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Predicting Reference Evaporation for the Ethiopian Highlands

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Abstract

Water is likely the most limiting factor in increasing agricultural production in large parts of Africa. Reference evaporation (ET_0) is a key hydrological parameter to use efficiently the scarce supply. Several methods are available for predicting reference evaporation, but the accuracy of any of the methods has not been established for the Ethiopian highlands. The objective of this study is, therefore, to select the best methods for calculating the reference evaporation ET_0. For the section, meteorological data of the Bahir Dar station were used, because all data needed for this study including the Class A pan Evaporation were recorded on a daily basis. Pan evaporation was considered as the best estimator of the reference evaporation. The results showed that the FAO-Penman Monteith (using solar radiation, wind speed, temperature and relative humidity) and Enku method (using only maximum daily temperatures) have acceptable daily ET_0 ranges and predicted to Class A pan evaporation with correlation coefficients greater than 90% in a monthly basis. Next best was the Thornthwaite's method with correlation coefficient of 89% with pan evaporation. Piche methods performed relatively well with correlation coefficient of greater than 70%. Blaney-Criddle, Priestley & Taylor, and Hargreaves performed the poorest in predicting pan evaporation. These methods should be recalibrated for local condition and therefore not recommended for use in the Ethiopian highlands. In summary, the FAO-Penman Monteith is recommended for locations where the input data are available; otherwise, the Enku method using maximum daily temperature is best for estimating the reference evaporation.

Keywords

Pan, Piche, Africa, Potential Evaporation, FAO-56

1. Introduction

Throughout Africa, good quality water is being recognized as a finite resource that is in short supply-limiting development in many cases [1]. The Blue Nile basin is one of areas in Africa of extreme water scarcity: nearly 150 million people are dependent on the Blue Nile river with a discharge of less than 85 billion m^3 [2] [3]. Understandably, careful assessment of the use of water needs to be made because in the future, it will be increasingly important to match the supply (*i.e.*, excess rainfall) in the Ethiopian highlands with the demand by irrigation systems, industry, and population in the basin. Estimating reference evaporation provides fundamental information on water abstraction in the highlands and downstream when used in combination with crop coefficients [4].

Estimating reference evaporation (ET_0) has taken many forms ranging from direct measurement to indirect methods employing meteorological measurements. One of the direct measurements is the Class A evaporation pan. The pan evaporation can be related to reference evaporation with coefficients developed by Pereira *et al.* [5] and Allen *et al.* [6]. The disadvantage of Class A evaporation pans are only their availability at a few locations in developing countries. Indirect methods are, therefore, a good alternative and range from locally developed, empirical relationships to physically based energy- and mass-transfer models [7]. The meteorological data required vary with the type of indirect methods. The Penman and Priestley and Taylor methods require most meteorological data and the Penman is generally considered as the most accurate one [8] [9] [10] [11] [12], but as for the Class A pan data, the required data is only collected at few meteorological stations. Thornthwaite Mather, which is used frequently in Ethiopia, needs fewer climatic data (temperature and sunshine hour). The Hargraves, Blaney-Criddle, and Enku (locally developed) need only temperature to estimate the reference evaporation. Finally, methods that use the measurements of a Piche evaporimeter to calculate the reference evaporation were developed by [13] and [14].

Reference evaporation is defined by Meyer [4] as the rate of evaporation from a hypothetical crop with an assumed crop height of 12 cm and fixed canopy resistance of 70 s m^{-1} and an albedo of 0.23 and would give the same evaporation rate as envisioned by Smith *et al.* [9] of an extensive surface of green actively growing completely shading the ground and not short of water. It is of course difficult to replicate the conditions that define the reference evaporation. Several methods have been used to validate the direct and indirect methods. In the literature, these validation methods are divided in four categories. The first category uses the evaporation measured with Class A pan [15] [16] [17]. Other studies employ the ET_0 of FAO-Penman Monteith for validation [7] [10] [11] [18] [19] [20] [21]. Limited experimental studies have used the ET_0 calculated from Piche data for validation [19]. The final method used for validation of calculated reference evaporation are lysimeters [22] [23] [24] [25] but these are expensive to construct and operate and therefore not available in most developing countries.

Agronomists and hydrologists have little guidance [15] [26] to choose among the many available methods to estimate reference evaporation in the Ethiopian highlands where the density of weather station is low [27] [28] and often only measure temperature and precipitation. The objective of this study is, therefore, to select the most accurate method for estimating reference evaporation for the Ethiopian highlands. The Bahir Dar meteorological station was chosen for this study because as the only station in the Ethiopian highlands, all the meteorological variables were measured required for calculating the reference evaporation for all the methods considered. The data recorded on a daily basis included maximum and minimum temperature, relative humidity, wind speed, and sunshine hours and evaporation measured with the Piche and Class A pan.

2. Material and Methods

2.1. Site Description and Data Set

The Ethiopian highlands is the region in Ethiopia above 1500 m and covers a total area of 537,000 km^2 (43% of Ethiopia) [29] [30]. It constitutes more than half of all the highland areas of Africa [31]. Most of the area of the highlands is cultivated land and land degradation is a major threat. One of the main rivers is the Blue Nile with a watershed of 180,000 km^2. It has a monsoonal climate with rainfall varying between 800 and 3000 mm per year and evapotranspiration between 1400 and 1681 per year [32]. The major rain phase for the highlands of Ethiopia is between June and September.

One of the difficulties in the Ethiopian highlands is that pan evaporation data is measured only at the Bahir Dar Station for long period. It is located 2.2 km from Lake with latitude of 11˚35'59" and longitude of 37˚21'36". The elevation is 1805 m (**Figure S1** in the Supplementary Material). The station has more than 30 years of data but Pan Evaporation started only in 2005 (**Table S1** in the Supplementary Material list the collected data). Daily maximum and minimum temperature, relative humidity, sunshine hour, wind speed at 2 meter, pan and Piche evaporation data were obtained for the 11 years from 2005 to 2015 from Bahir Dar Meteorology Directorate.

2.2. Reference Evaporation: Description of the Selected Methods

FAO-Penman Monteith, Priestley & Taylor, Hargraves, Thonthwaite, Blaney-Criddle, Enku, Pan-Allen, Pan-Pereira, Piche-Stanhill and Piche-Adam & Ahmed methods were selected. The first four are used locally by experts and by researchers for hydrological modeling and in computations of irrigation water requirement. Piche-Stanhill and Piche-Adam & Ahmed methods were included because of availability Piche readings in several weather stations in the Ethiopian highlands. Pan-Allen and Pan-Pereira methods were used for validation of the rest of the empirical models. Since the Penman has not been validated for the Ethiopian highlands, the Class A pan data using coefficients proposed by *Pereira et al.* [5] and Allen *et al.* [6] are used as the direct measure of reference evaporation against which the calculated values are compared.

1) *FAO-Penman Monteith Method* (*FAO-PEN*)

FAO-Penman Monteith method computes reference evapotranspiration (ET_0) from meteorological data. It has been recommended as the standard method for computation of the reference evapotranspiration. The method considers all parameters that govern energy exchange and corresponding latent heat flux and requires air temperature, relative humidity, sunshine intensity/hour, wind speed data and elevation as input parameters.

The modified Penman-Monteith equation can be written as [6]:

$$ET_0 = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

where ET_0 reference evapotranspiration [mm day^{-1}], R_n net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], T mean daily air temperature at 2 m height [˚C], u_2 wind speed at 2 m height [m s^{-1}], e_s saturation vapor pressure [kPa], e_a actual vapor pressure [kPa], $e_s - e_a$ saturation vapor pressure deficit [kPa], Δ slope vapor pressure curve [kPa ˚C^{-1}], γ psychrometric constant [kPa ˚C^{-1}]. Further details how these parameters are calculated are given in the Supplementary Material Section.

