International Scholars Journals

African Journal of Tropical Agriculture ISSN 2375-091X Vol. 4 (11), pp. 001-009, November, 2016. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Full Length Research Paper

Seasonal temperature-based models for reference evapotranspiration estimation under semi-arid condition of Malawi

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Accepted 07 July, 2016

The importance of evapotranspiration in agricultural water management has been widely reported without doubt. The FAO Penman Monteith (FPM) equation is the sole recommended estimation method of reference evapotranspiration (ETo), but its application is limited due to large number of meteorological data required. In such circumstance, Hargreaves (HGR) and Blaney-Criddle (BCR) temperature-based empirical models are still used in Malawi, regardless of their accuracy in some semiarid areas. This study explored the potential of using HGR and BCR temperature-based models, in Ngabu and Chileka, located in Southern Malawi, where decade climatic data required for FPM equation was collected from 1985 to 2004. The data sets were divided into dry and rainy season to take into account the tendency of over and under estimation of ETo by the models. It was found from this study, that splitting the data into dry and rainy season improves the accuracy of the temperature-based models. From the statistical comparison with FPM, in both sites, HGR performed better than BCR during dry season while BCR showed superior performance over HGR during rainy season. Therefore, seasonal consideration is strongly recommended when temperature-based models are applied under semiarid climatic condition like Malawi where radiation (r = 0.87) and wind speed (r = 0.89) affects ETo. Finally, seasonal temperature- based models are determined and recommended in this study to be used as alternatives of FPM for ETo estimation in Ngabu and Chileka of Malawi.

Key words: Irrigation, agricultural water management, crop water requirement, wind effect, modeling.

INTRODUCTION

The required climatic data for estimating reference evapotranspiration (ETo) by using the FAO Penman Monteith (FPM) model which is recommended across the world is not always available in the agricultural extension services of Malawi. Hence in most areas it is not easy to estimate ETo based on FPM model. The difficulty of using FPM method provided an impetus to explore the potential of using the existing temperature-based models in order for estimating ETo to their equivalent in the FPM model, because temperature data is always available in the agricultural extension services. Therefore, the objective of this study is to determine an easy and reliable method of estimating ETo in semiarid climatic condition of Malawi, specifically in Chileka and Ngabu.

Reference evapotranspiration (ETo), defined as the potential evapotranspiration of a hypothetical surface of green grass of uniform height, actively growing and adequately watered, is one of the most important hydrological variables for scheduling irrigation systems and water balance models computation (Gong et al., 2006). Evapotranspiration is an important component of the hydrological cycle, which accurate calculation at the local and regional scales is needed to achieve an appropriate management of agricultural water resources. According to Igbadun et al. (2006) the importance of evapotranspiration data in both agricultural and hydrological fields may have simulated development of several approaches to quantifying the parameter. These approaches range

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Figure 1. Map of Africa and Malawi showing location of the study sites.

approaches range from direct measurement of evapotranspiration to empirical models that use climatic data as input variables. The direct measurement of evapotranspiration is tedious, time consuming and expensive, hence the use of weather data to indirectly estimate evapotranspiration offers an easy and very reliable alternative. A high degree of precision in estimating crop evapotranspiration may permit important water savings in the planning and management of irrigated areas (Perez et al., 2008). For agricultural purpose, Xiaoying et al. (2005); Donatelli et al. (2006) indicated that reliable estimation of evapotranspiration is required for an efficient water management. Careful estimation of ETo is important for irrigated area, because it is the fundamental for obtaining high water productivity.

Malawi explored in this study is one of the Sub-Saharan African countries with her farmers exposed to increased droughts and floods, tremendously affecting food security. The government of Malawi is now putting much emphasis on irrigated agriculture by assigning more funds in irrigation sector in order to increase agri-cultural productivity. There is a great need in the country to have proper approach of saving water for agricultural purposes. This is challenging because of the high cost for establishing irrigation facility and lack of appropriate planning system for an efficient use of water. Accurate estimation of ETo can help to carry out a standard design and management of irrigation schemes (Clarke et al., 1998; Struzik et al., 2001). However, many researchers have tried to estimate the evapotranspiration through the indirect methods using penman monteith procedure, but some of these techniques require the data which can not be easily obtained (Christiansen, 1996; Burman, 1976; Rosenberry et al., 2007).

