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Comparative Analysis and Performance of Empirical Radiation Models for Estimating Crop Water Requirement in Semi – Arid Region of Northern Environment of Nigeria

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ABSTRACT
Water's pivotal role in urban planning and hydrological development is crucial for sustainable progress and fostering a green economy. With 97% of the Earth's surface covered by water, its proper utilization in domestic, industrial, and agricultural sectors is paramount. The study is aimed at determining the comparative analysis and performance of empirical radiation models for estimating crop water requirement in semi – arid region of northern environment of NigeriaIn a recent study, the comparison of empirical radiation equations with the Food and Agricultural Organization's Penman-Monteith 56 model, renowned for its efficacy in modeling reference evapotranspiration across various climatic zones, revealed insightful findings. The analysis highlighted the efficacy of empirical models in estimating reference evapotranspiration in semi-arid and arid regions. Notably, in the comparison between the FAO 56 PM model and newer models, such as the Stephen-Stewart (S-S) and the new ETo model, significant differences in performance were observed. For instance, in Kukawa, the R^2 coefficient was 31.98% for the FAO 56 PM model compared to 99.96% for the S-S and new ETo models. Similarly, the comparison yielded R^2 values of 31.98% and 98.46%, respectively, against the new model. In Jada, the comparison showcased varying levels of success with different models. The FAO 56 PM model achieved a success rate of 51.3%, while the S-S model scored 99.99% in comparison. Additionally Caprio models demonstrated R^2 values of 81.41% and 99.74%, respectively, against the new model. These findings underscore the importance of selecting appropriate models for estimating reference evapotranspiration, especially in arid and semi-arid regions, to enhance the accuracy of hydrological assessments and urban planning initiatives.

Keywords:
Comparative analysis,
Empirical models,
Statistical models,
Agricultural field,
Semi-arid region,
Nigeria.

INTRODUCTION

Water is indeed a critical resource in agriculture, especially as the world's population grows. Agriculture heavily relies on water for various purposes like irrigation, pesticide and fertilizer application, and sustaining livestock (Chartzoulakis and Bertaki 2015; Boretti and Rosa 2019; Islam and Karim 2019). The comparative analysis and performance of empirical radiation models for estimating crop water requirements in a semi-arid region of Northern Nigeria are crucial for optimizing water usage and enhancing agricultural productivity in this specific climatic zone. Research in semi-arid climates emphasizes the significance of evapotranspiration (ET) in agriculture, where the transition of water from liquid to vapor phases influences crop water demand significantly (Raza et al., 2023)

Understanding solar radiation is crucial for various purposes such as architectural planning, weather prediction, solar power utilization, agricultural productivity assessment, electricity generation, and advancements in science and technology (Ibeh et al., 2019). This is particularly significant in the context of comparing and evaluating different empirical radiation models to estimate crop water needs in the semi-arid region of Northern Nigeria.

Empirical models and equations have been proposed and applied to estimate the reference evapotranspiration from green plants and or evaporation from water surface (Antonopoulos and Antonopoulos, 2018; Edebeatu and Okujagu, 2015). These empirical models belong to one of the four categories used in estimating evapotranspiration such as;

i. Radiation model (Antonopoulos and Antonopoulos, 2018)
ii. Temperature model (Edebeatu & Okujagu, 2015; Ototu et al., 2020)
iii. Radiation – Temperature model (Koffi et al., 2020)
iv. Mass transfer method (Edebeatu et al., 2019)
v. Simple linear Regression based models (Edebeatu, 2018) and
vi. Vapour – Temperature methods (Edebeatu, 2017)

MATERIALS AND METHODS

Materials

Metadata - the research was centred in the Sahel Savannah region of Northern Nigeria of Borno and Adamawa States, comprising Jada and Kukawa each respectively

Jada

Jada lies within the Guinea Savanna region Adamawa State Nigeria as its geographical location, between longitude 12.49^0 N and Latitude 8.66^0 E of Greenwich meridian with annual fall of 1004 mm (Allen et al., 1998) and at an elevation of 321 m above mean sea level (MSL). It is locally boarded North by Fofore LGA, Mayo-Belwa to the West, Ganye to the South with international boundary to the East with the Republic of Cameroon (David et al., 2020). The region is characterized by hot and rainy seasons (Ishaku et al., 2011). Peak of rainfall is mostly July to September (Umara et al. 2012). Mean annual rainfall is 1750 mm. (David et al., 2011).

