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ESTIMATION OF EVAPORATION RATE IN UYO, NIGERIA USING THE MODIFIED PENMAN EQUATION

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ABSTRACT

The rate of evaporation in Uyo (5°18'53.7''N, 7°59'39.3''E) has been estimated. The estimation is based on five meteorological data which include solar radiation, wind speed, relative humidity, pressure and temperature. These data were collected from the Nigeria Meteorological Agency in Uyo and covered a period of five years (2004 to 2008). The estimated rate of evaporation was obtained to be 2.75 ± 0.46mm/day which is very much close to that of the measured value of 2.78 ± 0.42mm/day. A high value of coefficient of determination $R^2 = 0.98$ was obtained by plotting a linear relation between the observed and the estimated evaporation. Seasonal effects were also observed in the rate of evaporation as different rates were recorded during the wet and dry seasons.

Keywords: Uyo, evaporation, estimation, seasonal.

INTRODUCTION

Evaporation involves the conversion of liquid water to water vapour at the evaporating surface such as water bodies, pavements, soils and wet vegetations. Allen and Smith (1994) observed that direct solar radiation and the ambient temperature of the air provide the necessary energy for evaporation. The rate of evaporation at any time and place depends on since meteorological factors such as wind, temperature, pressure, relative humidity and solar radiation (Thompson, 1988).

Several empirical models have been developed to estimate the rate of evaporation. Shuttleworth (1993) modified and adapted the foremost Penman equation by using SI unit to calculate evaporation. Iruthayaraj and Morachan (1977) developed appropriate local relationship between a sunken screen open pan evaporimeter and a can evaporimeter in order to determine the relationship between meteorological parameters and evaporation. It was observed that the sunken screen open pan evaporimeter recorded much lower values of evaporation than the can evaporimeter. Johnson and Sharma (2008) analyzing evaporation records in Australia observed that pan evaporation trends were mainly negative with a significant level of 5% while Penman evaporation trend was positive win no statistical significance. Rim (2004) in his study observed that solar radiation was the most sensitive meteorological factor affecting evaporation while wind speed was the least sensitive factor. Other studies on the estimation of the rate of evaporation include that of Surinder and Mahesh (2008) and Ahonsi (2004). The parameters used in estimating evaporation rate include average temperature, relative humidity, wind speed, sunshine hour, solar radiation and air pressure. In this study we develop models that correlate monthly daily evaporation with some meteorological parameter for Uyo in the Southern Nigeria.

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MATERIALES AND METHODS

Methodology

Data on daily solar radiation, relative humidity, maximum and minimum temperature, pressure and wind speed were obtained from the Nigeria Meteorological Agency in Uyo. The data covered the period of five years (2004 to 2008). Uyo is located on latitude 5°18'53.7''N, longitude 7°59'39.29''E and altitude of 180m above the sea level. It has equatorial climate season having much rain between March and October and dryness between November and February. Monthly averages of the data were computed and used for the analyses. The estimated evaporation rate obtained by using Penman equation modified by Shuttleworth (1993) was compared with the observed evaporation. The equation is given by

$$E_{mass} = \frac{m\,R_n + \gamma \times 6.43\,(1+0.536 \times u_2)\,\delta_e}{\lambda_v\,(m+\gamma)} \qquad (1)$$

where

E_{mass} = Evaporation rate (mm day^{-1})
m = Slope of the saturation vapour pressure curve (kPaK^{-1})
R_n = Net irradiance (MJ m^{-2} day^{-1})
γ = Psychrometric constant = $\frac{0.0016286 \times P}{\lambda_v}$ (kPaK^{-1})
U_2 = Wind speed at 2m height (m s^{-1})
δ_e = Vapour pressure deficit (kPa)

λ_v = Latent Heat of Vapourisation (MJ kg^{-1})

Estimation of Evaporation

The Shuttleworth (1993) equation given by Equation 2.2 was used to estimate the rate of evaporation in Uyo for the 5 year period (2004 – 2008). The slope of the saturation pressure curve (m) in ($kPaK^{-1}$) is given by the equation

$$m = \frac{4098\left[0.6108 \times e^{\frac{17.27 \times T}{T+237.3}}\right]}{(T+237.3)^2} \qquad (2)$$

where T is the average maximum and minimum monthly temperature (FAO, 2008).