ETo can be obtained by many estimation methods, but the factors such as data availability must be considered when choosing the ETo calculation technique (Shih et al., 1983). The Penman-Monteith method is maintained as the sole standard method recommended by the FAO for the computation of ETo from complete meteorological data (Allen et al., 2006; Smith et al., 1990). Nevertheless, the main shortcoming of the FPM method is that it requires data for large number of climatic parameters that are not always available for many locations. Several models such as Hargreaves (HGR) and Blaney-Criddle (BCR) have been proposed to predict ETo, however Traore et al. (2008) reported that, these models do not have universal consensus for different climatic conditions. Studies done under diverse climatic conditions have revealed a widely varying performance of alternative equations which local calibration is required (Allen et al., 1998; Pereira et al., 2006; Stockle et al., 2004). Furthermore, Smith et al. (1996) concluded that these alternatives models require rigorous local calibration

Table 1. S.ummary of average climatic characteristics of 20 years data for Chileka.

Month	T_{min} ^{o}C	T_{max} ^{o}C	T_{amp} ^{o}C	Humidity (%)	Wind speed (km/day)	Sunshine (hrs)	Rain (mm)
Jan	20.5	28.5	8.0	80	198	5.9	241.5
Feb	20.1	28.6	8.5	77	208	6.8	178.8
Mar	19.8	29.1	9.3	77	223	7.1	125.5
Apr	18.2	27.6	9.4	74	247	8.4	43.2
May	16.0	26.4	10.4	68	248	8.8	7.5
Jun	14.1	24.7	10.6	65	249	8.0	1.6
Jul	14.0	24.4	10.4	61	271	7.6	0.7
Aug	15.1	26.5	11.4	57	280	8.3	2.9
Sep	17.7	29.7	12.0	51	297	8.8	3.9
Oct	19.8	31.2	11.4	52	301	8.8	29.5
Nov	20.8	31.5	10.7	57	283	8.1	90.7
Dec	20.8	29.9	9.1	69	231	6.7	159.6
STDEV	2.6	2.3	1.2	10.1	34.0	1.0	83.8
Average	18.1	28.2	10.1	66	253	7.8	73.8

STDEV: Standard deviation, T_{min}: Minimum temperature, T_{max}: maximum temperature, T_{amp}: temperature amplitude.

Table 2. Summary of average climatic characteristics of 20 years data for Ngabu.

Month	T_{min} ^{o}C	T_{max} ^{o}C	T_{amp} ^{o}C	Humidity (%)	Wind speed (km/day)	Sunshine (hrs)	Rain (mm)
Jan	23.4	32.9	9.5	74	156	6.3	224.5
Feb	22.9	32.3	9.4	75	125	6.6	214.7
Mar	22.9	32.8	9.9	72	135	7.0	169.5
Apr	21.1	31.8	10.7	71	131	7.7	59.3
May	16.3	30.2	13.9	70	118	7.5	2.2
Jun	15.9	28.5	12.6	70	114	7.3	0.2
Jul	15.7	28.1	12.4	66	147	6.7	0.9
Aug	17.2	30.6	13.4	61	192	8.2	0.0
Sep	20.0	34.0	14.0	55	258	8.7	0.9
Oct	22.4	35.7	13.3	52	306	8.2	5.0
Nov	23.8	36.2	12.4	58	283	8.5	57.8
Dec	23.8	34.7	10.9	72	215	6.9	188.8
STDEV	3.3	2.6	1.7	7.9	68.2	0.8	93.7
Average	20.4	32.3	11.9	66	182	7.5	77.0

STDEV: Standard deviation, T_{min}: Minimum temperature, T_{max}: maximum temperature, T_{amp}: temperature amplitude.

before they can be used for the estimation of ETo in irrigation scheduling. Blaney-Criddle and Hargreaves considered as temperature methods and using few weather input are still used in areas where the complete data required for ETo estimation is complex (Jensen et al., 1997; Lee et al., 2004).

