campbell, Swartman–Ogunlade, Chen 1 and 2, and Adeala and the Hassan model. *MAE* ranged from 0.58 to 1.44 MJ·m^{-2}·day^{-1}, 0.56 to 1.72 MJ·m^{-2}·day^{-1}, and 0.33 to 1.46 MJ·m^{-2}·day^{-1} for Nsukka, Abakaliki and Awka respectively while *MPE* ranged from –3.49 to 1.83%, –7.26 to –0.39% and –5.57 to 4.02% for Nsukka, Abakaliki and Awka respectively. Across all sites, there was tremendous improvement in model performance with the new constants. For example, *RMSE* decreased ranging from 32.9 to 88.9%, 32.4 to 91.8% and 26.4 to 91.74% at Nsukka, Abakaliki and Awka stations respectively. Similar decrease was also observed for other statistical indices as shown in Figure 1.

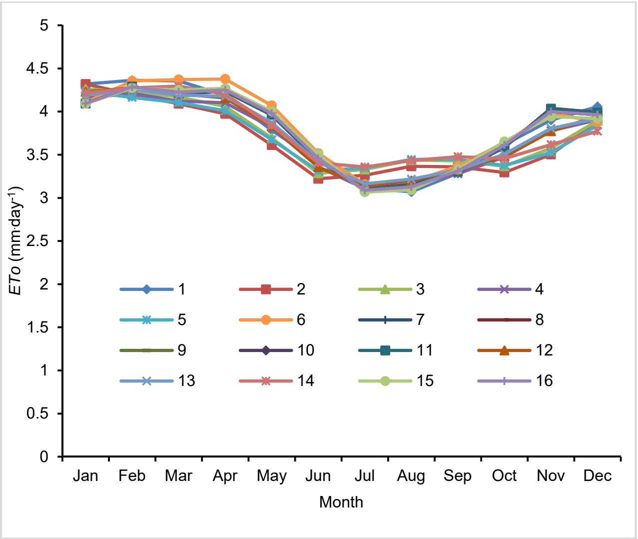
PERFORMANCE OF *ETo* CALCULATED FROM *Rs* ESTIMATES

ETo was calculated using the FAO-PM equation. *ETo* estimates computed using measured *Rs* was compared with *ETo* estimated using calibrated empirical *Rs* models. The temporal variation of *ETo* computed using both methods is shown in Figure 2. It is observed that there was a close match between *ETo* determined using measured *Rs* and *ETo* estimated by the calibrated *Rs* models. The variation of *ETo* across the months is similar to the climate of the region. That is, maximum *ETo* estimates were observed during the dry season (November–March) and minimum *ETo* estimates were observed during the wet season (April–October). The *ETo* trend observed in this study agrees with the report of ECHIEGU *et al.* [2016], ADEKUNLE *et al.* [2017], and DAVIES [1966]. It also agrees in trend but disagree in magnitude with ADEBOYE *et al.* [2009] and EJIEJI [2011].

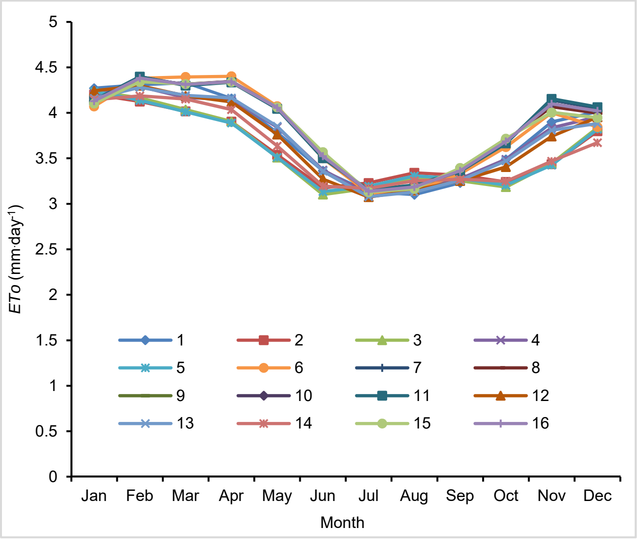
A maximum *ETo* of 4.18 and 4.3 mm·day^{-1} was obtained using measured *Rs* and empirical *Rs* for Awka station. For Abakaliki, maximum *ETo* of 4.4 and 4.3 mm·day^{-1} was obtained using measured *Rs* and empirical *Rs* while a maximum *ETo* of 4.2 and 4.3 mm·day^{-1} was obtained using measured *Rs* and empirical *Rs* for Nsukka station. The results agree with the work of ECHIEGU *et al.* [2016] and ADEKUNLE *et al.* [2017]. ECHIEGU *et al.* [2016] and ADEKUNLE *et al.* [2017] reported a maximum *ETo* of 4.67 and 4.03 mm·day^{-1} for Enugu and Umudike respectively. These areas are within the same agro-ecological zone as our study area.

