

Original Research Article

Predictive performance of Hargreaves model in estimating solar radiation in Yola, Adamawa state Nigeria using minimum climatological data.

ABSTRACT

Mathematical models have been very useful in reducing challenges encountered by researchers due to the inability of having solar radiation data or lack of instrumental sites at every point on the Earth. This work aimed at investigating the prediction performance of Hargreaves-Samani's model in estimating global solar radiation (GSR) out of the many other empirical models so far formulated for this purpose. This model basically uses maximum and minimum temperature data and basically used in mid-latitudes. The paper attempts to assess the predictive performance of Hargreaves-Samani's model in the Savanna region using Yola as the case study. Estimated values of GSR from one month data adapted from the Meteorological station of the Department of Geography, Federal University of Technology, Yola, Nigeria was used for this purpose. Using this model shows a 95% index of agreement (IA) with the observed values; which suggests a good model performance and can also be used in estimating global solar radiation in the Savanna region particularly in areas with little or no such climatic data.

Key words: *Global Solar radiation, air temperature, model validation, extraterrestrial radiation*

INTRODUCTION

The energy transferred from the sun in the form of radiant to the earth's surface is normally referred as the solar radiation. In any solar energy conversion system, the knowledge of global solar radiation is important for the optimal design and prediction of the system performance [1]. Thus, the urgent requirement for daily weather data such as minimum ($T_{\min}$) and maximum ($T_{\max}$) air temperatures, rainfall, and global solar radiation (GSR) become necessary in order to effectively model the tools or mechanisms involved in management of phenomena employing these weather data, such as those mentioned previously [2]. The potential amount of radiation that can reach the Earth's surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons.

The best way of knowing the amount of global solar radiation at a site is through recorded data. Daily solar radiation data are often required in agro-metrological calculations particularly in computing a water budget for irrigation or to run a crop growth simulation model but these are measured only at a few stations [3]. In fact, at global scale, the ratio of weather stations collecting solar radiation data relative to those collecting temperature data is estimated to be a ratio of 1:500 [4].

Solar radiation data on the earth's surface is required for engineers, agriculturists and hydrologists in many applications. Solar energy is free, clean and inexhaustible source of energy. Its effective harnessing and utilization are of importance to the world especially at this time of rising fuel costs and environmental effects such as depletion of the ozone layer and greenhouse effect. The potential amount of radiation that can reach the Earth's surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons [2].

A number of formulae and methods have been developed to estimate GSR. Many studies have been calculated to estimate incoming solar radiation in Nigeria [5]. Angstrom (1924) was the first scientist known to suggest a simple linear relationship to estimate global solar radiation. Later on Prescott (1940) put the correlation in a convenient form as:

$$\frac{R_s}{R_a} = a + b \frac{S}{S_o} \quad (1)$$

Where:

R_s – the global solar radiation ($\text{MJ m}^{-2}\text{day}^{-1}$),

S – the real sunshine (h),

S_o – the day's length (h),

R_a – the extraterrestrial radiation ($\text{MJ m}^{-2}\text{day}^{-1}$),

a and b are coefficients of Angstrom's formula.

Different models use different approaches for estimating the coefficient “ a ” and “ b ” [5].

Hargreaves and Samani (1982) correlated solar radiation (R_s) with temperature and extraterrestrial radiation. Allen (1997), calculated mean global solar radiation following the work of Hargreaves and Samani (1982), [5].

HARGREAVES-SAMANI EQUATION

Based on the knowledge that the difference between the maximum ($T_{\max}$) and minimum ($T_{\min}$) air temperature is influenced by the degree of cloud cover, humidity and solar radiation [1]. Hargreaves and Samani (1985) used the phenomenon as an indicator of the fraction of extra-terrestrial radiation (R_a) that reaches the earth's surface namely global solar radiation (R_s). They formulated a model that is empirical in nature with the form:

$$R_s = R_a K_r (T_{\max} - T_{\min})^{0.5} \quad (2)$$

Where $T_{\max}$ and $T_{\min}$ are the mean daily maximum and the minimum air temperature ($^{\circ}\text{C}$) respectively, k_r is adjustment coefficient, which is empirical in nature and has different values for 'interior' and 'coastal' regions. For 'interior' locations, where land mass dominates and air masses are not strongly influenced by a large water body, k_r is approximately 0.16. For 'coastal' locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, k_r is about 0.19. The extraterrestrial radiation, R_a is given in Hargreaves and Samani (1985) as:

$$R_a = \left(\frac{24(60)}{\pi} \right) G_{sc} dr \{ W_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin W_s \} \quad (3)$$

