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Comparison of Evaporation Schemes and Methods of Class a Pan Coefficient at Tharandt

Antensay Mekoya[*]

Ethiopia Environment and Forest Research Institute (EEFRI), Ethiopia

ABSTRACT

At Tharandt, Germany for the summer half-year of 2004-2013, methods of estimation of Potential Evapo-Transpiration (PET) according to Haude, Wendling, and Penman and Class A pan evaporation (Ep) were compared with each other with respect to the reference evapo-transpiration (ETo) using box plot, trend check, linear regression model, and model evaluation statistics. Similarly, Class A pan coefficients (Kp) from the equation of Snyder and Frevert as well as a trial method of estimation of Kp were compared using box plots. For the calculation of ETo, calibrated values of as=0.014 and bs=0.50 were used. The total amount of summer half-year evaporation schemes were >459 mm while the precipitation was 478.8 mm; this implied that the climate water balance was close to zero. The result of the comparison showed that all the evaporation schemes had a very good correlation with the reference method and all were considered suitable methods of estimation of evaporation or evapo-transpiration. Comparatively, first to fourth ranks were given to PET and Ep defined by different researchers. Similarly, the trial method of estimation of Kp gave the most accurate estimates. As compared to Kp from the equation of Snyder, Kp from the equation of Frevert gave better estimates for fetch distances of 10 m, 20 m, 100 m, and 500 m.

Keywords: Summer half-year; Class A pan evaporation; Class A pan coefficient; Potential evapo-transpiration; Reference evapo-transpiration; Tharandt

Abbreviations: SHY: Summer Half-Year; Ep: Class A Pan Evaporation; PETs: Potential Evapo-Transpiration; Ep: Evaporation Schemes; ETo: Reference Evapo-Transpiration; Kp: Class A Pan Coefficient; VPD: Vapor Pressure Deficit; RH: Relative Air Humidity; T: Air Temperature; Rn: Net Solar Radiation; Rs: Global Solar Radiation; u2: Wind Speed at 2 mt

INTRODUCTION

Evaporation or evapo-transpiration which is a major component of the global water cycle and the hydrologic budget or water balance of small or large irrigation areas, reservoir or lake, and a catchment is an important consumer of energy. Measurement and estimation of evaporation and using evaporation as basic data has been used in agricultural, hydrological, hydro-meteorological, irrigation, and soil and water conservation applications. For each of these applications estimating evaporation or evapo-transpiration from meteorological data or Class A evaporation pan measurements are preferred. For the estimation of evapo-transpiration from meteorological data numerous methods have been developed [1]. However, the methods result in different estimates due to the different hypotheses (different data requirements, different climate regions, etc) they are based on. Hence, for a particular climate region, the most reliable method(s) has to be selected from the available numerous methods or a new method has to be generated suitable for that particular climate condition.

Therefore, in this article, the performance of three methods for estimation of PET which are suitable for the climate condition of Germany and measured Class A pan evaporation (E_p) are compared with reference to the standard Food and Agricultural Organization Penman-Monteith (FAO56-PM) method of estimation of reference evapo-transpiration (ET_o). Similarly, three methods of estimation of Class A pan coefficient (K_p) are also compared with reference to K_p calculated as the ratio of ET_o and E_p. The significance of the study for policymakers and the local community is to provide a reliable climate water balance (precipitation minus evaporation)

Correspondence to: Antensay Mekoya, Ethiopia Environment and Forest Research Institute (EEFRI), Ethiopia, Telephone: +251900544311; E-mail: antensaymekoya@yahoo.com

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information of a site which in turn is useful for efficient water management practices in agriculture, water, and forest developmental sectors.

For Tharandt, Germany for the summer half-year, methods of estimation of evaporation, evapotranspiration, and Class A pan coefficient (K_p) were compared. The reference evapotranspiration (ET_o) and K_p according to Allen et al. were used as the reference methods. Similarly, K_p from the equation of Snyder and Frevert et al. as well as a trial method of estimation of K_p were compared using box plots (Figure 1).

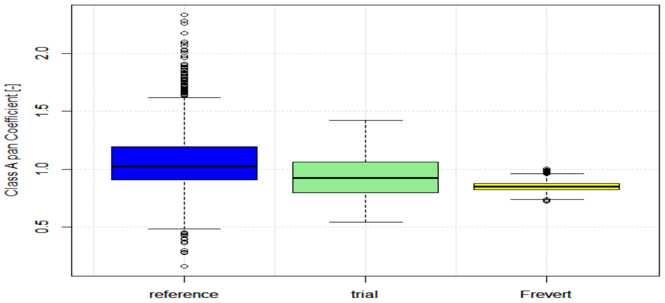

Figure 1: Box plots of K_p from the reference, 'trial', and Frevert methods at Tharandt.

