Evaluation of the FAO Penman–Montheith, Priestley–Taylor and Hargreaves models for estimating reference evapotranspiration in southern Malawi

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ABSTRACT

This study evaluated the performance of the Food and Agriculture Organization (FAO) Penman–Monteith (PM) reference evapotranspiration (ET_0) method for various limited data scenarios in southern Malawi. The study further evaluated the full data PM method against the radiation-based Priestley–Taylor (PT) and the temperature-based Hargreaves (HAG) methods, which are less data-intensive approaches commonly used to estimate ET_0 in data-scarce situations. A comprehensive daily climate dataset observed at the Nchalo Sugar Estate in southern Malawi for the period 1971–2007 was the basis of the study. The results suggested that lack of data on wind speed and actual vapour pressure did not significantly affect the PM ET_0 estimates. However, the estimation of radiation using various combinations of observed wind speed and relative humidity all resulted in significant deviations from the PM ET_0. Further, the HAG and PT methods significantly underestimated the PM. However, the PM method computed with estimated climate variables instead of observed climate variables still outperformed both the PT and HAG methods if their original parameters and estimated radiation were used. Thus, new monthly parameters for the PT and the HAG methods are proposed for more accurate daily ET_0 estimates.

Key words | FAO Penman–Montheith, Hargreaves, Malawi, Priestley–Taylor, reference evapotranspiration

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INTRODUCTION

Actual evapotranspiration (ET), the combined process of soil water evaporation, interception loss and transpiration (Trajkovic 2010), plays a significant role in the global water balance and in the energy balance at the Earth's surface (Tateishi & Ahn 1996; Chen *et al.* 2005). ET is also central in long-term water resources planning and management, as it is a consumptive water use that cannot be recovered (Committee on Opportunities in the Hydrologic Sciences 1991). Global estimates indicate that up to 64% of the land-based average annual total precipitation of 750 mm is returned to the atmosphere as evaporation (Fisher *et al.* 2005; Sumner & Jacobs 2005). However, ET is among the most difficult parts of the hydrological cycle to quantify due to the complex interaction between the land surface, vegetation and atmosphere (Xu & Singh 2005; Fang *et al.* 2012).

ET can be directly estimated using hydrological approaches (e.g. soil water balance, weighing lysimeters), micro-meteorological methods (e.g. energy balance and Bowens ratio, aerodynamic and eddy correlation method) and plant physiological approaches (e.g. sap flow and chambers system methods) (Rana & Katerji 2000). Due to complexities in the direct quantification of ET, the potential evaporation (ET_p) provides the theoretical basis for the estimation of ET (Xu & Chen 2005; Xu & Singh 2005; Gong *et al.* 2006; Xu *et al.* 2006). ET_p can be defined as the maximum amount of water capable of

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being lost as water vapour, either by evaporation or transpiration, in a given time by actively growing vegetation completely shading the ground, of uniform height and with adequate water in the soil profile (Chattopadhyay & Hulme 1997). The influence of surface types in ET_p is removed by using the concept of reference evapotranspiration (ET_0), which is defined as the rate of ET from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of $70\,s\,m^{-1}$ and an albedo of 0.23, closely resembling the ET from an extensive surface of green grass of uniform height, actively growing, well watered and completely shading the ground (Allen *et al.* 1998). ET_0 expresses the evaporative demand of the atmosphere for a grass reference evapotranspiring surface with abundant water supply and can therefore be estimated from meteorological data alone (Xu *et al.* 2006; Sentelhas *et al.* 2010).

There exists a variety of models for estimating ET_0 that are classified based on the climate input needed (Singh & Xu 1997a, b; Xu & Singh 2000, 2001, 2002). These include: mass-transfer-based methods (e.g. Dalton 1802; Thornthwaite & Holzman 1939; Kuzmin 1957); temperature-based approaches (e.g. Thornthwaite 1944; Blaney & Criddle 1950; Hargreaves 1975); radiation-based methods (e.g. Makkink 1957; Priestley & Taylor 1972); and combination methods based on the mass transfer principle and the energy balance (e.g. Penman 1948) and Food and Agriculture Organization (FAO) Penman–Montheith, or PM (Allen *et al.* 1998).

Among the various ET_0 estimation methods, the PM method by Allen *et al.* (1998) was adopted in this study as the standard reference tool. The method has been evaluated for a wide range of climatic conditions and found to be more comparable to lysimeter measurements than other methods (Jensen *et al.* 1990; Allen *et al.* 1998; Ventura *et al.* 1999; Pereira & Pruitt 2004; Gavilán *et al.* 2006; Lopez-Urrea *et al.* 2006; Benli *et al.* 2010). The PM method is a physically based approach incorporating physiological and aerodynamic parameters that can be used globally without much need for additional adjustments of parameters (Allen *et al.* 1998; Sentelhas *et al.* 2010). Input data required include observed air temperature, relative humidity, solar radiation and wind speed. Apart from air temperature readings, the other climatic variables are not commonly measured at many climate stations, even in developed countries (Gavilán *et al.* 2006). Consequently, the PM method has had limited application in many developing countries where infrastructure and equipment that directly measure ET_0 or ET are almost non-existent. As a result, there is a limited understanding of the role of ET in data-scarce regions, despite it being a key water balance component. There is therefore a need in such regions for evaluating the performance of alternative approaches that only require readily available meteorological variables. Furthermore, the PM method as outlined in Allen *et al.* (1998) provides procedures for estimating ET_0 with missing climate data. Such procedures, however, require the assessment of their accuracy in various climates, as addressed by numerous studies (e.g. Xu & Singh 2002; Popova *et al.* 2006; Gavilán *et al.* 2006; Jabloun & Sahli 2008; Sentelhas *et al.* 2010; Azhar & Perera 2011).

Malawi, located in south-eastern Africa, has a predominantly agro-based economy. Accurate quantification of ET is therefore critical for the better management of water resources and agricultural production in the country. The country experiences a wide range of climatic differences due to the combined influence of water bodies and different altitude. Such contrasting settings require a comprehensive understanding of the spatial and temporal variability in ET for water resources management.

Literature on ET_0 studies in Malawi is very scarce. Wang *et al.* (2009) recently evaluated the applicability of the PM method at a monthly scale for various sets of missing data at five climate stations in Malawi. The study found that particular missing data on wind speed and relative humidity in high wind speed areas affected the calculated ET_0. Other previous ET-related studies as presented by Mandeville & Bachelor (1990) include: Pike (1961), who estimated monthly free water evaporation using the Penman formula at 23 stations during 1952–1961; World Meteorological Organization (WMO 1976), which estimated the average annual evaporation from Lake Malawi from a relationship between the Lake Chilwa water balance and adjacent evaporation pans; van der Velden (1979), who analysed pan measurements at 38 stations in Malawi and found the highest evaporation rates in low-lying areas along Lake Malawi and in the lower Shire River valley; Dandaula (1979), who found approximately equal estimates of open water evaporation and ET_p using the Penman method at 19 stations for the period 1972–1979 (obtaining different open water evaporation estimates from Pike (1961)); and Mandeville & Bachelor (1990), who assessed the applicability of the catchment water balance, Thornthwaite's method, Penman method and three complimentary relationship-based approaches in estimating ET, and recommended the catchment water balance as a yardstick. However, these previous studies applied input-data-demanding models (e.g. Penman method by Dandaula (1979)), which are not observed in many stations.

The aim of this study was to evaluate the performance of methods for estimating ET_0 in southern Malawi, a sparsely gauged area with limited stations observing meteorological data of acceptable quality for a useful length of time. As ET is a significant process in the water balance of this hot and low-rainfall region of Malawi, a more accurate estimation of ET_0 is clearly much needed.

MATERIALS AND METHODS

Study region

The study area is located in southern Malawi in south-eastern Africa (Figure 1). Malawi has a total area of 118,484 km^2, of which 94,080 km^2 is land and 24,404 km^2 is occupied by lakes and rivers. The topography is dominated by the Great Rift valley from north to south of the country which contains Lake Malawi. The landscape around the valley consists of large plateau at an elevation of around 800–1,200 m above sea level (a.s.l), but with peaks as high as 3,000 m a.s.l. The climate is mild tropical with an austral summer rainy season between November and April and a dry winter season between May and October. Rainfall depends on the position of the Inter-Tropical Convergence Zone (ITCZ) and varies in its timing and intensity from year to year.

