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A Comparative Method of Estimating Energy Limited Evapotranspiration over a Tropical Humid Station in Ibadan, Nigeria

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Abstract: The performance of 2 models for estimating monthly energy limited Evapotranspiration (E_e) was compared for the tropical humid region of the rainforest belt of Nigeria. The models are Thornthwaite, which depends on temperature as the only parameter input and Hargreaves, which utilizes solar radiation and air temperature input. The reference data were obtained from the International Institute for Tropical Agriculture, Ibadan, Nigeria. Performance analysis for the estimated values of the collected meteorological data was made. The Standard Error of Estimate (SEE) and the model error were calculated both on monthly and seasonal basis. The estimated values were correlated with the observed values from lysimeter and it was found that Thornthwaite and Hargreaves models have correlation coefficients of 0.65 and 0.77, respectively and 0.93 and 0.89, respectively in dry season; both have the same coefficient of 0.98 for wet season. The SEE for Thornthwaite and Hargreaves are, respectively 0.68 and 0.90. On the model error for the 2 models, it was found that Thornthwaite gives a smaller error of about -1.22% (i.e., underestimation of about 1 mm yr^{-1}) compared with Hargreaves which is 9.28% (having an overestimation of 4 mm yr^{-1}). Both methods have high significant correlations but Thornthwaite's has a better SEE compared with Hargreaves, except for its overestimation during the dry and underestimation in wet season. The two models, if properly calibrated for the environment in question, are recommended for use as practical methods for estimating energy-limited evapotranspiration when considering the availability and reliability of the input data.

Key words: Energy-limited evapotranspiration, tropical humid, lysimeter, model error, performance

INTRODUCTION

Evapotranspiration in hydrological cycle is considered as the transfer of water from the earth into the atmosphere; it could be by evaporation from surface water and soil and transpiration from vegetation. Energy-limited evapotranspiration is the condition when the soil water is not limiting. It is a potent factor in yield models for drought predictions, irrigation scheduling and soil traficability (Karim, 1991). Thus, it is required that measurement of this evapotranspiration should be carried out from time to time. There are various methods of measuring evapotranspiration, some are direct and others indirect, these methods have been reported widely in literatures. The direct method involves the use of lysimeters (Fritschen *et al.*, 1977) and with an eddy correlation method (Hicks *et al.*, 1975; Moore, 1976; Thompson, 1979). The direct methods are quite laborious, costly, time consuming and difficult to carry out in remote areas. In view of the above associated problems with the direct approaches, the use of the indirect method was encouraged. Some of the indirect methods include the Bowen Ratio/energy balance method (Demead, 1969; Black and McNaughton, 1971; McNaughton and Black, 1973; Droppo and Hamilton, 1973; Gash and Stewart, 1975) the aerodynamic method (Stewart and Thom, 1973; Thom *et al.*, 1975) an eddy correlation/energy balance method (McCaughey, 1978; Tan *et al.*, 1977; Milne, 1979; Spittlehouse and Black, 1980) a stomatal diffusion resistance method (Tan *et al.*, 1977) and a soil water balance method (Calder, 1976; Nnyamah and Black, 1977; Scholl, 1976).

The indirect methods can be classified into three categories (Karim 1991) which are briefly enumerated as follows:

- Models which are based on the physics of evaporation and transpiration, the research of Penman (1948, 1956) is a good example of this approach. The combination equation of Penman account for the effects of temperature, solar radiation, atmospheric humidity and wind speed on evapotranspiration by considering the energy balance and aerodynamic
- Models which are based on temperature. The methods of Thornthwaite (1948) and Blaney and Criddle (1950) are the typical example of this approach.

- Models which are based on the use of radiation as well as temperature. The methods of Jensen and Haise (1963) and Hargreaves (1975) are popularly known for this approach. Other method in this approach include that of Baier and Robertson (1965) who developed eight regression equations that utilize three to six different meteorological variables and the radiation method of Makkink (1957a, b) as described by Doorenbos and Pruitt (1975).

In this research we have chosen two models from the categories a and b above, namely Thornthwaite (1948) and Hargreaves (1975) to simulate the actual evapotranspiration for Ibadan, Nigeria. This is because the parameters required are readily available in any meteorological station in Nigeria. The integrity of the parameters used for this study is high.

