Australian Journal of Basic and Applied Sciences, 6(7): 26-32, 2012
ISSN 1991-8178

Comparison of Four Empirical Models for Estimating Crop Evapotranspiration in Semi-Arid Nigeria

[1]B.G.Umara, [2]M.M. Aliyu, [3]A.B. Umaru and [4,5]A.S. Abdullahi

[1]Department of Agricultural and Environmental Resources Engineering
University of Maiduguri, Borno State, Nigeria
[2]Department of Civil Engineering, Ramat Polytechnic Maiduguri, Nigeria.
[3]Department of Agricultural Engineering, Federal University of Technology Yola, Nigeria.
[4]Agricultural and Bioresource Engineering Programme, Abubakar Tafawa Balewa University, Bauchi, Nigeria
[5]Department of Biological and Agricultural Engineering University Putra Malaysia, 43400 Serdang Selangor, DE. Malaysia.

Abstract: The study predicted Evapotranspiration of Maize Grain and wheat using FAO 56-Penman-Monteith (FPM), FAO 24-Blaney-Criddle (FBC), Jensen-Haise (JHM) and Hargreaves (HGM) methods. To achieve this, Four ETo prediction models were evaluated using daily meteorological data. Three of the models were compared with FAO 56 Penman-Monteith equation as the standard recommended for semi-arid region by FAO. Climatic data comprising of rainfall distribution from 1996-2005 of Maiduguri, Borno State Capital and suitable crop coefficients (Kc) were employed to predict ETo and crop evapotranspiration (ETc) of maize grain and Wheat for this region. The predicted ETc values were first compared using regression analysis and were further examine using correlation analysis. Results from these analyses shows that, HGM ($R^2 = 0.978$) gave the best result for predicting ETc of Maize grain with correlation coefficient of 0.989. Meanwhile, JHM ($R^2 = 0.910$) yields the best estimate for predicting ETc of Wheat (winter crop) with correlation coefficient of 0.954. In view of the foregoing, it is recommended that, HGM can be used for summer crops for predicting ETc, while JHM can be adopted for winter crops in the event of non availability of reliable climatic data to embark upon FPM for predicting ETc in this region. It is also recommended that further studies should be carried out on other winter and summer crops adopting this approach with a view to re- validating the outcome of this research.

Key words: Evapotranspiration, Prediction, Maize, Wheat, Semi- Arid.

INTRODUCTION

Drought is one of the major problems threatening food security in the Sub-Sahelian Region. Borno State, located in semi-arid zone of North-eastern Nigeria is one of the states that experiences acute aggravated drought due to desertification, particularly the northern part of the state. This is a recurring hazard and one of the most serious ecological problems in the State. The intensity of the problem when it occurs, however, increases northward towards the Sahara. Drought results in the wilting of crops due to insufficient precipitation resulting into wide-spread crop failure, drying up of rivers, lakes, ponds, falling groundwater table among others (Anon 2003).

Other implications of drought, according to (Anon, 2003) are the loss of livestock, diseases, famine, rural-urban migration, and other hardships. During the drought years of 1972/73 and 1983/84 some stations in Borno, towns like Monguno, Kukawa, Damasak and Mallam Fatori, recorded less than 250 mm of rainfall and this cause a concern to agriculturists, meteorologists, hydrologists and environmental scientists Anon(2003). Hence, the need for efficient and accurate application of irrigation water to ensure sustainable management of water resources cannot be overemphasise. This can be achieved by obtaining accurate and reliable Evaporation Data. Hence, the need for a simple, suitable and reliable model for predicting reference evapotranspiration (ETo) that requires less climatic data is very vital for the design of suitable irrigation system. To achieve this, ETo prediction models are to be evaluated using daily meteorological data.

Evapotranspiration is a combination of two processes, evaporation and transpiration. Evaporation is the process whereby liquid (water) is converted to water vapour (vaporization) and removed from the evaporating surface.

Transpiration on the other hand, consists of vaporization of liquid contained in plant tissues and the vapour removal to the atmosphere. The combination of these processes is termed as ET and is been controlled by factors such as: crop type, crop management, crop growth stage and environmental factors.

Corresponding Author: A.S. Abdullahi, Department of Biological and Agricultural Engineering University Putra Malaysia, 43400 Serdang Selangor, DE. Malaysia
E-mail: aasadiq68@yahoo.com

Several methods for evaluating ET exist. However, (Moreno *et al*., 2009) classify the methods of estimating ET into two major groups; the empirical with lower data requirements and the physically-based ones which requires proportionately more data. The main objective of this study is to predict Evapotranspiration of Maize Grain and wheat using FAO 56-Penman-Monteith (FPM), FAO 24-Blaney-Criddle (FBC), Jensen-Haise (JH) and Hargreaves methods. Predicted values of the three empirical models are to be compared with the FPM which is considered accurate and reliable for this region as recommended by many literatures.