2) *Priestley* & *Taylor Method* (*PT*)

The Priestley & Taylor form of the equation is [15] [33] [34]:

$$ET_0 = \frac{\alpha \frac{\Delta}{\Delta + \gamma}(R_n - G)}{\lambda} \tag{2}$$

where;

$$\alpha = 1 + \frac{\gamma}{\Delta + \gamma} * \frac{r_s}{r_a} \tag{3}$$

where; r_s is surface resistance [s m^{-1}] which is 70 s m^{-1} for the grass reference surface, r_a is aerodynamic resistance which helps to determine the transfer of heat and water vapor from the evaporating surface into the air above the canopy. The aerodynamic resistance r_a [s m^{-1}] for the grass reference surface becomes:

$$r_a = \frac{208}{u_2} \tag{4}$$

where u_2 is the wind speed [m s^{-1}] at 2 m.

3) *Hargraves Method* (*HAR*)

This method requires daily maximum and minimum air temperature, and extraterrestrial solar radiation, which is computed from the latitude of the study site. The Hargreaves and Samani [35] equation is defined as follows:

$$ET_0 = 0.0023(T_{\max} - T_{\min})^{0.5}(T_{mean} + 17.8)R_a \tag{5}$$

where $T_{\min}$ daily minimum temperature [˚C], $T_{\max}$ saturation vapor pressure at daily maximum temperature and R_a extraterrestrial radiation [MJ m^{-2} day^{-1}].

4) *Thornthwaite Method* (*TH*)

This formula is based mainly on temperature with an adjustment factor for the number of daylight hours. The potential evapotranspiration, calculated on a monthly basis, is [36]:

$$PE' = 16\left(\frac{10\overline{T_m}}{I}\right)^a \tag{6}$$

where the subscript m indicates the months 1, 2, 3, …, 12, T_m is the monthly mean temperature (˚C), I is the heat index for the year, given by:

$$I = \sum i_m = \sum\left(\frac{\overline{T_m}}{5}\right)^{1.5} \tag{7}$$

where, i_m is monthly values of heat index and a is empirical coefficient defined as

$$a = 6.7\times10^{-7} I^3 - 7.7\times10^{-5}\times I^2 + 1.8\times10^{-2} + 0.49 \tag{8}$$

Therefore,

$$ET_0 = PE'\left(\frac{d}{12}\right)\left(\frac{N_m}{30}\right) \tag{9}$$

where, N_m is the monthly adjustment factor related to hours of daylight, ET_0 reference evaporation [mm/day], d duration of daylight [hr].

5) *Blaney-Criddle Method* (*BC*)

The Blaney-Criddle equation has been used to calculate the reference crop evapotranspiration ET_0 when pan evaporation is not available. It can be expressed as [37]

$$ET_0 = p\left(0.46T_{mean} + 8\right) \tag{10}$$

where ET_0 is reference crop evapotranspiration (mm/day) averaged over the month T_{mean} = mean daily temperature (˚C), and p is mean daily percentage of annual daytime hours and varies between 0.26 and 0.29 for Bahir Dar.

6) *Enku's Simple Temperature Method* (*ENKU*)

The new simple empirical temperature method, which was named by "Enku's simple temperature method", was developed [19] and tested in Ethiopia with Penman Montieth reference Evaporation and the Piche Evaporimeter. The equation is:

$$ET_0 = \frac{\left(T_{\max}\right)^n}{k} \tag{11}$$

where ET_0 is the reference evapotranspiration (mm day^{-1}); n = 2.5 for the Lake Tana area; k is the coefficient, which is calibrated for local conditions ranging from about 600 for lower mean annual maximum temperature areas to 1300 for higher mean annual maximum temperature areas. The coefficient, k, was found by Enku and Melesse [19] as $k = 48 * T_{mm} - 330$ for combined wet and dry conditions or $k = 73 * T_{mm} - 1015$ for the dry phase, and $k = 38 * T_{mm} - 63$ for the rain phase, where T_{mm} (C) is the long term daily mean maximum temperature for the seasons under consideration.

7) *Pan Methods*

The evaporation rate from Class A Pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth. Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface [6].

There are two types of Pan Models to estimate reference evaporation.

a) *Pereira Model* (*PAN-P*)

According to Pereira *et al.* [5], the reference evaporation, ET_0 from pan data calculated with:

$$ET_0 = E_{pan} \cdot K_1 \tag{12}$$

where; ET_0 reference evapotranspiration [mm/day], K_1 pan coefficients [-], E_{Pan} Class A pan evaporation [mm/day].

$$K_1 = \frac{0.85(\Delta + \gamma)}{\left[\Delta + \gamma(1 + 0.33u_2)\right]} \tag{13}$$

b) *Allen Model* (*PAN-A*)

As Allen *et al.* [6], ET_0 from pan data calculated with:

$$ET_0 = E_{pan} \cdot K_2 \tag{14}$$

The pan coefficient K_2 for Class A pan with green fetch can be found as [6]:

$$\begin{aligned} K_2 = {} & 0.108 - 0.0286u_2 + 0.0422\ln(F) + 0.1434\ln(RH) \\ & - 0.000631\left[\ln(F)\right]^2 \ln(RH) \end{aligned} \tag{15}$$

where F is fetch or distance of the reference grass (m) and RH is the relative humidity in percent.

8) *Piche Methods*

The Piche evaporimeter is a type of atmometer used to measure the rate of evaporation from a wet disc of absorbent paper. It is used mainly in hot, dry climates where water loss through evaporation must be observed regularly. Since the results are dependent on wind speed past the disc, as well as the wet bulb saturation deficit, it is almost essential to expose the evaporimeter inside a meteorological screen [14] [38] [39].

There are two types of Piche models used in this study to estimate evapotranspiration.

a) *Stanhill Method* (*PI-S*)

Stanhill [13] suggested that it may be possible to estimate the second term in Penman's equation from available sheltered Piche evaporation data (E_{pi}) as follows.

$$ET_0 = \frac{\Delta R_n}{\Delta + \gamma} + aE_{pi} + b \tag{16}$$

where a slope and b is intercept of a linear relation with the aerodynamic term of Penman equation:

$$aE_{pi} + b = \frac{\gamma}{\Delta + \gamma} E_a \quad (17)$$

where;

$$E_a = f(u)(e_s - e_a) \quad (18)$$

where $f(u)$ is an aerodynamic wind function and ($e_s - e_a$) is the difference between saturated vapour pressure and actual vapour pressure in hPa, evaluated at mean air temperature and at 2 m above the ground or water surface.

The equivalent to the wind function of Penman [40] is

$$f(u) = 0.263(a_u + b_u a) \quad (19)$$

where u is the wind speed in m s^{-1} at 2 m elevation, and a, and b, are empirical coefficients. Penman [40], Penman [41] suggested using values equivalent to 1 and 0.537 for a, and b, respectively for a short grass cover when u is measured in m s^{-1}.

b) *Adam & Ahmed Method* (*PI-ADAH*)

Adam and Ahmed [14] showed that the ratio of Penman estimated and Piche evaporation have relation with relative humidity exponentially. That is:

$$\frac{ET_0}{E_{Pi}} = ae^{bRH} \quad (20)$$

where a and b are constants that can be find from the exponential relation and the RH humidity in percent

2.3. Methods of Data Analysis

The collected meteorological data for Bahir Dar (2005-2015) was of good quality with less than 5% of missing data. A simple arithmetic mean was used to determine the missing data. Reference evaporation was computed at daily and monthly time step using the 10 methods listed above after data preparation.

In addition, we compared the calculated reference evaporation with the ten methods using three techniques: visual inspection, descriptive statistics and statistical methods to test methods of efficiency and their standard error. The visual inspection of plotted ET_0 prediction methods reveals whether the calculated reference evaporation is in agreement with either other methods or an outlier. Descriptive statistics like maximum, absolute minimum, median value, total range of values, standard deviation, and coefficient of variation were used to compare the ET_0 prediction methods.

In this study, every single model was correlated with the pan ET_0s to assess the model performances and standard error. Pearson's correlation and root mean square error (RMSE) equations were used for this purpose.

The formula for the Pearson product moment correlation coefficient, r, is:

$$r = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sqrt{\sum(x - \bar{x})^2 \sum(y - \bar{y})^2}} \quad (21)$$

The equation for the standard error of the predicted y is:

$$\sqrt{\frac{1}{n-2}\left[\sum(y-\bar{y})^2-\frac{\left[\sum(x-\bar{x})(y-\bar{y})\right]^2}{\sum(x-\bar{x})^2}\right]} \tag{22}$$

where $\bar{x}$ and $\bar{y}$ are the sample means.