MATERIALS AND METHODS

The study area is Tharandt, Germany. Topographically Tharandt station is located 220 m above sea level at latitude 50°58'42.06" N and longitude 13°34'52.69" E. All meteorological data required for the calculation of E_p and ETs were used from 2004 to 2013 as described [2]. However, in this article, only the Summer Half-Year (SHY) which is the time from April to September is considered.

For the calculation of ETs, two methods (Haude and Wendling) are selected based on their particular suitability for the climate condition of Germany. Another two methods (Penman-1963 and FAO56-PM) are chosen because of their high global acceptance as well as their suitability for the climate condition of Germany. Then, these methods and E_p are compared with each other with reference to ET_o using model evaluation statistics like the coefficient of determination (R^2), Nash-Sutcliffe Efficiency (NSE), Mean Absolute Error (MAE), Mean Square Error (MSE), Root Mean Square Error (RMSE), RMSE-observations standard deviation ratio (RSR), Percent of Error (PE) and Mean Percent of Error (MPE) (in %) [3-5]. The model evaluation statistics were applied by considering reference methods as measured (observed) values while the rest values were taken as estimated (simulated) values.

Note that model evaluation statistics such as R^2, RMSE, MPE, NSE, MAE, RSR, and p-value are mainly used to compare the methods because the graphical methods of comparison of methods (the box plot and trend check) were not enough (see the results and discussions part). Note also that the slope (a) and y-intercept (b) of the linear regression line (y=ax+b) is used to indicate how well simulated or estimated data (y) match measured data (x). "The slope indicates the relative relationship between simulated and measured values. The y-intercept indicates the presence of a lag or lead between model predictions and measured data, or that the data sets are not perfectly aligned [4].

Class A pan evaporation

Class A pan evaporation (Ep) is used for the calculation [6].

Potential evapo-transpiration according to Haude

Haude's approach for the estimation of PET is originally developed for the climatic conditions of Germany. It considers the water vapor pressure deficit in mbar (hPa) of each day measured or estimated at 2 pm at 2 m above ground and introduces a calibrated factor (f) referring to the plant cover. Also, f which is calibrated for mid-latitudes has been successfully applied in arid (dry-land) climates [7].

$$\mathrm{PET}_{\mathrm{Haude}} = f.(e_s - e_a) \quad \text{(Equation 1)}$$

Where $\mathrm{PET}_{\mathrm{Haude}}$ is Potential Evapo-transpiration (in mm d^{-1}), (e_s-e_a) is water vapor pressure deficit (in hPa), and f is a calibrated factor (Table 1).

Table 1: f (mm d^{-1} hPa^{-1}) for short grass.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
f	0.22	0.22	0.22	0.29	0.29	0.28	0.26	0.25	0.23	0.22	0.22	0.22

f: Calibration factor

Saturation vapor pressure (e_s) in kPa is calculated [8].

$$e_s(\mathrm{T}) = 0.6108.\exp[\frac{17.27 \times T}{(T + 237.3)}] \quad \text{(Equation 2)}$$

where T is air temperature (in °C).

Replacing T with T at 2 pm (T_{2pm}), saturation vapor pressure (e_s) in hPa is calculated as

$$e_s(\mathrm{T}_{2pm}) = 0.6108.\exp[\frac{17.27 \times T_{2pm}}{(T_{2pm} + 237.3)}] \quad \text{(Equation 3)}$$

Note that care has to be taken in selecting a suitable equation for the calculation of e_s as the equations used in literature are not consistent. For instance, Weiß used (equation 1) for the calculation of PET [9].

$$e_s = 6.11.\mathrm{e}[\frac{17.62 \times T}{(243.12 + T)}] \; if \; T_{2pm} > 0, \text{(Equation 4)}$$

$$e_s = 6.11.\mathrm{e}[\frac{22.64 \times T}{(272.62 + T)}] \; if \; T_{2pm} < 0, \text{(Equation 5)}$$

Whereas, Seiler and Gat used (equation 6) for the calculation of PET and (equation 7) and (equation 8) for the calculation of e_s as given below:

$$\mathrm{PET}_{\mathrm{Haude}} = \sum_1^{i-days} 0.75 \times f \times (e_s - e_a) \text{ (mm/i-days) (Equation 6)}$$

$$e_s = 6.11 \times 10[\frac{17.62 \times T}{(243.12 + T)}] \; if \; T_{2pm} > 0, \text{(Equation 7)}$$

$$e_s = 6.11 \times 10[\frac{22.64 \times T}{(272.62 + T)}] \; if \; T_{2pm} < 0, \text{(Equation 8)}$$

In another literature, Wittenberg used (Equation 1) for the calculation of PET; where e_s is calculated as

$$e_s = 6.11 \times 10(\frac{7.48 + T_{2pm}}{237 + T_{2pm}}) \text{ (Equation 9)}$$

In this article, (Equation 3) is used for calculation of e_s because it had resulted in a better estimate of PET_{Haude} (Equation 1).

