COMPARISON OF METHODS FOR DETERMINING EVAPOTRANSPIRATION RATE ON CASSAVA FARM IN BENUE NORTH CENTRAL NIGERIA

Yahaya, T.I.
Department of Geography,
Federal University of Technology
Minna, Niger State, Nigeria.

Abstract

Evapotranspiration (ET) is the combined processes of evaporation from soil and plant surfaces and transpiration from plant tissues. Its rate is a very significant factor for supporting irrigation management decisions. Many mathematical models have been developed to explain its behavior and to determine the ET rate. In this study, the rate is estimated using the Bowen Ratio (BR) method, which is based on characteristics of the energy budget associated with atmospheric fluxes. All necessary parameters were measured at the experimental site located in a cassava farm in Benue State from June 2005 to May 2005. The BR results were then compared with the results obtained by the modified Penman-Monett (MPM) method. The comparative results showed that measurements from BR are lower than those of MPM. In terms of economic feasibility, the BR method is more suitable than the MPM method for irrigation planning.

Introduction

Evapotranspiration (ET) is the loss of water from a vegetated surface through the combined process of soil evaporation and plant transpiration (Berger et al., 2005). Its rate is useful in accurately estimating daily water usage and assisting irrigation managers to decide when to apply water and how much water to apply (Brown, 2000). However, the accurate measurement of ET rate is difficult. Various physical parameters of the soil water balance in lysimeters are required to determine this value. Thus, accurate measurement of ET is usually very expensive and can only be fully exploited by well-trained research personnel (FAO, 2005). Therefore, previous researchers have tried to develop indirect methods for evaluating the ET rate, so that it is economically feasible, but can still obtain fairly accurate measurements.

In this study, the Bowen Ratio (BR) (Berger, et al., 2005) and Modified Penman-Monett (MPM) (CIMIS, 2005; Tayo, 2006) mathematical models were used to evaluate the ET rate. All necessary meteorological parameters were measured from the experimental site located in Benue from June, 2005 to May, 2006 (Tayo, 2006). Additionally, this study investigated the sensitivity of ET rates to various significant meteorological factors such as the net radiation, the ambient temperature, the wind speed, and the vapor pressure in both models. All the results are included in this study and are being used to help determine a suitable indirect method for evaluating ET.

In previous studies, ET rate was found to vary with the physicochemical and biological properties of the surface, such as soil moisture, plant type, the stage of plant development, and various meteorological conditions. Thus, it is important to determine the uncertainties arising from the generalization of results from one region to another (Brown, 2000). It is intended that the findings in this study will be used as a database for describing ET for a surface that is commonly found throughout the states in middle belt.

Methodology

Measurements of necessary meteorological parameters were carried out over a spacious uniform level stand in a cassava firm located in Benue from June 2005 to May 2006. Based on measured parameters, the evapotranspiration (ET) rate was evaluated using the Bowen Ratio (BR) method (Berger, et al., 2005) and Modified Penman-Monett (MPM) method by Pruitt and Doorenbos (International Round Table Conference on Evapotranspiration, Budapest, Hungary, 1997). The BR method is based on characteristics of the energy budget associated with atmospheric fluxes. In the environment, energy is partitioned by the energy budget equation (Equation (2.1)) (Berger, et. al., 2005).

$$Rn = G + H + \lambda E \qquad (1)$$

Where Rn is the net radiation (W/m^2); G, the soil heat flux (W/m^2); H, the sensible heat flux (W/m^2); and λE, the latent heat flux (W/m^2). In Equation (1), the term flux refers to flux density, which represents the amount of energy that flows through a horizontal surface of unit area per unit time. However, energy terms related to biological processes, such as photosynthesis and the storage of heat in plant biomass, are considered negligible and thus, are not included in the energy budget. Furthermore, energy terms related to the horizontal transfer of heat are also not included because they are assumed to be small compared to the vertical transfer of heat. From the Bowen Ratio definition (Berger, et. al., 2005):

$$B = H / \lambda E \qquad (2)$$

The sensible heat flux (H, W/m2) can be determined from Equation (3).

$$H = \rho a\ cp\ KH\ (dT/dzt) \qquad (3)$$

Where ρa, the density of air (g/cm^3); cp, the specific heat of air at a constant pressure (cal/g/^{0}C); KH, the turbulent transfer coefficient of heat in air (cm^2/s); and dT/dzt, the temperature gradient near the Earth's surface (^{0}C/cm).