Countrywide rainfall varies from 725 mm in the low-lying rift valley to 2,500 mm in the highlands (Ngongondo *et al.* 2011). Temperatures are also controlled by the

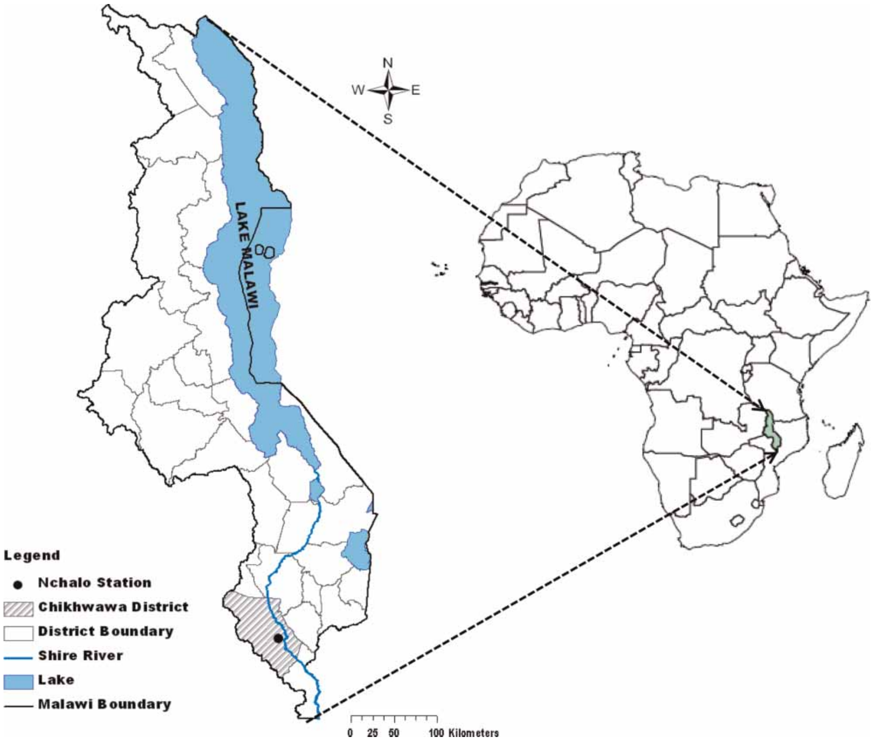

Figure 1 | Map of Malawi showing the location of the Nchalo Sugar Estate Station in Chikhwawa District.

varying altitude and fall within the range 22–27 °C in the summer months. Day temperatures drop to around 18 °C, whereas night temperatures can be as low as 5 °C in the winter months from May to August (Jury & Mwafulirwa 2002). According to Mandeville & Bachelor (1990), average annual runoff expressed as a percentage of the average annual rainfall varies from 4% in the drier parts of plateau areas to 54% in the highlands, where most streams are perennial. Pan evaporation measurements from 38 stations countrywide for the period 1971–1978 showed a mean annual range of 1,500–2,000 mm in the plateau areas, 2,000–2,500 mm along the Lake Malawi shore and the Shire River valley and below 1,500 mm in the cooler high-rainfall areas (van der Velden 1979).

Data availability

The study used observed daily weather data of maximum and minimum temperature (°C), relative humidity (%), wind speed (m s^{-1}), incoming shortwave solar radiation (MJ m^{-2} d^{-1}) and rainfall (mm) from the Nchalo Illovo Sugar Estate Station for the period 1971–2007. The data were sourced from the Malawi Department of Climate Change and Meteorological Services and Illovo Sugar Company's Nchalo Estate in Chikhwawa District. The station received a mean annual rainfall of 722 mm during this period. Table 1 presents some daily mean values of the climate variables used in computing ET_0 for the station. The monthly mean variation of rainfall, wind speed, mean temperature and mean relative humidity during the year is shown in Figures 2(a) and 2(b).

The data are of reasonably high quality with missing data accounting for only 0.038% (or 5 days) during the entire 36-year period. The data were nevertheless subjected to standard quality control procedures using the AnClim software (Stepaneck 2007). The software allows the completion of gaps in the data using single-station testing procedures due to the lack of nearby stations with a similar record length. The data passed this test and outliers were not detected. Missing data were filled with long-term daily averages for similar dates.

Table 1 | Daily mean values of climate variables at the Nchalo Station (1971–2007), altitude 64 m a.s.l., 16.27°S, 34.92°E

T_{min} (°C)	20.00
T_{min} (°C)	32.04
R_s (MJ m^{-2} d^{-1})	21.90
u_2 (m s^{-1})	1.89
RH_{max} (%)	81.08
RH_{min} (%)	51.32
Sunshine (hours)	8.09

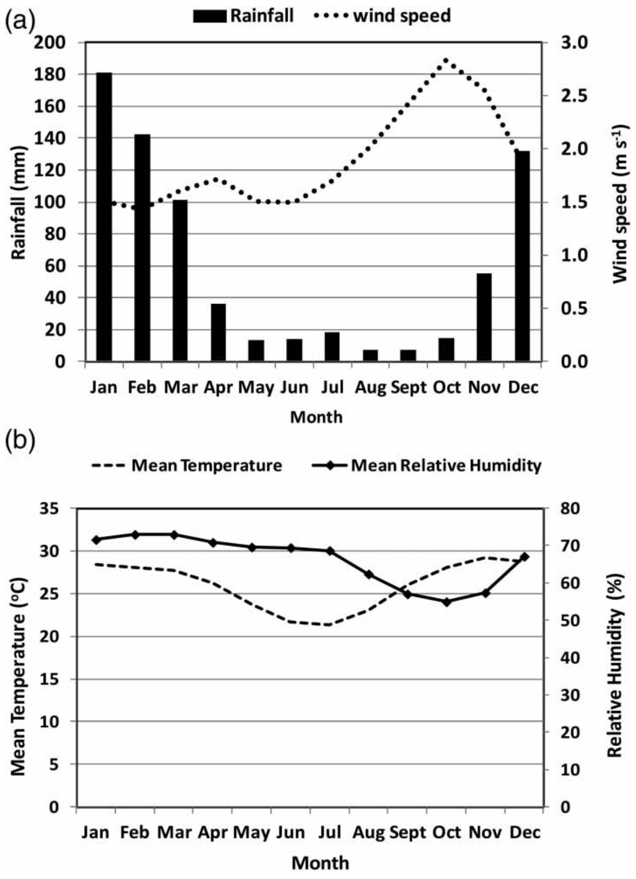

Figure 2 | Nchalo Station (1971–2007): (a) monthly mean rainfall (mm) and mean daily wind speed (m s^{-1}); and (b) monthly mean temperature (°C) and relative humidity.

ET_0 methods

The performances of the PM, Hargreaves (HAG, temperature-based) and Priestley–Taylor (PT, radiation-based) methods were evaluated. Data requirements for a particular model and the available data at the station were the main factors in selecting the alternative methods for comparison. The full data PM method (PM1) was used as a standard against which the other methods were compared. This is considered to be more accurate, even when the majority of its input data must be estimated (Allen *et al.* 1998). However, it has a relatively large input data requirement. Finally, the parameters of the PT and HAG methods were locally calibrated against the PM1 method. All computations were performed at daily time steps from which monthly mean daily ET_0 were derived.

The FAO Penman–Montheith method

The PM method (Allen *et al.* 1998) derives ET_0 as:

$$ET_0 = \frac{0.0408\Delta(R_n - G) + \gamma\dfrac{900}{(T+273)}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 is the reference evapotranspiration (mm d^{-1}); R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}); Δ is the slope of the saturation vapour pressure function (kPa $^\circ C^{-1}$); G is the soil heat flux (MJ m^{-2} d^{-1}); T is the average air temperature ($^\circ$C) at 2 m height; u_2 is the wind speed (m s^{-1}) at 2 m height; 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); and γ is the psychometric constant (0.0677 kPa $^\circ C^{-1}$). G is considered negligible for computations at daily or lower timescales and was set equal to zero. u_2 was set equal to the global average estimate of 2 m s^{-1} in some of the computations. R_n was estimated following Allen *et al.* (1998):

$$R_n = R_{ns} - R_{nl} \tag{2}$$

$$R_{nl} = \sigma\left(T^4_{\max K} + T^4_{\min K}\right)(0.034 - 0.14\sqrt{e_a}) \times \left(1.35\frac{R_{SR}}{R_{SO}} - 0.35\right) \tag{3}$$