MATERIALS AND METHODS

Study area:

The study was conducted in Maiduguri (11.51^o N, 13.05^{o}E, and 345m above mean sea level) in the semi-arid zone of North-eastern region of Nigeria. The region has a climate, which is hot and dry for a greater part of the year all through, while the southern part of the state is slightly milder. The period of wet season varies from place to place due to the influence of the various climatic factors such as the direction of the rain bearing winds and topography, but generally the rainy season is normally from June to September (Kindersley 1999).

The area is highly susceptible to drought. Both wind and water erosion are evident, but wind erosion is more pronounced. The average relative humidity of the area is about 49% and evaporation of 203 mm per year Algon (2005).

Empirical Models:

Models credited to FAO Penman-Monteith, Modified FAO-24 Blaney-Criddle, Hargreaves and Jensen-Haise was employed in this study. Each of the models requires climatic data for the computation of ET_o and actual crop evapotranspiration (ET_c) for Maize grain and Wheat. Weather data comprising of the mean monthly rainfall, relative humidity and wind speed, maximum and minimum temperature were collected from Federal Ministry of Aviation, Meteorological agency, Maiduguri, Borno state**.**

F.A.O Penman-Monteith:

F.A.O Penman-Monteith used to evaluate the reference evapotranspiration for the respective growing seasons of the crops under study. The F.A.O Penman-Monteith model is expressed as:

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

-Where:-

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

$R_n = Net\ radiation\ at\ the\ crop\ surface\ (mJm^{-2}d^{-1})$

$G = Soil\ heat\ flux\ density\ (mJm^{-2}d^{-1})$

$T_{mean} = Mean\ air\ temperature\ at\ 2m\ height$ (^{o}C)

$u_2 = Wind\ speed\ at\ 2m\ height\ (ms^{-1})$

$(\rho_s, \rho_a) = Saturated\ and\ actual\ vapour\ pressure\ respectively\ (K_{pa})$

$\Delta, \gamma = Slope\ vapour\ pressure\ curve\ and\ Psychometric\ constant\ respectively, K_{pa}$ ^{o}C

The monthly values of :

$\Delta, R_n, G, U_s,$

$\rho_s and\ \rho_a\ as\ defined\ from\ the\ above\ equation\ was\ calculated\ and\ some\ are\ obtained\ as\ follows$:

$$ETo = \frac{4098\left[0.6108\,exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)\ (Allen\ et\ al.,1998)$$

Where:-

T=Mean monthly air temperature (^{o}C)

$$R_n = R_{ns} - R_{nl} \tag{3}$$

$$R_{ns} = (1-\alpha)R_s \tag{4}$$

$R_n = K_{RS} \times (T_{max} - T_{min})^{0.5} \times R_a$ (Allen *et al*., 1998)

$$T_{mean}K^4 = \frac{T_{max}K^4 + T_{min}K^4}{2} \tag{5}$$

$$R_{nl} = \frac{\sigma T_{max} K^4 + T_{min} K^4 (0.34 - 0.14\sqrt{\rho_a})\left(1.35 \frac{R_s}{R_{so}} - 0.35\right)}{2} \quad (6)$$

$$R_{so} = (0.75 + 2 \times 10^{-5} \times Z) R_a \,.. \quad (7)$$

$$G = \frac{(C_s T_i - T_{i-1} \times \Delta_z)}{\Delta_z} \quad (8)$$

The monthly values of soil heat flux density G were calculated as follows:-

$$G = 0.07(T_{month\ i} + 1 - T_{month,} i - 1) \quad (9)$$

Or, if T_{month}, i-1 is unknown;

$$G_{month} = 0.14(T_{month} - T_{month i-1}) \quad (10)$$

$$G_{month} = 0.14(T_{i+1} - T_{month}), if\ T_{month}, i - 1\ is\ unknown.$$

The psychometric constant (γ) was obtained from based on the latitude of the area under study by interpolation. The monthly values of wind speed obtained from meteorological station at 10m height were converted to 2m height as follows:

$$U_2 = \frac{U_z 4.87}{l_n(67.87 - 5.42)} \quad (11)$$

Where:-

$U_2 = Wind\ speed\ at\ 2m\ above\ ground\ surface\ (ms^{-1})$

$U_z = measured$ wind speed at Zm above ground surface (ms^{-1})

