International Journal of the Physical Sciences Vol. 6(9), pp. 2239-2248, 4 May, 2011
Available online at http://www.academicjournals.org/IJPS
DOI: 10.5897/IJPS11.166
ISSN 1992 - 1950 ©2011 Academic Journals

Full Length Research Paper

Comparative study on estimating reference evapotranspiration under limited climate data condition in Malawi

Yu-Min Wang[1]*, Willy Namaona[2], Lennox Alexander Gladden[2], Seydou Traore[2] and Lian-Tsai Deng[1]

[1]Department of Civil Engineering, National Pingtung University of Science and Technology, Neipu Hsiang, Pingtung 91201, Taiwan.
[2]Department of Tropical Agriculture and International Cooperation, National Pingtung University of Science and Technology, Neipu Hsiang, Pingtung 91201, Taiwan.

Accepted 04 April, 2011

The Food and Agriculture Organization (FAO) missing data procedure was employed in this study to verify its suitability under the climatic environment of Malawi. The performance of the procedure was analysed by regressing ETo estimated from the world wide recommended FAO penman Monteith (FPM) model with full data set versus FPM value computed with limited data. The coefficients of determination (r^2), standard errors of estimates (SEE) and estimates rates (Rate) were used for evaluating the model performance in five production sites in Malawi including Karonga, Chitedze, Kasungu, Chileka and Ngabu. The study shows the suitability of the FAO procedure to estimate other climatic variables which are required in FPM model when only temperature data is available under the semiarid environment of Malawi. However in areas of high wind speed like Karonga and Chileka, care must be taken while applying the procedure when both wind and relative humidity are missing. Additionally, it is observed that the model performances improved while seasonal based estimation is applied. Therefore, the seasonal based consideration should be recommended accounting for the climatic variation between the seasons. The missing data estimation procedure may help to solve part of the irrigation planning and management problem due to the meteorological data unavailability in some areas of Malawi.

Key words: Evapotranspiration, missing data, seasonal based, irrigation management, wind speed, semiarid environment.

INTRODUCTION

Reference evapotranspiration (ETo) is of significant importance in scheduling irrigation systems, preparing input data to hydrological water balance models and calculating evapotranspiration for a region (Gong et al., 2006; Wang et al. 2009a). ETo can be computed as a function of weather parameters. These parameters can either be acquired from observed climatic data or from numerical models for example General Circulation Models (GCM's) which are utilized by regional and national climatic centers to represent the physical process in the atmosphere and land surface when actual weather data is lacking.

Many studies have been conducted world wide to find the proper method of accurate ETo estimation. So far, there is only one equation; the FAO Penman Monteith (FPM) which has been recommended to be used across the world. The FPM model which incorporates thermodynamic and aerodynamic aspects has proved to be a relatively accurate method in both humid and arid climates. It is however not possible in many location to use the FPM model because its complete data requirement is not always available. Consequently, it becomes very hard to compute ETo particularly in African semiarid regions where there exists poor data situation

*Corresponding author. E-mail: wangym@mail.npust.edu.tw.

(Wang et al. 2008) especially in regards to availability and more so accessibility. There is a problem of accessibility because of the existence of sophisticated gridding technologies, for example the Land Surface Analysis Satellite Application Facility (LSA SAF) which is able to estimate with some degree of accuracy the data required to calculate ETo. Therefore complete data availability and in the case of some countries in Africa the inaccessibility to data, has forced many scientists to conduct studies for alternative ETo estimation methods to overcome the challenge. Numerous temperature-based models have been proposed and used to estimate ETo (Wang et al. 2007). Several studies done under diverse climatic conditions have revealed a widely varying performance of alternative equations in which local calibration are required (Allen et al., 1998; Pereira et al., 2006; Stockle et al., 2004). Several models such as Hargreaves (HGR) and Blaney-Criddle (BCR) have been proposed to predict ETo; however Traore et al. (2008) reported that, there is no universal consensus on the suitability of any given model for a given climate. Furthermore, Smith et al. (1996) concluded that these alternatives models require rigorous local calibration before they can be used for the estimation of ETo in irrigation scheduling. Blaney-Criddle and Hargreaves are considered as temperature methods and using few weather input are suitable to areas where the complete data required for ETo estimation is complex (Jensen et al., 1997; Lee et al., 2004).