Furthermore, statistical analysis of each model is analysed and presented in Table 4 using *RMSE*, *MBE*, *MAE* and *MPE*. As seen, the mean error analysis varied from

a) Nsukka



b) Abakaliki



c) Awka

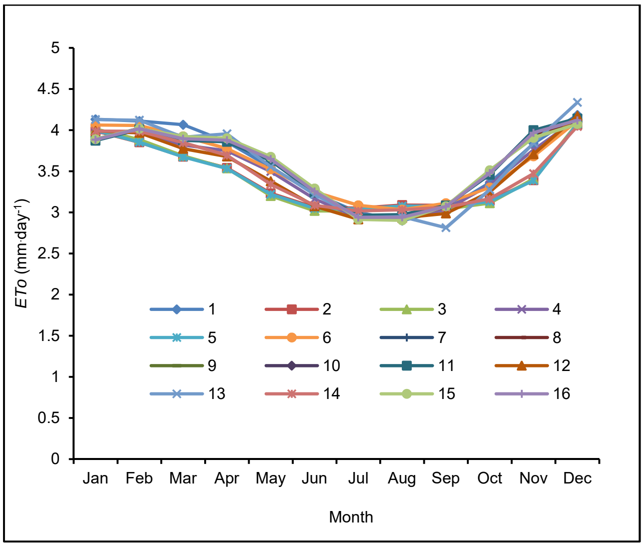


Fig. 2. *ETo* estimates from measured and calibrated *Rs* for: a) Nsukka, b) Abakaliki, c) Awka; models numbers as in Table 1; source: own study

Table 4. Statistical analysis of *ETo* estimates

Model	Nsukkka					Abakaliki					Awka				
	R^2	*RMSE*	*MBE*	*MAE*	*MPE*	R^2	*RMSE*	*MBE*	*MAE*	*MPE*	R^2	*RMSE*	*MBE*	*MAE*	*MPE*
1	0.738	0.2528	–0.1733	0.2219	–4.3842	0.828	0.2271	–0.1152	0.2016	–2.6554	0.838	0.2402	–0.1463	0.2166	–3.5090
2	0.751	0.2507	–0.1838	0.2125	–4.7762	0.844	0.2034	–0.0620	0.1829	–1.1777	0.854	0.2386	–0.1625	0.2036	–4.0747
3	0.939	0.1077	–0.0791	0.0857	–2.0350	0.980	0.1243	–0.0842	0.1051	–2.0100	0.988	0.0644	–0.0197	0.0493	–0.4040
4	0.735	0.2558	–0.1791	0.2217	–4.5687	0.821	0.2298	–0.0831	0.2112	–1.6390	0.839	0.2455	–0.1612	0.2133	–3.9760
5	0.931	0.0908	–0.0285	0.0807	–0.5178	0.919	0.1398	0.0450	0.1108	1.3537	0.911	0.1532	0.0675	0.1312	1.8761
6	0.940	0.1159	–0.0134	0.0912	–0.1739	0.949	0.1088	–0.0069	0.0861	–0.0259	0.942	0.1502	0.1020	0.1285	2.8284
7	0.959	0.1120	–0.0139	0.0940	–0.2078	0.948	0.1098	–0.0069	0.0859	–0.0200	0.935	0.1485	0.0925	0.1226	2.5995
8	0.951	0.1128	–0.0136	0.0923	–0.1924	0.949	0.1083	–0.0070	0.0862	–0.0356	0.939	0.1485	0.0968	0.1235	2.7013
9	0.951	0.1128	–0.0136	0.0923	–0.1924	0.949	0.1083	–0.0070	0.0862	–0.0356	0.939	0.1485	0.0968	0.1235	2.7013
10	0.937	0.1178	–0.0131	0.0916	–0.1502	0.949	0.1095	–0.0069	0.0861	–0.0214	0.942	0.1510	0.1036	0.1308	2.8758
11	0.899	0.1440	–0.1191	0.1248	–3.2029	0.977	0.0970	–0.0466	0.0868	–1.0463	0.984	0.0785	–0.0518	0.0636	–1.3285
12	0.918	0.1003	–0.0180	0.0720	–0.6432	0.975	0.1037	–0.0367	0.0900	–0.7301	0.983	0.0750	–0.0370	0.0588	–0.8875
13	0.858	0.1785	–0.1272	0.1561	–3.2576	0.849	0.1920	–0.0106	0.1560	0.1941	0.890	0.2068	–0.1372	0.1755	–3.4005
14	0.964	0.1150	–0.0142	0.0974	–0.2132	0.940	0.1157	–0.0072	0.0948	–0.0423	0.922	0.1529	0.0843	0.1259	2.4196
15	0.951	0.1128	–0.0136	0.0923	–0.1924	0.949	0.1083	–0.0070	0.0862	–0.0356	0.939	0.1485	0.0968	0.1235	2.7013