Relative Humidity (RH) in % expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation (e_s) vapor pressure at the same temperature [8]. Rearranging the equation of RH and replacing RH with RH at 2 pm (RH_{2pm}), e_a is calculated as given (Equation 10):

$$e_a = 100 \times \frac{RH_{2pm}}{e_s} \text{ (Equation 10)}$$

Potential evapo-transpiration according to Wendling

PET as the amount of water that evaporates from a well-watered plant stand is dependent on radiation, air temperature, humidity, and wind velocity as formulated below (Equation 11) [9].

$$\text{PET}=g \times [\frac{G}{410} + (0.5 + 0.54 + u_2) \times (100 - RH) \times \frac{N}{905}] \text{ (Equation 11)}$$

Where, PET is potential evapo-transpiration in mm d^{-1}, RH is relative humidity in %, G is daily sum of global radiation in J cm^{-2}; G in Jcm^{-2}=8.4·R_s in W m^{-2} d^{-1}N is day length (the daylight hour) in hr; g is a function which depends on air temperature in °C (equation 12), and u_2 is wind speed at 2 m above ground in m s^{-1} (equation 13)

$$g = 2.4 \frac{(T + 22)}{(T + 123)} \text{ (Equation 12)}$$

$$u_2 = \frac{u_2 \times 4.2}{(3.5 + \ln(z))} \text{ (Equation 13)}$$

Where, u_2 is the wind speed at height z above ground in m s^{-1} and z is the height above ground in m. Note: except for PET according to Wendling, for all other cases, u_2 is calculated.

Potential evapo-transpiration according to Penman 1963

Penman was the first to calculate evaporation by combining the mass-transfer and energy-balance approaches; without using surface temperature data [9]. The following equation gives the so-called "the classical form of the Penman equation" [10].

$$\text{PET}=(\frac{\Delta}{\Delta + \gamma}(R_n - G) + K_w \frac{\gamma}{\gamma + \Delta}(a_w + b_w.u_2)(e_s - e_a)) / \lambda \text{ (Equation 14)}$$

Where,

- Δ: slope of vapor pressure curve (in kPa °C^{-1}),
- γ: psychrometric constant (γ) (in kPa °C^{-1}),
- Kw: a unit constant,
- aw and bw: wind function coefficients,
- Rn: net radiation (in MJ $m^{-2}d^{-1}$),
- G: daily soil heat flux density (in MJ $m^{-2}d^{-1}$),
- u2: wind speed at 2 m above ground (in m s^{-1}),
- es and ea: saturated and actual vapor pressure (in kPa),
- λ: latent heat of vaporization (in MJ kg^{-1})

The value of λ varies only slightly over normal temperature ranges; λ=2.45 MJ kg^{-1} for standardized calculations. For PET in mm d^{-1}, K_w=6.43. "The values for a_w and b_w for the original Penman equation, first applied in 1948 to open water and implicitly to grass, and later in 1963 to clipped grass were a_w=1.0 and b_w=0.537, respectively, for wind speed in m s^{-1}, e_s-e_a in kPa and grass ET_o in mm d^{-1}" [10].

In this paper, Penman method is used for the calculation of PET. In the case of PET according to Penman, note that e_s is based on mean daily air temperature (≈ 8.92°C) only [10]. Also, for the calculation of e_a, daily RH is used rather than RH_{max} and RH_{min}.

Reference evapo-transpiration

The FAO Penman-Monteith method "...is maintained as the sole standard method for the computation of ET_o from meteorological data" [7]. The calculation of grass ET_o is entirely taken from Allen [8].