MATERIALS AND METHODS

Two empirical formulae were used to simulate evapotranspiration in Ibadan- a tropical humid station. They are that of Thornthwaite (1948) and Hargreaves (1975) which are, respectively described below:

$$E_T = 16\,(N/360)\,(10T_a/I)^t \text{ (Thornthwaite, 1948)} \quad (1)$$

Where I is the temperature index calculated from

$$I = \sum_{1}^{12} \left(T_m/5\right)^{1.514} \quad (2)$$

and

$$t = (6.75\times10^{-7})I^3 - (7.71\times10^{-3})I^2 + (1.79\times10^{-2})I + 0.49 \quad (3)$$

Where T_m is the monthly average temperature; N is the day length in hours and E_T is the estimated actual evapotranspiration using Thornthwaite's model.

The meteorological parameters required for the above scheme is the monthly average temperature which is available in any weather observatory station.

The other scheme that is authored by Hargreaves (1975) is defined as follows.

$$E_H = 0.0135(T_a + 17.78)\,R_s/L \text{ (Hargreaves, 1975)} \quad (4)$$

Where T_a is the average daily temperature in Kelvin, R_s is the global radiation in Watt/m^2 and L is the latent heat of vaporization of water in MJm^{-3}.and E_H is the estimated actual evapotranspiration using Hargreaves' model.

Table 1: Instrumentation at the site and their accuracies

Weather parameters	Instruments	Accuracy
Temperature	HMP35C Temperature/H Probe	±0.2°C
Solar radiation	LI200X Pyranometer	±3%
Evapotranspiration	Lysimeters	±0.2 mm

Table 2: Agroecological characteristics of weather station at Ibadan

Features	Ibadan
Zone	Subhumid
Rainfall	Bimodal
First season	October-April
Second season	September-March
Maximum temperature	27-34
Minimum temperature	20-25
Annual rainfall	1200-1400

The rate of evaporation depends on a number of factors, the 2 most important are the difference between the saturation vapour pressure at the water and the vapour pressure of the air and the existence of a continual supply of energy of the surface. The 2 major weather parameters required by the two models are temperature and solar radiation. Solar radiation is the major source of energy supply to promote the rate of evapotranspiration particularly in the tropics. It is a function of the air temperature and the atmospheric temperature depends largely on the receipt of solar temperature at the earth's surface. Thus, the two models are using the level of energy receipt at the earth surface to predict the rate of evapotranspiration.

Data acquisition and evaluation: Data were collected from the International Institute for Tropical Agriculture (IITA), an agricultural research institute based in Ibadan, Nigeria. Ibadan, the largest city in Africa is located at latitude 7°26'N and longitude 3°5'E and situated near the forest-grassland boundary of southwestern, Nigeria. Infact, the word Ibadan is derived from Eba-Odan, which literally means near the grassland. In Ibadan, we have two seasons namely; the dry-and wet-seasons. The occurrence of which is greatly influenced by its latitudinal location, which is characterized by West African Mosoonal Climate Data collected were both the daily averages of parameters needed in the estimation of energy-limited evapotranspiration based on the models that were used in this study (Table 1). For Thornthwaite and Hargreaves models, weather parameters such as air temperature, solar radiation, day length, E_0 were collected. The instruments used in collecting the weather parameters are listed in Table 2. The reference data (collected with lysimeters) are used to compare the estimated values (from the application of the parameters to each of the models) to the observed values. Data collected were both on daily and monthly averages for a period of 5 years (1990 to 1994).

Data collected were evaluated on monthly basis. Energy-limited Evapotranspiration was then simulated from the two models using Origin Software, version 7.0 .

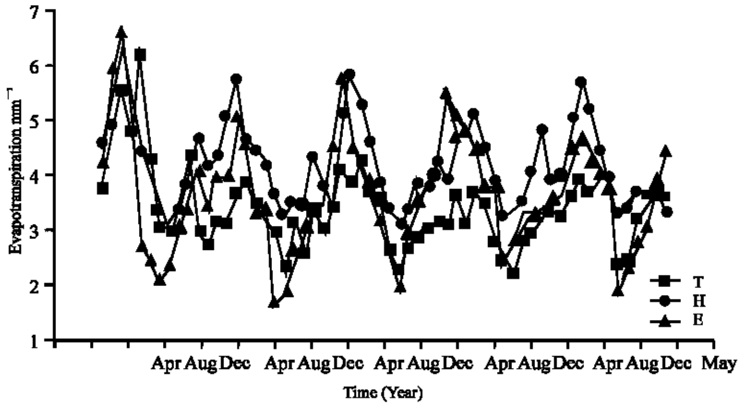

Fig. 1: The graph showing the comparison in the variation trend of the two models with the observed data (E-observed values; T-Thornthwaite's model; H-Hargreaves' model)

