

New Correlation for Estimating Reference Evapotranspiration in A Semi – Arid Region



Physics

Keywords: New Evapotranspiration model, temperature – based ET models, semi – arid region, Nigeria.

EDEBEATU, CHINEDU C.

DEPARTMENT OF PHYSICS & INDUSTRIAL PHYSICS, MADONNA UNIVERSITY, ELELE CAMPUS, RIVERS STATE, NIGERIA.

OKUJAGU, CHARITY U.

DEPARTMENT OF PHYSICS, UNIVERSITY OF PORT HARCOURT, PORT HARCOURT, RIVER STATE, NIGERIA.

ABSTRACT

Water is an essential component of human existence and survival and exists in different forms such as rainfall, rivers, etc and man – made stream called irrigation. In agriculture and modern farming, irrigation is essential for all year round food crop production, agricultural management practices and irrigation scheduling. Food crop production is needed in the face of climate change to overcome food security challenges in the developing countries like Nigeria. This implies the determination of water requirement of any field via evapotranspiration. Different methods have been developed and deployed in modeling evapotranspiration. The need for accurate weather data has led scientists, engineers and researchers to develop different methods for the measurement and models for its estimation. In this work, we developed a new evapotranspiration ETo model for estimating evapotranspiration in a semi – arid region. The new ETo model showed significant agreement with the established Standard of the Penman – Monteith.

1. Introduction

Evapotranspiration ET is major component of the hydrology cycle and its understanding is essential for agricultural crop production and irrigation water management (Edebeatu *et al.*, 2014). Reliable ET estimates are essential to identifying temporal variations on irrigation, improve water resources allocation, evaluate the effect of land use and management changes on the water balance (Orteag-Farias *et al.*, 2009). Accurate quantification of reference evapotranspiration is a basic component for the design, operation, implementation and management of irrigated systems, and a prerequisite for computing crop water use (Adeboye *et al.*, 2009). Determining evapotranspiration is a complex process and has led scientists and water engineers to develop empirical models for its quantification mainly that which is suitable for a particular region.

Third world countries have relied so much on rainfed agriculture which is seasonal, and with the changing climate precipitation patterns of West Africa is drastically changing such that rainfed agriculture is no longer reliable thus increase in food challenges. Climate change also results in water scarcity which is a major challenge facing (Adaboye *et al.*, 2009) the world today especially developing nations. The vulnerability impact of climate change is more prominent in the sub – Saharan Africa, though contributes little to the effects of climate change (Edebeatu, 2014). In the sub – Saharan Africa, drought and desertification are major threats to crop, food production and other agricultural management practices. Northern Nigeria located in the semi – arid region experiences this acute challenge. This increasing rate of drought has been considered a very serious ecological problem and its becoming a reoccurring hazard (Umaru *et al.*, 2012). The consequence of this drought is the witting of crops leading to crop failures, poor harvest by farmers, drying of surface water bodies, decrease in ground water level and loss of livestock due to hydration, famine, diseases, rural to urban migration (Umaru *et al.*, 2012).

The weather data for modeling evapotranspiration is not readily available especially in the third world countries like Nigeria (Chineke *et al.*, 2011; Edebeatu *et al.*, 2014). Therefore, it becomes necessary that empirical models be designed to accommodate the need for evaporative water demand of a region like the arid and semi – arid facing the threat of climate change. Many empirical models have been developed, ranging from simple temperature – based, radiation – based to the full combination model of Penman – Monteith 56 (FPM-56). These empirical models require only maximum and minimum air temperature and

solar radiation for its estimation. The use of these simple less climate data demanding models has been found to be very effective and reliable in many climates especially when its empirical coefficient is modified or calibrated to suit the region under survey

2. Materials and Methods

2.1 Study area



Figure 1: Location of study sites

2.2 Methods

2.2.1 Hargreaves model

The Hargreaves (1985) ET_0 model is a temperature – based empirical evapotranspiration model. It requires only maximum and minimum air temperature and the extra – terrestrial radiation R_s . The Hargreaves model is written as;

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}Ra \dots\dots 1$$

where;

- ET_0 = reference evapotranspiration (mm/d);
- T_{mean} = mean monthly daily air temperature (°C);
- T_{max} = maximum monthly daily air temperature (°C)
- T_{min} = minimum monthly daily air temperature (°C);