Mean annual evapotranspiration is about record is about 203 mm to1200 mm (NiMET, 2020, Umara et al. 2012). Annual relative humidity is less than 50% and mean minimum and maximum air temperatures of 15.2^o C and 39.7^o C (NiMET, 2020)

Kukawa

Kukawa L. G. A. is in Borno State, North East Nigeria and with geographical coordinators of 12^0 55' 33'' N and 13^0 m 34''12'' E. Elevation of 277 m above mean sea level (MSL) located in Sahel savannah. Kukawa has three weather regimes per year as;

i. Long dry season which starts from November and ends around May;
ii. Short rainy season commencing June and ending September while;
iii. Cold harmattan sets in around December to January;
iv. Annual rainfall ranges between 500 mm to 1000 mm;
v. Average temperature range stood at $(25 – 40)^0$C.

Kukawa is considered as an oil prospecting area by the Nigerian National Petroleum Corporation (David et al., 2020)

Data Extraction

The weather data for this research were retrieved from the archives of the Climate Research Unit (CRU) of the International Water Management Institute (IWMI), University of East Anglia. CRU is an open gridded weather data set. (http://dw.iwmi.org/IDIS_DP/clickandplot.aspxb http://dw.iwmi.org/clickplot/Parameter.aspx?). The data retrieved ranged for a period of ten (10) years and include; minimum and maximum mean daily monthly air temperatures (^{0}C) respectively.

Method

The Abtew (1996) method

The Abtew (1996) method is given after (Faybishenko, 2012) as;

$$ET_{o(ABT)} = k\frac{R_s}{\lambda} \quad (1)$$

Where;

$ET_{o(ABT)}$ = reference evapotranspiration modeled by the Abtew (1996) model (mm/d);

R_s = solar radiation (MJ/m^2/d); k = 0.58

λ = latent heat of vapourization (MJ/kg) = 2.501 – (2.361 Tm x 10^{-3}).

T_{mean} = 2.54 (MJ/kg).

The latent heat of vapourization assumes to be constant at 2.54 MJ/kg.

k = is recalibrated to be 0.88 in this research.

Stephen – Stewart method (S-S)

The Stephen – Stewart (S-S) method is given after Chineke et al., (2008) as;

$$ET_{o(S-S)} = 0.01476(T_m + 4.905)\frac{R_s}{\lambda} \quad (2)$$

Where;

$ET_{o(S-S)}$ = reference evapotranspiration predicted by the Stephen – Stewart model (mm/d);

T_m = mean air temperature (^{0}C);

R_s = solar radiation (MJ/m^2/d);

λ = latent heat of vapourization (MJ/kg) = 2.501 – (2.361 x 10^{-3}) T_{mean} = 2.54 (MJ/kg). The latent heat of vapourization assumes to be constant at 2.54 MJ/kg.

The Caprio (1974) ETo model

The Caprio model is referenced in (Xystrkis and Matzarakis, 2011) as;

$$ET_{o(CAP)} = \frac{6.1}{10^6}(1.8T_m + 1.0)R_s \quad (3a)$$

And used in this work in the form;

$$ET_{o(CAP)} = \frac{6.1}{10^3}(1.8T_m + 1.0)R_s \quad (3b)$$

Where; $ET_{o(CAP)}$= reference evapotranspiration estimated by the Caprio model (mm/d);
T_m = mean air temperature (^{0}C); R_s = solar radiation (MJ/m^2/d).

The compared ETo model

This is a formulation of a new empirical model-based radiation model developed by the authors in the course of the research. Ten years of weather data of temperature and solar radiation were employed in an attempt to calibrate the local empirical coefficient of the proposed reference evapotranspiration model. The model was developed by adopting the simple linear equation of the form;

$$y = ax + c \quad (4)$$

And the model is written as;

$$ET_{o(PROPSED)} = \alpha(1.8T_m + 7.91)R_s \quad (5a)$$

Where; $ET_{o(PROPSED)}$ = new proposed ETo model (mm/d);
T_m = mean air temperature (^{0}C); R_s = solar radiation (MJ/m^2/d);
α = 0.0069 local empirical coefficient for the prediction of reference evapotranspiration in the Sahel savannah of West Africa and at the same time its adjustable to any other climate region;
The final model for the newly proposed ETo model is written as;