RESULTS AND DISCUSSION

The variation of the monthly estimated values compared with the observed values is shown in Fig. 1. The variation of the estimated values is in agreement with the observed values (Fig. 1a). From this figure it is observed that the peaks oscillate between March and April while the dips oscillate between July and August. However, the seasonal variation of the estimated value of the energy-limited evapotranspiration reflects the strong influence of the weather parameters used in each method. Figure 2 is the comparison of the annual estimated values of the energy-limited evapotranspiration compared with the observed values. Hargreaves model which is based on solar energy input shows higher values compared with Thornthwaite's model having values ranging from 52.75-55.11mm yr^{-1}. Meanwhile, Thornthwaite's model which, is based on only temperature input yields values which range from 39.11 mm yr^{-1} in 1994 to 51.98 mm yr^{-1} in 1990. Further comparisons of the results for methods were carried out by computing the relative errors of the calculated/estimated actual evapotranspiration (Table 3). From the table it is seen that on annual basis, Thornthwaite gives a smaller error of about 1.22% (i.e., underestimation of about 1 mm yr^{-1}) compared with Hargreaves' model which is 9.28% (having an overestimation of 4 mm yr^{-1}). However, the mean annual error for the 2 models is less than 5%. The above result is also confirmed from the annual mean values as shown in Fig. 1 and 2. From the results, it is found that throughout the period (i.e., 1990-1994) under consideration, Hargreaves' model overestimated energy-limited evapotranspiration while Thornthwaite exhibits the trend of underestimation. On the seasonal behaviour of the 2 models, in wet season, both overestimated evapotranspiration with Hargreaves (with model error

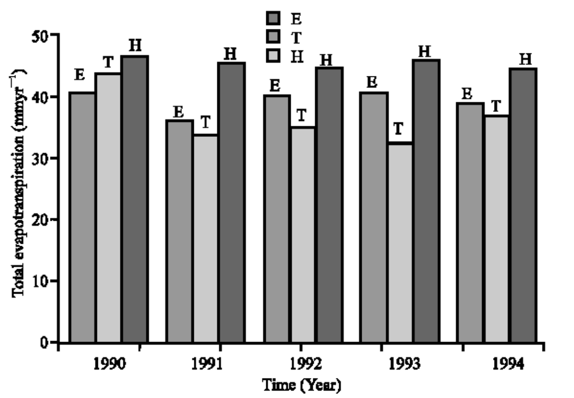

Fig. 2: Total annual evapotranspiration estimates compared with the observed E-observed values; T-Thornthwaite's model; H-Hargreaves' model

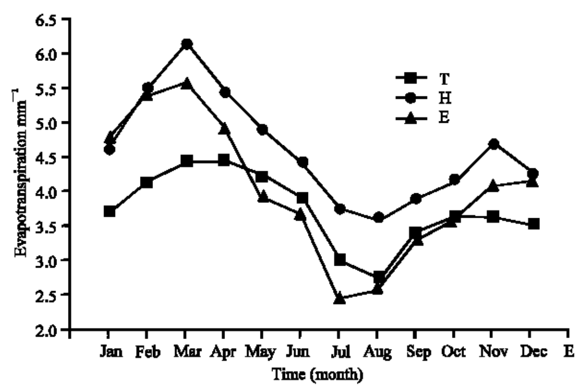

Fig. 3: The comparison of the monthly and seasonal variations of the estimated and the observed values

of 0.26%) overestimation h igher than Thornthwaite (with model error of 0.04%). However, in dry season, the model error for Thornthwaite is -0.20 and 0.05% for

Hargreaves. This is clearly shown on the graph of the monthly mean values (Fig. 3).

The wet season for the location under consideration occurs between May and October while the dry season is between November and April. The situation described by the graph agrees with the seasonal behaviour of the model outlined in Table 3.