MATERIALS AND METHODS

Study areas description

The two weather stations selected in this study are located in Southern region of Malawi. These sites are; Chileka located at 15.68°S, 34.96°E, 767 m above sea level and Ngabu located at 16.5°S, 34.95°E and 102 m above sea level (Figure 1). Climatic data sets in decade (10 days) for the period of 20 years from 1985 - 2004 collected in both locations were used. The data is composed of minimum and maximum temperature (°C), relative humidity (%), wind speed (km/day), sunshine duration (hours) and rainfall (mm). The climatic characteristics of the study sites are given in Tables 1 and 2. The weather data in the study areas is divided into rainy season starting from November to March and dry season starting from April to October. Chileka receives an annual average rainfall of 885.6 mm, while Ngabu receives 924 mm. Both study sites have the maximum and minimum average monthly temperature recorded in November and July, respectively. Minimum and maximum air temperature ranges from 14.0 to 20.8°C and 24.4 to 31.5°C in Chileka, 16.7 to 23.8°C and 28.1 to 36.2°C in Ngabu respectively.

The relative humidity mean in Chileka is 61% during dry season and 72% during rainy season, while for Ngabu it is 63.6% during dry season 70.2% during rainy season. Wind velocity for Chileka, recorded at 2 m above the ground has a maximum monthly average of 301 km/day in October and minimum of 198 km/day in January. Similarly, for Ngabu the maximum monthly average wind velocity of 306 km/day and minimum of 114 km/day are recorded in October and June respectively. In summary, from the climatic characteristics, Ngabu experiences relatively high temperature than Chileka, while for the wind speed the opposite is true.

Reference evapotranspiration estimation

Three models of estimating ETo used in this study were Hargreaves, Blaney-Criddle and FAO Penman Monteith. Hagreaves and Blaney-Criddle models are temperature-based, and they were evaluated and adjusted basing on the FAO Penman Monteith model, which was used as a reference:

i) The FAO Penman-Monteith equation for calculation of the reference evapotranspiration assumes the reference crop evapotranspiration as that from a hypothetical crop with an assumed height of 0.12 m having a surface resistance of 70 s m^{-1} and an albedo 0.23, closely resembling the evaporation of an extension surface of green grass of uniform height, actively growing and adequately watered, which is given by (Allen et al., 1998).

$$o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \text{ -------------- (1)}$$

Where ETo is the reference evapotranspiration (mm/day); R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}); G is the soil heat flux density (MJ m^{-2} day^{-1}); T is the mean daily air temperature (°C); u_2 is the wind speed at 2 m height (m s^{-1}); e_s is the saturation vapour pressure (kPa); e_a is the actual vapour pressure (kPa); e_s - e_a is the saturation vapour pressure deficit (kPa); is the slope vapour pressure curve (kPa°C^{-1}) and is the psychrometric constant (kPa °C^{-1}).

ii) Blaney-Criddle (BCR) method is based on temperature data only, can be expressed as:

$$ETo = p(0.46T_{mean} + 8.13) \text{ ----------------------------- (2)}$$

Where T_{mean} is mean temperature ^{o}C and p is the mean daily percentage of annual daytime hours according to the latitude.

iii) Hargreaves (HGR) method (Hargreaves et al., 1985) calculated the ETo when sunshine data, relative humidity data and wind speed data are missing. This method estimates ETo using only the maximum and minimum temperature with the following equation:

$$ETo = C_o (T_{max} - T_{min})^{0.5} (T_{mean} + 17.8) R_a \text{ -------------- (3)}$$

Where ETo reference evapotranspiration (mm/day), T_{max}, T_{min} and T_{mean} are maximum, minimum and mean temperature ^{o}C respectively; R_a is the extraterrestrial radiation (mm/day), C_o is the conversion coefficient (C_o = 0.0023).

Data analyses

Average decade and monthly ETo values for the period of 20 years (1985 to 2004) were calculated for the 2 study areas using 3 different models. The estimated ETo were evaluated for Chileka and Ngabu according to the time step considered in this study. A statistical pair test was used to compare the decade and monthly ETo for the 3 models. Firstly, comparison was made between the 2 temperature based models and then between each temperature based model and the FAO Penman Monteith model. The coefficients of determination (r^2) and standard error of estimate (SEE) were used to identify the best temperature- based method. The SEE is an estimate of the mean deviation of the regression from the estimated FPM method values. The equations for r^2 and SEE are represented as follow:

$$r^2 = \frac{\left[\sum_{i=1}^{N} (y_i - \bar{y})(y_i' - \bar{y}')\right]^2}{\sqrt{\sum_{i=1}^{N} (y_i - \bar{y})^2 \sum_{i=1}^{N} (y_i' - \bar{y}')^2}} \text{ -------------------- (4)}$$

$$SEE = \sqrt{\frac{\sum_{i=1}^{N} (y_i - y')}{(N - 2)}} \text{ --- (5)}$$

Where y_i represents the FPM observed ETo, y'_i is the regression estimated ETo for the ith values, $\bar{y}_i$ and $\bar{y}_i'$ represent the average values of the corresponding variable and N represents the number of data considered. Linear regression y= ${}_0$+ ${}_1$x was used, where y is the dependent variable (FPM); x is the independent variable (temperature-based model); ${}_0$ the intercept and ${}_1$ the slope.

