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COMPARATIVE STUDY ON EVAPORATING DEMAND OF THE ATMOSPHERE USING ENERGY BALANCE METHODS

[1*] Peter. J. M., [2]Hashimu, M.U

Department of Physics, University of Maiduguri, Borno State.
Corresponding Author's email: 2016peterjohn@gmail.com

ABSTRACT

In this study, two models are computed which are modified penman's monteith and Hargreaves – Samani model. The essence is to provide qualitative information related to the antagonistic effect of climate change on sustainable crop production through qualitative understanding of evaporation and transpiration processes in simple term evapotranspiration (ET_o). This is computed using climatic parameters obtained from Abubakar Tafawa Balewa University; Agro weather station, Bauchi for the period of three years. This describes the two processes of water loss on plants, at first, through transpiration and on another note, on the soil surface by evaporation. The study deduced a comparative analysis on aforementioned Methods to determine the evaporating power of the atmosphere in improving crops yield and production through estimating the amount of water needed at the root zone of the plant and also, the seasonal variation during the study. The result of this study shows a little deviation in the two models. The model based on Modified Penman's Monteith displays optimal evapotranspiration. This makes the model satisfy its creation for estimation of reference evapotranspiration. In May, June, September, and October for 2013-2015, high trends are recorded. While In July and August low trend was recorded between climatic parameter and the estimated evapotranspiration. The statistical analyses also show that there is a linear relationship between the two estimated models. In the above months, it shows that application of water is needed for the healthy growth of crops and improved crops yield.

Keywords: temperature; solar radiation; relative humidity; atmospheric pressure; evaporation; transpiration and crops production.

INTRODUCTION

The two most common processes of water (vapor) loss from Soil and vegetated surface to the atmosphere are Evaporation and Transpiration. Therefore, there is need for accurate estimation of reference; Evaporation and Transpiration (evapotranspiration). This two processes plays an important role in agriculture, hydrology, engineering and scientific studies. Both processes occur simultaneously but depends greatly on meteorological parameters such as solar radiation, wind speed, relative humidity (i.e. vapor pressure deficit), maximum and minimum air temperature (Canales, 2012).

Some factors that affect the rate of transpiration are crop characteristics, environmental aspects, and cultivation processes. Different plants have different transpiration and growth rates; these factors should be put into consideration when assessing transpiration (Murlidaran *et al*., 1993). For Instances, water is predominately lost by the soil through evaporation when the crops are small. It did not cover the soil surface. But once the plant is well developed and completely covered the soil, transpiration becomes the main process of water lost to the atmosphere (Allen *et, al.* 1989).

Evaporation can be defined as the process where liquid (water) is converted into a gaseous state or (Vapor) which can only occur on a surface with the availability of water. In this case, the humidity of the atmosphere is less than the evaporating surface (no evaporation at 100 % relative humidity). A large amount of energy is needed in evaporation. For example, it requires 600 calories of heat energy to evaporate one gram of water (Singh, 2011).

Transpiration is the process by which plants loses water through a narrow opening on their leaf called stomata. Water and nutrient are transported from soil to the root of plant which helps in keeping the plant tissues from overheating. A small opening on the leaf; the nutrients, minerals, and water that plants derives from the soil are largely lost to the atmosphere. Transpiration is a passive process largely controlled by humidity of the atmosphere and the moisture content of the soil (Khandelwel, 2013a). Only 1% of transpired water passing through the plant is used in the growth process. Some plants can open and close their stomata in a dry environment. The adaptation by these plants is to control the loss of water and nutrient from their tissues. Without this adaptation, the plants will not withstand drought (Khandelwal, 2013b).

For many decades, numerous empirical methods were developed to estimate evapotranspiration from different climatic parameters. One of these derived penman's monteith equation which is well known for estimation of evaporation from open water, bare soil, and grass (called evapotranspiration) is based on the combination of aerodynamic formulae and energy balance, given as:

$$\lambda E = \frac{(\Delta(R_n - G)) + (\gamma \lambda E_a)}{(\Delta + \lambda)} \quad \dots (1)$$

Where E=evaporative latent heat flux (MJ$m^{-2}day^{-1}$), $\Delta =$ slope of the saturated vapour pressure curve,e^{o} =saturated vapor pressure (Kp_a) and T_{mean} =daily mean temperature(o_C); R_n= net radiation flux (MJ$m^{-2}day^{-1}$), G = sensible heat flux into the soil (MJ$m^{-2}day^{-1}$), γ= psychometric constant ($kp_a{}^{O}C^{-1}$), and E_a= vapor transport of flux (mmday^{-1}).