Nevertheless, Allen et al. (1998) suggested the missing data estimation procedure which can be applied for computing accurate ETo from limited weather data. The proposed methodology uses temperature data for estimating the other climatic variables required by the recommended FPM. The procedure has been applied around the world for computing accurate ETo from limited weather data. Studies using the FAO missing data estimation procedure done in North China environment by Liu and Pereira (2001), Pereira et al. (2003) and Cai et al. (2007) have showed a sound agreement with the ETo from full observed data. In Southern Bulgaria, Popova et al. (2006) also found successful results with the FAO missing data estimation procedure for computing the ETo. In their study, they found that such methodology can yield accurate ETo only from maximum and minimum temperature in the driest regions of Bulgaria, Western Europe. This methodology has been reported as a good alternative for searching the ETo estimation that fits the datasets available. However, to the knowledge of the authors, it is found that no research has been reported yet using such methodology for computing ETo in African semiarid regions where a full meteorological data availability is very poor.

Therefore, the present study explores applicability of such methodology in the wide agro-climatic zone of Malawi. In Malawi irrigation planning is done on annual basis, hence the average monthly data for twenty years period (1985 to 2004) was used to evaluate performance of the methodology in the semiarid climatic condition of Malawi.

MATERIALS AND METHODS

Study areas description

The five weather stations selected in this study are located in Malawi, which is situated in southern east of Africa, between latitude 9º22" and 17º03"S, and longitude 33°40" and 35°55"E. These locations are; Karonga in the northern region, Kasungu and Chitedze in central region, and Chileka and Ngabu in southern region of the country (Figure 1). Monthly climatic data sets for the period of twenty years from 1985 to 2004 collected in all locations were used. The data is composed of minimum and maximum temperature (°C), relative humidity (%), wind speed (km/day), hours of sunshine (hours) and rainfall (mm). The description of the different weather stations is given in Table 1. These locations were used because they cover almost all the latitudes in Malawi (from 9.95ºS to 16.5ºS) and they are situated at different elevations above sea level.

All the study areas are characterized by two main seasons, which are dry and rainy. Dry season starts from October to March or April, while rainy season elapses from April to September. Table 2 presents the average climatic characteristics using 20 years of collected historical weather data for dry and rainy season. There are differences in the climatic variables between the seasons, for instance, it can be seen that minimum, maximum temperature and humidity are higher in rainy than in the dry season. Wind speed and sunshine are higher in dry than rainy season in the study sites. Generally, wind speed is higher in Karonga and Chileka than the other sites. Wind speed has a higher variation among the study sites in both dry and rainy seasons than the rest of the variable. Temperature in Malawi is greatly influenced by topography, being for example warmer in the low lying areas than in the highlands. This explains the relatively higher temperature regardless of the season in Karonga and Ngabu, because they are situated in the low lying areas than the rest of the study sites.

Reference evapotranspiration estimation

Average monthly ETo values for the period of twenty years (1985 to 2004) were calculated for the five study areas using the FPM model. The FAO Penman-Monteith equation for calculating 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) as

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

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 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); Δ is the slope vapour pressure curve (kPa°C^{-1}); and γ is the psychrometric constant (kPa °C^{-1}).

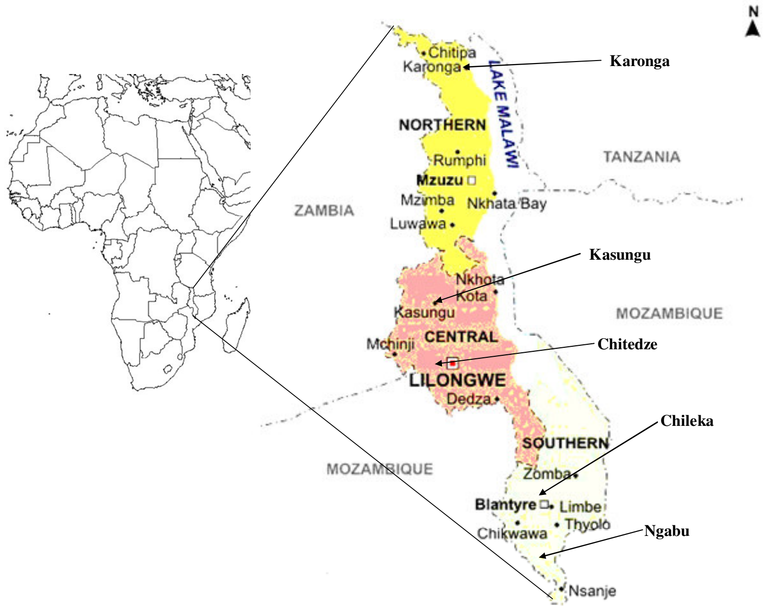

Figure 1. Sketch map of Africa and Malawi.

Table 1. Description of the weather stations.

Station	Latitude (ºS)	Longitude (ºE)	Altitude(m above sea level)
Karonga	9.95	33.88	529
Kasungu	13.02	33.46	1015
Chitedze	13.98	33.38	1149
Chileka	15.68	34.58	767
Ngabu	16.5	34.95	102

Table 2. Climatic characteristics of the study sites using 20 years (1985 to 2004) data.