$$ET_{o(PROPOSED)} = 0.0069(1.8T_m + 7.91)R_s \quad (5b)$$

RESULTS AND DISCUSSION

Results

Kukawa Station

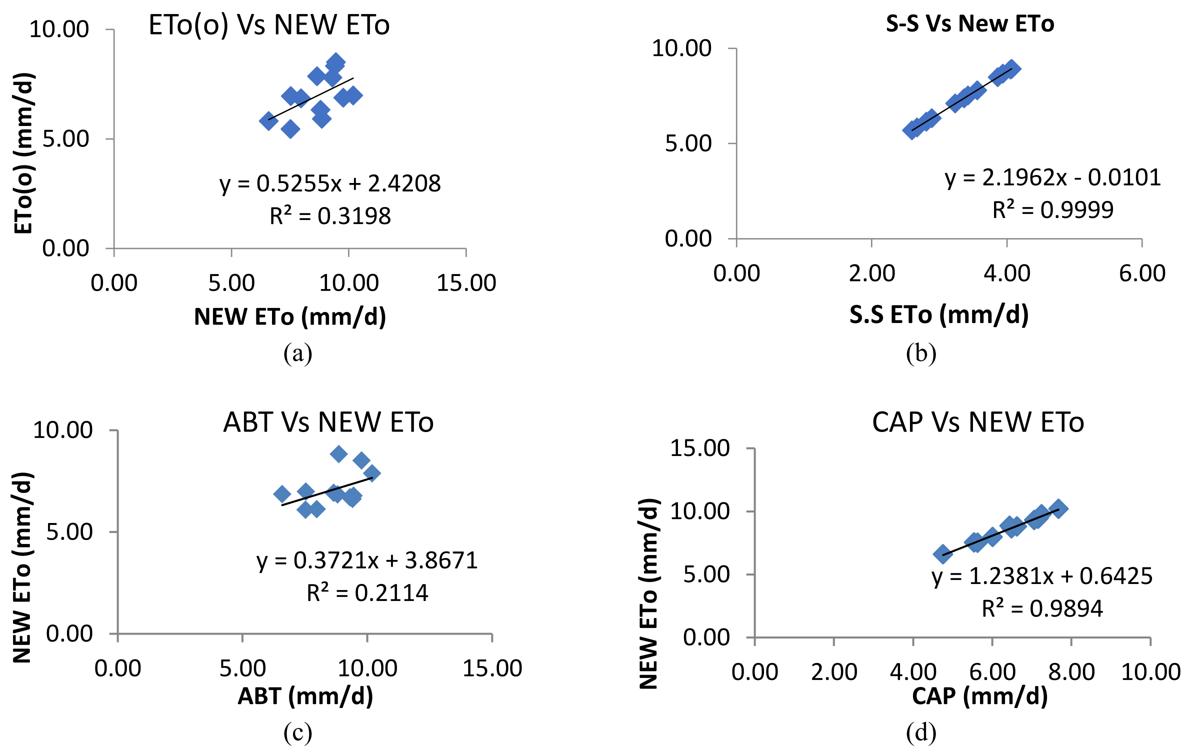

Figure 1: Comparison between (a) FPM 56 & New ETo, (b) S-S & New ETo, (c) and (d) CAP & New ETo (mm/d) in Kukawa station