Sensitivity analysis of climatic variable on ETo

To estimate the relative participation of climate variables to the calculated ETo, a sensitivity analysis was performed. There are several approaches available for sensitivity analysis studies, as reported by Bois et al. (2008). This study used Pearson correlation coefficients on a monthly basis for maximum, minimum mean and amplitude air temperatures, wind speed, relative humidity, sunshine and radiation. The Pearson correlation can be described as the following:

$$r = \frac{\sum_{i=1}^{N} (x - \bar{x})(y - \bar{y})}{\sqrt{\sum_{i=1}^{N} (x - \bar{x})^2 \sum_{i=1}^{N} (y - \bar{y})^2}} \text{ (6)-----------------}$$

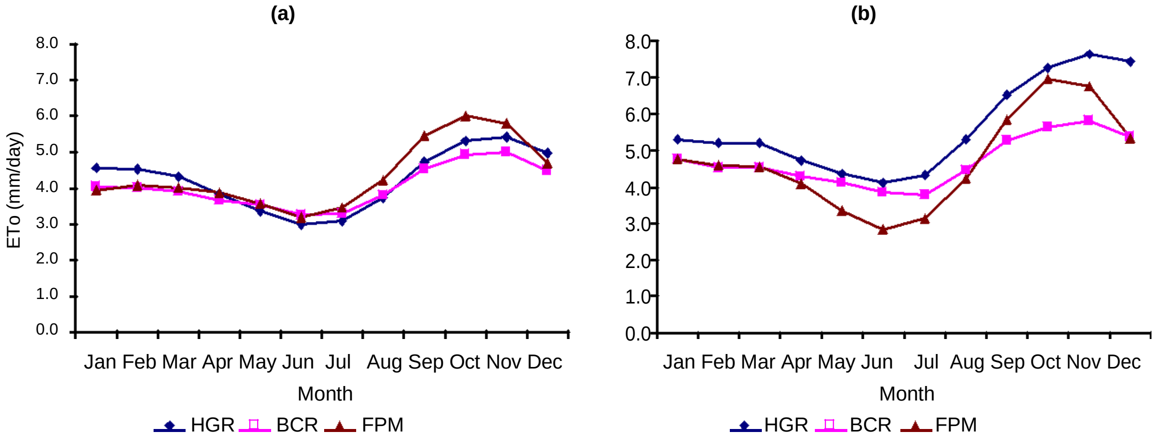

Figure 2. Illustration of Mean monthly ETo trends for Chileka (a) and Ngabu (b).

Where X is the observed climatic variable; y is the estimated ETo by FPM; $\bar{x}$ and $\bar{y}$ are their mean values. The coefficients were used to determine the most influential climatic variables on ETo in the study areas.

RESULTS AND DISCUSSION

ETo trend

From the results of this study, as illustrated in Figure 2 it was observed that ETo estimated by all the 3 methods is low from May to July in both the study sites. The ETo is high from August to November due to probably high air temperature, low relative humidity, high wind speed and more of sunshine hours than during the rest of the months. It was also observed that, in Chileka, HGR and BCR models underestimate ETo during the dry season (April to November). BCR starts underestimating increasingly more than HGR in August. In Ngabu, HGR overestimate ETo for the entire year, while BCR overestimate from March to August and underestimate from August to December. The temperature-based models underestimated and overestimated ETo because they do not capture the influence of some important factors that affect ETo. Jensen et al. (1997) and Temesgen et al. (2005) have also suggested possible overestimation of ETo by HGR under humid environments and underestimation under windy conditions, compared to the Penman–Monteith combination equations. Study done by Wang et al. (2007) also reported that, ETo is sensitive to wind and the performance of the estimation method may also be influenced. Based on the general ETo trends, the temperature-based models underestimate in dry season and overestimate in rainy season. Under this seasonal fluctuation and trends of ETo values consideration, the data used in this study have been split according to rainy and dry season. The seasonal based concept has been employed because there is variation among the climatic parameters that affect ETo between the seasons. Similar approach has also been reported by Igbadun et al. (2006) for ETo estimation of the Great Ruaha River Basin in Tanzania by using Hargreaves and Jensen-Haise models.