$$R_{SO} = \left(0.75 + 210^{-5}z\right)R_a \tag{4}$$

$$R_{ns} = 0.77_{SR} \tag{5}$$

where R_{ns} is the net solar radiation (MJ m^{-2} d^{-1}); R_{nl} is the net outgoing longwave radiation (MJ m^{-2} d^{-1}); σ is the Stefan–Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} d^{-1}); $T_{\max K}$ and $T_{\min K}$ are the maximum and minimum temperatures in degrees Kelvin, respectively; R_{SR} is the observed solar shortwave radiation (MJ m^{-2} d^{-1}); and R_{SO} is the clear sky radiation (MJ m^{-2} d^{-1}) at altitude z above sea level (m). R_a is the extraterrestrial radiation (MJ m^{-2} d^{-1}) estimated using the procedures in Allen *et al.* (1998):

$$R_a = \frac{24(60)}{\pi}G_{sc}d_r[\omega_s \sin(\phi)\sin(\delta) + \cos(\phi)\sin(\delta)\sin(\omega_s)] \tag{6}$$

where $G_{sc} = 0.0820$ MJ m^{-2} min^{-1} is the solar constant,

$$\omega_S(\text{rad}) = \arccos[-\tan(\phi)\tan(\delta)]$$

is the sunset angle at latitude ϕ (rad),

$$d_r(\text{rad}) = 1 + 0.033\ \cos\left(\frac{2\pi J}{365} - 1.39\right)$$

is the inverse relative Earth–Sun distance and

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

is the solar declination on a day of the year J between 1 January and 31 December ($J = 1, \ldots, n$; $n = 365$ or 366).

R_{SR} was estimated for cases where it is not observed following Allen *et al.* (1998):

$$R_{SR} = K_{Rs}\sqrt{T_{\max} - T_{\min}R_a} \tag{7}$$

where R_{SR} is as defined above, $T_{\max}$ and $T_{\min}$ are maximum and minimum temperature ($^\circ$C) and K_{Rs} is an adjustment coefficient ($^\circ C^{-0.5}$) that varies from 0.16 for 'interior' areas (where the influence of moist air masses are less dominant) to 0.19 (for 'coastal areas' where the air masses are strongly influenced by adjacent water bodies). The Nchalo Station is located in a low-lying inland area and the study therefore adopted a K_{Rs} value of 0.16.

In evaluating the performance of the PM method in data-limited situations, 12 scenarios were considered as shown in Table 2. It was assumed that the most accurate

Table 2 | Climate variables included in the various scenarios for calculating ET_0 using the PM method, where 'Y' indicates the variable was observed or computed from observations

	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8	PM9	PM10	PM11	PM12
T_{min}	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
T_{max}	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
T_{dew}	–	e_a est. from $T_{dew} = T_{min}–3$	–	–	–	e_a est. from $T_{dew} = T_{min}–3$	–	e_a est. from $T_{dew} = T_{min}–3$	–	e_a est. from $T_{dew} = T_{min}–3$	–	e_a est. from $T_{dew} = T_{min}–3$
RH (%)	Y	–	Y	Y	Y	–	Y	–	Y	–	Y	–
u_2	Y	Global mean 2 m s^{-1}	Observed monthly mean	Global mean 2 m s^{-1}	Observed daily mean	Y	Y	Observed monthly mean	Observed monthly mean	Y	Global mean 2 m s^{-1}	Global mean 2 m s^{-1}
R_{SR}	Y	Via Allen *et al.* (1998)	Y	Y	Y	Y	Via Allen *et al.* (1998)	Via Allen *et al.* (1998)	Via Allen *et al.* (1998)	Via Allen *et al.* (1998)	Via Allen *et al.* (1998)	Y

ET_0 estimates were those derived from PM1. Procedures for estimating the internal variables and other missing weather data are outlined in Equations (2)–(7) following the steps given in Chapter 3 of FAO paper 56 by Allen *et al.* (1998).

Hargreaves method

The HAG method is a commonly used temperature-based method for estimating ET_0 in areas where meteorological information is scarce. In addition to temperature data which are readily available, the extraterrestrial radiation (R_a) required as input variables can be sourced from tables or estimated based on equations for different latitudes and day of the year (Allen *et al.* 1998; Xu & Singh 2001; Igbadun *et al.* 2006).

This study used the HAG ET_0 version by Hargreaves & Samani (1982, 1985), which proposes several improvements to the original equation by Hargreaves (1975). ET_0 is calculated as follows:

$$ET_0 = C_H R_a T_D^{0.5}(T_a + 17.8) \tag{8}$$

where $C_H = 0.0023$ is the original parameter proposed by Hargreaves & Samani (1982); T_D is the difference between maximum and minimum daily temperature (°C); T_a is the mean temperature (°C); and R_a is the extraterrestrial radiation expressed in equivalent evaporation units in mm d^{-1} calculated from Equation (7). The parameter C_H was also locally calibrated in this study. The HAG model was recommended by Allen *et al.* (1998) as the best alternative to the PM method when only temperature data are available.

Priestley–Taylor method

This radiation-based method was proposed by Priestley & Taylor (1972) as a simplified version of the combination equation (Penman 1948) for use when surface areas are generally wet. ET_0 is calculated as:

$$ET_0 = \alpha_{PT} \frac{\Delta}{\Delta + \gamma} \frac{R_n}{\lambda} \tag{9}$$

where ET_0 is in mm d^{-1}; λ is the latent heat of vapourization (2.45 MJ kg^{-1}); R_n is the net radiation in MJ m^{-2} d^{-1}

calculated from Equation (3) and the other terms are as defined in Equation (2). In the PT method, the aerodynamic component in the Penman (1948) equation is removed and instead the energy component is multiplied by a coefficient $\alpha_{PT} = 1.26$ (Xu & Chen 2005). The coefficient α_{PT} was also locally calibrated in this study as recommended when applying the PT method at different sites (Castellvi *et al.* 2001; Xu & Chen 2005; Xu & Singh 2005). ET_0 was estimated using R_n computed from both observed and estimated R_{SR} (Equation (7)). The PT method is widely applied due to its acceptable performance in humid regions as well as its limited data requirements (Suleiman & Hoogenboom 2007).

Evaluation criteria

PM1 was used as the standard for comparison with the various data scenarios and alternative ET_0 estimation methods. The methods were compared using the following indices as performance evaluation criteria: mean bias error (MBE), root mean squared error (RMSE), relative error (RE) and the ratio of the averages of each of the two methods under comparison R (Xu & Chen 2005; Gavilán *et al.* 2006):

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n} (y_i - x_i)}{n} \tag{10}$$

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

$$\mathrm{RE} = \frac{\mathrm{MBE}}{\bar{x}} \times 100 \tag{12}$$

$$R = \frac{\bar{y}_i}{\bar{x}} \tag{13}$$

where y_i is the estimated ET_0 with mean $\bar{y}_i$ and x_i is the PM1 ET_0 with mean $\bar{x}$. MBE is a measure of under- (over-) prediction for $\mathrm{MBE} > 0$ (<0); $\mathrm{MBE} \cong 0$ represents the best estimate. RMSE assesses the model performance based on observed and estimated variables with the best estimates having $\mathrm{RMSE} \cong 0$ (Jacovides & Kontoyiannis 1995). The best estimates will also have $R = 1$ and $\mathrm{MBE} = 0$ (or close to these values).

To calibrate each of the alternative models based on their performance against PM1, a linear regression line of the form $y = bx + a$ was forced through the origin ($a = 0$). The slope b (the regression coefficient) was used as a factor for adjusting the ET_0 estimates according to PM1, thereby approximating the line with slope $b = 1$ and $a = 0$. The locally calibrated parameters for the HAG and PT methods were obtained by multiplying the slope b by the original parameters C_H and α_{PT}. The period 1971–1997 was used for calibration whereas the performances of the alternative methods with calibrated parameters were tested during 1998–2007. Statistical significance of the two samples was determined using a two tailed z-test (Haan 2002) for the sample means $(\bar{x}_1, \bar{x}_2)$ with known variances (σ_1^2, σ_2^2) under the null hypothesis that the means are not different $(\bar{x}_1 - \bar{x}_2 = 0)$ at the significance level $\alpha = 0.05$.

RESULTS AND DISCUSSION

Performance of the PM method at Nchalo Station

Figure 3(a) shows the seasonal variation of mean monthly ET_0 (expressed in mm d^{-1}) estimated by the 12 data scenarios of the PM method. Figures 3(b) and 3(c) show the RMSE and MBE values for the scenarios. Evaluation of the PM1 method for the various data scenarios at Nchalo Station is presented in Table 3.