Jada Station

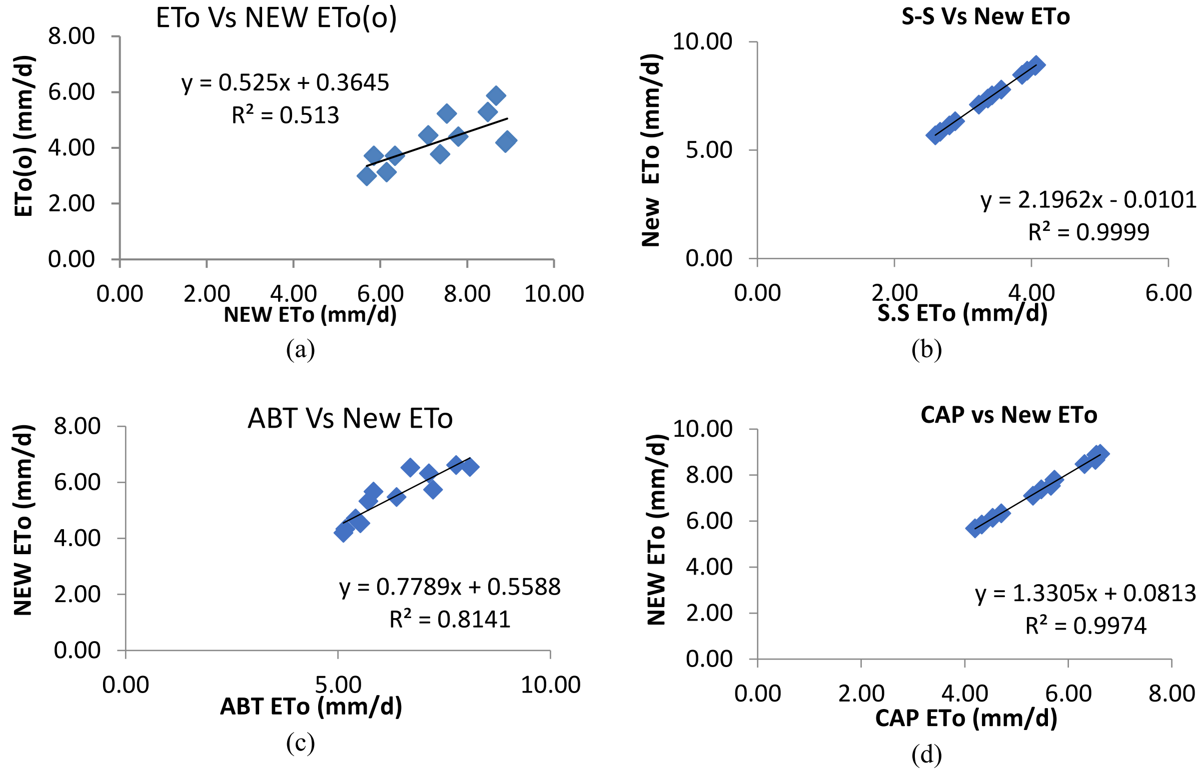

Figure 2: Comparison between (a) FPM 56 & New ETo, (b) S-S & New ETo, (c) and (d) CAP &New ETo (mm/d) in (mm/d) in Jada station

Discussion

Kukawa Station

The FAO-56PM model recorded two (2) standard ETo values in the first growing season and it occurred in November and February. The months of March to June as the second growing season recorded two (2) standard ETo values at 7.87 mm/d and 7.80 mm/d respectively. The third planting of the year fall within the rainy season. Three standard values of the ETo mmodels were recorded in the months of July at 6.85 mm/d, September at 6.33 mm/d and October at 6.99 mm/d. The S-S model under estimated the entire seasons, a condition that requires the re-calibration of its local empirical coefficient. The Abtew (1996) ET_o model in the first planting season recorded half ($^1/_2$) seasonall standard values. The second and the third planting seasons had ($^4/4$) or full seasonal standard ETos. The Caprio had in the first planting season a half ($^1/_2$) valued standard seasonal modelling of the ETo. The second quarter of the growing season recorded ($^4/_4$) or full seasonal standard ETo, while the final quarter of the growing season were with ETo values of three – quarter ($^3/_4$) seasonal standard. The proposed model recorded half ($^1/_2$) standard values in the first and third growing seasons of the period under review, whereas the second growing season were entirely over estimated.

The mean annual average daily ETo values of the models were observed as follows; S-S at 3.95 mm/yr, its RMSE at 0.87 mm/yr.; MBE at 0.89 mm/yr. and IR at 1.78 mm/yr. Abtew (1996) at 7.09 mm/yr with RMSE value at 0.33 mm/yr; MBE at 0.17 mm/yr. and IR at 1.00 mm/yr. Caprio at 6.48 mm/yr and RMSE ETo value of 0.24 mm/yr; MBE 0.08 mm/yr and IR at 1.08 mm/yr. The minimum and maximum mean ambient air temperatures were recorded as follows; T_{max} 36.4 ^{0}C, T_{min} 20.56 ^{0}C, T_{mean} 28.49^0 C and (Tmax – Tmin) or Td 15.84^0 C. The mean annual average daily solar radiation is 20.47 MJ/m^2/yr.

The statistical error analysis (SEA)

Jada Station

The FAO-56PM model ETo and the estimated model of the S-S at the site of Jada recorded low ETo values respectively. The entire seasonal ETo values were under predicted by the both models. The implications of under prediction by any ETo model implies the modification of its empirical local coefficient, especially if the model is being applied in another climate region as a result of climate change and global warming. The FAO-56PM and S-S models recorded maximum under estimation at 5.87 mm/d and 4.7 mm/d in the month of March and November respectively, while minimum ETo values were at 2.99 mm/d and 2.60 mm/d both in the month of

August apiece. The Abtew (1996) ETo model recorded standard seasonal ETo signatures between the months of January to March, and October and November with a maximum ETo value in the month of November at 7.78 mm/d. The minimum under predicted ETo value occurred at 5.12 mm/d in the month of August. The Caprio ETo model had only four (4) months of standard Value predictions. Maximum ETo value occurred in the month of November at 6.62 mm/d, whereas the minimum ETo value is 4.20 mm/d and it occurred in the month of August again. The newly introduced ETo model recorded six (6) months of standard ETo signatures in January, April to June and then September and October. July and August were under estimated, while the rest to the months were over estimated.