Calibration of a_s and b_s: The actual duration of sunshine in hours is derived from Angstrom formula (equation 15).

$$R_s = (a_s + b_s \frac{n}{N})R_a \text{ (Equation 15)}$$

Where,

- R_s: solar or shortwave radiation (in MJ m^{-2} d^{-1}),
- n: actual duration of sunshine (in hr),
- N: maximum possible duration of daylight (in hours),
- $\frac{n}{N}$: relative sunshine duration (no unit),
- R_a: extraterrestrial radiation (in MJ m^{-2} d^{-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)

Solving equation 15 for n and b_s while using measured R_s, we get:

$$n = \frac{N}{b_s}(\frac{R_s}{R_a} - a_s) \text{ (Equation 16)}$$

$$b_s = \frac{N}{n}(\frac{R_s}{R_a} - a_s) \text{ (Equation 17)}$$

Calibration of a_s is needed if (Equation 16) results in unacceptable values (negative values or values greater than N). For example, negative values of n can be corrected by using a locally calibrated value of a_s which is set to the minimum of R_s/R_a.

Daily soil heat flux: A robust estimate of soil heat flux (G) (in MJ m^{-2} d^{-1}) is 0.1 × net radiation (R_n).

$$G = 0.1R_n \text{ (Equation 18)}$$

"Soil heat flux density (G) was calculated using the following equation (van Wijk and de Vries) and effective soil depth was taken as 0.18 m [5].

$$G = C_s d_s (T_i - T_D) \text{ (Equation 19)}$$

Where

- G: Soil Heat Flux Density (MJ m^{-2} d^{-1})
- C_s: Soil Specific Heat Capacity, taken as 2.1 MJ m^{-3}°C^{-1}
- d_s: Effective Soil Depth (m)
- T_i: Current Day's Mean Air Temperature (°C); and
- T_D: Mean Air Temperature over previous three days (°C)"

G=Daily soil heat flux density is assumed to be approximately zero [8].

$$G_{day} \approx 0 \quad \text{(Equation 20)}$$

Class A pan coefficient

From Snyder's equation for the relation of ET_o and E_{pan}, replacing K_{pan} with K_p and E_{pan} with E_p and rearranging, the 'reference' Class A pan coefficient (K_p) is calculated as given below:

$$K_p = \frac{ET_o}{E_p} \quad \text{(Equation 21)}$$

Where, ET_o is reference evapo-transpiration (in mm d^{-1}), K_p is pan coefficient from Class A pan (dimensionless), and E_p is pan evaporation from Class A pan (in mm d^{-1}). Note that if E_p has values close to zero, K_p will have misleadingly very large values. Thus, in this study, K_p was calculated for values of $E_p \geq 1$ mm d^{-1}.

Numerous derived equations are also available for the estimation of K_p. For example, for the calculation of daily values of K_p as a function of daily RH, u_2, and upwind-fetch (F) (in m) for low-growing vegetation; Frevert developed a polynomial equation where the coefficients of the equation were later rounded off by Cuenca as given below [4,6].

$$K_p = 0.475 - (0.24\times10^{-3}u_2) + (0.516\times10^{-2}RH) + (0.118\times10^{-2}F) - (0.16\times10^{-4}RH^2) - (0.101\times10^{-5}F^2) - (0.8\times10^{-8}RH^2u_2) - (0.1\times10^{-7}RH^2F) \quad \text{(Equation 22)}$$

Where, u_2 is the daily average wind speed in km d^{-1}; K_p, RH, and F are as defined before.

Snyder also proposed a simpler logarithmic equation to calculate daily K_p as a function of F, RH, and u_2 as

$$K_p = 0.482 + [0.24\ln(F)] - (0.000376u_2) + (0.0045RH) \quad \text{(Equation 23)}$$

For the summer half-year, for Tharandt and for places with similar climate condition with Tharandt, daily Class A pan coefficient can be calculated from measured solar or shortwave radiation (R_s) in MJ m^{-2} d^{-1}, maximum air temperature (T_{max}) in °C, and minimum relative air humidity (RH_{min}) in % as in the 'trial' equation given below [11].

$$K_p = 1.44 - 0.2(0.372R_s + 0.1312T_{\max} - 0.028RH_{\min} + 1.4866)/3.24 \quad \text{(Equation 24)}$$

RESULTS AND DISCUSSIONS

Comparison of evaporation schemes

At Tharandt from 2004 to 2013, the summer half-year total amount of PET estimated according to Haude, Wendling, and Penman methods were 480.4 mm, 514.8 mm, and 522.3 mm respectively. Whereas, the SHY total amount of precipitation was 478.8 mm. For very humid climates, the climate water balance (precipitation minus evaporation) is assumed to be positive. Tharandt has a very humid climate based on De Martonne's aridity index (AI); $AI = \frac{P}{10+T}$ where P and T are mean annual precipitation (mm) and air temperature (°C), respectively; P=879.82 mm and T=8.92°C were used [12]. At Tharandt the SHY total amount of evaporation is assumed not to exceed precipitation [13]. Also note that on average, across all continents about 70% of precipitation reaching the land surface evaporates; in dry regions (e.g., Australia) this ratio is higher and can reach up to 90% and in Europe to approximately 60% of the annual rainfall [1,14].