Where:

R_a is extraterrestrial radiation $\{\text{MJ m}^{-2} \text{ day}^{-1}\}$;

G_{sc} is solar constant $= 0.0820 \{\text{MJ m}^{-2} \text{ min}^{-1}\}$;

dr , inverse relative distance Earth-Sun,

ω_s , sunset hour angle $\{\text{rad}\}$,

φ , latitude $\{\text{rad}\}$,

δ , solar declination $\{\text{rad}\}$.

Hargreaves-Samani model explicitly accounts for solar radiation and temperature. Although relative humidity is not explicitly contained in the equation, it is implicitly present in the difference in maximum and minimum air temperature. The temperature difference is linearly related to relative humidity [6].

Other predictive modeling techniques which have been developed by Scientist in the past to predict thermal performance of solar energy system has shown that a knowledge-based machine learning model can help precisely predict the performances of some energy systems utilizing some simple independent variables as the computational inputs. With a proper machine learning algorithm, people only need to acquire a sufficient experimental database as well as perform the model training and testing, and then a predictive model can be acquired.

[7]

Machine learning is a powerful technique for numerical prediction, classification and pattern recognition, which has been widely used in chemical, medical, biological, environmental and energy areas **[8]**. Fortunately, machine learning, as a powerful technique for nonlinear fitting, is able to help us precisely acquire the values of coefficient of thermal performance (CTP) with the knowledge of some easy-measured independent variables. With a sufficiently large database, a machine learning technique with appropriate algorithms can “learn” from the numerical correlations hidden in the dataset via a nonlinear fitting process and perform precise predictions. Machine learning has also proven to be a powerful technique during the past decades. Artificial neural network (ANN), as one of the most popular machine learning algorithms, has been widely applied to various areas. However, their applications for catalysis were not well-studied until recent decades. **[9]**. Machine learning methods includes; Principles of an artificial neural network (ANN), Training of an ANN and Testing of an ANN. **[8]**.

Support Vector Machine (SVM) is also a powerful machine learning method based on statistical learning theory. On the basis of the limited information of samples, SVM has an extraordinary ability of optimization for improving generalization. The main principle of SVM is to find the optimal hyperplane, a plane that separates all samples with the maximum margin. The plane helps improve the predictive ability of the model and reduce the error which occurs occasionally when predicting and classifying **[10]**

MATERIALS AND METHODS

The study area, Yola is located on latitude 9.23° North of the Equator and longitude 12.46° East of the Greenwich Meridian a dry large mass land that lies within the savanna region.

Temperatures can rise up to about 40°C around March/April. The wind speed within this region is averagely 2 ms⁻¹ and possibly exhibits inversion properties unlike what is obtainable in the mid-latitudes. The samples for this study shown in Table. 1 were adopted from the Meteorological station, Geography Department, Federal University of Technology, Yola recorded between March 1st and 31st 2011. The samples include minimum (T_{min}) and maximum (T_{max}) air temperatures with their corresponding global solar radiation observed value. Table 2, shows the results of Equations (1) and (2) done in Microsoft Excel environment. It includes the extraterrestrial radiation (Ra) and the calculated global solar radiation (Rs).

Model Testing and Assessment

Index of Agreement (IA) can be an alternative to r (correlation coefficient) and r² (coefficient of determination) [11] and IA is a relative and bounded measure, while r and r² are not consistently related to the accuracy of prediction [12]. The “high” or statistically significant values of r or r² may be misleading as they often are unrelated to the size of difference between observed (O_i) and predicted (P_i) values. IA determines the extent to which mean magnitudes of O_i are related to the predicted deviations about O_i, and allows for sensitivity toward differences in O_i and P_i as well as the proportionality changes [1]. IA is given by

$$IA = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i - O_i| + |P_i + O_i|)^2}, \quad 0 \leq IA \leq 1 \quad (4)$$

Also, index of agreement IA is a statistical measure of the correlation of the predicted and measured concentrations [1]. The index of agreement calculated for the predicted and observed value in this study is 95%. This shows that there is very good agreement between the observed and predicted values of GSR, indicating a good model performance.