Season	Variable	Karonga	Kasungu	Chitedze	Chileka	Ngabu
	Tmin (℃)	19.1	13.4	11.8	16.4	18.6
	Tmax (℃)	29.6	27.1	26.3	27.2	31.3
Dry	Humidity (%)	62.8	60.9	59.6	61.0	63.6
	Wind (km/day)	247.3	198.4	128.0	270.5	180.9
	Sunshine (h)	9.3	9.1	8.7	8.4	7.8
	Tmin (℃)	22.3	19.8	17.8	20.4	23.4
	Tmax (℃)	30.9	28.5	27.7	29.4	33.8
Rainy	Humidity (%)	70.5	73.2	72.6	72.2	70.3
	Wind (km/day)	195.9	177.6	106.4	228.6	182.9
	Sunshine (h)	6.7	6.6	6.2	6.9	7.1

Missing data estimation procedure

The Penman-Monteith equation is a function of air temperature, sunshine, relative humidity and wind speed, which means these variables are important in ETo estimation. In this study, wind speed, relative humidity and sunshine have been considered as missing variables when using the FAO missing data estimation procedure. This means that the data considered as missing are estimated through the missing data estimation procedure before estimating ETo. Table 3 illustrates the data structures when estimating ETo

Table 3. FPM missing data estimation model data composition in Malawi.

Model	Description
FPM_Wind	Wind data is missing
FPM_RH	Relative humidity data is missing
FPM_Sun g	Sunshine hour data is missing
FPM_Wind & RH	Wind and relative humidity data are missing
FPM_Wind, RH & Sun	Wind, relative humidity and sunshine hour data are missing

with the FAO missing data estimation procedure.

Missing radiation data

Temperature difference method was used, based on the fact that differences between maximum and minimum temperature are closely related to the existing solar radiation in a given location (Allen et al*.,* 1998)

$$R_s = k_{Rs}\sqrt{T_{max} - T_{min}}\,R_a \qquad (2)$$

where R_s and R_a are solar and extraterrestrial, radiation, respectively ($MJm^{-2}day^{-1}$), T_{max} is the maximum air temperature (ºC) T_{min} is the minimum air temperature (ºC), K_{Rs} is the adjustment coefficient. The adjustment coefficient K_{Rs} is empirical and differs for "interior" or "coastal" region: for interior location, where land mass dominates and air masses are not strongly influenced by a large water body, $K_{Rs} \approx 0.16$; for coastal locations situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body, $K_{Rs} \approx 0.19$. Extraterrestrial radiation is estimated as the following (Allen et al., 1998)

$$R_a = \frac{24(60)}{\pi} G_{sc} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)] \qquad (3)$$

where G_{sc} is the solar constant = 0.0820 $MJm^{-2}min^{-1}$, d_r is the inverse relative distance earth-Sun (rad), ω_s is the sunset hour angle (rad), φ is the latitude (rad), and δ is the solar declination (rad). The inverse relative distance earth-sun, d_r and the solar declination, δ, were estimated by

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365} J\right) \qquad (4)$$

$$\delta = 1 + 0.409\sin\left(\frac{2\pi}{365} J - 1.39\right) \qquad (5)$$

Where J is the number of the day in the year between 1(1 January) and 365 or 366 (31 December). J at the middle of each month (M) of the year was used as the monthly value, which was calculated as

$$J = 30.4M - 15 \qquad (6)$$

The sun set hour angle is given by

$$\omega_s = \cos^{-1}[-\tan(\varphi)\tan(\delta)] \qquad (7)$$

Missing relative humidity data

The relative humidity (RH) expresses the degree of saturation of the air as the ratio of the actual (e_a) to saturation (e^o(T)) vapour pressure at the same temperature. Relative humidity was estimated as the following

$$RH = 100\frac{e_a}{e^o(T)} \qquad (8)$$

The saturation vapour pressure was calculated from the air temperature (T) expressed as

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

An estimate of actual vapour pressure was obtained by assuming that dew point temperature (T_{dew}) is near the minimum temperature T_{min}. This implicitly assumes that at sunrise, when temperature is close to T_{min}, the air is nearly saturated with water vapour and the relative humidity is nearly 100%. In semi arid region T_{dew} is estimated by subtracting 2℃ from T_{min} because it is slightly greater than T_{dew}. Equation (9) was therefore also used to estimate actual vapour pressure by substituting T by adjusted T_{dew}.

Missing wind data

A default value for light to moderate wind of 172 km/day recommended by Allen et al. (1998), which is the average value over different weather stations around the globe, was used as a temporary estimate for wind speed.