The above equation rages from the most complex energy balance equation to the simpler equations; therefore, ReferenceEvapotranspiration (ET_O) is defined as the rate at which readily available soil water is vaporized from specified vegetated surfaces (Sondhi et al., 1989). It can be computed from meteorological data which requires detailed climatological data (Penman's-Monteith, Allen, 1989). But the simpler energy balance equations requires limited data. (Blaney – Criddle, 1950) Hargreaves-Samani, 1982, 1985). Penman's Monteith equation is accepted worldwide as a standardized model for estimation of reference evapotranspiration (ET_O) due to its detailed in the theoretical base.

However, the detailed climatological data required for ET_O using modified penman's monteith are not available especially in developing countries. Under such conditions, when there is scanties of climatological data, the Hargreaves-Samani method (Hargreaves-Samani, 1985) can give a good estimation of Reference evapotranspiration (ET_O) where only extraterrestrial solar radiation data and air temperature are available.

Raul *et. al*, (2011) and Singh *et. al*, (2010) use the Hargreaves – Samani method in the estimation of reference evapotranspiration (ET_O). Jhaghairia and Dhiman (2006) use revised Blaney Criddle, Christiansen, and Thornthwaite methods for a humid regional area. The research is built on two models to compare the penman's Monteith model and that of Hargreaves-Samani Model to assess their effect during transpiration and evaporation processes in a semi-Arid region.

The primary objective of this study is to deduce a comparative analysis on Hargreaves – Samani method and modified penman's monteith method to determine the evaporating power of the atmosphere, in improving crops yield and production through estimating the amount of water needed at the root zone of the plant and also the seasonal variation during the of this studies.

MATERIALS AND METHOD

Description of the study area

Bauchi – State is located between latitudes 9° 3´ and 12° 3´ north and longitudes 8° 50´ and 11° 0´ in the north-eastern part of Nigeria with a total land area of 49119km^2 representing about 5.3% of the country's total landmass area. It is characterized with two vegetation zones, namely Sahel savanna and Sudan savanna. The southern part of the state is cover by Sudan savanna; it's getting rich and richer towards the South. The Sahel type of savanna manifests from the mid of the state as one moves from southern to the northern part of the state. The southern part of the state is mountainous in the case of Jos – Plateau axis, while the northern part of the state is sandy soil. The state has a record of rainfall within the range of (1300 -700) mm per annum both in the south and far North. The study area is watered by many rivers and dams such as Gongola and Jama'are rivers, Gubi, and Tilden Fulani Dams.

Research Design

The study is developed to estimate the evaporation power of the atmosphere (reference evapotranspiration) based on comparative analysis of different energy balance equations by using meteorological data.

Instrument for data collection

The automatic weather station (PC-based support software) is the only instrument that was used to gather all the required data: all the meteorological data for research were collected at Agro-weather Station Abubakar Tafawa Balewa University, Bauchi from 2013-2015.

Techniques for data analysis and presentation

Penman's monteith equation and Hargreaves – Samani were used to estimate the evaporating power of the atmosphere (Evapotranspiration). Statistical analysis was employed to test the fitness of the two empirical relations. The estimated result is presented in the table and chart.

3.5 FAO-56 Penman's Monteith equation

The FAO-PM equation recommended for dailyET_o (mmday^{-1}) estimation (Allen et al., 1998) may be written as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T_{av}+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad (2)$$

Where R_n is the net radiation at the crop surface (MJm^{-2}day^{-1}), G the soil heat flux density (MJm^{-2}day^{-1}), T_{av} the mean air temperature ^{O}C. $U_2$the wind speed at 2m height (m/s), e_s the vapor pressure of the air at saturated (kp_a). e_a the actual vapor pressure (kp_a). Δ the slope of the vapor pressure curve (kp_a), and γ psychrometric constant (kp_a).

Hargreaves-Samani equation

The Hargreaves-Samani method (Hargreaves – Samani 1985) can be written as:

$$ET_o = 0.0023 \times R_a \times (T_{av} + 17.8) \times \sqrt{T_{max}} - T_{min} \qquad (3)$$

ET_o Reference evapotranspiration = evaporating power of the atmosphere (mmday^{-1}). Ra is the extraterrestrial solar radiation (mmday^{-1}).