However, at Tharandt this was maintained only in the case of ET_o and E_p which had SHY total amounts of 476.4 mm and 459.1 mm respectively. Hence, based on the climate water balance concept, only E_p and ET_o gave acceptable estimates. However, in most countries ET_o is taken as the sole standard (reference) method for the calculation or estimation of evaporation or evapotranspiration. Therefore, the methods used for estimation of PET and E_p are compared with reference to ET_o.

First, the methods are compared using box plots (Figure 2). However, from the box plot alone it was not possible to compare the methods as they had performed in a pattern that was difficult to compare using naked eyes. Therefore, the comparison of the evaporation schemes with respect to ET_o was performed using a linear regression model.

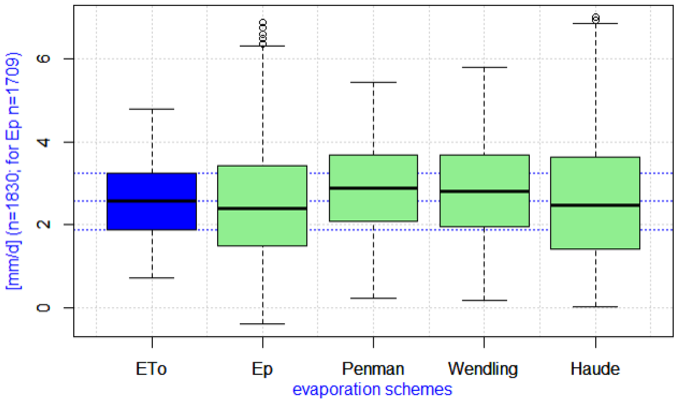

Figure 2: Comparison of summer half-year E_p and PET estimated according to Haude, Wendling, and Penman with ET_o.

A first check for using the linear regression model is to check whether a systematic trend exists or not. Generally, the existence of a significant increasing trend of PETs and a significant decreasing trend of E_p was observed for increasing values of ET_o (Figure 3). Although E_p decreased for increasing values of ET_o and the trends were significant for all evaporation schemes, the trend or the existence of a systematic increase or decrease was not strong ($R^2 \leq 0.15$) except for PET according to Wendling. Generally, from Figures 2 ad 3 it was clear that PET estimated according to Wendling and Penman methods had over-estimated ET_o for more days; this was true particularly for larger values of ET_o (Figure 3). Hence, the first rank of '1' was given for E_p and PET according to