A sensitivity analysis was carried out to evaluate the percentage response of calculated ET_0 to selected weather variables. Changes of model outputs and their variability induced by change in weather variables were evaluated. The change in variables was analyzed for values 25% above and 25% below the mean value.

Mann Kendall trend test was used to indicate whether there are trends in the ET_0 computed using the ten methods. Non-parametric Mann Kendall Trend Test is useful to examine the temporal variation trend. It is based on the significance of differences, not directly on the random values. Therefore the trend that's been determined is less affected by outliers [42]. The nonparametric Mann-Kendall trend test has been applied in many studies to identify whether monotonic trends exist in hydro-meteorological data such as temperature, rainfall and stream flow [43]. The Mann Kendall Trend Test, S is calculated by using the equation below [44] [45].

$$S=\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\operatorname{sgn}(x_i-x_j),\operatorname{sgn}(x_i-x_j)=\begin{cases}+1\rightarrow x_i-x_j>0\\0\rightarrow x_i-x_j=0\\-1\rightarrow x_i-x_j<0\end{cases} \tag{23}$$

where x_j and x_i are the sequential data value and j greater than i, N is the length of the data set.

As indicated in Mann [44] and Kendall and Stuart [46], when $N \geq 8$, the distribution of S approaches the Gaussian form with mean $E(S) = 0$ and variance $Var(S)$ given by:

$$Var(S)=\frac{N(N-1)(2N+5)-\sum_{m=1}^{N}t_i(m-1)(2m+5)m}{18} \tag{24}$$

where: t_i is the number of ties of length m.

The statistic S is then standardized (Z), and its significance can be estimated from the normal cumulative distribution function.

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{V(s)}}\rightarrow S>0\\0\rightarrow S=0\\\dfrac{S+1}{\sqrt{V(s)}}\rightarrow S<0\end{cases} \tag{25}$$

The positive Z value indicates an increasing trend while a negative Z value indicates a decreasing trend. When testing two sided trends at a selected level of significance a, the null hypothesis (H_0) of no trend is rejected if the absolute value of Z is greater than $Z_{a/2}$ where a represents the chosen significance level (5% with $Z_{0.025} = 1.96$).

3. Results

Reference Evaporation: Calculated Values

The reference evaporation, ET_0, was calculated for a daily and monthly time step. In Figure 1, as an example, the 2005 ET_0 for the ten methods are depicted. Values calculated for the other years are shown in tabular form in Table S2 in the supplementary material. The minimum reference evaporation calculated was 0 mm/day (Thornthwaite) and 16.3 mm/day (Hargraves and Priestley-Taylor). Blaney-Criddle has the smallest range (the difference in daily maximum and minimum values) while Priestley-Taylor has the largest range of values. The FAO-Penman and Enku methods have acceptable daily ET_0 ranges between 1.5 and 6.5 mm/day [6] [15] [47].

Seasonally, the reference evaporation of each of the methods is greater during the dry phase from February to May when the temperature is high and there are few clouds than during the rain phase from June to September when it is cloudy and less warm (Figure 1, Figure 2). In addition, the reference evaporation decreases in December and January for some of the methods (Figure 1, Figure 2) due to cloudiness caused by of easterlies carrying moisture from Arabian Sea.

In equatorial countries like Ethiopia, the difference in sunshine duration between months is minimal and the difference in ET_0 is due to cloud cover mainly and temperature and relatively humidity secondly. This is different from temperate climates where the day length is the primary factor that determines the magnitude of the reference evaporation during the year.

The methods by Enku, Class A pan (both), FAO-Pennman Monteith and the Adam and Ahmed Piche evaporimeter had all the same annual average reference evaporation of 1460 mm y^{-1} (Figure 3). The predictions of the Blaney-Criddle and Thornthwaite are slightly more at 1754 mm y^{-1} (Figure 3). The last three

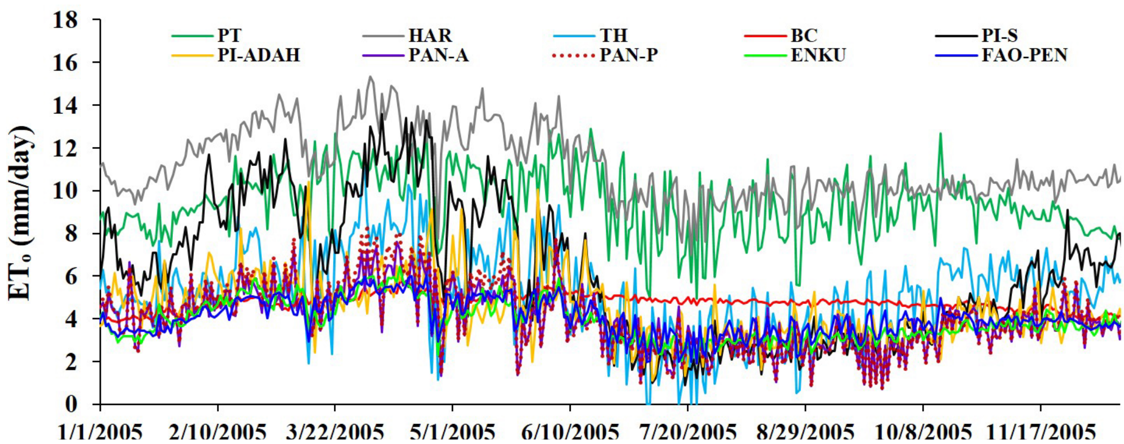

Figure 1. Daily plot of reference potential evaporation (ET_0) of the ten methods for 2005 for the Bahir Dar meteorological station. The following abbreviations are used: FAO-PEN is FAO-Penman Monteith (Equation (1)), PT is Priestley & Taylor (Equation (2)), HAR is Hargraves (Equation (5)), TH is Thornthwaite (Equation (9)), BC is Blaney-Criddle (Equation (10)), ENKU is the Enku's simple temperature method (Equation (11)), PAN-P is the Pan-Pereira (Equation (12)), PAN-A is the Pan-Allen (Equation (14)), PI-S is the Piche-Stanhill (Equation (16)) and PI-ADAH is the Piche-Adam and Ahmed (Equation (20)).

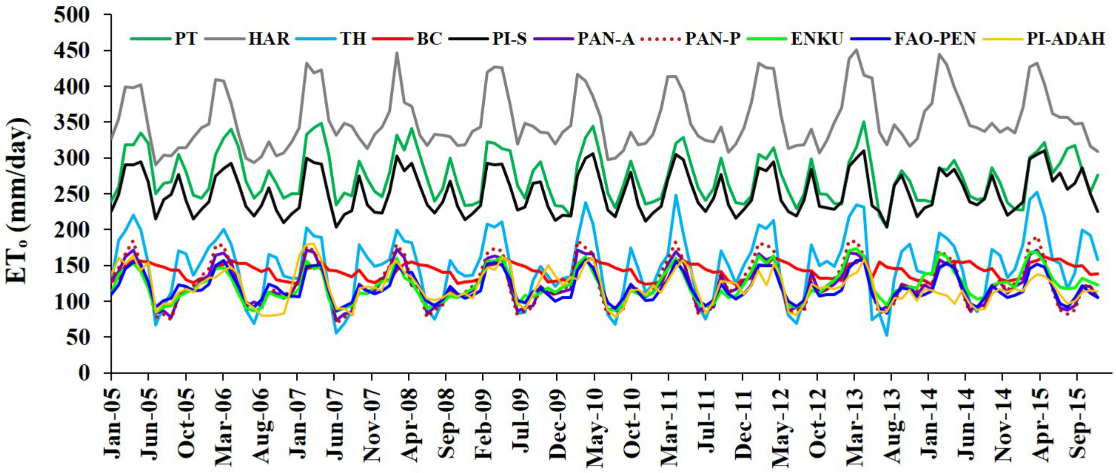

Figure 2. Monthly plot of ET_0 of the ten methods for the Bahir Dar meteorological station from 2005 to 2015. Abbreviations of the reference evaporation methods are listed under **Figure 1**.