Estimated Mean Temperature

The average monthly maximum and minimum air temperature in degree Celsius (^{o}C) are required. Where only the mean monthly temperature is available, the calculation can still be executed using below equation.

$$T_{av} = \frac{T_{max} + T_{min}}{2} \qquad (4)$$

Wind Speed

The daily wind speed in (m/s) is required, measured 2m above the ground level. It is important to verify the height at which wind speeds measured at different heights above the soil surface differ. The wind speed measured at heights other than 2m can be adjusted according to the given equation.

$$U_2 = U_Z \frac{4.87}{\ln(67.8h - 5.42)} \quad (5)$$

Estimation of the slope of Saturated Vapor Pressure curve (Δ)

The slope of the relationship between saturated pressure and temperature is required for the calculation of evaporating power of the atmosphere.

$$\Delta = \frac{4098(0.6108 exp((\frac{17.27 \times T_{av}}{T_{av}+273.3})}{(T_{av}+273.3)^2} \quad (6)$$

Psychrometric Constant (γ)

The Psychrometric constant is related to the partial pressure of water in the air to the air temperature so that vapor pressure can be estimated using pairs dry and wet thermometer bulb temperature readings (Dobariya D.K, 2006).

$$\gamma = \frac{C_p P}{\varepsilon \lambda} = 0.000665 \quad (7)$$

Actual Vapor Pressure (e_a) derived from Relative Humidity

It can be obtained by assuming when the air temperature is closed to(eT_{min}), the air is nearly saturated with water vapor and the relative humidity in near 100% can be calculated using this relation.

$$e_a = \frac{RH_{mean}}{100} (\frac{eT_{max} + eT_{min}}{2}) \quad (8)$$

Extraterrestrial radiation (R_a)

The extraterrestrial radiation (R_a)for each day of the year and different latitudes can be estimated using solar constant, solar declination and time of the days in a year.

$$R_a = \frac{24(60)}{3.142} G_{sc} d_r (w_s sin\phi sin\delta) + (cos\phi cos\delta sin w_s) \quad (9)$$

Net Radiation (R_n) in equivalent of evapotranspiration (mmday^{-1})

To express the Net Radiation R_n in the equivalent of evapotranspiration (mmday^{-1}) is given by.

$$R_{ng} = 0.408 \times R_n \quad (10)$$

Comparison of ET_O values

Several comparisons were obtained through the simple linear regression analysis techniques and a set of statistical parameters. These statistical parameters are.

Root mean-square error

The root means-square error is used to find the fitness of the model. To assess the linear relative between penman's monteith model and that of Hargreaves – Samani model.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(y_i - x_i)^2}{n}} \quad (11)$$

Relative Error

The Relative Erroralso allows modifying the response variables (independent variable) during calculation or the index of error to be observed during estimation.

Relative Error (RE) = $\frac{RMSE}{\bar{y}} \times 100$ … (12)

3.13.3 Index of Agreement

The index of agreement (IA) is employed in this study to justify the values of the obtained RMSE.

$$(IA) = 1 - \frac{\sum_{i=1}^{n}(x_i - y_i)^2}{\sum_{i=1}^{n}((x_i - \bar{x}) + (y_i - \bar{y}))^2} \quad \ldots (13)$$

Where $x_i = ET_O(mmday^{-1})$ by Hargreaves – Samani method for an ith month, $y_i = ET_O(mmday^{-1})$ by penman's monteith method for the ith month n= number of data, $\bar{x}$= average of ET_O by Hargreaves – Samani method, $\bar{y}$ = average of ET_O by modified penman's method.

Result and discussion

Monthly mean values of ET_O were estimated for optimization of evaporative power of the atmosphere by Hargreaves - Samani method and Modified Penman's method. Results of the findings indicate that there is very little variation of ET_O estimated by both methods shown in (figure 1 – 3).

Table 1. Shows the result of statistical analysis performed on both methods to confirm their linear relationship by high values of coefficient of determination in a range of (0.992-0.994).

The values of Root Mean-Square Error (RMSE), Relative Error (RE) and Index of Agreement (IA) were found as 0.768mm/day, 15.48% and 0.994 in 2013, 0.907mm/day, 17.21% and 0.992 in 2014 and 0.798mm/day, 15.37% and 0.994 in 2015 concurrently. This illustrates optimal agreement between ET_O estimated by the two methods. Hence, it can be concluded that Hargreaves – Samani method can be used for the computation of monthly ET_0 in the absence of detailed climatological data.