Z=height of measurement above ground surface (m)

The monthly values of ρ_s and ρ_a were calculated as follows:-

$$\rho_s = \frac{\rho_{smax} + \rho smin}{2}$$

$$and\ \ \rho_a = \frac{RH_{mean} \times \rho_s}{100} \quad (12)$$

Where:-

$R_s = Solar\ or\ shortwave\ radiation\ (mJm^{-2}d^{-1})$

$R_{ns} = net\ solar\ radiation\ (mJm^{-2}d^{-1})$

$R_{so} = Clear - Sky\ solar\ radiation\ (mJm^{-2}d^{-1})$

$R_{nl} = net\ long\ wave\ radiation\ (mJm^{-2}d^{-1})$

$\alpha = Albedo\ or\ coefficient\ of\ reflectiveness$

$\sigma = Stefan - Boltzmann\ constant\ (4.903 \times 10^{-9} mJK^{-4}m^{-2}d^{-1})$

$C_s = Soil\ heat\ capacity\ (2.1\ mJm^{-3}\ ^{o}C^{-1})$

$T_i = Mean\ air\ temperature\ for\ next\ month$ (^{o}C)

$T_{i+1} = Mean\ air\ temperature\ for\ previous\ month$ (^{o}C)

$\Delta_Z = Efficient\ soil\ depth\ (m)$

$\Delta_t = length\ of\ time\ interval\ (day)$

$Z = Station\ elevation\ above\ mean\ sea\ level\ (m)$

Modified Blaney-Criddle Method:

The modified Blaney-Criddle approach used in evaluating ETo is presented as:-

$$ET_o = C[P(0.46T + 8)] \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (13) (Doorenbos\ and\ Pruitt, 1977)$$

Where:-

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

T= mean daily temperature in ^oC, over the month considered

P= mean daily percentage of total annual day time hours

C=adjustment factors which depends on minimum relative humidity, Sunshine hours and day time wind estimate.

ETo values for each month were estimated for the respective seasons using the values of P (0.46T+8) calculated.

Hargreaves method:

Hargreaves used to estimate the ETo for the respective growing seasons of the crops under study is presented as follows:-

$$ET_o = 0.0023 \times (T_{mean} + 17.8) \times (T_{max} - T_{min})^{0.5} \times R_a \ldots \ldots (14)\ (Allen\ et\ al., 1998)$$

Where:-

$ET_o = reference\ evapotranspiration\ (mJm^{-2}d^{-1})$

$T_{max} = Maximum\ air\ temperature\ in\ o_C$

$T_{min} = Minimum\ air\ temperature\ in\ o_C$

$R_a = Extraterrestrial\ radiation\ in\ \ (mJm^{-2}d^{-1})$

The values of ETo calculated using the above model were converted to mm/day by a conversion factor of 0.408. Meanwhile, the values of ETo computed using the above model was calculated for the respective growing seasons of the crops.

Jensen-Haise Method:

In this case, the ETo values were estimated using the constants C_T and T_X together with mean air temperature (T_{mean}) and solar radiation R_S, as shown below:-

$$ET_o = C_T(T_{mean} - T_X) \times R_s \qquad (15)$$

The constants C_T and T_X in equation (3.15) were calculated using the following equations:-

$$C_T = \frac{1}{\left[\left(45 - \frac{h}{137}\right) + \left(\frac{365}{\rho_{smax} - \rho_{max}}\right)\right]} \qquad (16)$$

$$T_X = 2.5 - 0.14 \times (\rho_{smax} - \rho_{max}) - \frac{h}{500}$$

$$R_s = K_{RS} \times (T_{max} - T_{min})^{0.5} \times R_a$$

$$K_{RS} = 0.16\ (Allen\ et\ al., 1998)$$

Crop coefficient (K_c):

The respective crop coefficient for Maize grain and Wheat, for the various growth stages were estimated using F.A.O irrigation and drainage paper-46 (Smith, 1992).

Crop Evapotranspiration (ETc):

The daily ET_c for the crops were estimated by multiplying ETo computed using the above mentioned models by the respective crop coefficients (K_c) mathematically as shown below:

$$ET_c = ET_o \times K_c \qquad (19)$$

The computed values of ETc were subjected to statistical analysis from which correlations of the three methods with that of the FAO 56-Penman-Monteith (FPM) equation as a standard for comparison were determined with a view to identifying a model that is simpler and requiring less climatic data than that of FPM.