The latent heat flux (λE; W/m^2) can be calculated using Equation (4).

$$\lambda E = (\lambda\, \rho a\, \varepsilon\, KV / p)\, de/dze \qquad (4)$$

Where λ, the latent heat of vaporization for water (cal/g); ε, the ratio of molecular weights of water vapor and air (0.622); *KV*, the turbulent transfer coefficient of vapor (cm^2/s); *p*, the ambient air pressure (mmHg); and *de/dze*, vapor pressure gradient near the Earth's surface.

Based on Equations (3) and (4), the Bowen Ratio can be evaluated from Equation (5)

$$B = [(p\, cp) / (\lambda\, \varepsilon)]\, [(T_u - T_l) / (e_u - e_l)] \qquad (5)$$

Where T_u and T_l, the temperatures at upper and lower reference points (^{0}C); and e_u and e_l, the vapor pressures at upper and lower reference points (mmHg).
From Equation (1) and (2)

$$R_n - G = B\, \lambda E + \lambda E = \lambda E\, (1 + B) \qquad (6)$$

The latent heat flux is considered in the form of used energy for converting water from liquid to vapor and transfers the vapor to the atmosphere in the ET process ($\lambda E = \lambda\, \rho w$ ET). Thus, Equation (6) can be rewritten as Equations (7) and (8). Equation (8) is the main equation for determining the ET rate by the BR method.

$$\lambda E = (R_n - G) / (1 + B) \qquad (7)$$

$$\mathrm{ET} = [(R_n - G) / \lambda\, \rho w]\, \{1 + [(p\, cp) / (\lambda\, \varepsilon)]\, [(T_u - T_l) / (e_u - e_l)]\} \qquad (8)$$

The MPM equation combines the energy balance with the mass transfer method (Refer to Equation (9)) (CIMIS, 2005).

$$\lambda\, \mathrm{ET} = \{\Delta\, (R_n - G) + p\, cp\, [(e_s - e_a) / R_a]\} / \{\Delta + \gamma\, [1 + (R_s / R_a)]\} \qquad (9)$$

Where Δ can be determined from $4099\, e_s / (T + 237.3)2$; *T*, mean hourly air temperature (^{0}C); γ, the psychometrics con[illegible]n be calculated from $p\, cp / \lambda\, \varepsilon$; and R_a and R_s, the aerodynamic and (bulk) surface r[illegible]nces.

Fr[illegible]uation (9), CIMIS (2005) explains the steps of this calculation, which is called the CIMIS e[illegible]n. Note that this study assumed that the ET rate was equal to the reference evap[illegible] rate (ET_0).

Results and Discussions

Evaluation of meteorological parameters

The experiment covered three seasons: rainy season (June to September), wet (October to January), and dry (February to May), respectively. The important meteorological parameters consist of net radiation, wind speed, vapor pressure deficit, and ambient temperature. In the ET theory (Brown, 2000), net radiation (*Rn*; W/m$_2$) contributes huge amounts of energy to vegetation in the desert, and thus is the meteorological parameter with the greatest impact on the ET process. Wind (expressed as wind speed *u* in m/s) is the second most important factor in determining the ET rate. Wind has two major roles. First, it transports heat that builds up on adjacent surfaces, such as dry desert or asphalt, to vegetation, which accelerates evaporation (a process referred to as advection). Moreover, wind also serves to accelerate evaporation by enhancing turbulent transfer of water vapor from moist vegetation to dry atmosphere. Then, the vapor pressure deficit (VPD: $e_s - e_a$; mmHg) is the meteorological variable used to quantify the drying power of the atmosphere. This factor estimates the difference (or gradient) in vapor pressure (concentration of water vapor) between the moist vegetation and the drier atmosphere above. The last parameter, ambient temperature (T_a; ^{0}C) impacts the ET process through its effect on the VPD and advection.

