Volume 1 No. 3, September 2011 ISSN 2224-3577
International Journal of Science and Technology

http://www.ejournalofsciences.org

Comparisons of Measured and Empirical Potential Evapotranspiration in Ilorin, Nigeria

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ABSTRACT

Four potential evapotranspiration (PET) prediction models were assessed for reliability in relation to actual evapotranspiration (ET) obtained from the soil water balance equation. The models tested were the modified Penman, Thornthwaite, Turc and Blaney-Morin-Nigeria (BMN). Using the crop coefficient (Kc) of the reference crop as the conversion factor, the actual ET computed from the soil water balance equation was transformed to its potential equivalent (ET_s) which was used as the standard of comparison for evaluating the other four ET models. Good correlation was found between the ET values computed by both the modified Penman and the Thornthwaite in relation to ET_s. Performance statistics showed that both the modified Penman and Thornthwaite models yielded similar results, followed by BMN and the Turc models in descending order. However, the Thornthwaite model with correction factors is recommended for the region because of the relative ease of data generation associated with its computation.

Keywords: *Soil water balance, evapotranspiration, crop coefficient, models performance*

1. INTRODUCTION

Good irrigation scheduling and agricultural water management require accurate estimates of potential evapotranspiration (PET). The methods used for calculating PET from weather data that have been developed and tested for varying geographical and climatologic conditions vary from simple empirical relationships to complex methods based on physical processes such as the Penman combination method [1]. Evidence from literature indicate that the modified Penman (Penman – Montheith) method is superior to all other commonly used models for computing reference crop evapotranspiration (ET) and it is now widely used by agricultural researchers for irrigation [2]. This is only applicable when the required data are available and reliable [3]; [4]. However, when the full range of meteorological data are not available, empirical relationship to estimate some of the variables have to be assumed and the Penman equation, although theoretically sound becomes increasingly empirical [5]; [6]. In such situations, the use of simpler PET models whose data requirements are less vigorous to generate than those of Penman becomes important. Such a scenario led to the use of an artificial neural network (ANN) for computing reference PET in Burkina Faso [7]. The availability of temperature data even in most remote areas of the world makes the use of the Thornthwaite method with correction factors still very attractive [4]; [8].

According to Fisher et al. [9], reference crop evapotranspiration is a major component in terrestrial water balance and net productivity models, but it is difficult to measure and predict. An understanding of the water balance of a catchment is necessary to appreciate the role of various management strategies in minimizing the losses and maximizing the utilization of water, which is the most limiting factor of crop production. Water requirements of crops are met by the supplies from soil, which acts as reservoir for water. The amount of water held by the soil depends on the inputs and losses from the system and the holding capacity of the soil. Major sources of water in the field are rainfall and irrigation, while losses include surface runoff, deep percolation out of the root zone or drainage, evaporation from the soil surface and transpiration from the crop canopy (evapotranspiration). With the soil water balance equation, one can identify periods of water stress or excesses which may have adverse effect on crop performance. To date, little or no studies have been conducted to test the reliability and predictive ability of different PET estimation methods in the northcentral region of Nigeria, especially when compared with measured ET values.

The objective of this study was to evaluate the reliability and predictive ability of four potential ET models as compared to that evaluated from the soil water balance equation using field and meteorological data generated in Ilorin, north central Nigeria.

2. THEORY AND METHODS

Experimental site

Two years study was carried out in Ilorin, northcentral Nigeria to ascertain the reliability and predictive ability of four potential evapotranspiration models in relation to the ET obtained from the soil water balance equation. Ilorin is 370 m above sea level and lies on Longitude 4° 30’ East and Latitude 8° 26’ North with average annual precipitation of about 1000 mm. Rainfall within the ecology is bimodal. Details of the study area have been reported elsewhere [10].

Reference crop evapotranspiration (ET)

Four empirical prediction models used in the study for the computation of ET_o were modified Penman using a computer software CRIWAR (Crop Irrigation Water Requirement of a Cropped Area), Thornthwaite, Turc and Blaney-Morin-Nigeria (BMN). The modified Penman and BMN models are of the combination type; Turc is radiation based, while Thornthwaite is temperature-based. The choice of the different methods was aimed at covering all commonly used approaches in the prediction of ET in relation to data availability.