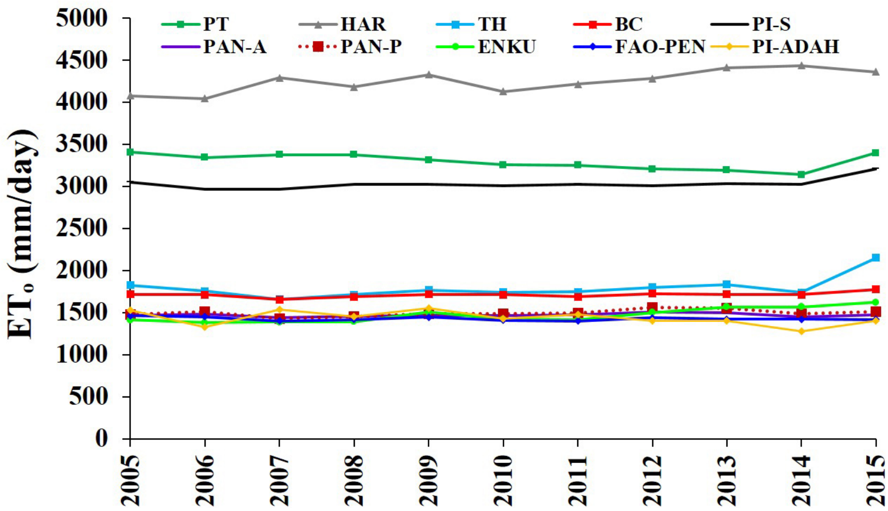

Figure 3. Annual reference evaporation, ET_0, of the ten methods for the Bahir Dar meteorological station from 2005 to 2015. Abbreviations of the reference evaporation methods are listed under **Figure 1**.

methods also over predicted pan evaporation in the Ethiopian highlands: the Stanhill Piche evaporimeter method predicted on the average 1571 mm y^{-1}, Priestley & Taylor methods as 1838 mm y^{-1} and Hargraves almost twice the pan evaporation ET_0 at 2792 mm y^{-1}. In addition, **Figure 3** showed that the year to year variation in reference evaporation was small, indicating that the amount of rainfall and soil moisture have little or no effect on the loss of water in the atmosphere.

4. Discussion

4.1. Reference Evaporation: Comparing the Methods

The data in **Figure 2** are further summarized in **Figure 4** where the monthly averaged reference evaporation, ET_0, of each of the 10 methods for the eleven years

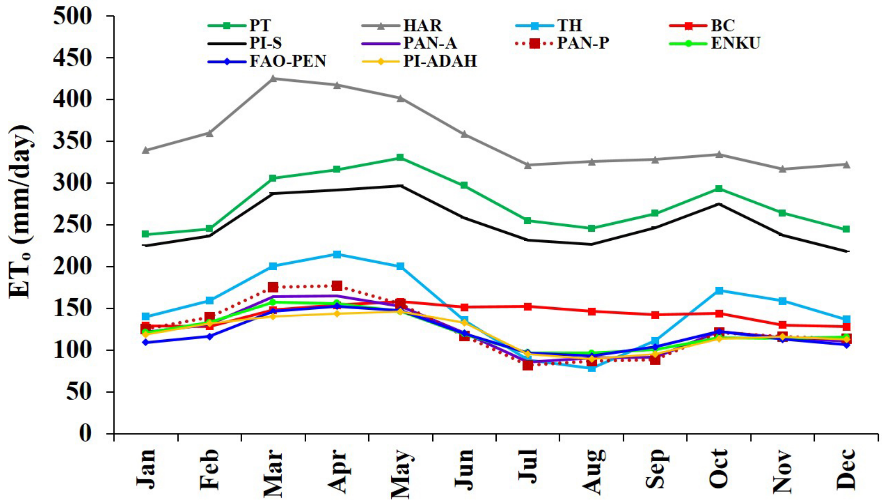

Figure 4. Long-term mean monthly evapotranspiration (2005-2015) of Bahir Dar for ten different prediction techniques. Abbreviations of the reference evaporation methods are explained Figure 1.

(2005-2015) are depicted. As in Figure 2 the Hargraves (HR), the Priestley & Taylor (PT) and the Piche-Stanhill method (PI-S) over predicts the reference evaporation greatly and will not be discussed in any detail. These three methods should not be applied in the Ethiopian highlands to calculate evaporation.

While all methods have the smallest reference evaporation during the rain phase (Figure 4), the Blaney-Criddle (blue solid line) is the exception. At the end of dry phase, the ET_0 calculated with the Blaney-Criddle method is in the same order as other indirect measurement that predicts realistically ET_0 such as the FAO-Penman and the Enku methods, but severely over predicts during the rain phase. It has also the smallest variability compared to all other methods (Figure 4). The reason is that the reference evaporation is calculated as linear function of the average monthly temperature (Equation (10)) which in the countries near the equator varies little during the year and thus the ET_0 values are within a narrow band as well (Figure 4, Figure 5). By replacing the constant values for the whole year in the Blaney-Criddle equation (Equation (10)), by monthly varying constants and calibrating these, the model will fit much better [48]. The modified Blaney-Criddle Equation becomes in this way similar to the Enku method (Equation (11)). Interestingly, in Figure 4 has shown that during the rain phase starting in May (when the first rains fell) through September (when the rains ended), the reference evaporation, ET_0, calculated with the three indirect methods (the FAO-Penman Monteith, the Thornthwaite and the Enku methods) compared well with the direct measurement of both pan evaporation methods and the Piche evaporimeter using coefficients proposed by Adam and Ahmed [14].

During the rain phase when precipitation exceeds evaporation, the condition of a well-watered surface on which the reference evaporation is based is similar to that in the Ethiopian highlands. So, during the wet phase the direct and indirect

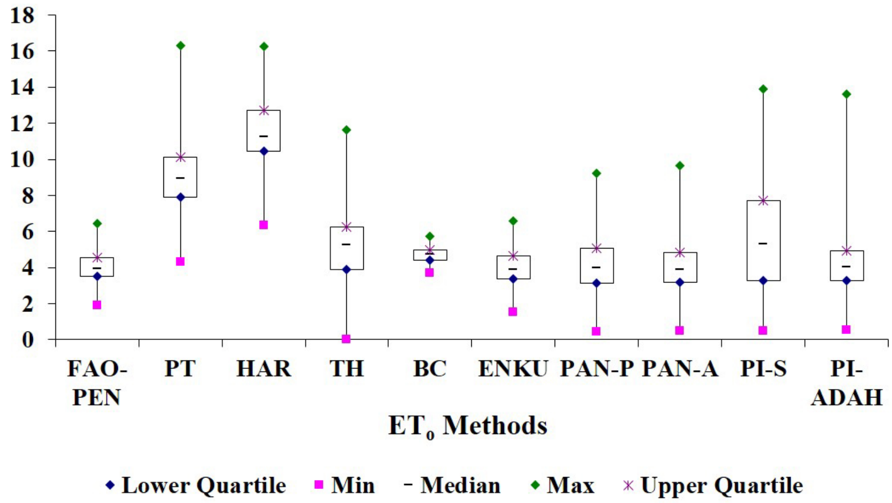

Figure 5. Box plots of daily ET_0 prediction methods for the Bahir Dar weather station. Abbreviations of the reference evaporation methods are explained **Figure 1**.

measurements should agree and they do for the FAO-Penman Monteith, the Thornthwaite and the Enku methods with the two pan methods and one of the Piche methods (**Figure 4**). During the dry phase, the reference evaporation for these seven methods started to deviate. Initially after the rains stopped and the surface of soil was still wet, only the Thorntwaite method predicted higher ET_0 values while the remaining five agreed well. In January to April when the landscape is very dry and rivers are without water, the direct measurements of the ET_0 are much greater than the calculated values using the meteorological data (**Figure 4**). The reason for the deviation can be explained with the complementary relationship of actual evaporation and apparent (or pan) evaporation originally introduced by Bouchet [49] and refined by Brutsaert and Stricker [50]. The theory is as follows: When the soil is dry and the evaporation is less than the reference evaporation, the energy that under wet conditions is used for evaporation is converted to the sensible heat and causes an increase in the evaporative demand of the atmosphere. The reference evaporation rates derived from the pan during the dry season are therefore greater than it would be during the wet season under otherwise similar atmospheric conditions. The FAO-Penman method predicts reference evaporation rates of a well-watered irrigation field independent of the condition of the landscape. Hence, the discrepancy between the direct and indirect methods under extreme dry conditions in the period is from January through April (**Figure 4**).