Additionally, the temperature influences the ET process in another way. When all other factors are equal, the ET rate will be higher for the warm vegetation than it is for cool vegetation because less energy is required to evaporate water from the warm vegetation. Temperature also affects the relative effectiveness of the radiant energy because this energy is more effectively utilized for the ET process when temperatures are high. In contrast, wind has a greater impact on the ET process when temperatures are low. In this study, the aforementioned meteorological parameters were measured at the experimental site and averaged for 24 hours. Their values are presented in Table 1.

Table 1: Important Meteorological Parameters Measured at the Site

Important Meteorological parameters	Season			Whole year
	Rainy	Wet	Dry	
Net radiation (R_n; W/m^2)	105.05	72.75	107.76	95.36
Wind speed (u; m/s)	1.27	1.04	1.47	1.3
Vapor pressure deficit ($e_s - e_a$; mmHg)	0.97	2.46	2.24	1.89
Ambient temperature (T_a; ^{o}C)	28.19	27.10	28.48	27.92

Sources: Author's Fieldwork

Evapotranspiration rate (ET; mm/hr) and seasonal variation

Based on the significant meteorological parameters in Table 1, the ET rate can be determined by the Bowen ratio (BR) method (Berger et al., 2005) and modified Penman-Monett (MPM) method by Pruitt and Doorenbos (International Round Table Conference on

Evapotranspiration, Budapest, Hungary, 1997). The results obtained in this study are presented in figures 1 to 3.

In the rainy season (Figure 1), the ET rates that were estimated by the BR and MPM methods were similar. They were high in daytime (8:00 to 17:00; Tayo, 2006) with an average value (8:00 to 17:00) of 0.30 mm/hr for BR method and 0.31 mm/hr for MPM method. The highest values occurred at 13:00 and were 0.49 mm/hr for BR method and 0.48 mm/hr for MPM method. Moreover, they became low or negative at night. These results demonstrated that the ET process was strongly dependent on solar radiation. The radiation energy determines the intensity of convection and the rate of vertical transfer. For water consumption, the maximum values occurred in the rainy season with an average value of 391 mm for BR method and 397 mm for MPM method. The water consumption was high in the rainy season because of the high evaporation rates from the soil and plant surface to the atmosphere in this season although the opening of plant's stomata deceased from the effects of wet conditions or high humidity in the atmosphere.