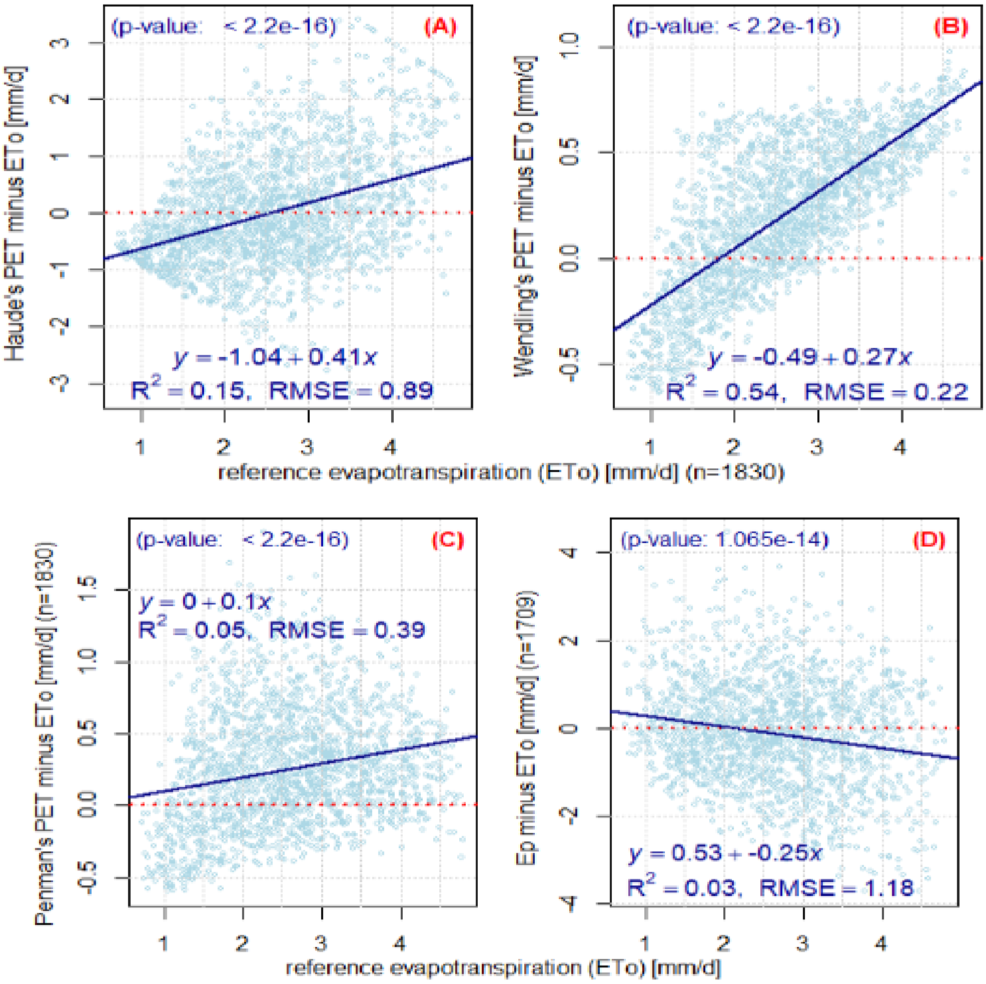

Figure 3: Checking trends of summer half-year PET according to Haude, Wendling, and Penman and E_p with respect to ET_o.

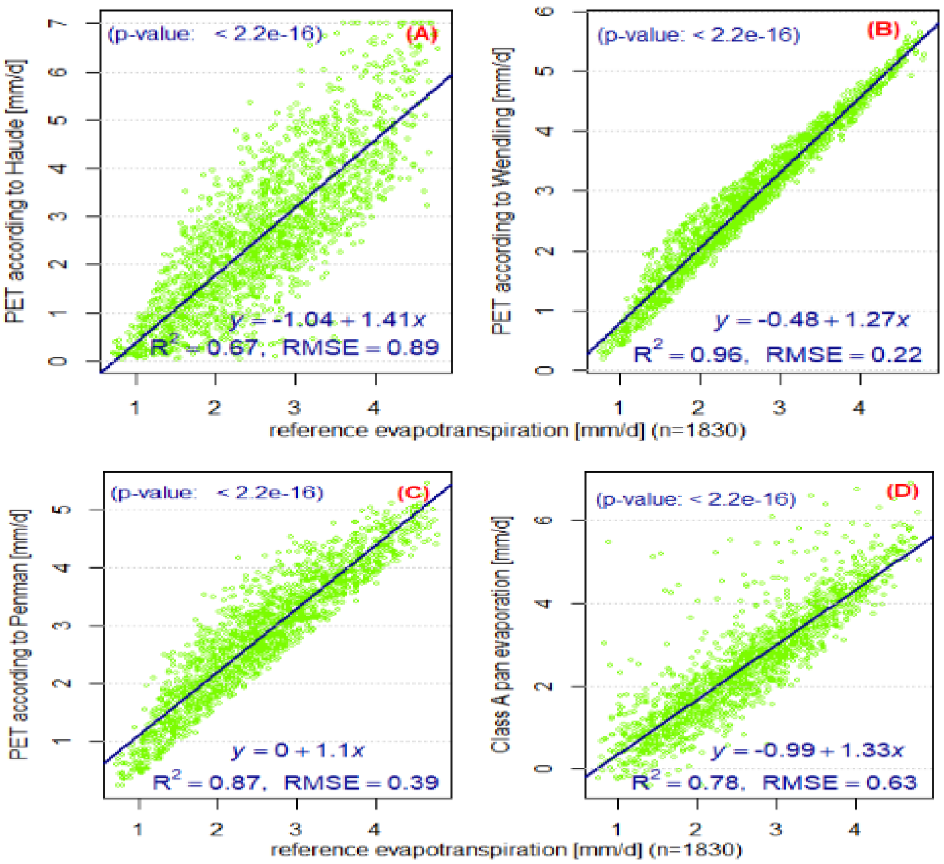

Figure 4: Comparison of summer half-year PET according to Haude, Wendling, and Penman and E_p with ET_o using a linear regression model.

Haude while the second rank of ‘2’ was given to PET according to Wendling and Penman [10].