Performance analysis of the missing data procedure

Average monthly ETo values for the study period were calculated for the five study areas using the FPM. The estimated ETo were evaluated for the five study sites according to different missing data conditions. The ETo estimated under different missing data situations were regressed to the ones estimated by FPM model with full data set required, linearly. Thus the linear relationship can be expressed as $y=\alpha_0+\alpha_1 y'$ was used, where y is the dependent variable (FPM); y′ the independent variable (ETo calculated by the missing data procedure); α_0 the intercept; and α_1 the slope. The coefficients of determination (r^2), standard error of estimate (SEE) and estimates rates (Rate) were used for the evaluation of the performance. The SEE is an estimate of the mean deviation of the regression from the estimated FPM method values and Rate is the percent at which the ETo values estimated using the FAO missing data procedure, deviated from ETo values estimated with the FPM method.

Table 4. Performance evaluation of proposed seasonal temperature-based models.

Site	Time step	Mode	Intercept	Slope	r^2	SEE
Karonga	Dry season	HGR	0.0951	1.1381	0.6417	0.9068
	Rainy season	BCR	-2.5002	1.7092	0.6524	0.6855
Kasungu	Dry season	HGR	-2.3197	1.5336	0.8869	0.5016
	Rainy season	BCR	-0.3770	1.1922	0.7715	0.2817
Chitedze	Dry season	HGR	-0.2702	0.9467	0.8742	0.5777
	Rainy season	BCR	-0.4522	1.0703	0.7795	0.3675
Chileka	Dry season	HGR	-0.5251	1.2986	0.8810	0.3964
	Rainy season	BCR	-1.6753	1.5040	0.7839	0.4306
Ngabu	Dry season	HGR	-2.1526	1.4558	0.9365	0.3676
	Rainy season	BCR	-1.7679	1.3285	0.7958	0.5097

Source: Wang et al. (2009b).

The results of this study were also compared with that of the recently proposed seasonal temperature-based models by Wang et al. (2009b). Table 4 shows the statistical parameters that were used for the evaluation of Hargreaves (HGR) and Blaney Cridle (BCR), in their study. According to their results it was discovered that HGR yielded a better performance during dry season, while BCR performed better in rainy season.

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.

RESULTS AND DISCUSSION

Performance of missing data procedure

ETo has been estimated by the FPM equation from the full set of the observed data and also from the missing data estimation procedure. Table 5 shows the comparison results while Figure 2 shows the comparison plots, between FPM using full set of observed data and estimated data from the missing data estimation procedure for computing ETo under the situation of the climatic data unavailability in the study sites.

Missing wind speed data

It is clearly shown in this study, that when only wind speed data is considered as missing in all the study sites, The FAO missing data procedure yielded good results which agree well with ETo estimation using full observed data set. The better performance of the procedure is evidenced by coefficient of determination ranging from 0.953 to 0.993. In Kasungu, Chitedze, and Ngabu there is mean annual ETo overestimation by 2.19, 10.03, and 2.53% respectively. For Karonga and Chileka, ETo is underestimated by 2.22 and 3.71% respectively.

Missing relative humidity data

The FAO missing procedure also showed good results when relative humidity data is considered as missing. The coefficient of determination ranges from 0.948 to 0.990. ETo is overestimated indicated by the positive rate of estimation in all the study sites except Karonga under the condition of missing relative humidity data. The small standard errors of estimates in all the study sites also showed the good performance of the FAO missing data estimation procedure, under the condition considered.

Missing sunshine data

From a statistical point of view, the procedure of FAO to estimate ETo, when sunshine data is not available showed well an agreement with the ETo estimation when using full observed data set. This can be explained by the relatively high coefficient of determination, small rate of over or underestimation, and also small standard error of estimation. The r^2, rate of estimation and SEE values range from 0.960 to 0.981, -3.75 to 3.73%, and 0.035 to 0.112 in respectively. Similar to the condition of relative humidity data unavailability, ETo is underestimated except in Karonga region where it is overestimated.

Table 5. Performance evaluation of the FAO missing data estimation procedure under different situations.