Effect of wind speed u_2

Various values of the wind speed u_2 are used in the different data scenarios to compute the PM ET_0 while keeping the other input data constant. PM3 uses the monthly daily mean u_2 (i.e. each month had its mean value for the entire period), whereas PM4 uses the daily mean value for the entire period ($u_2 = 1.89$ m s^{-1}) and PM5 uses the global average wind speed from 2,000 stations worldwide ($u_2 = 2$ m s^{-1}).

The results shown in Table 3 and Figures 3(b) and 3(c) suggest that the effect of different wind speeds (PM3, PM4 and PM5) on the daily ET_0 was minimal. This is confirmed by their respective low RMSE values (Figure 3(b)) within the

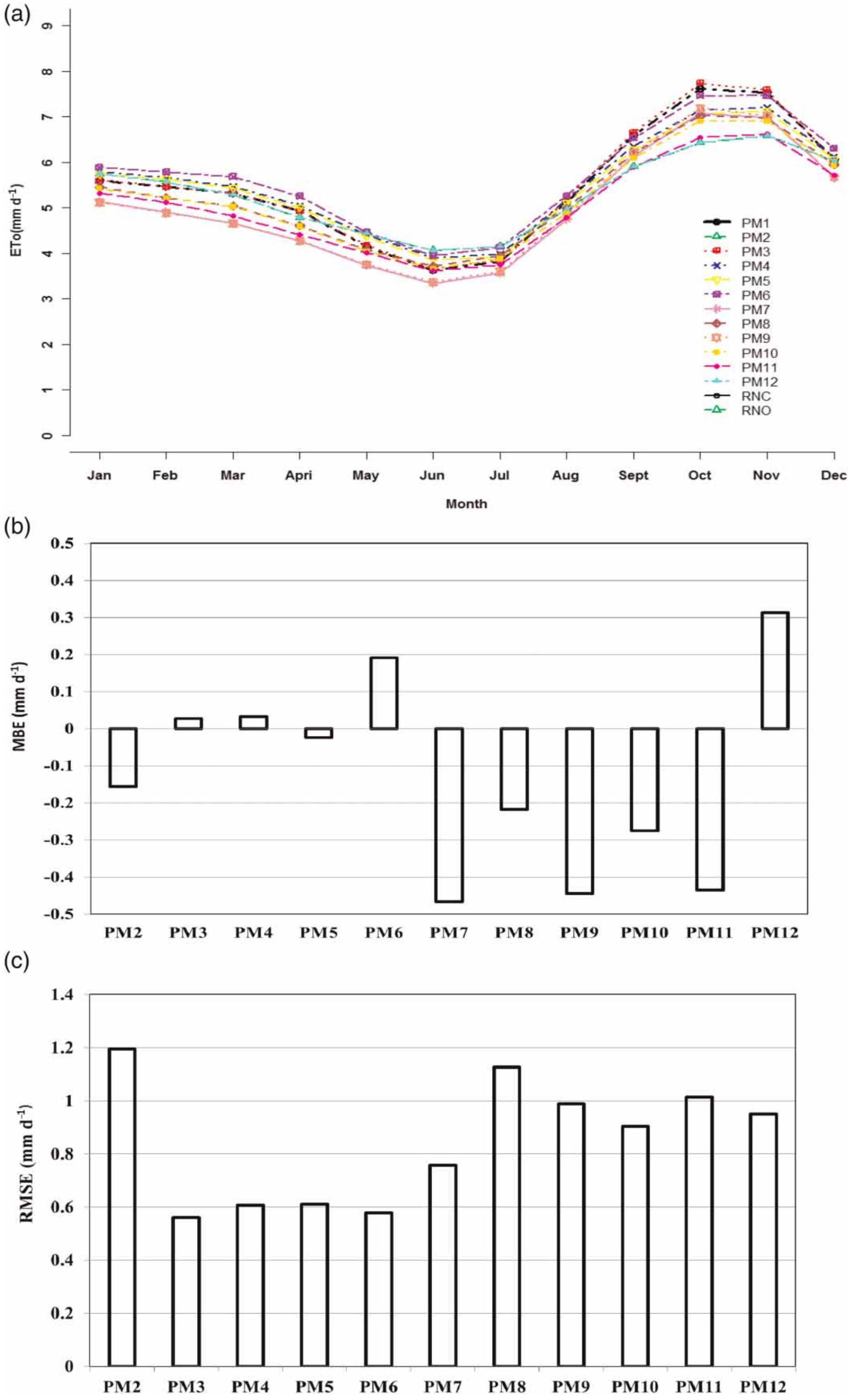

Figure 3 | (a) Comparison of monthly mean values of the PM method; (b) RMSE for ET$_0$ estimated by the PM method; and (c) MBE for ET$_0$ estimated by the PM method for the 12 data scenarios.

Table 3 | Results of the performance evaluation of the various PM data scenarios against the PM1 method (1971–2007)

Data Scenario	PM1	PM2	PM3	PM4	PM5	PM6	PM7	PM8	PM9	PM10	PM11	PM12
Mean (mm d^{-1})	5.48	5.33	5.51	5.52	5.46	5.67	5.02	5.27	5.04	5.21	5.05	5.80
RE (%)		–2.85	0.50	0.59	–0.45	3.49	–8.50	–3.97	–8.11	–5.01	–7.96	5.70
R		0.97	1.01	1.01	1.00	1.03	0.91	0.96	0.92	0.95	0.92	1.06
Slope b		1.04	0.99	1.00	1.01	0.97	1.09	1.04	1.08	1.06	1.09	0.96
R^2		0.96	0.99	0.99	0.99	0.99	0.99	0.96	0.98	0.98	0.98	0.98

range 0.56–0.61 mm d^{-1}. The MBE values suggest that PM3 and PM4 scenarios slightly overestimated ET_0, whereas PM5 slightly underestimated it (Figure 3(c) and Table 3). The minor differences were also reflected in high ratio values ($R \cong 1$), slopes ($b \cong 1$) and coefficients of determination ($R^2 \cong 1$). The *z*-tests showed that PM3, PM4 and PM5 were not statistically different from PM1 ($\alpha = 0.05$) in all cases. It is therefore suggested that, in the absence of wind speed data, the PM ET_0 can be estimated satisfactorily using the global average wind speed ($u_2 = 2\,\mathrm{m\,s^{-1}}$) in the region.

These results agree with other studies in different climatic settings (e.g. Jabloun & Sahli 2008), which have found that wind speed has a relatively small impact on ET_0 with the exception of arid and very windy areas (Martinez-Cob & Tejero-Juste 2004). The PM estimations using the global average wind speed $u_2 = 2\,\mathrm{m\,s^{-1}}$ in the studies by Jabloun & Sahli (2008) and Popova *et al.* (2006) also obtained results similar to PM1. From a study in Southern Ontario in Canada, Sentelhas *et al.* (2010) found that using wind speed data from a nearby station yielded PM estimates close to PM1.

Effect of relative humidity RH (%)

Relative humidity is used to compute the actual vapour pressure (e_a), which again is then used to determine the saturated vapour pressure deficit (e_s–e_a) in the PM method. When relative humidity data are missing, the actual vapour pressure can be estimated from the dew point temperature (T_{dew}) by setting $T_{dew} = T_{min} - 3$, where T_{min} is the daily minimum temperature (°C) (Allen *et al.* 1998) as in PM6 (Table 2). The performance of PM6 (Table 3 and Figures 3(a)–3(c)) is close to PM1 with $R^2 = 0.97$. The RMSE was 0.58 mm d^{-1} with the MBE, RE and R values of 0.19 mm d^{-1}, 3.49 and 1.03% respectively, suggesting some overestimation. The *z*-test showed that the overestimation was statistically significant at the $\alpha = 0.05$ level. However, the performance criteria indicate that PM6 is still acceptable and was closer to PM1 compared to those in various studies (e.g. Sentelhas *et al.* 2010).