Comparison of the performance of the hargreaves and thornthwaite model relative to the observed behaviour: The performances of the two methods were analyzed by computing the Standard Error of Estimate (SEE) of both the monthly and seasonal estimated values and the observed values. The SEE was computed using Irmak *et al*. (2003) equation.

$$SEE = \sqrt{\left[\frac{1}{\{n(n-2)\}}\right]\left[n\sum_{i=n}^{n} y_i^{2} - \left(\sum_{i=1}^{n} y_i\right)^{2} - \frac{\left[n\sum_{i=1}^{n} x_i y_i - \left(\sum_{i=1}^{n} x_i\right) x \left(\sum_{i=1}^{n} y_i\right)\right]^{2}}{n\sum_{i=1}^{n} x_i^{2} - \left(n\sum_{i=1}^{n} x_i\right)^{2}}\right]} \quad (4)$$

where x_i, $E_{observed}$
Y_i, $E_{estimated}$
n, sample size

Lower SEE implies better performance of the tested models. Table 4 shows the calculated average SEE on the monthly and seasonal basis for the two models in question. The calculated SEE using Thornthwaite's model is 0.68 and 0.90 for Hargreaves' model, the results which indicate that Thornthwaite will perform better than Hargreaves, on monthly basis in Ibadan. On the seasonal basis, in wet season the calculated SEE for Thornthwaite and Hargreaves are 0.65 and 0.70, respectively. However, during the dry season, Thornthwaite has a lower SEE of 0.40 while Hargreaves has a higher SEE of 0.80. This implies that they will both perform fairly alike during the wet season while Thornthwaite exhibits a higher performance tendency for Ibadan during the dry season than the Hargreaves method. Also, from the table, we

Table 3: Comparison of the observed actual evapotranspiration with the estimated values

Year	Et_{obs}/mm	Models errors* (%) Thornthwaite	Hargreaves
1990	48.28	7.7	14.2
1991	42.89	-6.8	25.7
1993	47.69	-12.2	11.2
1994	48.53	10.3	12.1
1995	46.08	-5.1	14.7
Mean	46.69	-1.22	9.28
Seasonal behaviour			
Wet season	23.26	0.040	0.26
Dry season	23.43	-0.204	0.05

* $Error(\%) = \frac{E_{estimated} - E_{observed}}{E_{observed}} x100$

Table 4: Standard Errors of Estimates (SEE) in mm mon^{-1} of the Estimated and the average ratio of the estimated/observed of Thornthwaite and Hargreaves spanning the years 1990-1994

Year	Performance indicator	Thornthwaite	Hargreaves
1990	SEE of monthly estimate	1.05	0.96
	Average ratio	1.04	1.14
1991	SEE of monthly estimate	0.50	0.83
	Average ratio	0.90	1.26
1992	SEE of monthly estimate	0.72	1.01
	Average ratio	0.88	1.11
1993	SEE of monthly estimate	0.51	0.78
	Average ratio	0.79	1.12
1994	SEE of monthly estimate	0.61	0.92
	Average ratio	0.95	1.15
Average	SEE of monthly estimate	0.68	0.9
	Average ratio	0.91	1.16
Seasonal performances			
Wet season	SEE of monthly estimate	0.65	0.70
	Average ratio	1.04	1.26
Dry season	SEE of monthly estimate	0.40	0.80
	Average ratio	0.80	1.05

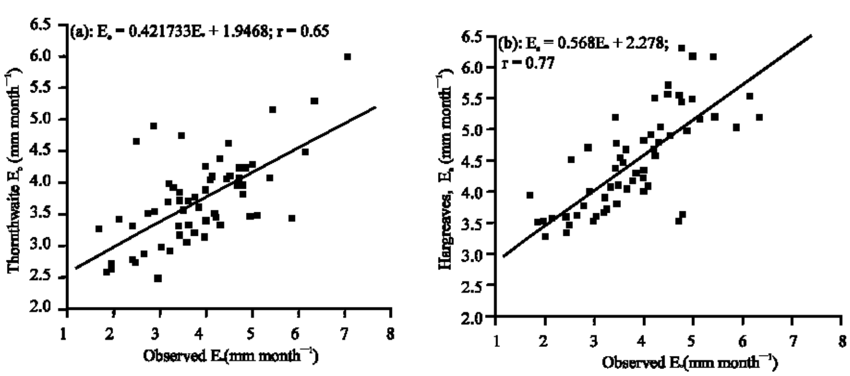

Fig. 4a: Regression analysis for the energy-limited evapotranspiration estimates of (a) Thornthwaite (b) Hargreaves with the observed values for evaluation years of 1990-1995 for Ibadan, Nigeria