Seasonal based models performance

Splitting the average decade and monthly data used in evaluating the models into rainy season and dry season improves the performance of HGR and BCR in both sites. During dry season, HGR model showed better performance than BCR and vise-versa during rainy season as shown in Tables 3 and 4. Both models performed better when the data was split on monthly than decade basis, regardless of the season (Table 3) . Despite slightly high coefficients of determination for the entire year than for rainy season, the corresponding models can not be suggested to be used on seasonal basis, as this can be explained by the dry season high coefficients of determination. Studies done by Trajkovic (2007) reported that HGR equation generally overestimate ETo for humid location. This proves the less performance of HGR during rainy season than dry season in the study site because it is humid in rainy season than dry season. From the statistic analysis, it is found that ETo estimated by HGR model is not significantly different from ETo estimated by BCR model in Ngabu. However ETo estimated by the 2 models were found to be significantly different in Chileka at $p < 0.001$. ETo estimated by both temperature-based models were significantly different to FPM. According to the coefficients of determination, ETo linear expressions can be fitted between the ETo of the FPM and HGR, in the study areas for dry season. Similarly, the expressions can be fitted between the ETo of FPM and BCR, for the rainy season in both sites. Temperature- based models were selected basing on their performance during season time step as presented in Tables 3 and 4. However to the

Table 3. Models performance according to decade and monthly data splitting.

Site	Time step	Model	Performance					
			Intercept		Slope		r^2	
			Decade	Monthly	Decade	Monthly	Decade	Monthly
Chileka	Dry season	BCR	- 0.8754	- 1.9357	1.3878	1.6616	0.7439	0.8690
		HGR	- 0.2315	- 0.5251	1.2227	1.2986	0.8448	0.8810
	Rainy season	BCR	- 0.2893	- 1.6753	1.1812	1.504	0.6458	0.7839
		HGR	- 1.3435	- 2.9082	1.2843	1.6123	0.6449	0.7705
	Annual	BCR	- 0.4922	- 1.4898	1.2622	1.5086	0.7012	0.8138
		HGR	- 0.3705	0.1094	1.0005	1.0621	0.6783	0.7040
Ngabu	Dry season	BCR	- 2.2174	- 4.0316	1.3900	1.7747	0.6931	0.8646
		HGR	- 1.5108	- 2.1526	1.3118	1.4558	0.858	0.9365
	Rainy season	BCR	- 0.0203	- 1.7679	0.9953	1.3285	0.6255	0.7958
		HGR	- 0.9017	- 2.9459	1.0887	1.4535	0.6078	0.7716
	Annual	BCR	- 1.5495	- 3.2328	1.2654	1.6064	0.6856	0.8469
		HGR	- 0.8084	- 1.4108	1.1154	1.2374	0.7745	0.8435

BCR: Blaney Criddle, HGR: Hargreaves

Table 4. Standard errors of estimate for BCR and HGR models.

Site	Method	Time step		
		Dry season	Rain season	Annual
Chileka	BCR	0.4159	0.4306	0.4664
	HGR	0.3964	0.4562	0.6157
Ngabu	BCR	0.5371	0.5097	0.5375
	HGR	0.3676	0.5214	0.5434

BCR: Blaney Criddle, HGR: Hargreaves.

knowledge of the authors, there is very limited literature for ETo estimation by using temperature based models on seasonal basis in these specific semiarid climatic environment.