Effect of estimated net radiation R_n

Net radiation (R_n) was computed from both observed and estimated R_{SR} as represented by data scenarios PM2, PM7, PM8, PM9, PM10, PM11 and PM12 in Table 2, with various combinations of available or missing wind speed (u_2) and vapour pressure deficit (e_s–e_a). The results in Table 3 and Figures 3(b) and 3(c) show that the estimated ET_0 has higher RMSE values than in the wind and RH scenarios, ranging from 0.76 mm d^{-1} (PM7) to 1.20 mm d^{-1} (PM2). The MBE values ranged between –0.47 mm d^{-1} (PM7) and 0.31 mm d^{-1} (PM12) with slopes ranging from 0.96 to 1.09. All scenarios suggest underestimations, the only exception being PM12. ET_0 estimates from scenarios with estimated R_n were statistically different from the PM1 ($\alpha = 0.05$). The influence of radiation (R_{SR}) on the annual pattern of ET_0 was further investigated by standardizing the monthly means as follows:

$$x = \frac{y - \bar{y}}{s} \tag{14}$$

where x is the standardized value of either observed or estimated R_{SR} or $ET_0(y)$ with mean $\bar{y}$ and standard deviation s. Figure 4 presents standardized values of monthly mean ET_0 and R_{SR} showing the effect of observed (RNO) and estimated (RNC) net radiation on the PM ET_0. The monthly daily mean variation pattern for both RNC and RNO in

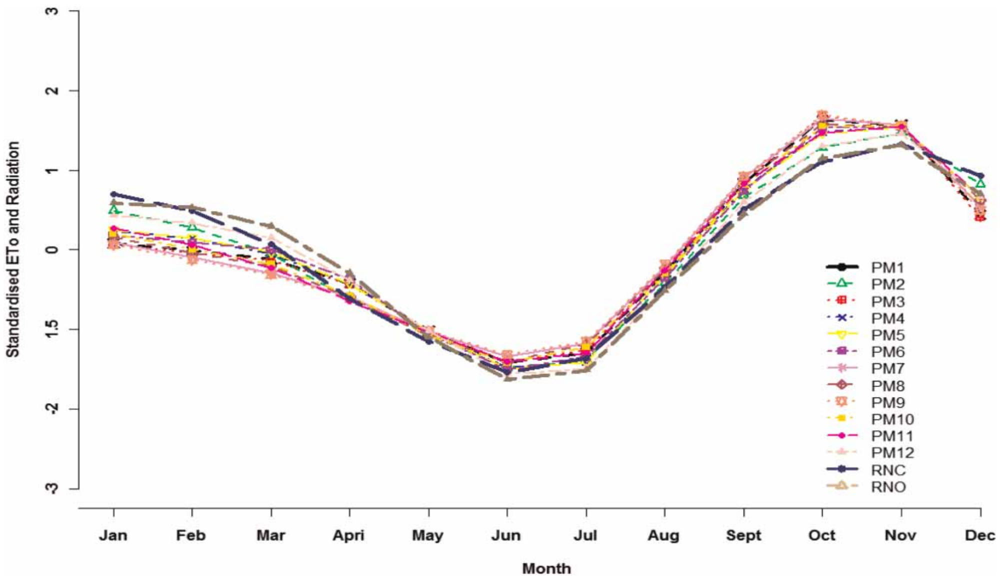

Figure 4 | Standardized FAO-PM monthly mean ET_0, observed RNO and calculated RNC.

Figure 4 agrees well, especially during the dry season from May to October (Figure 4). For most months in the rainy season (November to April), the RNC underestimated the RNO ($R^2 = 0.97$, slope $b = 0.85$).

Comparison of PM1 with HAG and PT methods

The performance of the daily PM1 and the limited data scenario PM2 were compared with the PT and HAG methods (Table 4). Since the PM method is accepted as the more precise method, even where all input variables are estimated, PM2 (with temperature as the only observed input) was included for comparison. The evaluation indices MBE, RMSE, RE and R in Table 4 show that PM2 performed better against PM1 than both the HAG and PT methods. The performance indices also show that the PT2 method, with observed R_{SR} and the original parameter ($\alpha = 1.26$), produced more accurate estimates than PM1 ($R^2 = 0.98$)

Table 4 | Performance evaluation of the daily PM2, HAG and PT methods against PM1

Method	PM2	HAG	PT1	PT2	HAGCAL	PT1CAL	PT2CAL
For the whole period 1971–2007							
MBE (mm d^{-1})	–0.16	–0.53	–0.75	–0.06			
RMSE (mm d^{-1})	1.20	1.27	1.39	0.88			
RE (%)	–2.85	–9.72	–13.65	–1.07			
R	0.97	0.91	0.86	0.99			
R^2	0.96	0.96	0.96	0.98			
Slope	1.04	1.11	1.16	1.01			
After calibration 1998–2007							
MBE (mm d^{-1})	–0.20	–0.56	–0.78	–0.08	–0.03	–0.04	–0.07
RMSE (mm d^{-1})	1.58	1.78	2.09	0.97	1.24	1.21	0.78
RE (%)	–3.50	–10.13	–14.18	–1.39	–0.64	–0.71	–1.33
R	1.04	1.11	1.16	1.01	1.00	1.00	1.00

as compared to the PM2, PT1 and HAG methods. The method slightly underestimated the PM1 ET_0 (by less than 1%) with an RE of only –1.07% and MBE and RMSE values of –0.06 and 0.88 mm d^{-1}, respectively. The slope $b = 1.01$ and the locally calibrated PT parameter for daily ET_0 estimations can then be derived from:

$$\alpha_{PT} = b \times 1.26 = 1.27 \qquad (15)$$

The calibrated α_{PT} is approximately equal to the normal original value. This suggests that if R_{SR} is observed, the PT method would be a good estimator for PM1. Despite the more accurate estimates there is a need for local calibration of the α_{PT} parameter even where R_{SR} is observed, as the *z*-test showed that the PT estimates with observed R_{SR} and the original parameter were statistically different from PM1 ($\alpha = 0.05$).

The PT1 method, with the original parameter $\alpha = 1.26$ and estimated R_{SR}, however resulted in an underestimation of the PM by 14% ($R = 0.86$) with an average RE value of -13.65% and relatively high MBE and RMSE values of –0.74 and 1.37 mm d^{-1}, respectively. The *z*-test confirmed that these values were statistically different from PM1 ($\alpha = 0.05$). Berengena & Gavilán (2005) found a similar range of underestimation using the PT in a highly advective semi-arid part of southern Spain. The regression coefficient (slope) was b = 1.16 ($R^2 = 0.96$), from which a locally calibrated α_{PT} of 1.46 can then be derived for daily ET_0 estimations.

The α_{PT} coefficient of 1.26 represents minimum advection conditions without edge effects and is suitable for ET_0 conditions without advective effects (Pereira & Villa Nova 1992; Eaton *et al.* 2001). The value of α_{PT} also depends on season and location relative to large water bodies (Castellvi *et al.* 2001). Under strong advective conditions, α_{PT} can have values up to 1.57 (Chuanyan *et al.* 2004); in arid and semi-arid areas, Jensen *et al.* (1990) reported values up to 1.74 and Tabari & Talaee (2011) found values up to 2.14 in Iran. For deep and large lakes, Eaton *et al.* (2001) reported values up to 2.32 and Viswanadham *et al.* (1991) reported α_{PT} values up to 3.12. Our result of an adjusted α_{PT} of 1.46 (with estimated R_{SR}) is therefore typical of rather dry areas. The α_{PT} parameter showed monthly variations however, as shown in Table 5 (where the monthly performance indices of both PT methods are also presented).

Table 5 | Monthly statistics of PT against FAO1 for Nchalo Station with calibrated α_{PT} values

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
From observed R_{SR}												
MBE (mm d^{-1})	0.59	0.62	0.49	–0.17	0.26	0.14	–0.23	–0.40	–0.38	–0.80	0.11	–1.18
RMSE (mm d^{-1})	0.79	0.79	0.69	–0.17	0.07	0.14	0.62	0.83	–0.38	1.31	0.11	2.73
RE (%)	10.41	11.35	9.25	0.58	–0.01	0.94	–5.92	–7.95	–5.78	–10.64	1.51	–15.76
R	1.12	1.11	1.32	1.11	1.13	0.62	1.14	0.98	1.04	0.89	1.05	0.49
Slope b	0.91	0.90	0.92	0.97	1.00	1.03	1.06	1.08	1.11	1.12	1.07	1.11
R^2	0.99	0.99	0.99	0.99	0.99	0.98	0.98	0.98	0.98	0.98	0.98	0.88
α_{PT}	1.12	1.11	1.13	1.19	1.23	1.26	1.30	1.33	1.37	1.37	1.32	1.37
From estimated R_{SR}												
MBE (mm d^{-1})	–0.12	–0.18	–0.42	–0.17	–1.28	0.14	–0.59	–0.99	–0.99	–1.63	–0.55	–1.32
RMSE (mm d^{-1})	1.18	1.07	1.06	–0.17	1.63	0.14	0.99	1.33	–0.99	2.07	–0.55	1.93
RE (%)	–2.02	–3.34	–7.97	0.58	–14.76	0.94	–15.45	–19.42	–15.13	–21.68	–7.29	–17.62
R	1.06	0.97	1.00	0.72	1.11	0.71	0.96	0.69	0.81	0.78	0.84	0.85
Slope b	1.03	1.02	1.09	1.19	1.17	1.17	1.18	1.23	1.25	1.27	1.22	1.06
R^2	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97	0.95
α_{PT}	1.30	1.29	1.38	1.50	1.48	1.47	1.49	1.56	1.58	1.61	1.54	1.34

From the monthly values in Table 5, the least accurate estimates in both cases were found in October which had the largest absolute values of MBE, RMSE and RE and R values. The most accurate estimates were seen in January, which has the lowest absolute values of MBE, RMSE and RE. The adjusted α_{PT} varied from 1.12 to 1.37 for the observed R_{SR} estimates and from 1.29 to 1.61 for the estimated R_{SR}.