The mean annual average ETo values of all the models showed that S-S and Caprio were under modelled, whereas only the Abtew (1996) and the newly proposed ETo model had valued standard mean annual daily average ETo of 6.34 mm/d and 7.40 mm/d respectively. The maximum and minimum ambient air temperatures were recorded at 37.55^0 C and 16.04^0 C in the months of March and January respectively. The maximum solar radiation occurred in the December at 23.39 MJ/m^2/d

The mean annual daily maximum and minimum surface air temperatures occurred at 33.12^0 C and 20.16^0 C, whereas the mean annual average daily solar radiation stood at 18.31 MJ/m^2/d.

The statistical error analysis (SEA) models of S-S recorded RMSE ETo value of 0.04 mm/d minimum in December and a maximum of 0.56 mm/d in the month of March. Both occurred in the first growing season of the year. The mean average value stood at 0.25 mm/d. MSE ETo values had standard values of 0.00 mm/d in the month of first growing season between November and December as minimum, while maximum MSE ETo of .034 mm/d was recorded in the month of March which is regarded as the transition period (eve of the growing season). The index of agreement IR recorded above 1.00 mm/d for the entire season with an average of 1.26 mm/yr. The Abtew (1996) statistical ETo models of RMSE and MSE recorded a maximum of 1.13 mm/d and 1.40 mm/d in December. IR maximum statistical ETo value was found to be 0.88 mm/d in the month of the transition periodd of March. Caprio RMSE and MSE ETo values had a synchronized maximum and minimum in November - December, and April respectively, while IR maximum and minimum occurred in the months of April and November - December respectively. The newly proposed model recorded RMSE and MSE ETo values in the months December and July as maximum and minimum values respectively, the IR were found to register in the months of April and December as maximum and minimum respectively.

Empirical Comparison of Simple Radiation Models

The NEW radiation ETo model were compared to the FAO – 56PM and the other empirical radiation models to ascertain the credibility and effectiveness of the NEWLY proposed model in its evaluation and performance process in the semi – arid Savanna for agricultural region of Nigeria (Sokoto and Maiduguri) which lay within the extreme North East and North West of Nigeria.

Kukawa

Penman – Montieth (FAO-56PM) and the NEW ETo yielded a coefficient of determination of R^2 of 0.3198 or 31.98%. S-S and NEW ETo had R^2 of 0.9996 or 99.96% accuracy. The ABT with NEW model n comparison yielded an R2 of 0.2114 or 21.14%, while CAP and NEW ETo model was found to record an R^2 of 0.9894 representing 98.94% success in the comparative analysis of the empirical radiation modelling of reference evapotranspiration.

Jada

The comparison of the modelled ETo values at the station of Jada showed that the FAO-56PM against the NEW ETo recorded a coefficient of determination R^2 of 0.523 representing 52.3% success of the agricultural farming. S-S and the NEW ETo recorded R^2 of 0.9999 which represents 99.99% accuracy of farming season and success in the agricultural yield. The ABT and NEW ETo had R^2 of 0.8522 which is 85.22% accuracy of the modelled values, while the CAP and NEW ETo recorded coefficient of determination of 0.9974 or 99.74% successful modelling of the agricultural field in the Semi – arid Savanna region.

CONCLUSION

In regions like Northern Nigeria, where water scarcity is a pressing issue, the evaluation and calibration of empirical models for estimating crop evapotranspiration play a critical role in sustainable agricultural practices. By leveraging empirical equations based on solar radiation and other easily measured parameters, farmers and policymakers can make informed decisions to optimize water use, enhance crop productivity, and mitigate the impact of arid conditions on agriculture. The findings of this study emphasize the importance of selecting appropriate models for estimating reference evapotranspiration, especially in arid and semi-arid regions, to enhance the accuracy of hydrological assessments and urban planning initiatives

DATA AVAILABILITY STATEMENT

The data is publicly available at (http://dw.iwmi.org/IDIS_DP/clickandplot.aspxb http://dw.iwmi.org/clickplot/Parameter.aspx?).

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