The question whether the direct or indirect measurement of the reference evaporation is more appropriate during the dry phase is a mood point because the evaporation for most of the landscape, where the soil is dry, is limited by the soil and not by the atmosphere. Only for irrigated fields and lakes, the reference evaporation determines the rate of evaporation during the dry phase. As pointed out by Bouchet [49] the upward wind site of an irrigated field, the evaporation rate is similar to the pan measurement while in the remaining of the area the evaporation rate is equal to reference evaporation calculated with the Penman Monteith.

In addition to plotting the averaged reference evaporation, ET_0, in **Figure 5**, it is also of interesting to investigate the variation in the reference evaporation for each of the 10 methods. Therefore, the maximum, minimum, mean, lower and upper quartile of the long term daily reference evaporation for the period are shown in **Figure 5** from 2005 to the end of 2015. **Figure 5** indicates that the Blaney-Criddle method has the least variation because it is only dependent of the average temperature that (despite what the Ethiopians claim) varies little throughout the year. The FAO-Penman Monteith has only a slightly larger variation in ET_0 than the Blaney-Criddle method because it calculates likewise the ET_0 based on meteorological variables that vary little throughout the year except for the cloud cover which is the reason of the additional spread in ET_0 values. The Enku method that depends on temperature has a larger variation than the Blaney-Criddle, because besides temperature it is dependent on a few other fitted functions so that it can simulate the lower ET_0 during the month with clouds. The two pan measurements have a large variation, because they are based on measured data. The measured ET_0 values have a large spread because of the sensible heat during the dry phase that increases the pan evaporation but is not included in any of the indirect methods.

In the Pearson correlation statistics, we looked the performance of eight reference evaporation methods with the pan evaporation methods (**Table 1**). As expected form the discussion above, the FAO-Penman Monteith and Enku simple maximum temperature methods were highly correlated with correlation coefficient of respectively 0.91 and 0.93 (monthly), and 0.64 and 0.69 (daily). Thornthwaite method holds the third place of good ET_0 monthly estimator with correlation of 0.89 for both pan ET_0 methods on a monthly basis.

Rácz *et al*. [15] stated that methods having smallest RMSE have the lowest systematic error in predicting ET_0. **Table 2** confirms our findings above that the Penman, Enku, Piche and Pan are most similar because they have the smallest RMSE (**Table 2**). It is surprising that the Blaney-Criddle model has such a small RMSE with the pan on daily time step. It is quirk of how the daily ET_0 values are calculated.

Table 1. Pearson's correlation between Pan ET_0 and ET_0 of prediction methods (2005-2015).

	PEN	PT	HAR	TH	BC	ENKU	PI-S	PI-ADAH
				Daily-Basis				
PAN-P	0.64	0.42	0.63	0.55	0.22	0.69	0.72	0.47
PAN-A	0.59	0.43	0.57	0.51	0.23	0.62	0.65	0.49
				Monthly-Basis				
PAN-P	0.91	0.58	0.84	0.89	0.21	0.93	0.7	0.75
PAN-A	0.93	0.65	0.84	0.89	0.26	0.91	0.75	0.79

Table 2. Root mean square error (RMSE) between modeled daily ET_0 and pan ET_0 (2005-2015).

	PEN	PT	HAR	TH	BC	ENKU	PI-S	PI-ADAH
Daily-Basis								
PAN-P	0.59	1.44	1.23	1.61	0.37	0.63	1.99	1.16
PAN-A	0.62	1.43	1.3	1.66	0.37	0.69	2.18	1.15
Monthly-Basis								
PAN-P	8.1	28.2	22.2	21.1	11	8.5	20.7	15.6
PAN-A	7.5	26.3	22.6	21.2	10.9	9.5	19.4	14.4

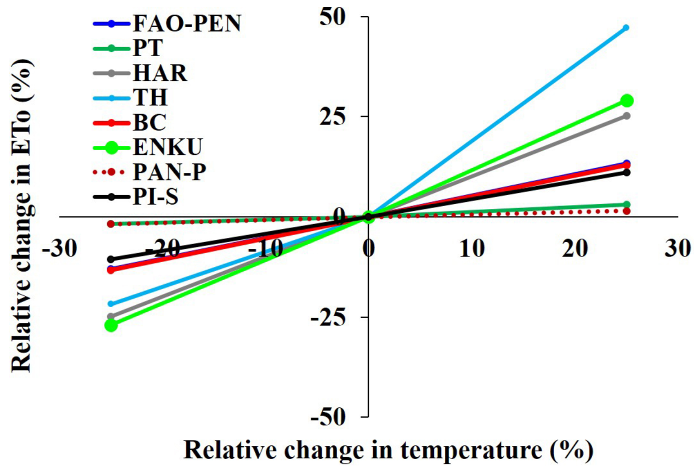

Figure 6. Relative change in reference potential evaporation of Bahir Dar station for the change of temperature between the year 2005 and 2015. Abbreviations of the reference evaporation methods are explained Figure 1.

4.2. Sensitivity Analysis

In the sensitivity analysis, we looked the relative effect on reference evaporation of a 25% change in temperature, sunshine hours, relative humidity and wind speed (Figure 6, Figure S2). As expected, an increase in temperature increased reference evaporation (Figure 6). For the indirect methods (Enku, Thornthwaite and Hargreaves methods), the reference evaporation increased the same percentage or more as the temperature. The direct methods were the least sensitive to the change in temperature. Changing sunshine hours, relative humidity and wind speed did not change or increased the reference evaporation with the exception that an increase in relatively humidity for the FAO-Penman Monteith and an increase in winds Speed for both pan methods decreased the reference evaporation (Figure S2).

4.3. Trend Analysis

The trend analysis results of the reference potential evaporation obtained by applying the Mann-Kendall method is shown in Table 3. To our surprise despite our short 11-year record, there were strong trends for the majority of the 10

Table 3. Mann Kendall trend test statistics for daily ET_0 of Bahir Dar station from 2005 to 2015.

ET_0 Methods	Mann-Kendall Statistic (S)	Kendall's Tau	Var (S)	p-Value (Two Tailed Test)	Alpha	Test Interpretation
FAO-PEN	0.041	327,438	7,199,473,160	0.0001	0.05	Reject H_0
PT	−0.063	−507,950	7,199,473,160	<0.0001	0.05	Reject H_0
HAR	0.085	682,662	7,199,473,160	<0.0001	0.05	Reject H_0
TH	0.046	367,257	7,199,469,652	<0.0001	0.05	Reject H_0
BC	0.053	427,721	7,199,382,783	<0.0001	0.05	Reject H_0
ENKU	0.126	1,000,816	7,193,567,805	<0.0001	0.05	Reject H_0
PAN-P	0.010	79,504	7,199,473,160	0.3488	0.05	Accept H_0
PAN-A	−0.012	−95,502	7,199,473,158	0.2604	0.05	Accept H_0
PI-S	−0.050	−401,899	7,198,567,007	<0.0001	0.05	Reject H_0
PI-ADAH	−0.071	−571,885	7,199,470,202	<0.0001	0.05	Reject H_0