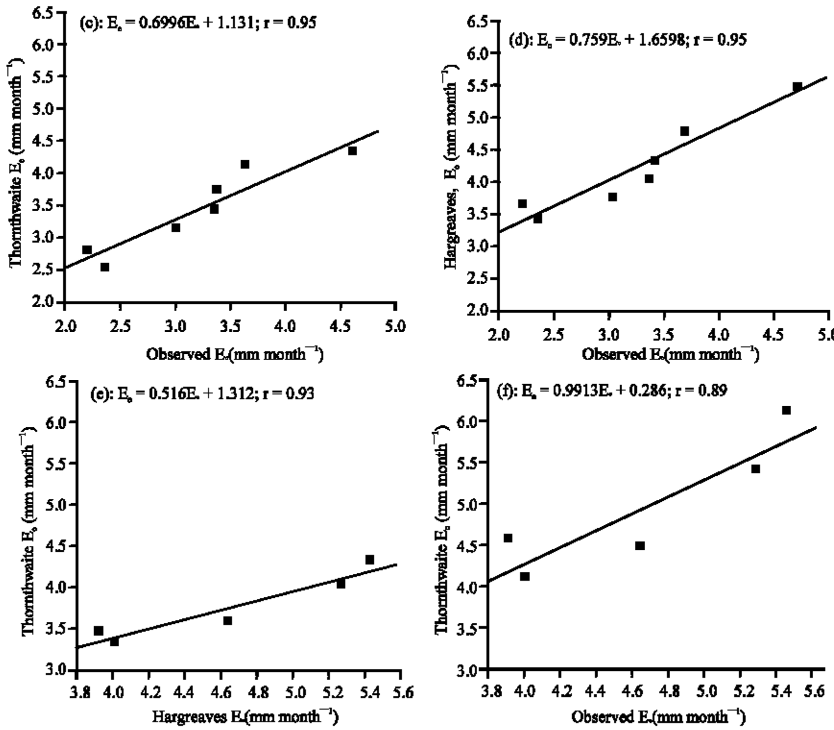

Fig. 4b: Regression analysis for the energy-limited evapotranspiration estimates of (c, e) Thornthwaite and (d, f) Hargreaves with the observed values for wet and dry season, respectively for Ibadan, Nigeria

have the average ratio, which is defined as the ratio of the $E_{estimated}$ to $E_{observed}$. The average ratio above and below 1.0 for different methods indicates overestimation and underestimation of the estimated values relative to the observed evapotranspiration. Table 4 shows that on monthly basis, the average ratio for Thornthwaite and Hargreaves are 0.91 and 1.16, respectively, which further confirms that Thornthwaite methods underestimates (<1.0) and Hargreaves' (>1.0) overestimates the observed values for Ibadan. For dry season in particular, Thornthwaite methods has an average ratio of 0.80 and Hargreaves' has 1.05 which implies underestimation for Thornthwaite and overestimation for Hargreaves. In wet season, the average ratio for the two models is above 1.0 and this indicates overestimation for both models. This result can be improved by a local calibration of the parameter values involved in each model (Xu and Chen, 2005). Recalibration of the parameter values was not done in this study because the main purpose is to examine the applicability and accuracy of the models in the tropical humid environment using their original values (Fig. 4a-f).

The correlation between the estimated and the observed values were carried out both on monthly and annual basis, using the simple linear regression equation

$$E_e = mE_0 + I \qquad (5)$$

Where E_e represents the computed energy-limited evapotranspiration values, E_0 is the observed values and m and I are constants representing the slope and the intercept of the regression graph, respectively. The resulting values are as shown on Fig. 4a and b. Hargreaves has a higher correlation of 0.77 compared with Thornthwaite's with a correlation of 0.65. The high correlation of energy-limited evapotranspiration for the Hargreaves model clearly shows the relevance of the incident radiation which was used along with temperature for the computation of energy-limited evapotranspiration as has been confirmed in similar studies (Othman Alkaeed *et al*., 2006). On the seasonal basis, the two models have the same correlation coefficient which is as high as 0.95, indicating a very good relationship between the estimated and the observed values during the dry season. However, in wet season, Thornthwaite's (r = 0.93) exhibits a better relationship with the observed than Hargreaves' (r = 0.89) (Fig. 4b).

CONCLUSION

The performances of the two methods were investigated both on the monthly and the seasonal basis by determining their respective standard error of estimate, model error and average ratio. It was found that on the annual basis that Hargreaves' model overestimates (model error is 9.28) while the Thornthwaite model underestimates (model error is -1.22) the observed values. However, the reverse is the case during the wet season. The performance of Thornthwaite model is better than that of Hargreaves' judging from their respective low and high standard error of estimates that were obtained. On the other hand, Hargreaves model exhibits a better significant correlation. In the circumstance where an instrument for determining energy-limited is not available, the 2 models may be considered as good alternatives in view of the few meteorological parameters which are always available in most weather stations.

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