2.2.2 The modified Hargreaves (Har_m)

The modified Hargreaves ETo model is written after Edebeatu *et al.*, (2014)

$$ET_0 = 0.00134(T_{mean} + 17.8)(T_{max} - T_{min})^{0.5}Ra \dots\dots 2$$

2.2.3 Makkink expressed in (Fernandes *et al.*, 2012);

$$ET_o = \frac{0.61WR_s - 0.12}{W} \text{ and } \Delta = \frac{\Delta + \gamma}{T + 237.3} \dots \dots 3$$

$$W = \frac{\Delta}{\Delta + \gamma} \dots \dots 4$$

$$\frac{2503 \exp(\frac{17.27}{T+237.3})}{(T+237.3)^2} \dots \dots 4$$

Rs = solar radiation (MJ/m²/d);
 Δ = slope of saturation vapour – temperature curve (kPa/°C);

2.2.4 New correlation ET_o model

The new ET_o model is an empirical temperature based model developed to estimate reference evapotranspiration in a semi – arid (probably arid) zones in the sub – Saharan Africa. The new proposed ET_o model is written as;

$$ET_o = \alpha(0.89T_{mean} + 0.00021)Ra \dots \dots 5$$

Where;
 T_{mean} = mean monthly air temperature;
 α = 0.0086
 R_a = extraterrestrial radiation, calculated as a function of day length and latitude.

3. Results and Discussion

3.1 Maiduguri

The maximum ambient temperature for Maiduguri varied from 32.57°C in the rainy season of August to 41.33°C in the hot dry month of April, table 1a below. The minimum temperature within this period ranged from 14.05°C in the cold dry month of January and extended into the month of May at 26.42°C which is the month of early rain. The maximum solar radiation occurred in February at 20.76MJ/m²/d, whereas the minimum occurred in August at 16.01MJ/m²/d. Four ET_o models were tested for its effectiveness in determining consumptive water use in the semi – arid region of Northern Nigeria. The Hargreaves (1985), Makkink model according to Fernandes *et al.*, (2012) far overestimated the ET_o in this location. The measured ET_o was undervalued while the modified Hargreaves (Edebeatu *et al.*, 2014) and the newly developed ET_o model had good estimation of the reference evapotranspiration in the location. In the later, the ET_o varied from 6.11mm/d in the month of September to 9.16mm/d in the month of November, and 5.45mm/d in the January to 7.91mm/d in October. The two ET_o models demonstrated that hot dry periods recorded the highest evaporation and cold dry period have water deficit. The rainy season recorded at the extreme lower end of the given standard by Allen *et al.*, (1998) where (6 ≤ ET_o ≤ 8) mm/d for temperatures greater than 30°C. This can be explained from the view that there is more water vapour in the atmosphere than the two previous seasons. The annual average records are presented in table 1b below.

Table 1a: Mean Monthly weather data for Maiduguri (1989 – 2009)

Months	T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	ET _{o(m)} (mm/d)	New ET _o (mm/d)	Har (mm/d)	Har(m) (mm/d)	Makkink (mm/d)
Jan	32.23	14.05	20.67	5.31	5.45	12.16	7.08	12.49
Feb	35.43	17.17	20.76	6.55	6.18	13.15	7.66	12.54
Mar	39.03	21.65	20.24	7.11	7.09	14.00	8.15	12.22
Apr	41.33	25.49	19.31	7.16	7.79	14.21	8.28	11.66
May	40.27	26.42	18.12	6.58	7.80	13.31	7.76	10.93

Jun	37.52	25.15	17.31	5.65	7.42	12.22	7.12	10.44
Jul	34	23.63	16.18	4.45	6.99	10.84	6.31	9.75
Aug	32.57	22.99	16.01	3.79	6.94	10.49	6.11	9.65
Sep	34.36	23.11	17.98	4.37	7.44	12.03	7.01	10.85
Oct	37.11	21.84	21.75	5.4	7.91	14.77	8.61	13.15
Nov	35.91	17.82	24.51	5.82	7.48	15.72	9.16	14.83
Dec	32.83	14.63	25.27	5.35	6.85	15.12	8.81	15.29

Table 1b: Annual Mean Weather data values for Maiduguri

T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	New ET _o (mm/d)	Har (mm/d)	Har ^(m) (mm/d)	Makkink (mm/d)	ET _{o(m)} (mm/d)
36.05	21.16	19.84	8.53	13.17	7.67	11.98	5.63