Location	Model	α_1	α_0	r^2	Rate (%)	SEE
	FPM_Wind	1.148	-0.602	0.979	-2.22	0.048
	FPM_RH	1.292	-1.212	0.978	-3.58	0.104
Karonga	FPM_Sun	0.984	0.258	0.977	-3.75	0.062
	FPM_Wind & RH	1.374	-1.323	0.925	-7.64	0.302
	FPM_Wind, RH & Sun	1.485	-1.186	0.794	-16.45	1.054
	FPM_Wind	1.182	-0.901	0.993	2.19	0.042
	FPM_RH	1.303	-1.383	0.978	1.23	0.082
Kasungu	FPM_Sun	0.928	0.277	0.960	0.85	0.049
	FPM_Wind & RH	1.535	-2.29	0.960	-0.50	0.164
	FPM_Wind, RH & Sun	1.664	-2.47	0.910	-5.69	0.320
	FPM_Wind	0.960	-0.219	0.959	10.03	0.207
	FPM_RH	1.026	-0.369	0.985	6.77	0.091
Chitedze	FPM_Sun	0.860	0.412	0.960	3.73	0.070
	FPM_Wind & RH	1.218	-1.520	0.986	14.58	0.408
	FPM_Wind, RH & Sun	1.161	-1.220	0.971	13.50	0.355
	FPM_Wind	1.131	0.412	0.970	-3.71	0.078
	FPM_RH	1.197	-1.183	0.948	4.94	0.140
Chileka	FPM_Sun	0.907	0.475	0.978	-1.19	0.035
	FPM_Wind & RH	1.146	-0.507	0.818	-3.17	0.221
	FPM_Wind, RH & Sun	1.209	-0.459	0.812	-9.12	0.425
	FPM_Wind	1.297	-1.544	0.986	2.53	0.140
	FPM_RH	1.117	-0.589	0.990	0.75	0.040
Ngabu	FPM_Sun	0.891	0.330	0.981	4.31	0.112
	FPM_Wind & RH	1.489	-2.281	0.951	-0.14	0.286
	FPM_Wind, RH & Sun	1.495	-2.197	0.957	-1.74	0.288

Missing wind speed and relative humidity data

The performance of the FAO missing data procedure also concurs with ETo estimation by FPM full observed data when wind speed and relative humidity are together considered as missing in Chitedze, Kasungu and Ngabu. However, the performance becomes poor (r^2=0.818) in Chileka. The results showed that, when wind speed and relative humidity data are missing in Karonga, the performance decreases up to 0.92 for the coefficient of determination. In general, the standard error of estimation is higher when wind speed and relative humidity data are missing than when one climatic variable is missing in all the study sites.

Missing wind speed, relative humidity and sunshine data

Similar to the condition of missing wind and relative humidity, the FAO missing data estimation procedure performs well in Kasungu, Chitedze, and Ngabu when wind speed, relative humidity, and sunshine data are missing. The results showed poor performance of the procedures in Karonga and Chileka yielding r^2 values of 0.794 and 0.812, respectively. Generally, the condition of single climatic variable such as wind speed, relative humidity and sunshine data unavailability gave lower values for standard errors of estimate and rate of estimation than when more than one variable are missing. From the procedure of estimating the missing variables, relative humidity is estimated from the temperature data while wind is taken from the global average of 2 m/s. This implies that humidity has a relationship with air temperature and yet wind is considered a constant. However there is an associated effect of wind and humidity on ETo which could be significant when wind is high. Alexandris et al. (2006) also found that the wind speed affect the ETo by an over/underestimation under various air relative humidity