The modified Penman equation is given as:

$$ET_o = \frac{\frac{Po}{P} \cdot \frac{\Delta}{\gamma} R_n + 0.26\,(1 + B_u)(e_a - e_d)}{\frac{Po}{P} \cdot \frac{\Delta}{\gamma} + 1} \qquad (1)$$

Where:

ET_o = the reference crop evapotranspiration (mm/day)

P_o and P = means air pressure at sea level and forcasted place (hP_a)

Δ = rate of change of the saturated vapour pressure with Temperature

γ = psychrometric constant

e_a = saturation vapour pressure (hP_a)

e_d = actual vapour pressure (hP_a)

R_n = net radiation in equivalent evaporation (mm/day)

u = mean daily wind speed at 2m height (m/s)

Bu = modified coefficient of wind speed.

The Thornthwaite equation is given as:

$$\text{PET (unadjusted} = 16\left[10\frac{T}{I}\right]^a \text{ mm/month.} \qquad (2)$$

Where:

T = mean monthly temperature, °C,

I = 'heat index' for the 12 months in a year, where

$I = (T/5)^{1.514}$ for each month in the year

$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.792 \times 10^{-2} I + 0.49239.$

The Turc equations are as follows:

$$ET_p = 0.4\,\frac{(T)}{T+15}\,(R_s + 50) \qquad (3)$$

for RH > 50% and

$$ET_p = 0.4\,\frac{(T)}{T+15}\,(R_s + 50)\,\frac{(1+50-RH)}{70} \qquad (4)$$

for RH < 50% and

where:

ET_p = potential evapotranspiration (mm/day)

T = mean air temperature, °C

RH = mean relative humidity, %

R_s = solar radiation (mm) evaluated as:

$$R_s = 90.25 + 0.5n/N)\,R_a \qquad (5)$$

in which n/N is the ratio between actual to maximum possible bright sunshine hours and R_s is the extra – terrestrial radiation. Values of R_a and N were obtained from standard tables for different latitudes and times of the year.

The Blaney-Morin-Nigeria (BMN) ET model has the form:

$$ET_p = r_f\ (0.45T + 8)(520 - R^{1.31})/100 \qquad (6)$$

Where r_f is ratio of maximum possible incident radiation outside the atmosphere to the annual maximum; T is temperature in °C; R is relative humidity, %. The mean monthly ET, is a daily mean (mm/day) by month computed using mean monthly weather data in the above equations.

Crop evapotanspiration (ET_{crop})

The actual evapotranspiration values for the reference crop (soyabean) where computed from the soil water balance equation given as:

$$ET_a = P - R - D \pm \Delta S \qquad (7)$$

Where:

ET_a = Actual evapotranspiration (mm)

P = Precipitation or rainfall (mm)

R = Runoff (mm)

D = Drainage (mm)

ΔS = Change in soil moisture storage (mm)

3. DATA COLLECTION AND ANALYSIS

Twelve runoff plots each measuring 3m x 15m were established to monitor runoff and change in soil moisture storage within the catchment. Runoff was measured using multi-divisor flumes, while soil moisture content was determined gravimetrically. Eight lysimeters were installed in eight of the twelve runoff plots planted to soybean. Soybean was also planted in each of the lysimeters. Drainage was measured directly from the drainage lysimeters installed in the runoff plots. Since drainage was recorded in depth (mm), it was assumed, that drainage in the lysimeter is the same with the plot housing it, irrespective of its surface area. Rainfall was measured at the National Centre for Agricultural Mechanization, Ilorin meteorological station where the study was carried out. Using the crop coefficient of the reference crop (K_c) as the conversion factor, the actual evapotranspiration (E_a) computed from the soil water balance equation was transformed to its potential equivalent (ET_s) which was used as the standard of comparison for evaluating the other four empirical models.