Because box plot and trend check alone (Figures 2 and 3) were not enough to compare the methods, the linear regression model together with the model evaluation statistics described before were used to compare the methods as presented in Figure 4 and Table 2. For all the methods, the p-value was less than 0.05 which indicated the existence of a significant relationship between the evaporation schemes and ET_o at 5% significant level. Finally, the methods are ranked based on the average ranks of the model evaluation statistics such as R^2, NSE, MAE, RMSE, RSR, and MPE values (Table 3). Accordingly, PET estimated according to Wendling and Penman had got the first and second ranks while E_p and PET according to Haude had got the third and fourth ranks, respectively.

Calibration of a_s and b_s for Tharandt site: Calibrated a_s value is used for the calculation of ET_o. Equation 8a had resulted in negative values of actual sunshine hours (n) with extreme maximum, extreme minimum and average values of ≈ 5.99, -7.11, and -0.34 hours, respectively when recommended values of a_s=0.25 and b_s=0.50 were used [8]. This result was not acceptable because the range of n is between 0 and daylight hours (N). Thus, calibration was made so that a_s is set to the minimum of $\frac{R_s}{R_a}$ (≈ 0.014) which resulted in extreme maximum, extreme minimum, and average values of ≈13.687 hours, 0.001 hours and 5.320 hours respectively; which is in the range of n (Figure 5). Therefore, for Tharandt, a_s ≈ 0.014 and b_s=0.50 are recommended.

Table 2: Comparison of summer half-year Class A pan evaporation (E_p) and PET according to Haude, Wendling, and Penman with ET.

	R^2	RMSE in mm d^{-1}	MPE	NSE	MAE in mm d^{-1}	RSR
Haude	0.67	0.89	-0.048	-0.19	0.77	1.09
Wendling	0.96	0.22	0.051	0.81	0.33	0.44
Penman	0.87	0.39	0.086	0.73	0.36	0.52
E_p	0.78	0.63	-0.014	-0.79	0.64	1.14

Table 3: Rank of summer half-year E_p and PET according to Haude, Wendling, and Penman as compared to ET_o.

	Box plot & trend check	R^2	RMSE	MPE	NSE	MAE	RSR	Average	Rank
Haude	1	4	4	2	3	4	3	3	4
Wendling	2	1	1	3	1	1	1	1.43	1
Penman	2	2	2	4	2	2	2	2.29	2
E_p	1	3	3	1	4	3	4	2.71	3

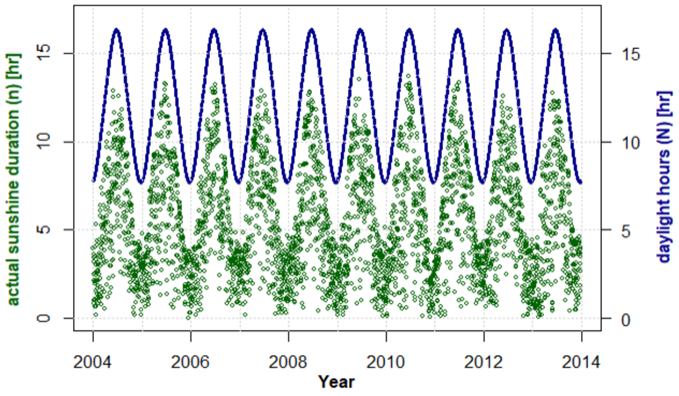

Figure 5: Actual sunshine duration (n) and daylight hours (N) at Tharandt.

Daily soil heat flux: Equation 18 is used for the calculation of soil heat flux (G). For the calculation of soil heat flux (G), (Equation 18) and (Equation 19) resulted in closely related values. Also, using (equation 20) (G=0) had also not significantly impacted the result of ET_o.

Comparison of methods of estimation of Class A pan coefficient

The summer half-year Class A pan evaporation (K_p) calculated from the ratio of ET_o and E_p was taken as the reference method which resulted in average, extreme maximum and extreme minimum values of 1.08, 2.33, and 0.16. K_p calculated from the equation of Frevert and K_p calculated from the equation of Snyder were compared with each other and with the reference method using box plot (Figure 6) [4].

The box plot shows that K_p from the equation of Frevert and K_p from the equation of Snyder under and overestimated the reference K_p, respectively (Equation 21) [4]. Comparatively, the first method gave better K_p values for fetch distances of 10 m, 20 m, and 100 m; also for F=500 m (not shown). This result also agrees with the finding of Irmak [6]. On the other hand, for fetch distances of 500 m and 1000 m, K_p calculated from the equation of Snyder (Equation 21) resulted in very large values (≥ 2.65).

A fetch distance of 20 m was used for the Tharandt site. Since Tharandt has a very humid climate and for F=20 m the Frevert method gave an average value of K_p=0.85 (between 0.70 and 0.88) [4].