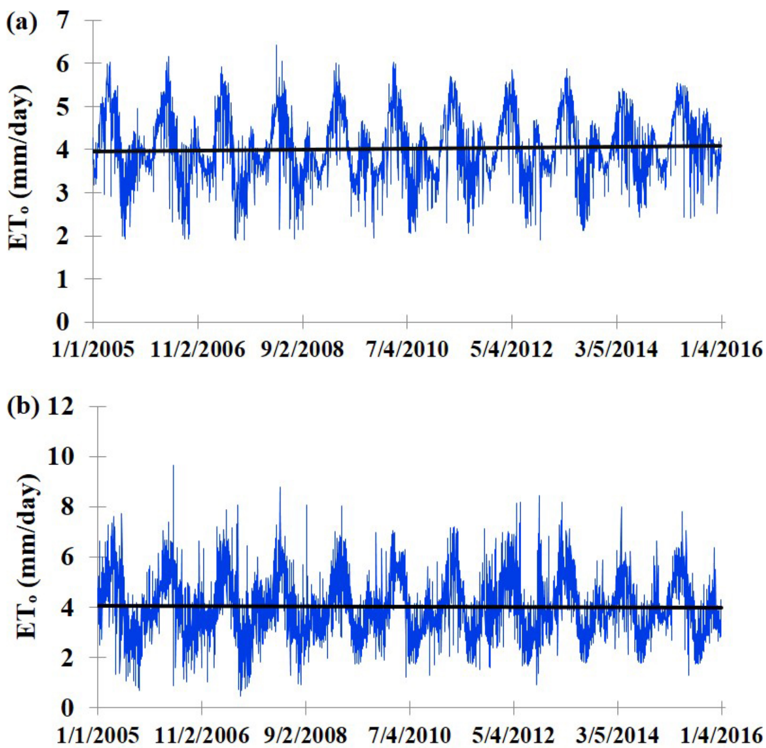

Figure 7. Time series plots of ET_0 for Bahir Dar station from 2005 to 2015: (a) FAO-Penman Monteith; (b) Pan-Pereira.

methods. Only the direct measurement of the ET_0 with the two pan methods did not change over the eleven year period (*i.e.*, accept the null hypothesis that there is not a trend in the ET_0 values, Table 3, Figure 7(b)). Methods that calculated the reference evaporation from meteorological data (e.g., FAO-Penman Monteith (FAO-PEN), Hargraves (HAR), Thornthwaite (TH), Blaney-Criddle (PT), Enku (ENKU)) increased with time (Table 3, Figure 7(a) and Figure S3). The

Priestly and Taylor methods that was ill suited for the Ethiopian highlands was an exception. Thus, since these methods were directly based on measured meteorological data (two only on temperature) it clearly indicates that the climate is changing in the Ethiopian Highlands. In other words, since three of the indirect methods were primarily based on temperature, it is getting warmer fast in Bahir Dar! Finally, the Piche methods that not directly depend on the measured standard indicated that the reference evaporation was decreasing.

This paradox of increasing reference evaporation calculated by indirect methods and either not changing (both pan measurements) or decreasing (Piche measurement) by direct measurement has been noted before in a slightly different context by Brutsaert and Parlange [51] as one of the first. They noted that pan evaporation rates were generally decreasing and related that to increased terrestrial evaporation because more runoff occurring with climate change. In terms of the complementary relationship introduced earlier, they explain that more of the incoming energy is used for evaporation and consequently less is converted to sensible heat. This in turn reduces pan evaporation. For the Bahir Dar meteorological station, the explanation might be slightly different. Temperatures in Bahir Dar are increasing either due to climate change or because of rapid urbanization. The dry season has been always so dry that all evaporative energy was converted to sensible heat and increasing temperatures did not affect pan evaporation. The Piche evaporimeter measurements were likely not affected either by the higher temperatures but the relatively humidity decreased due to the higher temperature decreasing the ET_0 value as can be seen from Equation (20).

5. Conclusions

Ten methods to predict the reference evaporation were tested for the Ethiopian highlands. The Priestley and Taylor, Hargreaves, and Piche-Stanhill methods over predicted ET_0 and should not be used without recalibration. In addition, the Blaney-Criddle method over predicted the reference evaporation during the rain phase. The reference evaporation calculated with the FAO-Penman and Enku methods resembles most closely the direct measurements with the Class A pan evaporation using confident introduced by Pareira and Allen. Thorthwaite's monthly ET_0 model performed well too.

A significant increasing trend in calculated reference evaporation using meteorological variables was found, indicating that temperatures were increasing during the past 11 years at the Bahir Dar weather station. The direct measurement by the Class A pan did not show this trend. More research is needed to research whether other parts of the Ethiopian highlands show similar trends in reference evaporation.

Our recommendation is that the FAO-Penman Monteith is recommended for locations where the input data are available. Otherwise, the Enku method using maximum daily temperature is best for estimating the reference evaporation.

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Supplementary Materials

Supplementary Material S1: Parameters of FAO-Penman Monteith Equation

The slope of the relationship between saturation vapor pressure and temperature, Δ, is

$$\Delta = \frac{4098\left[0.6108\exp\left(\frac{14.27T}{T+237.3}\right)\right]}{\left(T+237.3\right)^2} \quad \text{(A-1)}$$

where, T air temperature [˚C]. The actual vapor pressure can be determined from the difference between the dry and wet bulb temperatures, e_a

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^o\left(T_{\max}\right)+e^o\left(T_{\min}\right)}{2}\right] \quad \text{(A-2)}$$

where e_a actual vapor pressure [kPa], $e^o\left(T_{\min}\right)$ saturation vapor pressure at daily minimum temperature [kPa], $e^o\left(T_{\max}\right)$ saturation vapor pressure at daily maximum temperature [kPa], RH_{mean} is the mean relative humidity, defined as the average between $RH_{\max}$ and $RH_{\min}$.

As saturation vapor pressure is related to air temperature, it can be calculated from the air temperature. The relationship is expressed by:

$$e^o\left(T\right) = 0.6108\exp\left[\frac{14.27T}{T+237.3}\right] \quad \text{(A-3)}$$

where $e^o\left(T\right)$ saturation vapour pressure at the air temperature T [kPa], T air

Figure S1. Location of Bahir Dar principal meteorological station.

Table S1. Data used and overview of ET_0 methods calculation.

Date	Tmax, ˚C	Tmin, ˚C	Sunshine (hour)	Humidity (%)	Wind speed at 2m m/s	T mean	Δ (Kpa/˚C)	Elevation (m)	P(KP)	Y (Kpa/˚C)	e˚ (Tmax)	e˚ (Tmin)	□
12/30/2005	28.0	7.1	10.4	38	1.2	17.6	0.13	1805	78.16	0.052	3.78	1.01	→
12/31/2005	26.3	6.7	10.2	36	1.0	16.5	0.12	1805	78.16	0.052	3.42	0.98	→
1/1/2006	26.7	5.6	10.3	37	0.9	16.2	0.12	1805	78.15	0.052	3.50	0.91	→
1/2/2006	26.3	5.5	10.3	40	1.0	15.9	0.12	1805	78.14	0.052	3.42	0.90	→
1/3/2006	27.6	8.1	10.4	36	1.0	17.9	0.13	1805	78.13	0.052	3.69	1.08	→
1/4/2006	27.2	6.5	10.0	36	1.0	16.9	0.12	1805	78.12	0.052	3.61	0.97	→
1/5/2006	26.9	6.1	10.3	35	0.9	16.5	0.12	1805	78.11	0.052	3.54	0.94	→
1/6/2006	26.3	6.0	10.4	42	0.8	16.2	0.12	1805	78.10	0.052	3.42	0.94	→
1/7/2006	26.2	5.9	10.4	39	1.0	16.1	0.12	1805	78.09	0.052	3.40	0.93	→
1/8/2006	26.5	6.0	9.4	40	1.1	16.3	0.12	1805	78.08	0.052	3.46	0.94	→
1/9/2006	26.7	6.6	10.1	39	1.1	16.7	0.12	1805	78.07	0.052	3.50	0.97	→
1/10/2006	28.4	8.4	8.4	40	0.7	18.4	0.13	1805	78.06	0.052	3.87	1.10	→
1/11/2006	28.3	8.6	9.6	46	1.0	18.5	0.13	1805	78.05	0.052	3.85	1.12	→
1/12/2006	30.0	9.4	7.7	37	1.0	19.7	0.14	1805	78.04	0.052	4.24	1.18	→
1/13/2006	27.0	10.0	9.8	46	0.9	18.5	0.13	1805	78.03	0.052	3.57	1.23	→
1/14/2006	27.0	8.3	10.0	45	1.1	17.7	0.13	1805	78.02	0.052	3.57	1.09	→
1/15/2006	26.9	10.6	10.1	44	0.9	18.8	0.14	1805	78.01	0.052	3.54	1.28	→
1/16/2006	27.6	6.2	10.2	55	1.1	16.9	0.12	1805	78.00	0.052	3.69	0.95	→
1/17/2006	28.0	8.5	10.5	56	1.1	18.3	0.13	1805	77.99	0.052	3.78	1.11	→
1/18/2006	27.9	8.3	10.6	51	0.9	18.1	0.13	1805	77.98	0.052	3.76	1.09	→
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	

temperature [˚C], exp[..] 2.7183 (base of natural logarithm) raised to the power [..].