FAO 56-Penman-Monteith model was used as the standard for comparison with the other three models because it has been recommended for adoption by panel of experts as a new standard for predicting reference evapotranspiration. Additionally, the equation has been tested and compared by (Jensen *et al*., 1990; Lee *et al*., 2004; Yodel *et al*., 2005; Nghi *et al*., 2006; Rasul and Mahmud, 2006; Alkaeed *et al*., 2007; Moreno *et al*., 2009; Trajkovic and Gocic, 2010; Latha *et al*., 2011) with direct methods of measuring ET such as Piche, Pan Evaporation and Lysimeters in different regions of the world, where it has been found to be the best, reliable, most accurate and most suitable model to use for predicting ETo.

RESULTS AND DISCUSSION

Table 1 shows the values of monthly ETc for Maize crop predicted for the four Empirical models used. From the result it shows that FPM has the least average ET value of 4.1 mm/day. This clearly indicates that FPM and JHM are the best in terms of performance to reveal evapotranspiration of maize crop. Figure 1 also shows the plots of ETc using FPM versus ETc computed using the other three methods. Coefficient of determination (R^2) has been widely used for the evaluation of ''goodness of fits'' of ET models, as such it was also employed in this study. However, to minimise the level of errors that may arise due to the application of R^2 as noted by (Yoder *et al*., 2005) correlation coefficients of each of the three tested models against the standard equation were determined.

Table 1: Predicted ETc using the four models for Maize crop through the growing season

Month	FBCM ETc (mm/day)	HGM ETc (mm/day)	JHM ETc (mm/day)	FPM ETc(mm/day)
June	3.3	2.4	2.9	2.7
July	5.9	4.3	4.0	3.9
August	6.9	5.1	4.3	4.6
September	7.7	6.4	5.8	5.3
October	5.9	5.8	5.9	4.7
November	3.7	4.4	4.8	3.8
Average Seasonal ETc (mm/day)	5.6	5.0	4.6	4.1

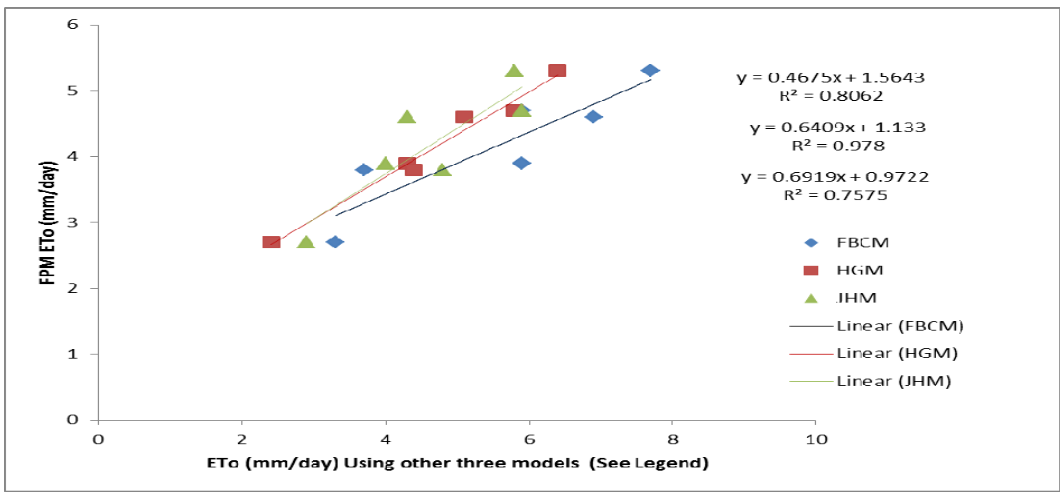

Fig. 1: ETo (mm/day) of FPM against ETo(mm/day) of other three methods for Maize Grain from June-November

The study revealed that Hargreaves method (HGM) yields the best comparison (R^2=0.978), followed by modified FAO24 Blaney-Criddle model (FBCM) with (R^2=0.8062), while the least estimator is the Jensen-Haise method (JHM) with (R^2=0.7575) for maize grain in the study. Furthermore, additional examination of the regression analysis was made using correlation analysis, yielding correlation coefficients of 0.989, 0.898 and 0.870 for HGM, FBCM and JHM respectively. Thus, confirms the results obtained using the regression analysis. These results reaffirmed the suggestion of (Drooger and Allen, 2002) that HGM can be used as a good alternative for estimating ET where data are not available for the adoption of FPM. Table 2 shows the predicted ETc for the wheat crop in this region through the crop's growing season. Figure 2 shows that, JHM (R^2=0.910) is the best estimator, followed by FBCM (R^2=0.896), while the least estimator is the HGM (R^2=0.472) which overestimates the ETc at upper range and some portions of the middle range (See Figure 2). In addition to the above analysis, correlation analysis was also applied to confirm the results and correlation coefficients of 0.954, 0.946 and 0.687 were found for JHM, FBCM and HGM respectively. It therefore, confirms the results obtained using the regression analysis.