Explanations: models numbers as in Table 1.
Source: own study.

one model to another. It is also observed that the models gave a reasonable accuracy for estimating *ETo* as there was a reduction in magnitude in error compared with *Rs*. This was also observed by Aladenola and Madramootoo [2014], and Tabari *et al.* [2016]. This is attributed to more inputs being involved in calculating *ETo*. In summary, R^2 ranged from 0.83 to 0.98, 0.82 to 0.98 and 0.73 to 0.96 for Awka, Abakaliki, and Nsukka respectively. *RMSE* ranged from 0.064 to 0.24 $\text{mm}\cdot\text{day}^{-1}$, 0.097 to 0.22 $\text{mm}\cdot\text{day}^{-1}$ and 0.0908 to 0.255 $\text{mm}\cdot\text{day}^{-1}$ for Awka, Abakaliki, and Nsukka respectively.

Based on *MBE* values, all models overestimated *ETo* except Hargreaves–Samani, Bristow–Campbell, Swartman–Ogunlade, Chen 1 and 2, Adeala and Hassan models for Awka station. For Abakaliki station, all models estimated *ETo* except El-Sebaii model while in Awka, all the models underestimated *ETo* ranging from –0.18 $\text{mm}\cdot\text{day}^{-1}$ to –0.0131 $\text{mm}\cdot\text{day}^{-1}$. Based on R^2 and *RMSE*, the Adeala (R^2 = 0.983, *RMSE* = 0.075 $\text{mm}\cdot\text{day}^{-1}$) and Swartman–Ogunlade models (R^2 = 0.988, *RMSE* = 0.064 $\text{mm}\cdot\text{day}^{-1}$) performed best while the Hargreaves–Samani (R^2 = 0.83 and *RMSE* = 0.24 $\text{mm}\cdot\text{day}^{-1}$) and Chen 1 models ($R^2$ = 0.83, *RMSE* 0.24 $\text{mm}\cdot\text{day}^{-1}$) performed least for the Awka station. In the same vein, Chen 2 (R^2 = 0.97, *RMSE* = 0.097 $\text{mm}\cdot\text{day}^{-1}$) and Swartman–Ogunlade models (R^2 = 0.98, *RMSE* = 0.1243 $\text{mm}\cdot\text{day}^{-1}$) yielded the best *ETo* estimates while Chen 1 (R^2 = 0.82, *RMSE* = 0.22 $\text{mm}\cdot\text{day}^{-1}$) and Hargreaves–Samani models (R^2 = 0.82, *RMSE* = 0.227 $\text{mm}\cdot\text{day}^{-1}$) gave the least performance at the Abakaliki station. At Nsukka, the Angstrom–Prescott–Page (R^2 = 0.96, *RMSE* = 0.11 $\text{mm}\cdot\text{day}^{-1}$) and El-Sebaii model ($R^2$ = 0.93, *RMSE* = 0.0908 $\text{mm}\cdot\text{day}^{-1}$) performed best while Chen 1 (R^2 = 0.73, *RMSE* = 0.25 $\text{mm}\cdot\text{day}^{-1}$) and Hargreaves–Samani models (R^2 = 0.73, *RMSE* = 0.25 $\text{mm}\cdot\text{day}^{-1}$) model performed least.

MBE ranged from –0.18 to –0.013 $\text{mm}\cdot\text{day}^{-1}$, –0.115 to 0.045 $\text{mm}\cdot\text{day}^{-1}$ and –0.16 to 0.103 $\text{mm}\cdot\text{day}^{-1}$ for Nsukka, Abakaliki and Awka respectively. *MAE* ranged from 0.072 to 0.22 $\text{mm}\cdot\text{day}^{-1}$, 0.085 to 0.21 $\text{mm}\cdot\text{day}^{-1}$ and 0.049 to 0.216 $\text{mm}\cdot\text{day}^{-1}$ for Nsukka, Abakaliki and Awka respectively while MPE ranged from –4.77 to 0.15%, –2.65 to 1.35% and –4.07 to 2.85% for Nsukka, Abakaliki and Awka respectively.