Seasonal based models

Figure 3 shows the linear relationship of the selected models with FPM for each area. All the coefficients in all the linear relationships for the selected models were significant at $p < 0.001$; hence the coefficients can be used to convert ETo estimated by the temperature-based models to their equivalent as estimated by FPM on seasonal basis. This study therefore establishes seasonal temperature-based models which are strongly recommended for estimating reference evapotranspiration in Chileka and Ngabu. The models are expressed as equations (7) and (8) in Chileka for dry and rainy season ETo estimation respectively. While equations (9) and (10) are for are for Ngabu.

$$ET_o = R_a T_{amp}^{0.5}(0.0029T_{mean} + 0.0532) – 0.5251 \text{ --------} (7)$$

$$ET_0 = p(0.6918T_{mean} + 12.2275) – 1.6753 \text{ -------------------} \quad (8)$$

$$ET_o = R_a T_{amp}^{0.5}(0.0033T_{mean} + 0.0596) - 2.1526 \text{ --------} \quad (9)$$

$$ET_0 = p(0.6111T_{mean} + 10.8007) – 1.7679 \text{ -----------------} \quad (10)$$

Where T mean °C is mean temperature; Tamp °C is the difference between maximum and minimum temperature; p is the mean daily percentage of annual daytime hours according to the latitude and Ra is the extraterrestrial radiation (mm/day).

Sensitivity of climatic variables on ETo

Results from the correlation of climatic variables to ETo show that all variables have a significant effect on ETo at $p < 0.0001$. Maximum temperature is the most influential factor in both study sites according to the correlation coefficients presented in Table 5. This finding also indicates that radiation which is computed from air temperature data has good correlation than most of the factors in the study sites. From Table 5, it is clearly seen

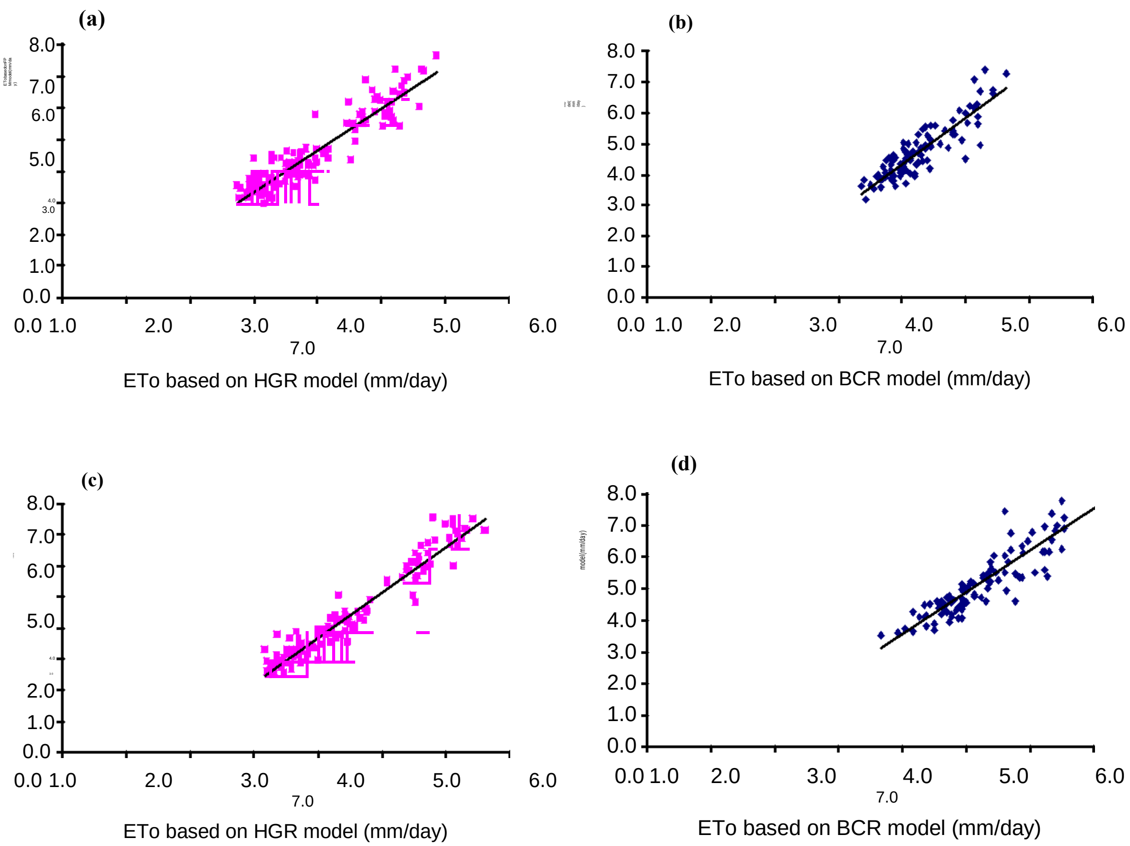

Figure 3. Relationship between models in; Chileka for dry season (a), rainy season (b); and Ngabu for dry season (c) rainy.