Year	RMSE (mmday^{-1})	Relative Error (RE %)	Index of Agreement (IA)
2013	0.768	15.48	0.994
2014	0.907	17.21	0.992
2015	0.798	15.37	0.994

Fig1: Through the findings, it estimated that there is a slight variation between Hargreaves – Samani method and Modified Penman's method. It signifies that in March ET_O based on Modified penman's monteith method is high but the value of ET_O based on Hargreaves – Samani method falls (dropdown). It is also shown in April, May, June, September, and October both methods recorded a high trend. This expresses the evaporating power of the atmosphere. In this case, application of water should be a habit not scientific to improved crop yield and production.

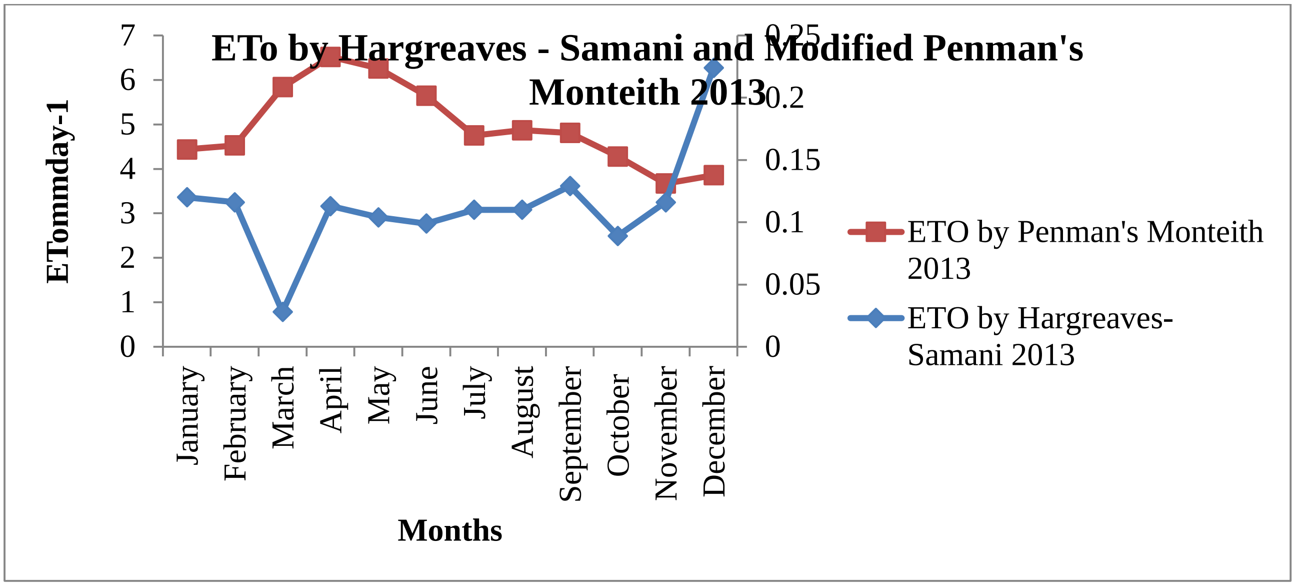

Fig1: Estimated ETo by Hargreaves-Samani Method and Modified Penman's Monteith Method.

Fig2: Shows a little deviation between Hargreaves – Samani method and Modified Penman's method. In April, May, September, and October, high values of ET_O are recorded, with a trend as Estimated ET_O based on Hargreaves – Samani increase and estimation ET_O based on Modified penman's monteith method will also increase. The following months above indicate that there is a need for the application of water to crops.