Equation 13 which is a trial method for calculation of K_p gave better estimates as compared to K_p calculated from the equation of Frevert for fetch distance of 20 m when K_p calculated as the ratio of ET_o and E_p is used as the reference method (Figure 1) [4].

Generally, K_p increases with increasing relative humidity and with decreasing wind speed [8]. For a very humid climate, the average value of K_p is between 0.70 and 0.88; however, for the summer half-year, it may differ [15]. However, in Tharandt, the average value of the SHY K_p was higher than 0.88; high RH (75%) and very light wind speed (0.42 ms^{-1}) could be the causes.

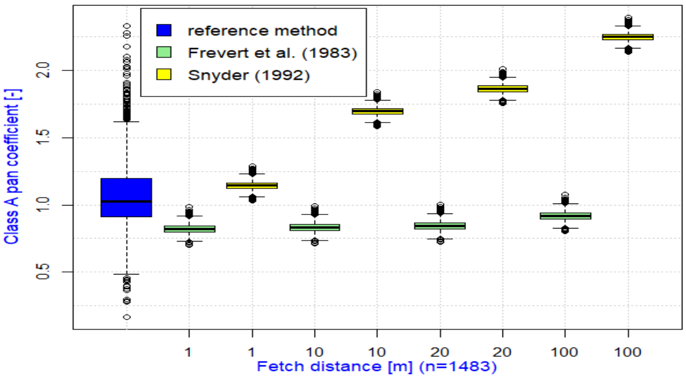

Figure 6: Box plots of summer half-year reference K_p and K_p calculated from the equation of Frevert and Snyder for different fetch distances at Tharandt.

CONCLUSION

At Tharandt from 2004 to 2013 selected methods for estimation of summer half-year evaporation schemes and Class A pan coefficient are compared.

The selected evaporation schemes were Class A pan evaporation (E_p) and Potential evapo-transpiration (PET) according to Haude, Wendling, and Penman. The evaporation schemes were compared with respect to the FAO56-PM method of estimation of reference evapo-transpiration (ET_o). The result of the comparison showed that all the evaporation schemes had a very good correlation with the reference method and all were considered suitable methods for estimation of evaporation or evapo-transpiration. PET according to Wendling and Penman had got the first and the second ranks while E_p and PET according to Haude were ranked from third and fourth, respectively. Generally PET according to Wendling, Penman, and Haude overestimated ET_o for lower values of ET_o and underestimated ET_o for higher values of ET_o. Therefore, at Tharandt and in places with similar climate conditions as Tharandt, in addition to ET_o, Wendling and Penman methods of estimation of PET and E_p were found to be very suitable methods for estimation of evapo-transpiration or evaporation.

For the calculation of ET_o, if actual sunshine hours are not in the range between 0 and the maximum possible duration of daylight hours, then a_s has to be calibrated. For calibration, a_s was set to a minimum of $\frac{R_s}{R_a}$. Therefore, for Tharandt calibrated values of a_s=0.014 and b_s=0.50 were used. Moreover, for the calculation of soil heat flux (G), as compared to setting G to be zero, using other more accurate equation is recommended particularly in warm places (also in cold places for the summer half-year) as the latter gives a more accurate estimate of G which in turn may have a significant impact on the result of ET_o. Also note that in applying the Haude method of estimation of PET, the limit of 7 mm d^{-1} can be maintained by replacing values of PET ≥ 7 mm d^{-1} with 7 mm d^{-1}.

K_p calculated from the equation of Frevert et al. and Snyder, as well as a trial method of estimation of K_p, were also compared using K_p calculated from the ratio of ET_o and E_p as the reference method. Comparatively, the trial method gave the best estimates while the equation of Frevert et al. gave better estimates than that of Snyder (1992). Note however that the trial method needs validation to be applied in places other than Tharandt.

The climate water balance (precipitation minus evaporation) for PET estimated according to Haude, Wendling, and Penman was negative (-1.6 mm, -36 mm, and -43.5 mm) while for ET_o and E_p it was positive (2.4 mm and 19.7 mm) respectively. Thus, broadly speaking, it can be concluded that the summer half-year evaporation amount at Tharandt was approximately equal to the SHY precipitation amount. This implies that in warmer places (also in humid or very humid places in the SHY), evaporation would be higher and would possibly exceed precipitation. Therefore, precise quantification of evaporation or evapo-transpiration is crucial for water, agriculture, and forest sectors particularly in warm and arid or semi-arid climates for many applications such as irrigation planning or scheduling.

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DATA AVAILABILITY STATEMENT

All data used during the study were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the Acknowledgements. Also, all models or code generated or used during the study are available from the corresponding author by request.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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