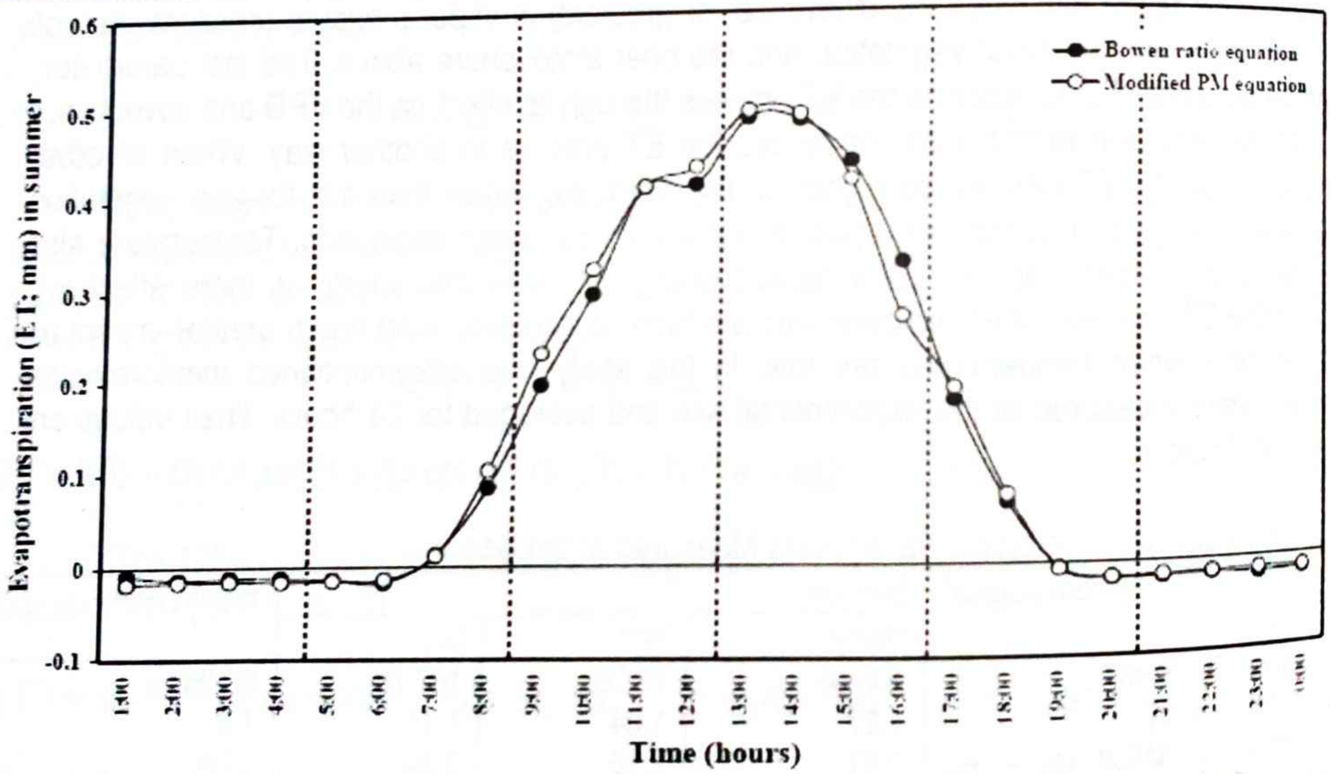

Fig. 1 Estimated ET rate by BR and MPM methods in the rainy season (June to September)

In the wet season (Figure 2), the trends of ET rate were similar to those observed in the rainy season. They were high in the daytime (8:00 to 17:00; Tayo, 2006) with average values (8:00 to 17:00) of 0.22 mm/hr for BR method and 0.26 mm/hr for MPM method. The highest values occurred at 14:00 and were 0.34 mm/hr for BR method and 0.40 mm/hr for MPM method. During the night, they became low or negative. For water consumption, the minimum values occurred in the Wet season with the average values of 232 mm for BR method and 303 for MPM method. The water consumption was low in the Wet season because of the low net radiation in this season, which is the result of the distance between the earth and the sun in the Wet being the greatest due to the earth's elliptical orbit. The low net radiation causes a decrease in the evaporation from the soil and plant surface and photosynthesis from plants' tissues because these processes are directly correlated with the net radiation (Brown, 2000).

Additionally, the estimates given by the two studied methods in the wet season had the greatest variation out of three seasons. From an analysis of the equations used for each method (refer to experimental section of this study), the BR method is derived from the energy balance without the mass transfer, but the MPM method combines them. Thus, the large difference in the estimated ET rates shows that the greatest influence of mass transfer on these values occurred in the wet season. This may be the caused by the high vapor pressure deficit (VPD) found in this season.