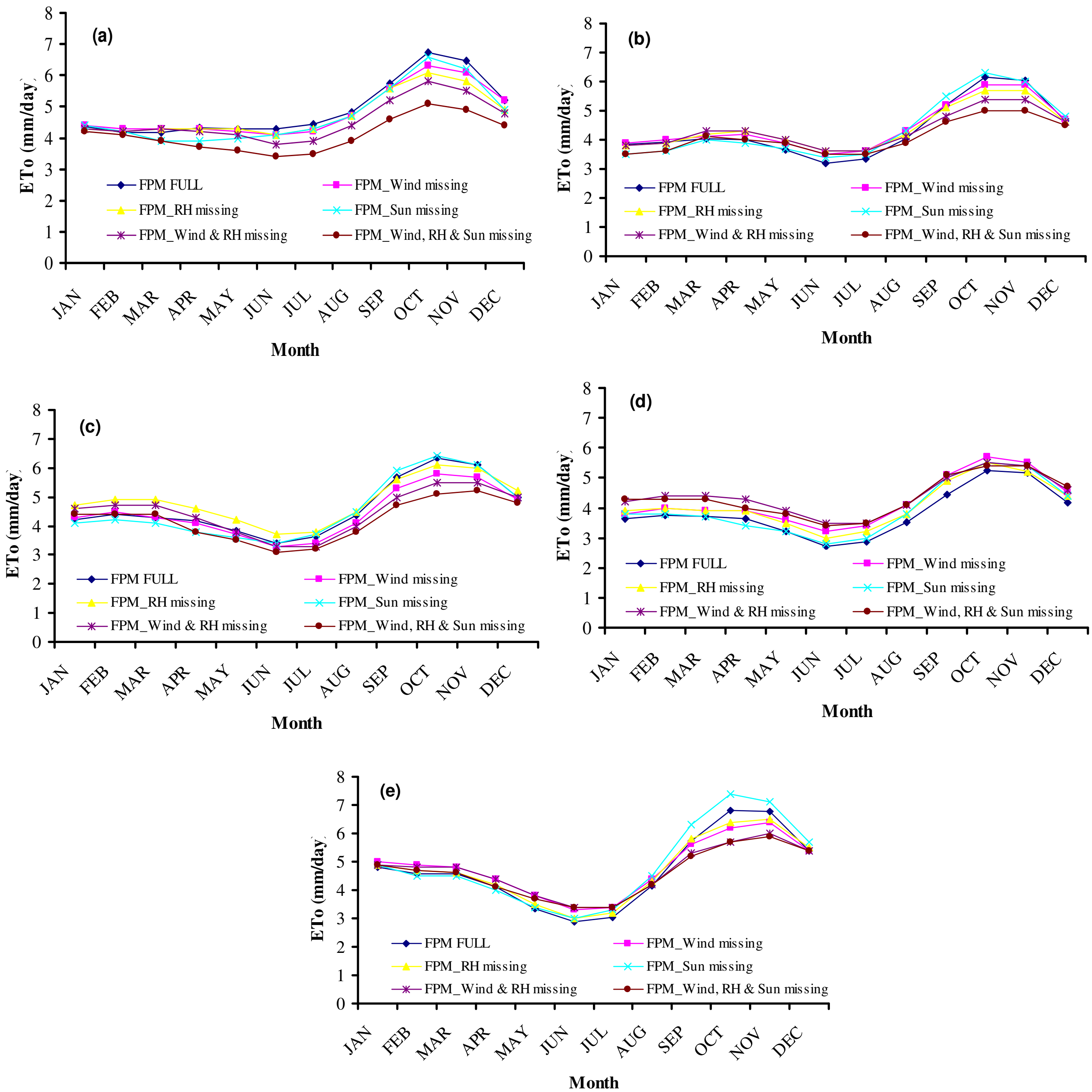

Figure 2. Comparison of FPM using full set of observed data and estimated data from the missing data estimation procedure for (a) Karonga (b) Kasungu (c) Chitedze (d) Chileka and (e) Ngabu.

regimes. They found that high humidity values (>75%) increases the effect of wind on ETo with an overestimate, and that there is underestimation of ETo, which becomes more pronounced under high wind speed regimes and for dry environment. According to the results of this present study ETo is overestimated under the condition of missing wind speed, relative humidity and sunshine in Chitedze where wind speed is relatively lower than the rest of the sites. Lopez et al. (2003) also reported that lack of wind data leads to underestimation of ETo during time of high wind speed. In this present study, there is a drastic decrease in the performance when both wind and relative humidity are estimated as missing in Chileka and Karonga due to the high wind speed compared to the other sites despite having almost the same average relative humidity and the estimated wind values 172

Table 6. Correlation coefficients of climatic variables to ETo for entire year.

Variable	Karonga	Kasungu	Chitedze	Chileka	Ngabu
Tmin	0.3529	0.4101	0.4320	0.5507	0.7108
Tmax	0.8004	0.8738	0.9163	0.8390	0.9131
Tamp	0.3220	0.0477	0.1212	0.4209	0.2114
Tmean	0.5956	0.6207	0.6813	0.7233	0.8481
Humidity	-0.7904	-0.6625	-0.4674	-0.6162	-0.5595
Wind	0.5916	0.6366	0.4559	0.5129	0.8362
Sunshine	0.5590	0.3816	0.2940	0.3787	0.4582
Radiation	0.8654	0.8508	0.8828	0.8393	0.8793

km/h. Moreover in the north China plain when only air temperature data is available, Pereira et al. (2003) computed ETo by using FAO missing data estimation procedure and obtained the r^2, 0.80 and 0.81 for Wang Du and Xiongxian regions, respectively. Cai et al. (2007) also found in arid and semiarid regions of China the performance of the FPM missing data estimation procedure ranged between 0.791 and 0.894 for the r^2. This indicates that in dry area the methodology of FAO missing data estimation does not always estimate the representing value of the wind speed. Despite having relatively lower variation in wind speed than the other sites, Karonga and Chileka have the average wind speed of 224.64 and 250.56 km/day respectively, which is above the global average (172 km/h) for ETo calculation by using the estimated missing data procedure. This can also be supported by the fact that there is pronounced underestimation in all the sites from august to October except for Chitedze with average wind speed of 259.2, 233.28, 155.52, 293.76, and 259.2 km/day in Karonga, Kasungu, Chitedze, Chileka and Ngabu, respectively.