Also, the Net irradiance in ($MJm^{-2}\ day^{-1}$) is given by the equation (FAO, 2008)

$$R_n = \sigma\left[T_{max}\,K^4 + T_{min}\,K^4\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left\{1.35\frac{R_s}{R_{so}} - 0.35\right\} \qquad (3)$$

where

R_n = net outgoing longwave radiation [MJ m^{-2} day^{-1}],

σ = Stefan-Boltzmann constant [4.903 10^{-9} MJ K^{-4} m^{-2} day^{-1}],

$T_{max,}$ K = maximum absolute temperature during the 24-hour period [K = °C + 273.16],

$T_{min,}$ K = minimum absolute temperature during the 24-hour period [K = °C + 273.16],

e_a = actual vapour pressure [kPa],

R_s/R_{so} = relative shortwave radiation (limited to ≤ 1.0),

R_s = measured or calculated Solar radiation [MJ m^{-2} day^{-1}],

R_{so} = calculated clear-sky radiation [MJ m^{-2} day^{-1}]

where $R_{so} = (a_s + b_s)\,R_a$ (4)

and R_a is the extra terrestrial radiation for the location given by (FAO, 2008)

$$R_a = \frac{24}{\pi} \times I_{sc}\left[1 + 0.33\cos\left(\frac{360}{365}\right) \times d_n\right] \times \left[(w\sin\phi\sin\delta) + (\cos\phi\cos\delta\sin w)\right] \qquad (5)$$

where I_{sc} is solar constant, d_n is the Julian day number.

and

$$w = \cos^{-1}(-\tan\delta\tan\phi) \qquad (6)$$

in which w is the sun set hour angle, δ is solar declination and Φ is the latitude.(Nwokoye, 2006).

Where no calibration has been carried out for improved a_s and b_s parameters, the values a_s = 0.25 and b_s = 0.50 are recommended (FAO, 2008).

For the purpose of this calculation, the coordinate system for the location of study is $5^0$18'53.7''N Latitude and for effective computations it is converted to decimals.

To convert, we use

$$5 + \left(18 \times \frac{1}{60}\right) + \left(53.7 \times \frac{1}{60} \times \frac{1}{60}\right) = 5.314917$$

Table 1 shows average d_n for the months of the year according to Nwokoye (2006).

Table 1. Average julian day number and declination for the months of the year.

Month	Average dn	Declination δ
January	17	-20.92
February	16	-12.95
March	16	-2.42
April	15	9.41
May	15	18.79
June	11	23.09
July	17	21.18
August	16	13.45
September	15	2.22
October	15	-9.60
November	14	-18.11
December	10	-23.05

Source: (Nwokoye, 2006)

An average of the maximum air temperature to the fourth power and the minimum air temperature to the fourth power is commonly used in the Stefan-Boltzmann equation for 24-hour time steps. The term $(0.34-0.14\sqrt{e_a})$ expresses the correction for air humidity, and will be smaller if the humidity increases. The effect of cloudiness is expressed by (1.35 R_s/R_{so} - 0.35). The term becomes smaller if the cloudiness increases and hence R_s decrease. The smaller the correct terms, the smaller the net outgoing flux of longwave radiation. The psychometric constant (γ) in SI Units of PaK^{-1}, relates the partial pressure of water in air to the air temperature.

It is given by the equation(FOA, 2008).

$$\gamma = \frac{(C_p)_{air} \times P}{\lambda_v \times Mw_{ratio}} \qquad (7)$$

where

$(C_p)_{air}$ = the heat capacity of air = 1.006 x 10^3J/Kg

P = average monthly atmospheric pressure

λv = Latent heat of water vapourization = 2.45 x 10^6 J/Kg

Mw_{ratio} = the molecular weight ratio of water vapour to dry air.

Molecular weight of water vapour = 18 g/mol

Molecular weight of dry air = 28.9 g/mol

$$Mw_{ratio} = \frac{18}{2.89} = 0.622$$

The vapour pressure deficit (δ_e) is the difference between the saturation vapour pressure (e_s) and the actual vapour pressure (e_a) for a given time period

i.e. $\delta_e = e_s - e_a$

Saturation vapour pressure (e_s) is related to air temperature and can be calculated from air temperature for time period such as a month. The saturation vapour pressure is computed using the maximum and minimum temperature for such month to avoid underestimation of the vapour pressure deficit, thus leading to the underestimation of the rate of evaporation for the location under study (FAO, 2008).

$$e_s = \frac{e^0(T_{max}) + e^0(T_{min})}{2} \quad (8)$$

where

$$e^0(T) = 0.6108 \exp\left[\frac{17.27T}{T+237.3}\right] \quad (9)$$

$$e^0(T_{max}) = 0.6108 \exp\left[\frac{17.27T_{max}}{T_{max}+237.3}\right] \quad (10)$$

$$e^0(T_{min}) = 0.6108 \exp\left[\frac{17.27T_{min}}{T_{min}+237.3}\right] \quad (11)$$

The actual vapour pressure (e_a) can be calculated from relative humidity data depending on the availability of the data.