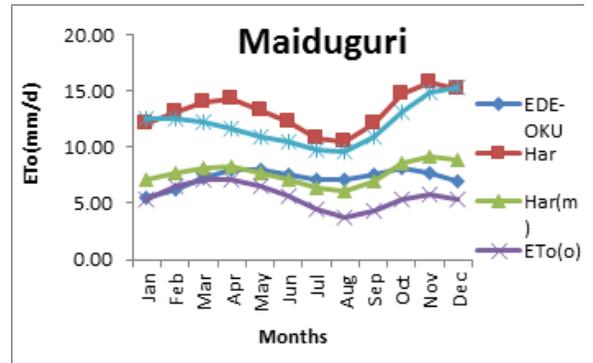


Figure 2: Mean monthly daily ET_o for Maiduguri

3.2 Kano

Table 3 below shows the ET_o values for both the observed and the estimated. The mean monthly values of the weather variables for Kano showed that ambient temperature is less than 40°C. The maximum temperature lies in the range of 29.79°C in January to 37.86°C in April. The minimum air temperature is between 13.53°C in January and 24.37°C in May, table 2a. The cold dry windy periods recorded least the temperature values followed by the rainy season of the year. The hot dry seasons were higher in both maximum and minimum temperatures. The cold windy season is a reflection or indication of the presence of North Easterly trade wind from the Sahara desert bringing in windy cold air dust and making the atmosphere hazy, dry with reduced visibility.

The maximum measured / observed ET_o at this location is 7.44mm/d which occurred in April, while the minimum occurred in August at 3.62mm/d. The models of Hargreaves and Makkink overestimated the ET_o when compared with the observed ET_o. The modified Hargreaves and the new correlation ET_o had similar characteristic trend of good estimation of the ET_o. Their estimation of reference evapotranspiration falls within the range of evaporative water demand according to Allen *et al.*, (1998). The modified Hargreaves had maximum ET_o value of 8.38mm/d in the month of November and minimum in the month of August at 5.53mm/d, an indication of overestimation and underestimation. The new model ET_o correlated well with the standard of Allen *et al.*, (1998) for a tropical sub – Saharan Africa (≤ 6 ET_o ≤ 8) mm/d like Nigeria. The maximum ET_o recorded by the new developed model at this site of study occurred in the month of October at 7.30mm/d and minimum ET_o of 5.14mm/d and 5.90mm/d in January and February respectively, and which is the only underestimation by the new ET_o model in Kano. The new ET_o model estimated better than the measured ET_o in Kano.

The mean annual values of the meteorological data for Kano are tabulated in table 2b below.

Table 2a: Mean Monthly weather data for Kano (1989 – 2009)

Months	T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	ET _o (mm/d)	New ET _o (mm/d)	Har (mm/d)	Har _(m) (mm/d)	Makkink (mm/d)
Jan	29.79	13.53	19.65	6.01	5.14	11.14	6.49	11.87
Feb	33.09	16.82	19.69	7.11	5.90	12.09	7.05	11.89
Mar	36.38	21.01	19.11	7.44	6.75	12.76	7.44	11.54
Apr	37.86	24.01	18.11	7.28	7.25	12.68	7.39	10.93
May	36.53	24.37	17.01	6.38	7.16	11.79	6.87	10.26
Jun	33.94	23.04	16.27	5.46	6.77	10.82	6.30	9.80
Jul	31.12	21.83	15.31	4.24	6.43	9.74	5.67	9.22
Aug	29.87	21.16	15.25	3.62	6.38	9.49	5.53	9.18
Sep	31.4	20.86	17.37	4.15	6.77	10.97	6.39	10.48
Oct	34	20.4	20.48	5.15	7.30	13.24	7.71	12.37
Nov	33.48	17.12	23.23	6.07	7.04	14.38	8.38	14.05
Dec	30.98	14.39	24.04	5.87	6.54	14.02	8.17	14.54

Table 2b: Annual Mean Monthly weather data for Kano

T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	New ET _o (mm/d)	Har (mm/d)	Har _(m) (mm/d)	Makkink (mm/d)	ET _o (mm/d)
33.09	16.82	19.69	5.90	12.09	7.05	11.89	7.11