Regression and correlation analyses were performed to examine the relationships between the mean monthly ET_o estimates from the four empirical methods and the mean monthly ET_s from the soil water balance equation. The regression equations computed were of the form:

$$Y = mX + C \quad (8)$$

where Y is the transformed water balance evapotranspiration (ET_S); X is the monthly predicted ET by each of the four empirical models; and m and C are slope and intercept, respectively. Root mean square error (RMSE) was used as the main parameter for assessing the reliability of the prediction models in relation to ET by the soil water balance [4]. Coefficient of determination (R^2), the slope of the regression and the absolute average deviation (AAD) between the calculated and predicted ET were also computed. The best prediction model is the one with the lowest absolute average deviation, the smallest RMSE, the highest coefficient of determination (R^2), C value closest to zero, and m value closest to unity [11].

4. RESULTS AND DISCUSSION

The weather data for the period of study are given in Table 1. No appreciable amount of rainfall was received between May and July in 1990 unlike the case in 1991. Rainfall was generally higher in 1991 than in 1990. The mean potential evapotranspiration (Modified Penman) was 4.2mm/day.

Table 1: Summary of climatological parameters for the observation period (1990 – 1991)

Month	Mean air Temp. °C	Rainfall (mm)	Relative Humidity (%)	Sunshine hours(h)	Windspeed (m/sec)
			1990		
May	27.0	83.6	82.0	195.3	1.7
June	26.9	25.9	80.0	180	1.8
July	25.0	206.5	87.0	114.7	1.8
Aug.	25.0	125.6	88.0	148.8	1.6
Sept.	25.3	175.0	88.0	159.0	1.5
			1991		
May	30.0	206.3	82.0	185.4	1.5
June	28.0	197.5	83.0	206.7	1.6
July	26.5	355.4	86.0	124.6	1.6
Aug.	26.0	130.2	87.0	83.7	1.9
Sept.	27.0	246.4	84.0	152.5	1.5

The mean monthly distribution of ET_o values for the four empirical ET models and the ET_s from the soil water balance (SWB) method are presented in Table 2. With the exceptions of the Modified Penman and Thornthwaite models, the other two models under predicted mean ET_s. The radiation based Turc and BMN models, grossly underestimated mean ET_s for the two years of study. The monthly amounts of ET obtained by the Turc model was less than the SWB ET by 39%, while that obtained by the BMN model was less by 23% on the average. Good correlation was found between the reference ET estimates computed by both the modified Penman and Thornthwaite models in relation to that of the ETs. On the average, the modified Penman and the Thornthwaite models were generally good in predicting the mean monthly ETo. The crop coefficient (K_c) generated in Table 2 can be used to plot a crop coefficient curve. The curve is a useful tool for scheduling irrigation of a reference crop under similar climatic and environmental conditions.

Table 2: Mean monthly ET_o for different ET models compared with ET_s from the Soil Water balance

Month	Mean monthly ET(mm/day)						
	K_c	Modified Penman	Thorthwaite	Turc	BMN	ET_a	ET_s
(a) Using measured data for 1990							
June	0.93	4.7	4.9	2.4	3.5	4.0	4.3
July	1.00	3.5	3.6	2.0	2.9	3.3	3.3
August	0.91	3.9	3.6	2.2	2.9	3.4	3.7
September	0.85	4.1	3.7	2.2	2.9	3.4	4.0
(b) Using measured data for 1991							
June	0.93	5.0	5.6	2.5	3.4	4.7	5.0
July	1.00	3.7	4.3	2.0	3.1	4.0	4.0
August	0.91	3.4	3.9	2.3	3.0	3.4	3.7
September	0.85	4.3	4.5	4.5	3.4	4.0	4.7

Table 3 presents summary statistics for the regression of mean monthly ET estimated by each of the four empirical models against that evaluated by the SWB approach. The results indicate that the Thornthwaite and the modified Penman models yielded similar results. Although the Thornthwaite equation has been reported as having some tendency of under predicting ET in semi-arid and arid climates [12], the data from this study show that ET estimates by the Thornthwaite method compared well and even better than some other ET models in sub-humid climates where variations in mean relative humidity and wind speed is not pronounced. The superiority of the Penman model over other ET prediction models in most locations generally has never been in doubt. However, considering the complexity of the formula and the enormity of its data requirements, especially in most developing countries with little or no instrumentation, the performance of simpler models like the Thornthwaite is a welcome relief. The outcome of the regression analyses for the two-year study attest to the reliability of the Thornthwaite method. Its predicted values were in very close agreement with the generally accepted "Standard" Penman model, and was also relatively better than both the BMN and Turc models. These statistical facts are pointers to the preference of the Thornthwaite model over others around the study area, especially during the wet season when the study was conducted. Thus, the simplicity of the Thornthwaite formula coupled with the availability of temperature data even in very remote parts of the country clearly support the adoption of this model over others in the region under reference.