Similarly, for the ET_0 computed with the HAG method, it is shown that using the original parameter $C_H = 0.0023$ resulted in an underestimation of the PM1 by 9% ($R = 0.91$) with MBE = –0.53 mm d^{-1}, RMSE = 1.27 mm d^{-1} and RE = –9.72%. The z-test confirmed that these values were statistically different from PM1 ($\alpha = 0.05$). Regression coefficient (slope) b = 1.11 implying that, at the daily time-step, the HAG parameter has to be adjusted as:

$$C_H = b \times 0.0023 = 0.0026 \quad (16)$$

In contrast to results from this study, the HAG method overestimated PM1 at most of the inland stations in Tunisia used in the study by Jabloun & Sahli (2008). Nchalo Station is located in an area that is dry and hot for most of the year, and the HAG method is known to underestimate ET_0 in such conditions (Xu & Singh 2002). Table 6 shows the monthly performance statistics of the HAG method using a calibrated C_H for each month. Similar to the PT method, October was found to have the highest values of MBE and RMSE indicating less accuracy in the month. The calibrated C_H lies within the range 0.0023–0.0028.

Figure 5(a) shows the monthly ET_0 by the PT and HAG methods without local calibration as compared to PM1 and PM2 from 1998 to 2007. In addition, the monthly long-term means during the period are shown in Figure 5(b). All approaches including PM2 considerably underestimate PM1. However, the PT2 approach with observed R_{SR} is somewhat better although it overestimates ET_0 in the summer (January–April), a finding similar to Trajkovic & Kolakovic (2009). Trajkovic & Živković (2008) attributed such overestimates to the effect of low wind speed, also suggested in Figure 2. As Figures 6(a) and 6(b) show, there is a significant improvement in the ET_0 estimates using calibrated parameters. PT1 deviated the most and has the largest absolute values of MBE, RMSE, RE and slope

Table 6 | Monthly statistics of the HAG method against the FAO1 for Nchalo Station with calibrated C_H values

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
MBE (mm d^{-1})	–0.01	–0.08	–0.27	–0.17	–1.00	0.14	–0.28	–0.71	–0.72	–1.41	–0.38	–1.12
RMSE (mm d^{-1})	1.15	1.02	0.98	–0.17	1.00	0.14	0.84	1.15	–0.72	1.90	–0.38	1.79
RE (%)	–0.25	–1.40	–5.07	0.58	–7.23	0.94	–7.40	–13.96	–11.04	–18.73	–5.04	–14.98
R	1.09	0.99	1.04	0.75	1.25	0.77	1.07	0.72	0.85	0.81	0.87	0.88
Slope b	1.01	1.02	1.06	1.13	1.08	1.05	1.08	1.15	1.19	1.22	1.18	1.04
R^2	0.96	0.97	0.97	0.97	0.97	0.97	0.96	0.97	0.97	0.97	0.97	0.96
C_H	0.0023	0.0024	0.0024	0.0026	0.0025	0.0024	0.0025	0.0027	0.0027	0.0028	0.0027	0.0024

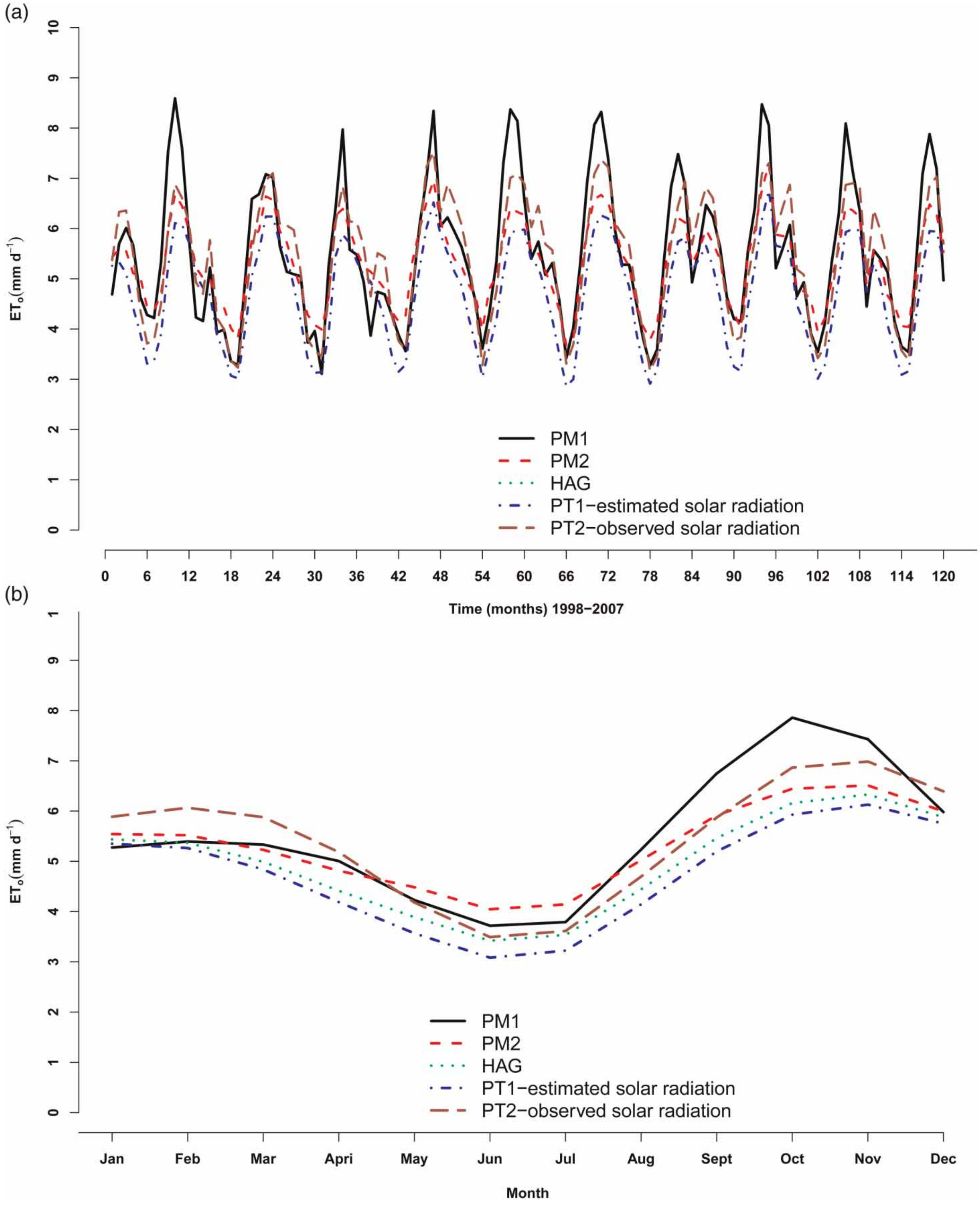

Figure 5 | (a) Comparison of ET$_0$ and (b) long-term monthly mean ET$_0$ computed from PM1, PM2 and PT1, PT2 and HAG methods (1998–2007).