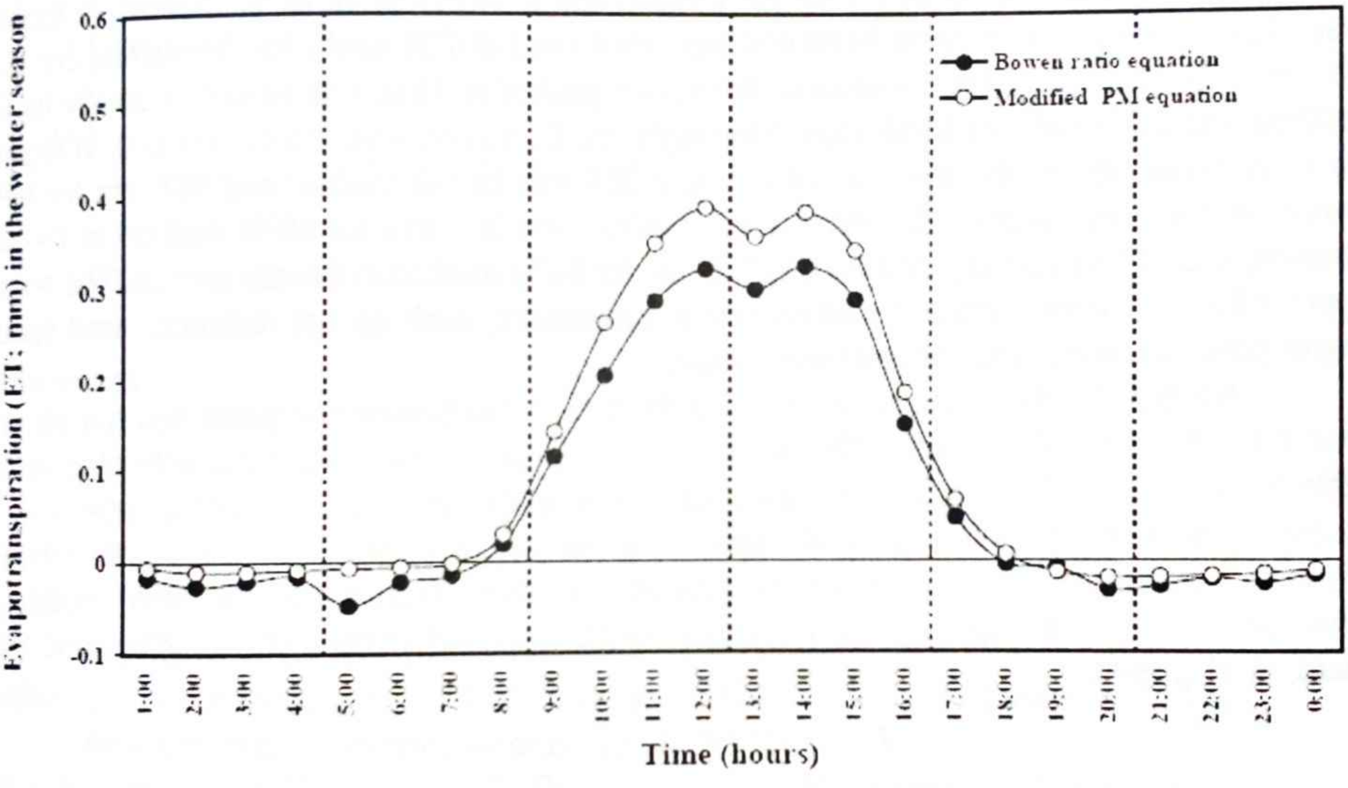

Figure 2 Estimated ET rate by BR and MPM methods in the winter season (October to January)

In the dry season (Figure 3), the ET rate patterns were similar to those found in the other two seasons. The ET rates were high in the daytime (8:00 to 17:00; Tayo, 2006) with average values (8:00 to 17:00) of 0.30 mm/hr for BR method and 0.33 mm/hr for MPM method. The highest values, which occurred at 13:00, were 0.50 mm/hr for BR method and 0.53 mm/hr for MPM method. The average values for water consumption were 347 mm for BR method and 385 mm for MPM method. Although the net radiation in this season was high and is effectively utilized for the

ET rate (Brown, 2000), other meteorological parameters, such as the relative humidity and the wind speed can also influence the ET process.

Conclusions and Recommendations

The evapotranspiration (ET) process is the combination of evaporation from soil and plant surfaces and transpiration from plant tissues. Its rate is an important factor for supporting irrigation management decisions. In this study, the Bowen ratio (BR) and the modified Penman-Monett (MPM) methods were used to determine the ET rate. Both methods rendered a similar trend of ET rates. Their values were high in daytime (8:00 to 17:00); (Tayo, 2006) with average values (8:00 to 17:00) of 0.30 mm/hr for BR method and 0.31 mm/hr for MPM method in the rainy season, 0.22 mm/hr for BR method and 0.26 mm/hr for MPM method in the Wet, and 0.30 mm/hr for BR method and 0.33 mm/hr for MPM method in the dry season. The highest values occurred at 13:00 in the rainy season and were 0.30 mm/hr for BR method and 0.34 mm/hr for MPM method. In the wet season, peak values occurred at 14:00 and were measured at 0.34 mm/hr for BR method and 0.40 mm/hr for MPM method. For dry season, the values peaked at 13:00 and were 0.50 mm/hr for BR method and 0.53 mm/hr for MPM. During the night, the ET values were low or negative. In regards to water accumulation, the average values were 391 mm for BR method and 397 mm for MPM model in the rainy season, 232 mm for BR method and 303 mm for MPM method in the wet season, and 347 mm for BR method and 385 mm for MPM method in the dry season. The results were influenced from important meteorological parameters, such as net radiation, wind speed, vapor pressure deficit, and ambient temperature.