Comparison of FAO procedure and seasonal temperature-based models

In trying to overcome the difficulty of estimating ETo due to climatic data unavailability in these study sites, Wang et al (2009b) also introduced and recommended seasonal temperature-based models by using Hargreaves (HGR) and Blarney Criddle (BCR) models. They found that ETo computation on seasonal basis i.e. dry and rainy season improves the performance of the ETo estimation models in this semiarid environment of Malawi. According to their performance evaluation results as presented in Table 2, they discovered that during dry season, HGR model showed better performance than BCR and vice versa, during rainy season. The results of Wang et al. (2009b) were compared with our results from the FAO missing data procedure in order to check its goodness. The missing data procedure shows better results than the seasonal temperature-based models, presented in Table 4. However it is important to note that the proposed seasonal temperature-based ETo estimation approach does not need any missing data estimation before computing ETo. The missing data procedure needs good skills and knowledge for computing the data missing by the first users whom are the irrigation practitioners. The procedure also requires a computer which is not always available in areas where irrigation is practiced. Under these circumstances an easy option can be the seasonal temperature-based method to manually compute ETo. In another way, if the above challenges are confronted, the FAO missing data is the reliable approach to overcome the difficulty of data unavailability in Malawi. If seasonal consideration is applied using FAO missing data procedure, a better result could be obtained.

Sensitivity of climatic variables

Results from the correlation of the climatic variables (Table 6) to ETo shows that statistically all variables significantly affect ETo, except temperature amplitude in Chitedze and Kasungu with correlation coefficients of 0.1212 and 0.0477, respectively, for annual estimation at $p<0.0001$. Likewise minimum temperature for these two sites; Chitedze and Kasungu does not significantly affect ETo during rainy season. Comparing the two seasons, the coefficient of correlation for minimum temperature is low in rainy season except for Karonga (cor=0.6703) Maximum temperature as indicated by high values of correlation ranging from 0.8004 to 0.9239 is the most influential factor in all the study sites. This finding also indicates that radiation has good correlation than most of the factors in the study sites with cor values ranging from 0.8393 to 0.8828. This implied that 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 increases. Generally, ETo is more sensitive to both relative humidity and wind speed than sunshine and temperature amplitude in all the study sites. Relative humidity has a negative correlation with ETo, that is, it decreases with increase in relative humidity. Wind speed, sunshine hours, relative humidity

Table 7. Correlation coefficients of climatic variables to ETo for dry season.

Variable	Karonga	Kasungu	Chitedze	Chileka	Ngabu
Tmin	0.4832	0.7896	0.5706	0.7559	0.7993
Tmax	0.8323	0.8825	0.9239	0.9022	0.9146
Tamp	0.2094	0.3438	0.2493	0.5522	0.3537
Tmean	0.7039	0.8520	0.8026	0.8568	0.8915
Humidity	-0.7498	-0.7441	-0.5723	-0.7507	-0.7987
Wind	0.5155	0.6556	0.5281	0.5875	0.8867
Sunshine	0.5551	0.3148	0.4490	0.4320	0.4722
Radiation	0.8634	0.8379	0.9297	0.8707	0.8694

Table 8. Correlation coefficients of climatic variables ETo for rainy season.

Variable	Karonga	Kasungu	Chitedze	Chileka	Ngabu
Tmin	0.6703	0.2120	0.2540	0.4877	0.5471
Tmax	0.9211	0.9146	0.9069	0.8117	0.8813
Tamp	0.6863	0.7760	0.8646	0.7392	0.8969
Tmean	0.8992	0.6320	0.7997	0.7816	0.8119
Humidity	-0.9282	-0.9492	-0.8877	-0.8937	-0.7771
Wind	0.7653	0.7033	0.5457	0.7233	0.8886
Sunshine	0.8817	0.8878	0.8678	0.7216	0.7924
Radiation	0.8937	0.9173	0.9074	0.7785	0.8475

and temperature amplitude have higher correlation during rainy than dry season in all the site. The relatively low correlation of wind speed, humidity and sunshine to ETo in Chitedze could also support the fact that ETo is overestimated, unlike the other sites when these climatic variables are missing. There is a pronounced gap between the correlation of wind speed and ETo in Chileka and Karonga than the rest of the sites between the seasons (Tables 7 and 8). The differences of the coefficient of correlation are 0.2498 and 0.1358 for Karonga and Chileka, respectively. This may also explain lower estimated results of the FAO missing data procedures in the two sites. It can therefore be emphasized that radiation, wind speed and relative humidity should not be overlooked when estimating ETo in these semiarid areas.

Conclusions

Accurate estimation of ETo is crucial for efficient management of agricultural water in Malawi. From this study, it has been found that when a single climatic variable such as wind speed, relative humidity or sunshine duration is missing, its estimated value from the FAO missing data procedure can be used for computing accurate ETo in Malawi. Furthermore, it was observed that, when more than one variable is missing, the estimated values from the FAO missing data estimation procedure did not perform well as in a single missing data situation. Probably, relative humidity may accentuate the effect of wind on the ETo, this could explain the poor performance of FAO estimation procedure when these two variables are missing in a windy area. It can be concluded that when only one variable is not observed in the regions studied, its estimated value produces accurate ETo values. While wind speed, relative humidity and sunshine duration are not observed together in Karonga and Chileka, their estimated values produce poor ETo values.