Table 2: Predicted ETc using the four models for Winter Wheat through the growing season

Month	FBCM ETc (mm/day)	HGM ETc (mm/day)	JHM ETc (mm/day)	FPM ETc (mm/day)
November	3.2	3.6	3.9	3.1
December	4.5	4.7	4.2	4.1
January	5.5	6.2	6.0	5.5
February	4.3	5.1	5.3	4.6
March	2.8	5.6	4.1	3.3
Seasonal ETc (mm/day)	4.1	5.0	4.7	4.1

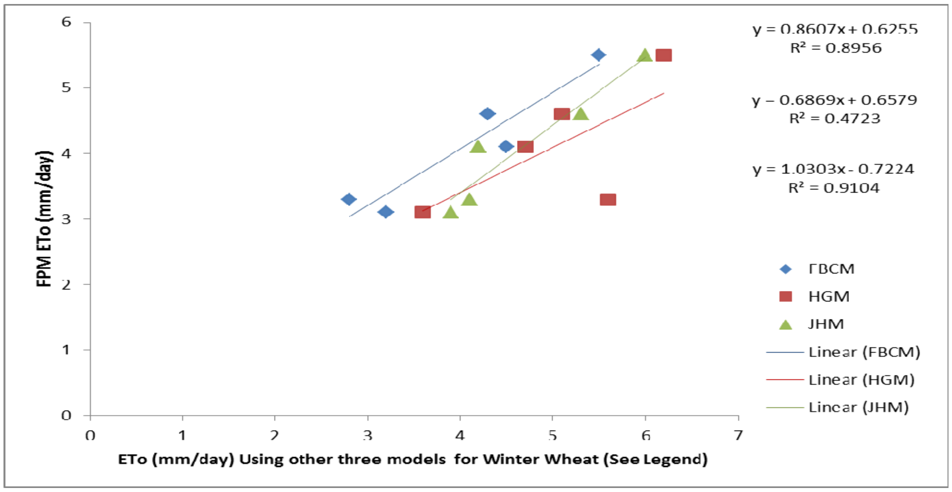

Fig. 2: ETo (mm/day) of FPM against ETo (mm/day) of other three methods for Winter Wheat from November to March

Conclusion:

Four empirical models for evaluating ETo namely:FAO56 Penman-Monteith (FPM), FAO24 Blaney-Criddle (FBCM), Hargreaves (HGM) and Jensen-Haise (JHM) were used to determine ETc of Maize grain and Wheat using meteorological data for Borno state, Nigeria. The FPM as recommended by FAO (Allen *et al.*, 1998) was used as the standard method for comparison with the other methods mentioned above. Two statistical analyses namely correlation and regression were used as the basis for comparing the standard and the other methods, so as to obtain the most simple, reliable and suitable equation in the event of non availability/unreliability of climatic data in the region.

The results showed that, HGM ($R^2 = 0.978$) has the best fits when compared with the other three methods using FPM as the standard for comparison for Maize grain, while JHM ($R^2 = 0.910$) gives the best estimate for winter Wheat. Further evaluation showed the same pattern of results obtained using regression, with HGM having correlation coefficient of 0.989 for Maize grain, while JHM has correlation coefficient of 0.954 for the Wheat crop as compared with the other two methods. The least estimator, therefore, is the JHM for the Maize grain, which underestimates ETc at both upper and lower range, mostly overestimation at the upper range with wider deviation from line of best fits. Meanwhile, for the Wheat the least estimator is the HGM which underestimates ETc with wider deviation at the middle range and overestimates ETc at the upper range with increase in the deviation from the line of best fits as the range increases.

Thus, it can be concluded that HGM is suitable for predicting ETc for summer crops in this region, while JHM can be used to predict ETc for winter crop whenever climatic data are insufficient to evaluate ETo using FPM.

It is also recommended that further studies should be carried out on other winter and summer crops adopting this approach with a view to re- validating the outcome of this research.

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