Therefore,

$$e_a = \frac{e^0 (T_{min}) \frac{RH_{max}}{100} + e^0 (T_{max}) \frac{RH_{min}}{100}}{2} \quad (12)$$

e^0 (T_{min}) = saturation vapour pressure at daily minimum temperature (KPa).
e^0 (T_{max}) = saturation vapour pressure at daily maximum temperature (KPa).
RH_{max} = maximum relative humidity (%)
RH_{max} = minimum relative humidity (%)

In the absence of maximum and minimum relative humidity data Equation 3.12 is used.

$$e_a = \frac{RH_{mean}}{100} \left[\frac{e^0(T_{max}) + e^0(T_{min})}{2}\right] \quad (13)$$

where RHmean is the mean relative humidity defined as the average between RH_{max} and RH_{min}.

All the parameters for the Shuttleworth estimation of evaporation were computed and are shown in table 2.

Table 2. Parameters for the Shutleworth Estimation of Evaporation.

Months	R_n ($MJm^{-2}day^{-1}$)	e_s(KPa)	e_a(KPa)	δe(KPa)	($KPak^{-1}$)	m($KPaK^{-1}$)
January	10.28	3.96	2.80	1.16	1.954	0.141
Feb.	10.27	4.32	3.11	1.21	1.934	0.140
March	5.59	4.19	3.34	0.85	1.940	0.140
April	2.97	3.95	3.27	0.68	1.960	0.141
May	1.84	3.79	3.17	0.62	1.967	0.141
June	1.22	3.61	3.11	0.50	1.980	0.128
July	0.37	3.47	3.10	0.37	1.961	0.128
August	0.70	3.46	3.06	0.40	1.980	0.128
Sept.	0.62	3.55	3.07	0.48	1.980	0.128
October	1.66	3.73	3.16	0.57	1.967	0.128
Nov.	3.52	3.85	3.17	0.69	1.987	0.141
Dec.	7.03	3.95	3.19	0.76	1.994	0.141

Table 3. Monthly observed and estimated values of the evaporation with different meteorological parameters.

Month	Evaporation Observed (mm/day)	Evaporation Estimated (mm/day)	Average Temperature (°C)	Pressure (mb)	Relative Humidity (%)	Solar radiation $MJm^{-2}day^{-1}$	Wind speed (m/s)
January	3.72	3.67	28.3	29.6	70.6	31.6	36.9
February	3.54	3.64	29.7	29.3	72	29.9	41.5
March	2.74	2.74	29.3	29.4	79.6	28.5	45.1
April	1.98	2.1	28.3	29.7	82.8	17.1	43.1
May	1.64	1.88	27.7	29.8	83.6	13.7	32.9
June	1.36	1.43	26.9	30	86.2	12	26.1
July	1.1	1.03	26.3	29.7	89.2	9.4	22.9
August	1.28	1.12	26.1	30	88.4	11.1	21.7
September	1.24	1.33	26.7	30	86.4	10.25	21.7
October	1.48	1.62	27.4	29.8	84.8	12.8	23
November	2.2	2.01	28	30.1	82.2	17.1	24.5
December	2.5	2.34	28.2	30.2	80.8	21.35	28.5

RESULTS AND DISCUSSION

The results of the monthly estimation of the evaporation with different meteorological parameters are presented in table 3.

Figure 1 shows the comparison between the observed and the calculated values of average evaporation over the five years period under the study. The correlation of these values is presented in figure 2, showing a high correlation coefficient of 0.98.

The rate ofnevaporation in Uyo over five years period using Shuttleworth model gives an estimated value of 2.08mm/day while the observed rate of evaporation is 2.07mm/day. It is observed that the estimated and the observed values are quite comparable. This is an indicator that the Shutleworth model used in estimating the rate of evaporation in Uyo is a good model given the meteorological and geographic parameter of the area. This model can therefore be used to estimate the rate of evaporation in the area with similar parameter where the observed data are not available.