171 Table 1.Diurnal predicted and observed values in Yola, March, 2011.

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S/N	OBSERVED R _s (KWH)	PREDICTED R _s (KWH)
1	19	17.58628
2	19	16.91505
3	18.5	17.62675
4	17.9	17.64927
5	19.4	18.34046
6	14.3	17.69883
7	21.5	19.35532
8	20.6	17.40948
9	21.5	19.1032
10	20.6	20.07083
11	20.5	19.48876
12	21.5	19.20837
13	19.5	18.5937
14	22	18.6317
15	20.6	17.99185
16	20	17.32361
17	20.1	19.41173
18	22	18.79661
19	21.4	19.50218
20	20.9	17.84592
21	20.9	19.59743
22	20.1	20.29109
23	20.6	19.02928
24	19.3	19.74865
25	15.1	16.56681
26	20.2	16.21119
27	21.3	16.25559
28	20.9	18.58567
29	22.2	18.63791
30	20.9	20.07723
31	19.8	19.79648

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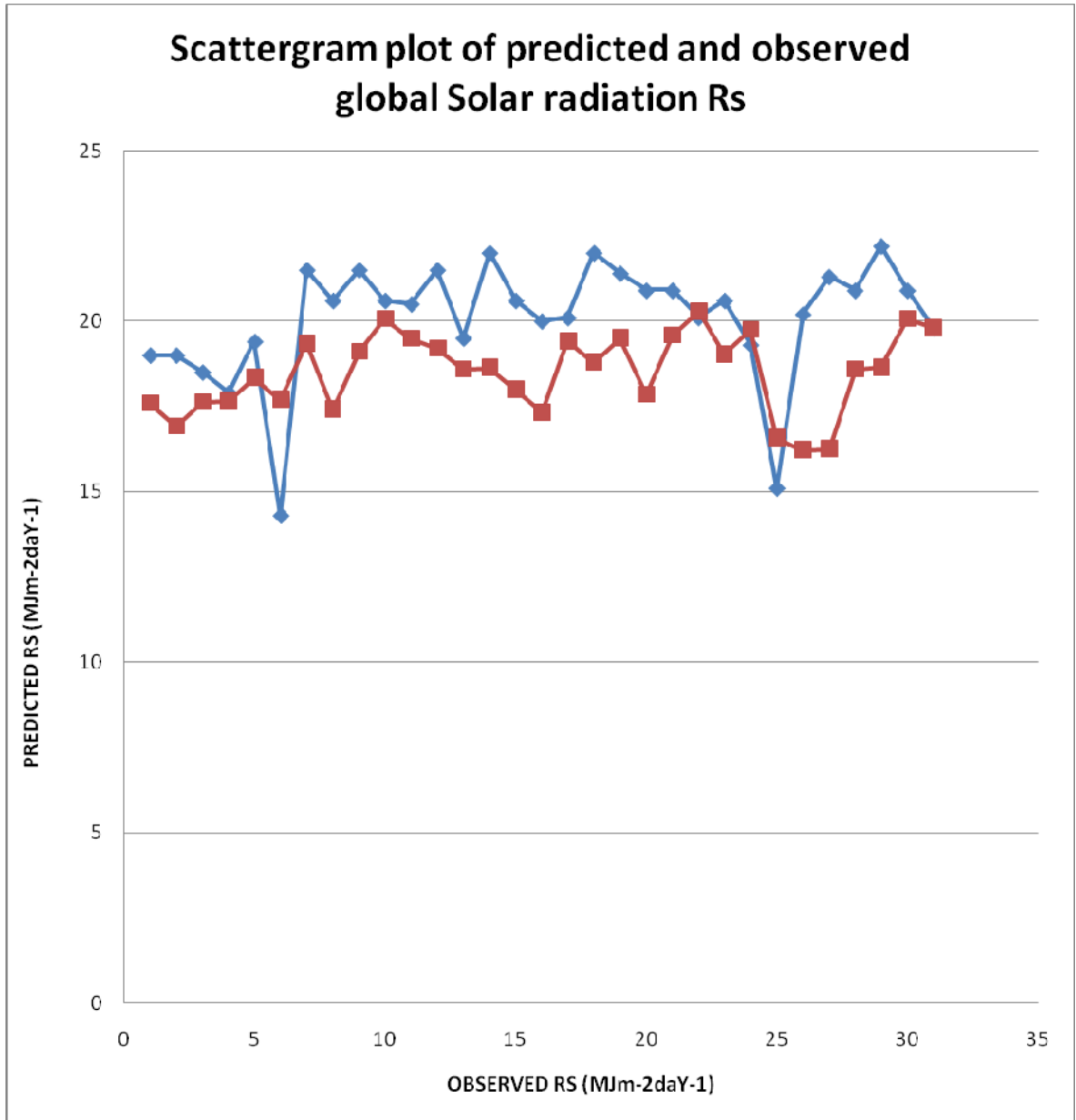
183 Table 2. Temperature measurement and solar radiation (MJ/m⁻²/day) Yola