Furthermore, it was observed that the FAO estimation procedure performance is better for ETo estimation on seasonal basis than the entire annual consideration. Using the FAO procedure to estimate ETo based on the seasonal consideration has presented the highest accuracy in Malawi. The approach for estimating ETo on seasonal basis is essentially recommended due to the specific difference between dry and wet seasons. The FPM missing data estimation procedure can solve part of the irrigation planning and management due to the meteorological data unavailability in Malawi.

ACKNOWLEDGMENTS

The authors would like to thank Taiwan's International

Cooperation and Development Fund (ICDF) and acknowledge the partial financial support from NSC Taiwan under the grant of 99-2625-M-020-001; without their unwavering supports this study would not be possible.

REFERENCES

Alexandris S, Kerkides P, Liakatas A (2006). Daily reference evapotranspiration estimates by the “Copais” approach. Agric. Water Manage., 82: 371-386.

Allen RG, Pereira LS, Raes D, Smith M (1998). Crop Evapotranspiration, guideline for computing water requirements. Irrigation Drainage Paper No 56, FAO, Rome, Italy.

Bois P, Pieri C, Van Leeuwen L, Wald F, Huard J, Gaudillere P, Saur E (2008). Using remotely sensed solar radiation data for reference evapotranspiration estimation at a daily time step. Agric. For. Meteorol., 148: 619-630.

Cai J, Liu Y, Lei T, Pereira LS (2007). Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages. Agric. For. Meteorol., 145: 22-35.

Gong C, Yu X, Chen D, Halldin S, Chen YD (2006). Sensitivity of penman monteith reference evapotranspiration to key climatic variables in the Changjiang (Yangtze River) basin. J. Hydrol., 329: 620-629.

Jensen DT, Hargreaves GH, Temesgen B, Allen RG (1997). Computation of ETo under non ideal conditions. J. Irrig. Drain. Eng., 123: 394-400.

Lee TS, Najim MMM, Aminul MH (2004). Estimating evapotranspiration of irrigated rice at the west coast of the peninsular of Malaysia. J. Appl. Irrig. Sci., 39: 103-117.

Liu Y, Pereira LS (2001). Calculation methods for reference evapotranspiration with limited weather data (in Chinese). J. Hydra. Eng., 3: 11-17.

Lopez M, Hess T, White S (2003). Estimation of reference evapotranspiration in the upper Aragon river basin with Penman-Monteith equation using easily available meteorological data. Eur. Geo. Soc., 5: 29-41.

Pereira AR, Green S, Nova NAV (2006). Penman–Monteith reference evapotranspiration adapted to estimate irrigated tree transpiration Antonio Roberto. Agric. Water Manage., 83: 153-161.

Pereira L S, Cai LG, Hann M J (2003). Farm water and soil management for improved water use in the North China plain. Irrig. Drain., 52: 299-317.

Popova Z, Kercheva M, Pereira LS (2006). Validation of the FAO methodology for computing ETo with limited data. Application to south Bulgaria. Irrig. Drain., 55: 201-215.

Smith M, Allen R, Pereira L (1996). Revised FAO methodology for crop water requirements. In proceeding of the ASAE International Conference on Evapotranspiration and Irrigation Scheduling, San Antonio, Texas, November 3-6, pp. 116-123.

Stockle CO, Jim K, Gianni B (2004). Evaluation of estimated weather data for calculating Penman-Monteith reference crop evapotranspiration. J. Irrig. Sci., 23: 39-46.

Traore S, Wang YM, Kerh T (2008). Modeling reference evapotranspiration by generalized regression neural network in semiarid zone of Africa. WSEAS Trans. Inf. Sci. Appl., 5(6): 991-1000.

Wang YM, Traore S, Kerh T (2007). Assessment of Evapotranspiration based on Data information models at Production sites in Burkina Faso. WSEAS Trans. Comp., 6(6): 880-887.

Wang YM, Traore S, Kerh T (2008). Neural Network Approach for Estimating Reference Evapotranspiration from Limited Climatic Data in Burkina. WSEAS Trans. Comp., 6(7): 704-713.

Wang YM, Traore S, Kerh T (2009a). Computational performance of reference evapotranspiration in semiarid zone of Africa. Sci. Res. Essays, 4(6): 577-583.

Wang YM, Namaona W, Traore S, Zhang ZC (2009b). Seasonal temperature-based models for reference evapotranspiration estimation under semi-arid condition of Malawi. Afr. J. Agric Res., 4(9): 878-886.