Table 3: Summary statistics for regression of mean monthly ET_o estimated by the four empirical methods against that from soil water balance method

	Method of Estimate			
Year	Modified Penman	Thorthwaite	Turc	BMN
		1990		
Regression	Y = 0.83x + 0.45	Y = 0.52x + 1.75	Y = 2.5x – 1.68	Y = 1.1x + 0.61
R^2	0.95	0.61	0.91	0.55
RMSE	0.25	0.37	1.64	0.81
AAD	0.23	0.33	1.63	0.78
		1991		
Regression	Y = 0.83x + 0.93	Y = 0.74x + 0.96	Y = 0.26x – 3.62	Y = 2.8x – 4.88
R^2	0.95	0.80	0.24	0.96
RMSE	0.29	0.36	1.75	1.18
AAD	0.25	0.33	1.53	1.13

Y = Estimated monthly soil water balance ET (mm/day)
X = Predicted monthly reference ET by each of the four models (mm/day)

The BMN model despite its additional meteorological parameters of relative humidity and radiation factor did not provide a more realistic picture of the mean monthly ET distribution over Ilorin compared to Thornthwaite and Penman models. It may therefore be inferred that air temperature and wind speed are the dominant prarameters controlling ET in Ilorin. More importantly, the data set for the formulation of the BMN model was generated in Zaria (semi-arid northwest Nigeria) and not representative of all sections of the country as pointed out by [13].

The regression parameters (Table 3) show that ET estimates by Thornthwaite and Penman are better than those of BMN and Turc models. These results were in good agreement with earlier findings [12] that ET estimates by Thornthwaite and Penman are quite close for humid stations.

The Turc model yielded the poorest correlation with the soil water balance ET. The great under prediction of ET_s by the Turc model is reflected in the high values of the RMSE and the inconsistent regression parameters of slope and intercept, respectively. This result is however, at variance with those presented by [4] where the Turc method was found as the best predictor of monthly ET among other models including Thornthwaite. The poor performance of the radiation based models could be explained by the conclusions of [4] in their study, namely that methods using directly measured radiation would be better than methods using calibrated data. They therefore suggested that existing equations relating net and solar radiation be verified for the area of application if possible.

Results obtained from this study tend to confirm that empirical ET models yield results that are both site and season specific. Therefore, no sweeping generalization can be made of the superiority of one model over the other except when tested with data from the particular area under reference. Thus, the Thornthwaite model with correction factors for the study region as suggested by [4] is recommended as a good empirical model for ET prediction in the northcentral region of Nigeria and other areas with similar climatic characteristics. The use of this model will make irrigation scheduling and management easy in virtually all communities without recourse to radiation, humidity and windspeed data which are hard to come by.

5. SUMMARY AND CONCLUSIONS

Four methods of estimating potential evapotranspiration consisting of the combination methods: Modified Penman and Blaney-Morin-Nigeria (BMN); the radiation method: Turc; and the temperature-based model: Thornthwaite were evaluated to estimate reference crop evapotranspiration using data from Ilorin, north central Nigeria. The estimates from the four methods were compared with the ET obtained from the soil water balance equation. Good correlation was found between the modified Penman method, Thornthwaite and the potential ET obtained from the soil water balance equation.

The statistical analysis for the 2-year experimental period attest to the reliability of the Thornthwaite model. Its predicted values of ET were in very close agreement with the generally accepted Penman model, and was relatively better than both the BMN and Turc models.

The superiority of the Penman model over other ET prediction models in most locations is never in doubt. However, considering the complexity of the formula, coupled with the enormity of its data requirements especially in most developing countries having little or no instrumentation, its use becomes less attractive in relation to simpler models. Thus, the simplicity of the Thornthwaite formula and the ease of its data generation even in very remote parts of the country tilts the balance in its favour over the other models in the region under consideration.

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