Saturation vapor pressure as a function of air temperature, e_s

$$e_s = \frac{e^o\left(T_{\max}\right) + e^o\left(T_{\min}\right)}{2} \quad \text{(A-4)}$$

Soil heat flux (G):

$$G_{month,i} = 0.14\left(T_{month,i} - T_{month,i-1}\right) \quad \text{(A-5)}$$

where $T_{month,i}$ mean air temperature of month i [˚C] and $T_{month,i-1}$ mean air temperature of previous month [˚C].

The psychrometric constant, γ, is given by:

$$\gamma = \frac{c_p P}{\varepsilon\lambda} = 0.665 \times 10^{-3} P \quad \text{(A-6)}$$

where γ psychrometric constant [kPa ˚C^{-1}], P atmospheric pressure [kPa], λ

latent heat of vaporization, 2.45 [MJ kg^{-1}], c_p specific heat at constant pressure, 1.013×10^{-3} [MJ kg^{-1} °C^{-1}], ε ratio molecular weight of water vapor/dry air = 0.622.

The atmospheric pressure, P, is the pressure exerted by the weight of the earth's atmosphere. Evaporation at high altitudes is promoted due to low atmospheric pressure as expressed in the psychrometric constant. The effect is, however, small and in the calculation procedures, the average value for a location is sufficient. A simplification of the ideal gas law, assuming 20˚C for a standard atmosphere, can be employed to calculate P:

$$P = 101.3\left(\frac{293 - 0.0065Z}{293}\right)^{5.26} \quad \text{(A-7)}$$

where P atmospheric pressure [kPa], and Z elevation above sea level [m]

The net radiation (R_n) is the difference between the incoming net shortwave radiation (R_{ns}) and the outgoing net long wave radiation (R_{nl}):

$$R_n = R_{ns} - R_{nl} \quad \text{(A-8)}$$

where;

$$R_{ns} = (1 - \alpha) R_s \quad \text{(A-9)}$$

where R_{ns} net solar or shortwave radiation [MJ m^{-2} day^{-1}], α albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop [dimensionless], R_s the incoming solar radiation [MJ m^{-2} day^{-1}].

If the solar radiation, R_s, is not measured, it can be calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \quad \text{(A-10)}$$

where R_s solar or shortwave radiation [MJ m^{-2} day^{-1}], n actual duration of sunshine [hour], N maximum possible duration of sunshine or daylight hours [hour], n/N relative sunshine duration [-], R_a extraterrestrial radiation [MJ m^{-2} day^{-1}], a_s regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days ($n = 0$), $a_s + b_s$ fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$). If no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values $a_s = 0.25$ and $b_s = 0.50$ are recommended.

The daylight hours, N, are given by:

$$N = \frac{24}{\pi}\omega_s \quad \text{(A-11)}$$

where ω_s is the sunset hour angle in radians

$$R_a = \frac{24 \times 60}{\pi} G_{sc} d_r \left[\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)\right] \quad \text{(A-12)}$$

where R_a extraterrestrial radiation in the hour (or shorter) period [MJ m^{-2} hour^{-1}], G_{sc} solar constant = 0.0820 MJ m^{-2} min^{-1}, d_r inverse relative distance Earth-Sun,

δ solar declination [rad], φ latitude [rad], ω_s sunset hour angle [rad].

$$\varphi[\text{Radians}] = \frac{\pi}{180}[\text{decimal degrees}] \quad \text{(A-13)}$$

The inverse relative distance Earth-Sun, d_r, and the solar declination, δ, are given by:

$$d_r = 1 + 0.033\cos\left(\frac{2\pi}{365}J\right) \quad \text{(A-14)}$$

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J - 1.39\right) \quad \text{(A-15)}$$

Table S2. Results overview of potential evaporation methods between 2005 and 2015 for Bahir Dar meteorological station. Abbreviations of the reference evaporation methods are explained Figure 1.

Date	FAO-PEN	PT	HAR	TH	BC	ENKU	PAN-P	PAN-A	PI-S	PI-ADAH
12/28/2005	3.7	7.6	10.3	5.5	4.1	3.7	4.4	4.1	6.8	3.3
12/29/2005	3.5	8.8	10.4	4.7	3.9	3.4	4.3	4.4	8.7	7.1
12/30/2005	4.0	8.3	11.1	6.1	4.2	4.2	4.0	3.8	7.9	4.1
12/31/2005	3.7	7.7	10.4	5.4	4.1	3.6	4.3	4.0	9.0	4.5
1/1/2006	3.6	7.6	10.7	4.8	4.0	3.7	3.9	3.6	6.8	3.5
1/2/2006	3.6	7.8	10.6	4.7	4.0	3.6	3.7	3.5	7.7	4.2
1/3/2006	3.8	7.7	10.9	5.9	4.2	4.1	5.0	4.6	6.8	3.4
1/4/2006	3.7	7.7	10.9	5.1	4.1	3.9	4.8	4.4	7.9	4.0
1/5/2006	3.7	7.6	10.8	5.0	4.1	3.8	4.1	3.8	8.5	4.2
1/6/2006	3.5	7.8	10.6	4.9	4.0	3.6	3.9	3.7	6.9	3.9
1/7/2006	3.7	8.0	10.6	4.8	4.0	3.6	3.7	3.5	7.2	3.8
1/8/2006	3.7	7.9	10.7	4.5	4.0	3.7	4.2	4.0	7.5	4.1
1/9/2006	3.8	8.1	10.8	5.0	4.1	3.7	3.6	3.4	6.9	3.7
1/10/2006	3.4	6.9	11.3	5.0	4.3	4.4	5.6	5.1	6.2	3.4
1/11/2006	3.8	8.1	11.3	5.7	4.3	4.3	4.4	4.2	7.4	4.6
1/12/2006	3.7	7.1	11.9	5.2	4.4	5.0	3.6	3.3	8.4	4.3
1/13/2006	3.7	8.0	10.5	5.9	4.3	3.8	3.7	3.5	8.2	5.1
1/14/2006	3.8	8.3	10.8	5.5	4.2	3.8	4.1	4.0	7.1	4.3
1/15/2006	3.7	8.0	10.4	6.2	4.3	3.8	3.7	3.5	6.4	3.8
1/16/2006	3.7	8.9	11.3	5.2	4.1	4.1	4.0	4.0	7.2	5.4
1/17/2006	3.9	9.3	11.3	6.2	4.3	4.2	3.7	3.8	8.1	6.2
1/18/2006	3.8	8.7	11.3	6.1	4.2	4.2	4.4	4.3	7.1	4.9
□↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓

where; J is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December). The sunset hour angle, ω_s, is given by:

$$\omega_s = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \quad \text{(A-16)}$$

Net long wave radiation (R_{nl}):

$$R_{nl} = \sigma\left[\frac{T_{\max,K}^4 + T_{\min,K}^4}{2}\right]\left(0.34 - 0.14\sqrt{e_a}\right)\left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad \text{(A-17)}$$

where R_{nl} net outgoing longwave radiation [MJ m^{-2} day^{-1}], σ Stefan-Boltzmann constant [4.903 × 10^{-9} MJ K^{-4} m^{-2} day^{-1}], $T_{\max,K}$ maximum absolute temperature during the 24-hour period [K = ˚C + 273.16], $T_{\min,K}$ minimum absolute temperature during the 24-hour period [K = ˚C + 273.16], e_a actual vapour pressure [kPa], R_s/R_{so} relative shortwave radiation (limited to ≤ 1.0), R_s measured or calculated solar radiation [MJ m^{-2} day^{-1}], R_{so} calculated clear-sky radiation [MJ m^{-2} day^{-1}].

$$R_{so} = \left(0.75 + 2\times10^{-5} Z\right) R_a \quad \text{(A-18)}$$

where; Z station elevation above sea level [m].