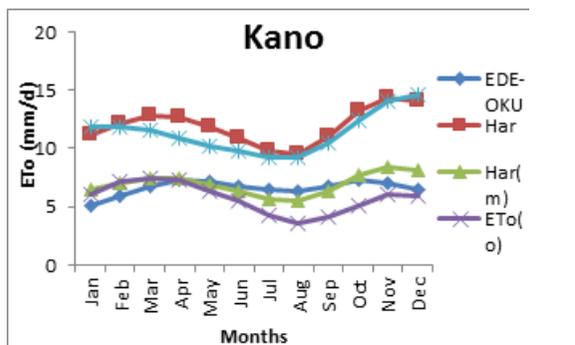


Figure 3: Mean monthly daily ET_o for Kano

3 Sokoto

The mean monthly weather values for this station varied from 41.04°C in the month of April in the hot dry season to 31.71°C in the month of August in the rainy period, while the cold dry windy / hazy season of December, January and February recorded ambient temperatures of 33.14°C, 31.83°C and 35.31°C of its maximum temperatures respectively. The minimum ambient temperature is a mirror reflection of the maximum temperature, table 3a below. It ranged between 26.74°C in April to 35.31°C in the cold dry season of January. The months of November, December, January and February recorded the lowest values of temperatures which we considered as cold dry season of the year in the semi – arid region of Nigeria. Thus, it may be considered that the region has three major seasons in a year. The ET_o recorded in Sokoto as measured lie between 4.21mm/d in August to 8.20mm/d in March. ET_o values were lower during the peak of rainy season followed by cold dry periods, whereas, the hot dry periods of February to April recorded the highest water evaporation. During the cold dry periods (mostly characterized by harmattan haze /fog and high moving wind) the at-

mosphere is filled with dust from the Sahara desert, making the atmosphere hazy with less visibility and cold due to high windy air. The mean annual weather data values are shown in table 3b below.

Table 3a: Mean Monthly weather data for Sokoto (1989 – 2009)

Months	T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	ET _o (mm/d)	New ET _o (mm/d)	Har (mm/d)	Har _(m) (mm/d)	Makkink (mm/d)
Jan	31.82	16.35	18.68	7.01	5.55	11.24	6.55	11.27
Feb	35.31	18.78	19.39	8.01	6.24	12.49	7.28	11.71
Mar	39.07	23.07	19.12	8.20	7.15	13.42	7.82	11.54
Apr	41.04	26.74	18.134	7.89	7.81	13.47	7.85	10.94
May	39.75	27.17	17.13	7.42	7.77	12.62	7.35	10.33
Jun	36.97	25.56	16.57	6.82	7.38	11.68	6.81	9.99
Jul	33.40	23.78	15.59	5.06	6.94	10.39	6.06	9.39
Aug	31.71	22.88	15.44	4.21	6.85	10.01	5.83	9.30
Sep	33.65	23.14	17.52	4.81	7.41	11.63	6.78	10.57
Oct	36.93	22.93	21.06	5.54	8.12	14.44	8.41	12.72
Nov	35.91	19.40	23.71	6.51	7.80	15.49	9.02	14.34
Dec	33.14	16.58	24.44	6.47	7.24	14.98	8.73	14.79

Table 3B: Annual Mean Weather and data values for Sokoto

T ^{max} (°C)	T ^{min} (°C)	Rs (MJ/m ² /d)	New ET _o (mm/d)	Har (mm/d)	Har _(m) (mm/d)	Makkink (mm/d)	ET _o (mm/d)
35.73	22.20	18.90	8.62	12.66	7.37	11.41	6.50

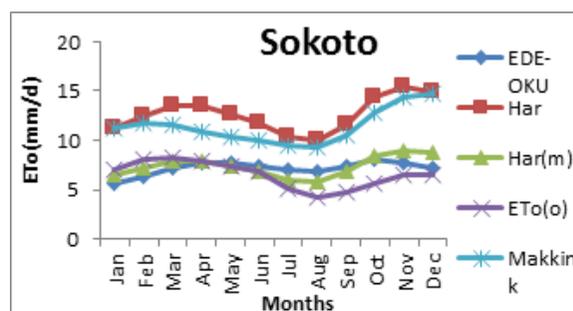


Figure 4: Mean monthly daily ET_o for Sokoto

Conclusion

A new model has been developed to estimate reference evapotranspiration in a semi – arid region of Nigeria. The new ET_o model is a temperature – based model that requires only maximum and minimum air temperature that is readily available and that can also easily be measured as a meteorological parameter. This is essential in the absence of full meteorological parameters as demanded by the FPM-56 model and few other radiation models. The new ET_o model showed a relatively good estimation of reference evapotranspiration as tested in the semi – arid region of Nigeria using three locations ranging from the North East to the North West.

Hence, the newly developed ET_o model is a reliable ET_o in estimating reference evapotranspiration and by proxy could be extended to other climate regimes by modification and or calibration of its empirical coefficient .

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