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s/n	J	dr(Rad)	δ (Rad)	Φ	ω_s	R_a (Rad)	$T_{\max}$ (⁰ c)	$T_{\min}$ (⁰ c)	R_s (KWH)
1	1	1.0033	-0.4010	0.161	1.597175	30.48472	39	26	17.58628
2	2	1.003298	-0.3995	0.161	1.597175	30.51846	38	26	16.91505
3	3	1.003296	-0.3980	0.161	1.597175	30.55487	40	27	17.62675
4	4	1.003292	-0.3963	0.161	1.597175	30.59392	40	27	17.64927
5	5	1.003288	-0.3945	0.161	1.597175	30.63559	42	28	18.34046
6	6	1.003282	-0.3926	0.161	1.597175	30.67982	39	26	17.69883
7	7	1.003276	-0.3905	0.161	1.597175	30.72661	40.5	25	19.35532
8	8	1.003269	-0.3884	0.161	1.597175	30.77590	40	27.5	17.40948
9	9	1.003260	-0.3861	0.161	1.597175	30.82766	42	27	19.10320
10	10	1.003251	-0.3837	0.161	1.597175	30.88186	42	25.5	20.07083
11	11	1.003241	-0.3813	0.161	1.597175	30.93844	41	25.5	19.48876
12	12	1.003230	-0.3786	0.161	1.597175	30.99737	41	26	19.20837
13	13	1.003218	-0.3759	0.161	1.597175	31.05860	40	26	18.59370
14	14	1.003205	-0.3731	0.161	1.597175	31.12208	41	27	18.63170
15	15	1.003191	-0.3702	0.161	1.597175	31.18776	40.5	27.5	17.99185
16	16	1.003176	-0.3671	0.161	1.597175	31.25560	39	27	17.32361
17	17	1.00316	-0.3640	0.161	1.597175	31.32554	40	25	19.41173
18	18	1.003143	-0.3607	0.161	1.597175	31.39753	40	26	18.79661
19	19	1.003125	-0.3573	0.161	1.597175	31.47151	40.5	25.5	19.50218
20	20	1.003106	-0.3538	0.161	1.597175	31.54743	41	28.5	17.84592
21	21	1.003087	-0.3503	0.161	1.597175	31.62522	41	26	19.59743
22	22	1.003066	-0.3466	0.161	1.597175	31.70483	41.5	25.5	20.29109
23	23	1.003045	-0.3428	0.161	1.597175	31.78619	42.5	28.5	19.02928
24	24	1.003022	-0.3389	0.161	1.597175	31.86925	41	26	19.74865
25	25	1.002999	-0.3349	0.161	1.597175	31.95393	37	26.5	16.56681
26	26	1.002975	-0.3308	0.161	1.597175	32.04019	40	30	16.21119
27	27	1.002950	-0.3266	0.161	1.597175	32.12794	40	30	16.25559
28	28	1.002924	-0.3223	0.161	1.597175	32.21712	40	27	18.58567
29	29	1.002897	-0.3180	0.161	1.597175	32.30766	41	28	18.63791
30	30	1.00287	-0.3135	0.161	1.597175	32.39950	41	26	20.07723
31	31	1.002841	-0.3089	0.161	1.597175	32.49256	41.5	27	19.79648

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186 J, Number of the day in the year between (1 January 365 or 366, 31 December), Dr, inverse
187 relative distance earth sun, δ , solar declination, Φ , latitude, ω_s , solar time angle, R_a ,
188 extraterrestrial radiation, $T_{\max}$, maximum air temperature, $T_{\min}$, minimum air temperature, R_s ,
189 solar radiation.