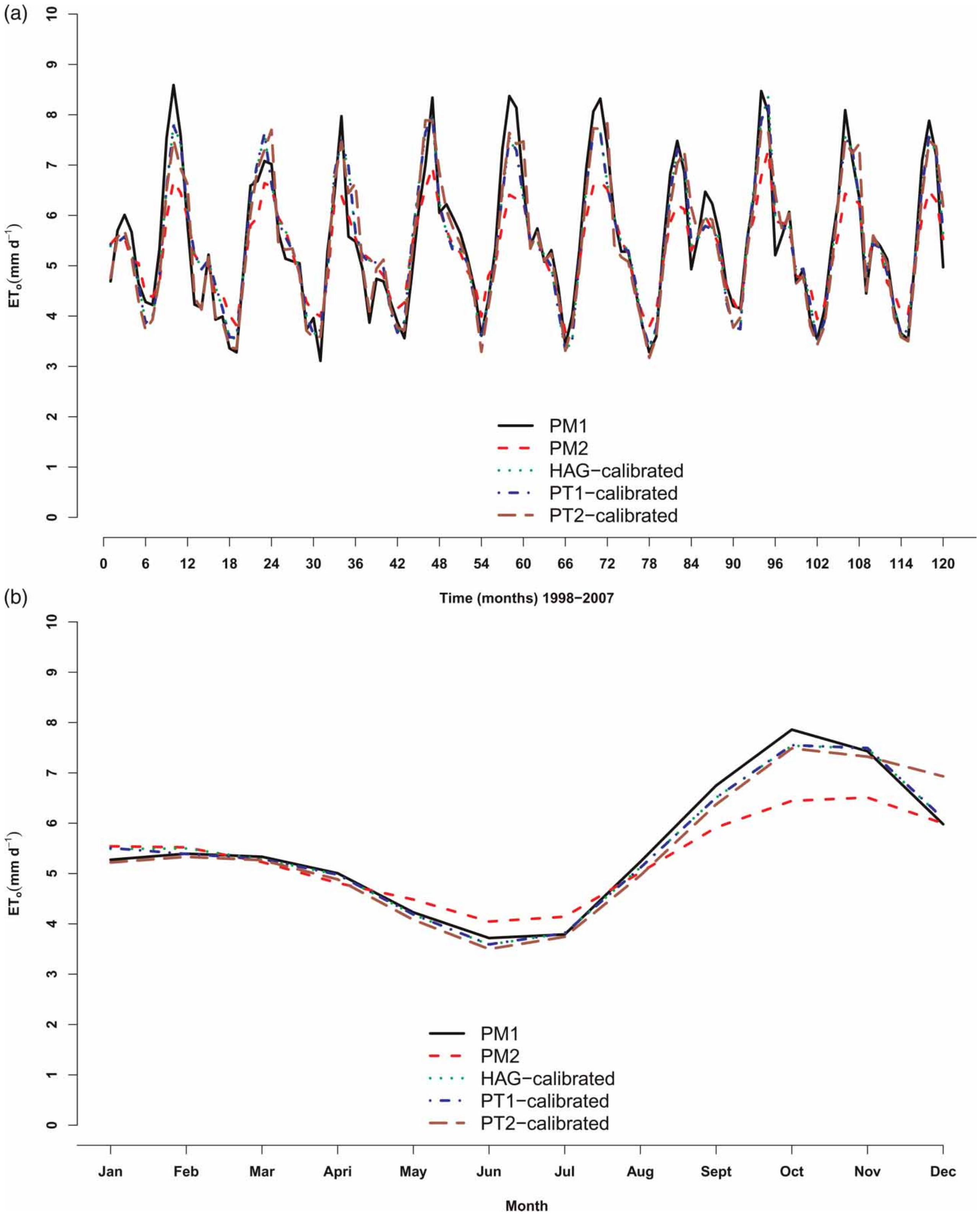

Figure 6 | (a) Comparison of PM1 and PM2 and (b) long-term monthly mean ET_0 of PM1, PM2 with calibrated HAG and PT methods.

(Table 4). Without local calibration, the PT2 method still approximates PM1 much better than any other approach (it has the lowest absolute values of MBE, RMSE and RE), although the *R* value suggests that it overestimated the daily PM1 by about 15% (Figure 5(b)). The *z*-tests for the HAG and PT estimates with calibrated parameters showed that these estimates were not statistically different from the PM1 ET_0 ($\alpha = 0.05$).

CONCLUSIONS

The performance of the PM ET_0 method was evaluated for 12 different data scenarios and alternative methods at the Nchalo Sugar Estate in the Lower Shire River basin in southern Malawi. The study found that using different expressions for the wind speed (u_2) and actual vapour pressure (e_a) did not significantly affect the PM ET_0 estimates. However, when net radiation is estimated using the FAO-56 procedures (Allen *et al.* 1998), the PM method significantly underestimated ET_0 ($\alpha = 0.05$) as compared to the full data ET_0. Among the alternative ET_0 methods, both the HAG and PT methods significantly underestimated PM1 ET_0 and both required local calibration. However, the performance of the PT method with observed R_{SR} and without local calibration provided the closest estimates. The HAG and PT approaches with locally calibrated monthly parameters considerably improved ET_0 estimates, with their performance better than PM2 with estimated variables. The results, despite being based on only one climatic station, may provide some key insights into the ability of commonly used ET_0 methods in other regions of Malawi and the southern Africa region when data are limited.

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REFERENCES

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 Crop evapotranspiration – guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO.

Azhar, A. H. & Perera, B. J. C. 2011 Evaluation of reference evapotranspiration estimation methods under Southeast Australian conditions. *Journal of Irrigation and Drainage Engineering* **137**, 268–279.

Benli, B., Bruggeman, A., Oweis, T. & Ustun, H. 2010 Performance of Penman-Montheith FAO56 in a semi-arid highland Environment. *Journal of Irrigation and Drainage Engineering* **136** (11), 757–765.

Berengena, J. & Gavilán, P. 2005 Reference evapotranspiration estimation in a highly advective semi-arid environment. *Journal of Irrigation and Drainage Engineering* **131** (2), 147–163.

Blaney, H. F. & Criddle, W. D. 1950 Determining water requirements in irrigated areas from climatological irrigation data. Soil Conservation Service Tech Paper No. 96, US Department of Agriculture, Washington, DC.

Castellvi, F., Stockle, C. O., Perez, P. J. & Ibañez, M. 2001 Comparison of methods for applying the Priestley–Taylor equation at a regional scale. *Hydrological Processes* **15**, 1609–1620.

Chattopadhyay, N. & Hulme, M. 1997 Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agriculture and Forest Meteorology* **87**, 55–73.

Chen, D., Gao, G., Xu, C.-Y., Guo, J. & Ren, G. 2005 Comparison of the Thornthwaite method and pan data with the standard Penman-Monteith estimates of reference evapotranspiration in China. *Climate Research* **28**, 123–132.

Chuanyan, Z., Zhongren, N. & Zhaodong, F. 2004 GIS assisted spatially distributed modeling of the potential evapotranspiration in semi-arid climate of Chinese Loess Plateau. *Journal of Arid Environments* **58**, 378–403.

Committee on Opportunities in the Hydrologic Sciences 1991 *Opportunities in the Hydrologic Sciences*. National Academy Press, Washington, DC.

Dalton, J. 1802 Experimental essays on the constitution of mixed gases: on the force of steam or vapor from water or other liquids in different temperatures, both in a torricelli vacuum and in air; on evaporation; and on expansion of gases by heat. *Proceedings and Memoirs of the Manchester Literary and Philosophical Society* **5**, 536–602.

Dandaula, H. E. 1979 Mean annual potential evapotranspiration and evaporation in Malawi. Malawi Met. Office Internal Report. Malawi Meteorological. Office, Blantyre, Malawi.

Eaton, A. K., Rouse, W. R., Lafleur, P. M., Marsh, P. & Blanken, P. D. 2001 Surface energy balance of the Western and Central Canadian Sub arctic: variations in the energy balance among five major terrain types. *Journal of Climate* **14**, 3692–3703.

Fang, X., Ren, L., Li, Q., Liu, L., Yuan, F., Zhao, D. & Zhu, Q. 2012 Estimating and validating basin-scale actual evapotranspiration using MODIS images and hydrologic models. *Hydrological Research* **43** (1–2), 156–166.

Fisher, J. B., DeBiase, T. A., Qi, Y., Xu, M. & Goldstein, M. A. 2005 Evapotranspiration models compared on a Sierra Nevada forest ecosystem. *Environmental Modelling and Software* **20**, 783–796.

Gavilán, P., Lorite, I. J., Tornero, S. & Berengena, J. 2006 Regional calibration of HAG equation for estimating reference ET in a semiarid environment. *Agricultural Water Management* **81**, 257–281.

Gong, L., Xu, C-Y., Chen, D., Halldin, S. & Chen, Y. D. 2006 Sensitivity analyses of the Penman–Monteith reference evapotranspiration estimates in Changjiang (Yangtze River) catchment and its sub-regions. *Journal of Hydrology* **329**, 620–629.