CONCLUSIONS

In this study, the performance of fifteen empirical solar radiation models and their impacts on *ETo* estimates using the Penman–Monteith (PM-56) equation in three sites in a humid tropical environment was evaluated. The results showed poor *Rs* estimates using original constant with high *RMSE* for most models. With new developed empirical constants for each site, there was a close match between the empirical models and observed *Rs* as indicated in the R^2 and *RMSE*. The Swartman–Ogunlade (R^2 = 0.96) and Adeala models (*RMSE* = 0.785 $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) yielded the best solar radiation estimate in Abakaliki, Swartman–Ogunlade (R^2 = 0.97) and Adeala (*RMSE* = 0.715 $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) models performed best in Nsukka while Chen 2 (R^2 = 0.98) and Swartman–Ogunlade models (*RMSE* = 0.43 $\text{MJ}\cdot\text{m}^{-2}\cdot\text{day}^{-1}$) yielded the best solar radiation estimate in Awka. The calibrated *Rs* models was then used to estimate *ETo*. Results showed that the calibrated models produced lesser deviations than the *Rs* estimates. In general, *RMSE* < 0.6 and R^2 > 0.7 was observed for all the models at all sites. Specifically, the Adeala and Swartman–Ogunlade models yielded the best *ETo* estimate at Awka, Chen 2 and Swartman–Ogunlade models performed best at Abakaliki while Angstrom–Prescott–Page, El-Sebaii, Swartman–Ogunlade and Adeala models performed best for Nsukka. The results of the calibrated models showed that simple temperature models like Hagreaves–Samani can give a reasonable and accurate *Rs* and *ETo* estimate. Our study harnessed the availability of remotely sensed data from NASA archives. It is also important that studies compare our results with weather stations. The findings of this study can be used as a platform in the South-East region of Nigeria, for irrigation planning, design and management.

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Ocena przydatności wyników równań promieniowania słonecznego do oszacowania ewapotranspiracji potencjalnej (*ETo*) w wilgotnym środowisku tropikalnym

STRESZCZENIE

Promieniowanie słoneczne (*Rs*) stanowi istotny czynnik w trakcie określania ewapotranspiracji potencjalnej (*ETo*) terenów uprawnych. Dokładne oszacowanie *ETo* jest pierwszym etapem ustalania zapotrzebowania na wodę pól uprawnych. Celem tego badania była ocena dokładności piętnastu empirycznych modeli *Rs* i oznaczenie wpływu tego parametru na szacunki ewapotranspiracji w trzech stanowiskach wilgotnego środowiska tropikalnego (Abakaliki, Nsukka i Awka). Wykorzystano archiwalne dane meteorologiczne NASA z lat 1983 do 2003 do wyprowadzenia empirycznych stałych (kalibracja) dla różnych modeli w każdej z trzech lokalizacji, a dane z lat 2006 do 2015 posłużyło do oceny. Wyniki wskazują na większą zgodność mierzonego *Rs* i oszacowanych wartości promieniowania wyznaczonego z zastosowaniem nowych stałych. Po kalibracji modele Swartmana–Ogunladego (R^2 = 0,97) i Chena 2 (*RMSE* = 0,665 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) dawały najlepsze wyniki, podczas gdy modele Chena 1 (R^2 = 0,66) i Bristowa–Campbella (*RMSE* = 1,58 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) były najmniej dokładne w wyznaczaniu *Rs* w Akabaliki. W stacji Nsukka modele Swartmana–Ogunladego (R^2 = 0,96) i Adeali (*RMSE* = 0,785 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) dawały najlepiej dostosowane wyniki oszacowania *Rs*, natomiast modele Hargreavesa–Samaniego (R^2 = 0,64) i Chena 1 (*RMSE* = 1,96 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) najmniej. Modele Chena 2 (R^2 = 0,98) i Swartmana–Ogunladego (*RMSE* = 0,43 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) okazały się najlepsze, a modele Hargreavesa–Samaniego (R^2 = 0,68) i Chena 1 (*RMSE* = 1,64 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) – najgorsze w ustalaniu promieniowania w stanowisku Awka. W oszacowaniach *ETo* modele Adeali (R^2 = 0,98) i Swartmana–Ogunladego (*RMSE* = 0.064 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) dawały najlepsze wyniki w przypadku danych ze stanowiska Awka, a modele Swartmana–Ogunladego (R^2 = 0,98) i Chena 2 (*RMSE* = 0,43 $\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$) okazały się najlepsze w przypadku danych ze stanowiska Abakaliki. W odniesieniu do stanowiska Nsukka najlepsze wyniki uzyskano, stosując modele Angstroma–Prescotta–Page'a (R^2 = 0,96) i El-Sebaii (*RMSE* = 0,0908 $\mathrm{mm \cdot d^{-1}}$).

Słowa kluczowe: *ewapotranspiracja potencjalna, kalibracja, ocena, promieniowanie słoneczne*