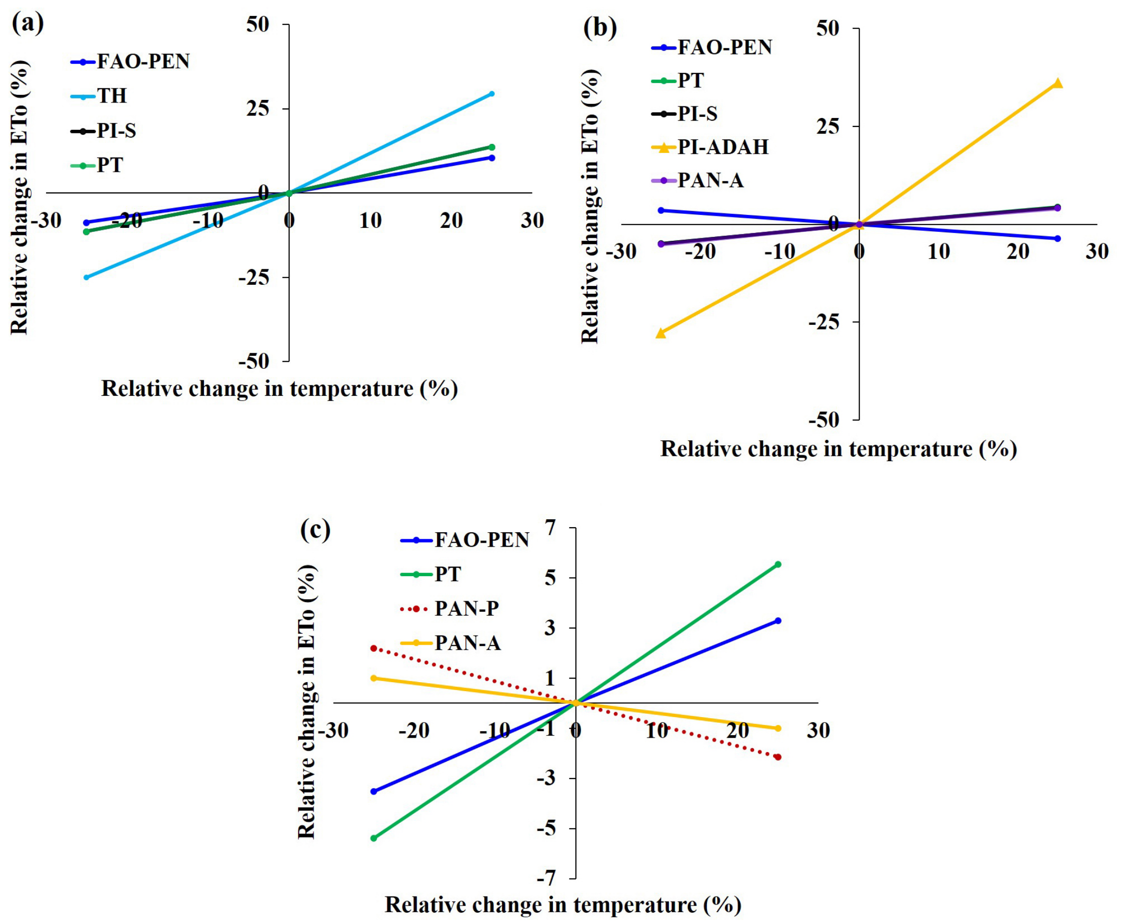

Figure S2. Relative change in reference potential evaporation of Bahir Dar station for the change of sunshine hour (a), relative humidity (b) and wind speed (c) between the year 2005 and 2015. Abbreviations of the reference evaporation methods are explained Figure 1.

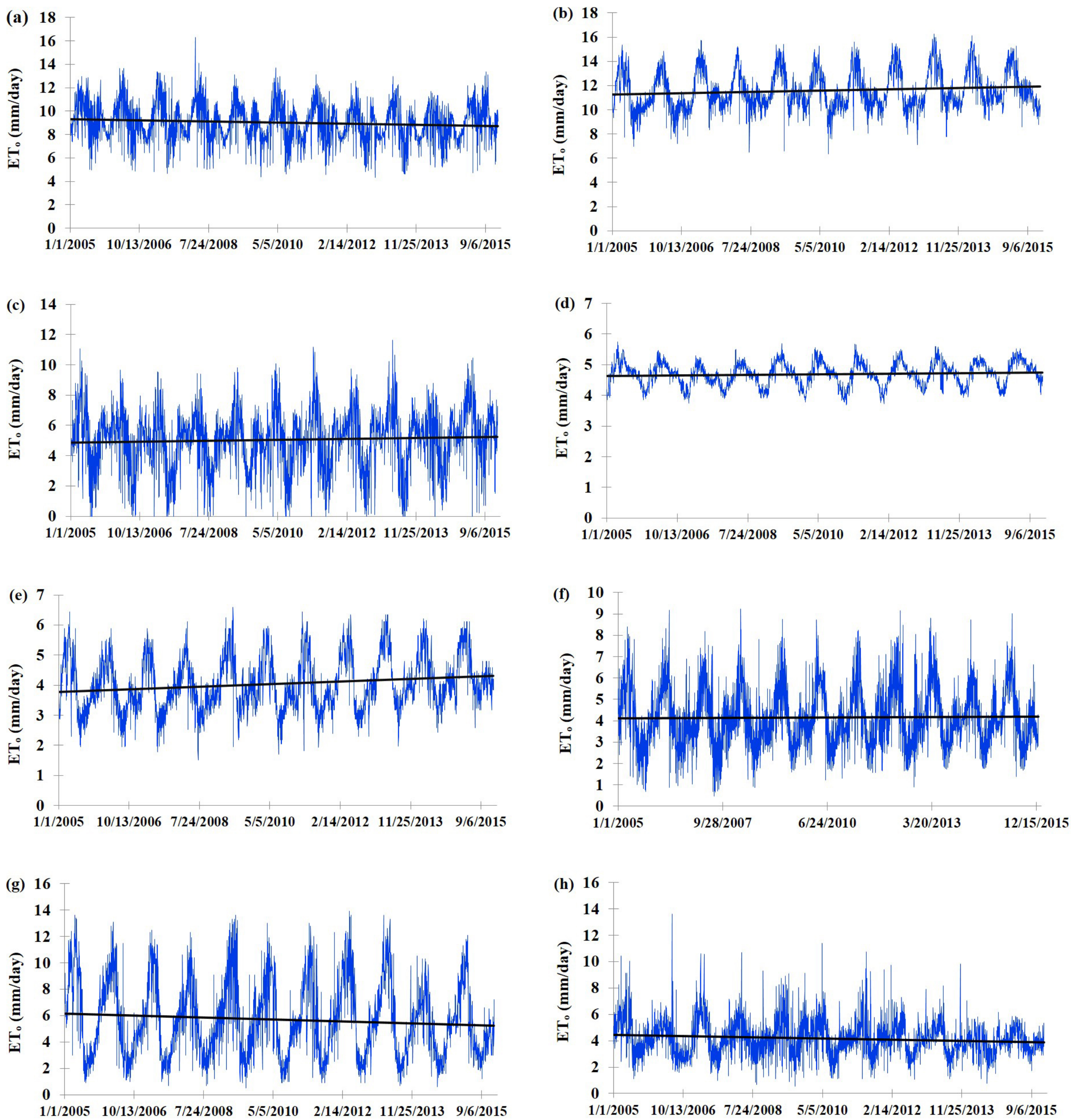

Figure S3. Daily time series plots of ET_0 for (a) Priestley & Taylor; (b) Hargraves; (c) Blaney-Criddle; (d) Enku; (e) Pan-Allen; (f) Piche-Stanhill; and (g) Piche-Adam and Ahmed.