Haan, C. T. 2002 *Statistics Methods in Hydrology*. Iowa State University Press, Ames, Iowa, USA.

Hargreaves, G. H. 1975 Moisture availability and crop production. *Transactions of ASAE* **18**, 980–984.

Hargreaves, G. H. & Samani, Z. A. 1982 Estimation of potential evapotranspiration. *Journal of Irrigation and Drainage Division* **108**, 223–230.

Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* **1**, 96–99.

Igbadun, H., Mahoo, H., Tarimo, A. & Salim, B. 2006 Performance of two temperature based reference evapotranspiration models in the Mkoji sub-catchment in Tanzania. *Agriculture Engineering International* **13**, 1–19.

Jabloun, M. & Sahli, A. 2008 Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: applications to Tunisia. *Agricultural Water Management* **95**, 707–715.

Jacovides, C. P. & Kontoyiannis, H. 1995 Statistical procedures for the evaluation of evapotranspiration computing models. *Agricultural Water Management* **27**, 365–371.

Jensen, M. E., Burman, R. D. & Allen, R. G. 1990 Evapotranspiration and irrigation water requirement. ASCE Manuals and Reports on Engineering Practices No. 70, 1st edition, pp. 332–333.

Jury, M. R. & Mwafulirwa, N. D. 2002 Climate variability in Malawi, part 1: dry summers, statistical associations and predictability. *International Journal of Climatology* **22**, 1289–1302.

Kuzmin, P. O. 1957 *Hydro Physical Investigations of Land Waters*. International Association of Scientific Hydrology Publishers, Rennes, Vol. 3, pp. 468–478.

Lopez-Urrea, R., Martin de Santa Olalla, F., Fabeiro, C. & Moratalla, A. 2006 Testing evapotranspiration equations using lysimeter observations in a semiarid climate. *Agricultural Water Management* **85**, 15–26.

Makkink, G. F. 1957 Testing the Penman formula by means of lysimeters. *Journal of Institute of Water Engineering* **11**, 277–288.

Mandeville, A. N. & Bachelor, C. H. 1990 Estimation of actual evapotranspiration in Malawi. Report No. 110, Institute of Hydrology, Wallingford, UK.

Martinez-Cob, A. & Tejero-Juste, M. 2004 A wind-based qualitative calibration of the Hargreaves ETo estimation equation in semiarid regions. *Agric. Water Manag.* **64**, 251–264.

Ngongondo, C., Xu, C.-Y., Gottschalk, L. & Alemaw, B. 2011 Evaluatuion of spatial and temporal characteristics of rainfall in Malawi: a case of data scarce region. *Theoretical and Applied Climatology* **106**, 79–93.

Penman, H. L. 1948 Natural evaporation from open water, bare and grass. *Proceedings of the Royal Society of London, Series A: Mathematical, Physical and Engineering Sciences* **193**, 120–145.

Pereira, A. R. & Villa Nova, N. A. 1992 Analysis of the Priestley–Taylor parameter. *Agriculture and Forest Meteorology* **61**, 1–9.

Pereira, A. R. & Pruitt, W. O. 2004 Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. *Agricultural Water Management* **66**, 251–257.

Pike, J. G. 1961 Evaporation and evapotranspiration in Nyasaland. Water Resources Department, Ministry of Works, Zomba, Nyasaland.

Popova, Z., Kercheva, M. & Pereira, L. S. 2006 Validation of the FAO methodology for computing ET_0 with limited data. Application to South Bulgaria. *Irrigation and Drainage* **55**, 201–215.

Priestley, C. H. B. & Taylor, R. J. 1972 On the assessment of surface heat fluxes an evaporation using large-scale parameters. *Monthly Weather Review* **100**, 81–92.

Rana, G. & Katerji, N. 2000 Measurements and estimation of actual evapotranspiration in the field under Mediterranean climate: a review. *European Journal of Agronomy* **13**, 125–153.

Sentelhas, P. C., Gillespie, T. J. & Santos, E. A. 2010 Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agricultural Water Management* **97**, 635–644.

Singh, V. P. & Xu, C.-Y. 1997a Evaluation and generalization of 13 equations for determining free water evaporation. *Hydrological Processes* **11**, 311–323.

Singh, V. P. & Xu, C.-Y. 1997b Sensitivity of mass transfer-based evaporation equations to errors in daily and monthly input data. *Hydrological Processes* **11**, 1465–1473.

Stepanek, P. 2007 AnClim. Software for time series analysis (for Windows). Department of Geography, Faculty of Natural Sciences, Masaryk University, Brno (1.47 MB).

Suleiman, A. A. & Hoogenboom, G. 2007 Comparison of Priestley-Taylor and FAO-56 Penman-Monteith for daily reference evapotranspiration estimation in Georgia. *Journal of Irrigation and Drainage Engineering* **133**, 175.

Sumner, D. M. & Jacobs, J. M. 2005 Utility of Penman–Monteith, Priestley–Taylor, reference evapotranspiration, and pan evaporation methods to estimate pasture evapotranspiration. *Journal of Hydrology* **308**, 81–104.

Tabari, H. & Talaee, P. H. 2011 Local calibration of the HAG and Priestley–Taylor equations for estimating reference evapotranspiration in arid and cold climates of Iran based on the Penman–Monteith model. *Journal of Hydrologic Engineering* **16** (10), 837–845.

Tateishi, R. & Ahn, C. H. 1996 Mapping evapotranspiration and water balance for global land surfaces. *ISPRS Journal of Photogrammetry & Remote Sensing* **51**, 209–215.

Thornthwaite, C. W. 1944 Report of the committee on transpiration and evaporation. *Transactions of the American Geophys Union* **25** (5), 683–693.

Thornthwaite, C. W. & Holzman, B. 1939 The determination of land and water surfaces. *Monthly Weather Review* **67**, 4–11.

Trajkovic, S. 2010 Testing hourly reference evapotranspiration approaches using lysimeter measurements in a semiarid climate. *Hydrological Research* **41** (1), 438–449.

Trajkovic, S. & Živković, S. 2008 Effect of actual vapor pressure on estimating evapotranspiration at Serbia. *Architecture and Civil Engineering* **7** (2), 171–178.

Trajkovic, S. & Kolakovic, S. 2009 Evaluation of reference evapotranspiration equations under humid conditions. *Water Resources Management* **23**, 3057–3067.

van der Velden, J. 1979 A summary of rainfall, pan evaporation and temperature data at pan evaporation stations in Malaga Report no. TP3. Water Resources Department, Ministry of Agriculture and Natural Resources, Lilongwe, Malawi.

Ventura, F., Spano, D., Duce, P. & Snyder, R. L. 1999 An evaluation of common evapotranspiration equations. *Irrigation Science* **18**, 163–170.

Viswanadham, Y., Silva Filho, V. P. & Andrr, R. G. B. 1991 The Priestley-Taylor parameter α for the Amazon forest. *Forest Ecology and Management* **38**, 211–225.

Wang, Y.-M., Namaona, W., Traore, S. & Zang, Z.-C. 2009 Seasonal temperature-based models for reference evapotranspiration estimation under semi-arid condition of Malawi. *African Journal of Agricultural Research* **4** (9), 878–886.

World Meteorological Organization (WMO) 1976 A water resources assessment of Lake Malawi. UNDP/WMO/Malawi Government Project Report no. 71/518, Geneva, Switzerland.

Xu, C.-Y. & Singh, V. P. 2000 Evaluation and generalisation of radiation-based equations for calculating evaporation. *Hydrological Processes* **14**, 339–349.

Xu, C.-Y. & Singh, V. P. 2001 Evaluation and generalization of temperature-based methods for calculating evaporation. *Hydrological Processes* **15**, 305–319.

Xu, C.-Y. & Singh, V. P. 2002 Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. *Water Resources Management* **16**, 197–219.

Xu, C.-Y. & Chen, D. 2005 Comparison of seven models for estimation of evapotranspiration and groundwater recharge using lysimeter measurement data in Germany. *Hydrological Processes* **19**, 3717–3734.

Xu, C.-Y. & Singh, V. P. 2005 Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions. *Journal of Hydrology* **308**, 105–121.

Xu, C.-Y., Gong, L., Jiang, J., Chen, D. & Singh, V. P. 2006 Analysis of spatial distribution and temporal trend of reference evapotranspiration and pan evaporation in Changjiang (Yangtze River) catchment. *Journal of Hydrology* **327**, 81–93.

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