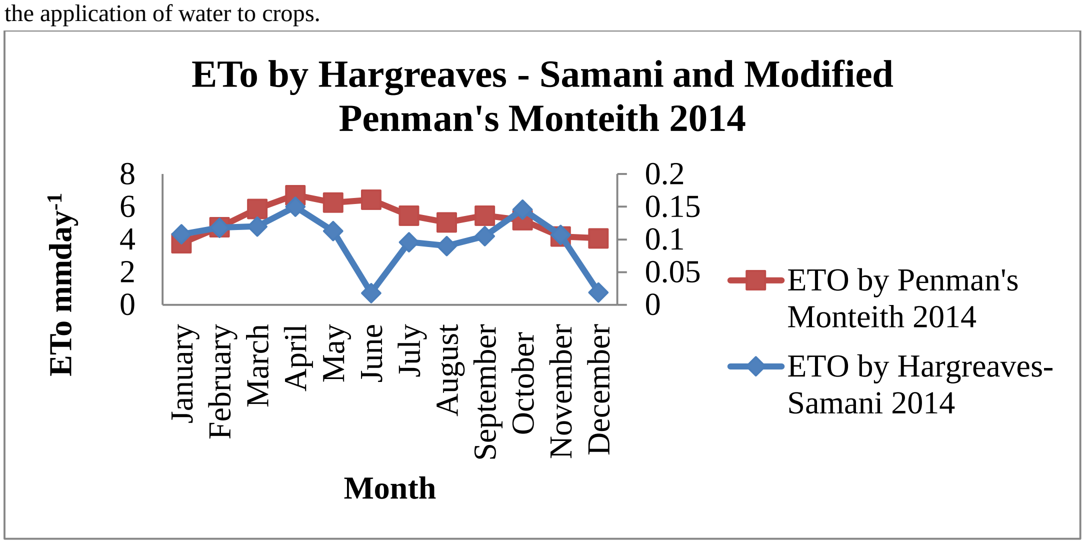

Fig2: Estimated ETo by Hargreaves-Samani Method and Modified Penman's Monteith Method.

Fig3: This shows that there is a trend between Hargreaves – Samani method and Modified Penman's method. It signifies that in May ET_O based on Modified penman's monteith method is high but the value of ET_O based on Hargreaves – Samani method falls (dropdown). It is also shown in April, May, June, September, and October the Modified Penman's method is chosen best for the estimating of ET_O with recorded high plots.

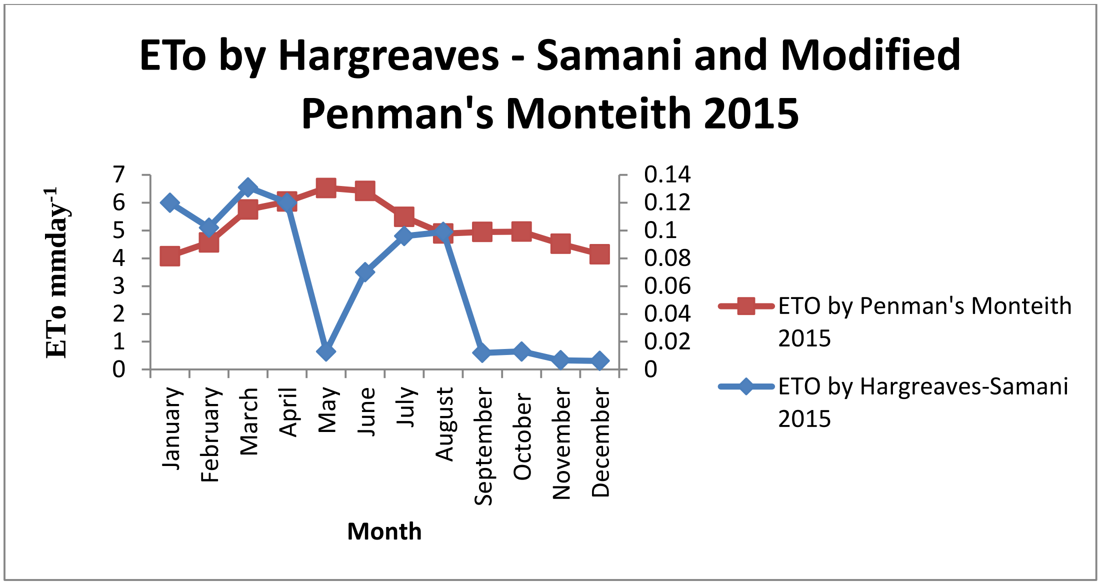

Fig3: Estimated ET_O by Hargreaves-Samani Method and Modified Penman's Monteith Method.

CONCLUSION

The Penman-Monteith equation is based on the physics formule from the original Penman combination equation that has proven effective if applied correctly with high-quality weather data. In **Fig (1-3)** it is shown that the model based on modified penman's monteith gives perfect plots than the model based on Hargreaves-Samani. It's appeared that ET_O equation based on modified penman's monteith meets the goals established for its creation. Therefore, both models were estimated using climatic parameters in Bauchi Metropolis. Based on empirical relation, implies that much water is needed for the optimal yield of crops. The result shows in May, June, October, and September, the soil surface is covered by grasses and crops. This made transpiration to be the major ways of taking water molecule to the earth surface where crops need this water for healthy growth Varshney, *et, al*. (2000). The necessary information about evaporating demand of the Atmosphere, the degree of the relationship between the two models have been given in this study.

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