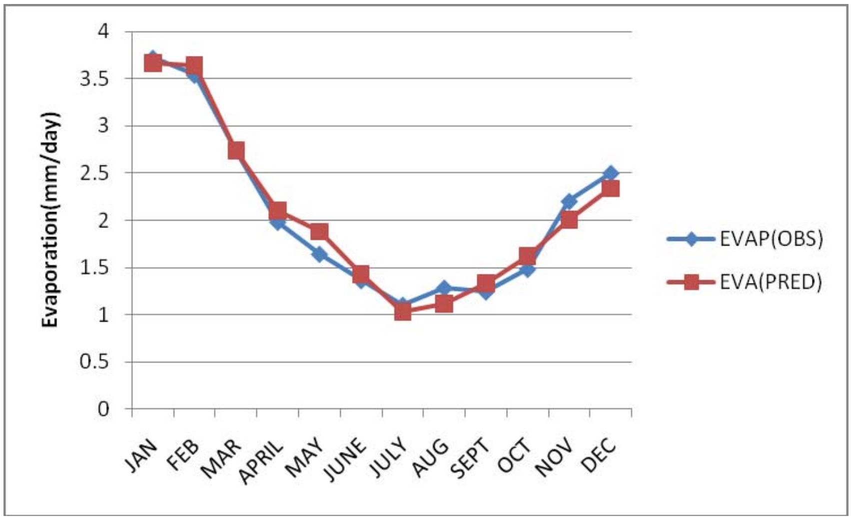

Fig. 1. Comparison of estimated and observed evaporation in Uyo.

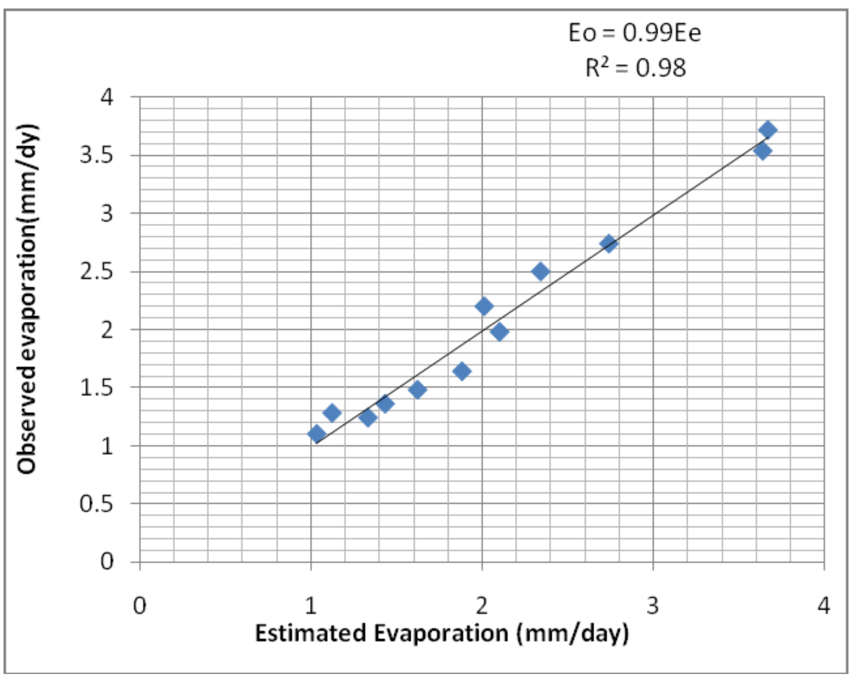

Fig. 2. Correlation between observed (Eo) and estimated (Ee) evaporation.

Comparing the results in Uyo with that of Jos in the northern part of Nigeria with evaporation rate of 5.4mm/day as observed by Ahonsi (2004), it is observed that evaporation rate in Jos is about twice higher than that of Uyo. The coefficient of determination R^2 which is a measure of how well the correlation equation fits the sample data is given in figure 2. It was observed that during the wet season which falls within the months of May and October the average rate of observed evaporation is low with the value of 1.35 ± 0.03mm/day, while that of estimated value of 1.40 ± 0.01mm/day is equally low. The low evaporation recorded during this season can be attributed to the prevailing meteorological factors of the season. These include low solar radiation, high relative humidity, and low temperature and pressure. The situation during the dry season is different. The average observed and estimated values of rate of evaporation are 2.78 ± 0.42mm/day and 2.75 ± 0.46mm/day respectively for the dry season which spands from November to April. These large values are also attributed to the prevailing meteorological factor during the period with high solar radiation, low relative humidity, and high temperature and pressure.

CONCLUSION

The rate of evaporation in Uyo has been estimated using Shuttleworth approximation with the average value of 2.75 ± 0.46 mm/day as compared with the average observed value of 2.78± 0.42 mm/day. A high value of coefficient of determination $R^2 = 0.98$ was obtained by plotting a linear relation between the observed and the estimated evaporation. Seasonal efffects are also observed on the rate of evaporation as different rates are recorded during the wet and dry seasons.

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