RESULTS AND DISCUSSION

Equation (2) estimates the extraterrestrial radiation (R_a) values for each day in the month of March, 2011. The values are shown in Table 2, which was calculated using equation (2) with the aid of Microsoft Excel software. The mean global solar radiation at the entrance into the earth's atmosphere known as extraterrestrial solar radiation (R_a) obtained for the period in Yola is 31.33 ± 0.01 , $\text{MJm}^{-2}\text{day}^{-1}$. The predicted mean global solar radiation (GSR), R_s for the month under study is 18.49 ± 0.1 , $\text{MJm}^{-2}\text{day}^{-1}$ and the observed is 20.36 ± 0.26 $\text{MJm}^{-2}\text{day}^{-1}$ for Yola. The correlation between the predicted and the observed global solar radiation R_s is 95%. The Index of Agreement (a measure of efficiency of a model) between the predicted and the observed monthly GSR values for Yola is about 95%.

This study has evaluated Hargreaves-Samani model for estimating daily radiation in urban area such as Yola using minimum-maximum air temperatures adopted from meteorological station, Federal university of Technology, Yola to handy. Also from the correlation , index of agreement results and the plot of observed and predicted values of global solar radiation the model has shown itself to be a robust and reasonably accurate method for estimating GSR also in the savanna region. The quality of these estimates varies with environment (urban-rural) and latitude, yet the errors expressed as RMSE between observed and estimated daily solar radiation were in the range of 0.1 to 0.26 MJm⁻²day⁻¹ and are not sufficiently significant. The model has the tendency to overestimate and under predict the lower and higher range of the observed distribution.

SUMMARY AND CONCLUSIONS

Considering the importance of global solar radiation and other climatological phenomena on the events on the Earth's surface including climate changes, agriculture (in the area of crop modeling), existence and so on, there is a need for methods which can estimate these variables with limited data. This paper evaluates one of such methods-Hargreaves-Samani model that estimates solar radiation from latitude and maximum and minimum air temperatures. An adopted minimum-maximum air temperature data from the meteorological station, Geography Department, Federal university of Technology Yola and used in Hargreaves-Samani model, resulted in predicted values that produced an index of agreement of over 95%. This is an excellent indication that the model performs equally well in the savanna region; a place that the environmental conditions are quite different from that of the mid-latitudes. However, considering the uniqueness of climatological data in each month of a year and other environmental factors, the model should be subjected to further validation involving several months data running over six years.

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APPENDIX I

Extraterrestrial radiation (Ra) calculation procedure

The extraterrestrial radiation, Ra, for each day of the year and for different latitudes can be estimated from the solar constant, the solar declination and the time of the year by:

$$R_a = \left\{ \frac{24(60)}{\pi} \right\} G_{sc} dr \{ W_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin W_s \} \quad (1)$$

Where Ra is extraterrestrial radiation [MJ m⁻² day⁻¹];

G_{sc} is solar constant = 0.0820 MJ m⁻² min⁻¹; dr, inverse relative distance Earth-Sun (Equation 2), ω_s, sunset hour angle (Equation 4) [rad], Φ, latitude [rad], δ, solar declination (Equation 3) [rad].

Ra is expressed in the aforementioned equation in MJ m⁻² day⁻¹

The inverse relative distance Earth-Sun, dr, and the solar declination, δ, are given by:

$$dr = 1 + 0.033 \cos(2\pi/365 J) \quad (2)$$

$$\delta = 0.409 \sin\{22\pi/(365 J) - 1.39\} \quad (3)$$

Where J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\{-\tan(\Phi)\tan(\delta)\} \quad (4)$$