Table 5. Pearson correlation coefficients for climatic variable with ETo in Chileka and Ngabu.

Variable	Chileka			Ngabu		
	Annual	**Dry season**	**Rain season**	**Annual**	**Dry season**	**Rain season**
T_{min}	0.5507	0.7559	0.4877	0.7108	0.7993	0.5471
T_{max}	0.8390	0.9022	0.8117	0.9131	0.9146	0.8813
T_{amp}	0.4209	0.5522	0.7392	0.2114	0.3537	0.8969
T_{mean}	0.7233	0.8568	0.7816	0.8481	0.8915	0.8119
Humidity	- 0.6162	- 0.7507	- 0.8937	- 0.5595	- 0.7987	- 0.7771
Wind	0.5129	0.5875	0.7233	0.8362	0.8867	0.8886
Sunshine	0.3787	0.4320	0.7216	0.4582	0.4722	0.7924
Radiation	0.8393	0.8707	0.7785	0.8793	0.8694	0.8475

T_{min}: Minimum temperature, T_{max}: maximum temperature, T_{amp}: temperature amplitude. T_{mean}: mean temperature.

that in dry season, high correlation coefficients were found between radiation and ETo as evidenced by the r values of 0.8707 and 0.8694 for Chileka and Ngabu, respectively. This indicates that the radiation is the largest energy source for changing the liquid water into vapour, which means that there is an increased potential for evapotranspiration when radiation is also increasing. It has been documented at least by Hupet et al. (2000) and Gong et al. (2006) that radiation has high effect on ETo.

Minimum temperature has a high effect on ETo in dry season than during the rainy season because it does not change very much during rainy than dry season. Wind speed has also a great impact on ETo in Ngabu than Chileka, in both rainy and dry season with an annual correlation coefficient value of 0.8362. The effect of wind speed can be probably explained by its high variation observed in Ngabu by high standard deviation (68.2 km/day). According to the correlation coefficients wind speed is the second important variable affecting ETo in Ngabu. Hess (1998) also found high correlation between ETo and wind speed in the East Arid Zone of Nigeria in West Africa. The high correlation of wind and relative humidity with ETo implies that, they should not be overlooked when estimating ETo in this semiarid condition, thus any temperature-based estimation method should be adjusted based on the FPM. In these semiarid areas, wind affects ETo even with small variation because it promotes the removal of water vapour from any evaporating or transpiring surface, hence creating high demand for evapotranspiration potential. Sunshine and temperature amplitude, despite their significant effect on ETo, have low correlation than the rest of the variables during dry season in the study sites.

Conclusion

Reliable estimation of ETo is crucial for agricultural water efficient management in Malawi. The performance of Hargreaves and Blaney-Criddle has been evaluated basing on FAO Penman Monteith method for the 2 study sites; Chileka and Ngabu. It is discovered from this study that ETo computation on seasonal basis that is, dry and rainy season, improves the performance of the temperature-based models. Beside, radiation and wind speed have been found to be the most effective variables affecting the ETo in the observed condition. The evaluation resulted in establishment of seasonal temperature-based models for the study sites, shows that the effect of wind on ETo could be explained by the variation of wind speed observed between the2 seasons. Therefore, from the results of this present study, it is concluded that, seasonal based approach should be implied when estimating ETo using temperature- based models, in the semiarid environment of Ngabu and Chileka. Moreover, care must be taken when collecting the wind data since ETo is sensitive to its effect. Finally, the determined seasonal temperature-based models are recommended to be used for estimating reference evapotranspiration to their equivalents, which are estimated by the FAO Penman Monteith model. This new approach opens huge opportunity for solving the current irrigation management difficulty by a rapid and accurate estimation of ETo in Malawi.

ACKNOWLEDGEMENTS

We would like to thank the Department of Meteorology in Malawi for providing the climatic data used in this study. Department of Civil Engineering at National Pingtung University of science and Technology is also acknowledged for the financial support provided for this study. Beside, the authors acknowledge the Department of Tropical Agriculture and International Cooperation for offering all the facility during this study.

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