Additionally, the estimated ET rates of the two methods were compared and this showed that the estimated values by the BR method were only slightly lower than the estimated values obtained by the MPM method. Their differences were in the range of 1.5 – 31%, depending on seasonal variation. Moreover, the MPM method requires more specific instrumentation than the BR method. Furthermore, the BR method is more economically efficient than the MPM method, a characteristic which is supported by the experimental results of Polson, et. al. (2004) and Stannard, et. al. (2004).

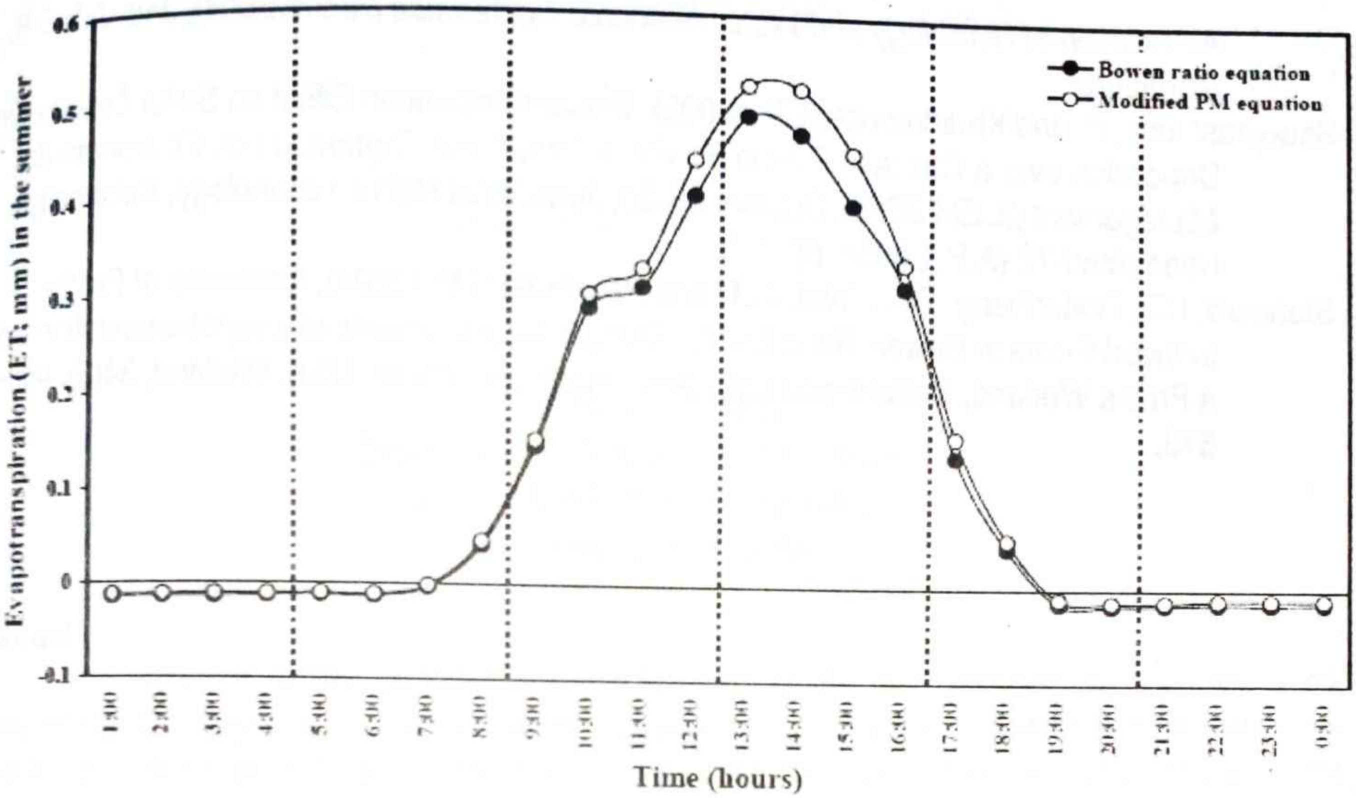

Fig. 3 Estimated ET rate by BR and MPM methods in the summer season (February to May)

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