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ORIGINAL PAPER

Comparison of Evaporation Schemes and Methods of Estimation of Class A Pan Coefficient at Tharandt, Germany

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Abstract

To find the most accurate evaporation or evapotranspiration estimation method(s) for the summer half-year (April to September) for a very humid temperate region, Tharandt, Germany, the class A pan evaporation (E_p) found from the water level difference of class A evaporimeter measurement and widely known potential evapotranspiration (PET) estimation methods, namely, Haude, Wendling, and Penman, have been employed. Data representation techniques such as box plot and trend check as well as linear regression model and model evaluation statistics such as R^2, RMSE, MPE, NSE, MAE, RSR, and p value have been used to compare the estimated values of PET and values of E_p with reference evapotranspiration (ET_o) values. ET_o was used as the reference method using calibrated values, $a_s = 0.014$ and $b_s = 0.50$, in Angstrom formula. The result showed that all the evaporation schemes had very good correlation with the reference method. The overall ranking shows merits in using Wendling and Penman methods. Moreover, a trial estimate of class A pan coefficient (K_p) was compared with K_p values estimated from the equation of Frevert et al. and Snyder. The empirically estimated trial method gave accurate estimates for fetch distances of 10 m, 20 m, 100 m, and 500 m.

Keywords Class A pan evaporation · Potential evapotranspiration · Reference evapotranspiration · Pan coefficient · Very humid climate · Summer half-year

Abbreviations

SHY	Summer half-year
E_p	Class A pan evaporation
PETs	Potential evapotranspiration (PET) according to Haude, Wendling, and Penman
Evaporation schemes	E_p, reference evapotranspiration (ET_o) and PETs
K_p	Class A pan coefficient

Highlights
• Consideration of the warmer season of a year in a very cold climate site.
• Use of methods very suitable for a very humid temperate climate.
• Consideration of both measured and estimated evaporation schemes.
• Use of a new formula for calculation of class A pan coefficient.

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Introduction

Evaporation or evapotranspiration is the main element in water balance. Also, it is a major component of the global water cycle. Measurement and estimation of evaporation and using evaporation as a basic data has been used in agricultural, hydrological, hydro-meteorological, irrigation, and soil and water conservation applications. As direct measurement of evapotranspiration is not a simple task, each of these applications illustrates most of the practical issues that arise in estimating evaporation or evapotranspiration from meteorological data or from class A evaporation pan measurements ([1] p. 1332).

For the estimation of evapotranspiration from meteorological data, numerous methods have been developed ([1] p. 1333). Pan evaporation which is extremely important for local and global action plans has been used in a number of researches to choose the most appropriate evaporation equation in various parts of the world ([2] p.3). However, the methods result in different estimates due to different data requirements, the 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 which is suitable for that particular climate condition has to be created.

Therefore, in this article, the performance of three methods for estimation of potential evapotranspiration (PET) which are suitable for the climate condition of Germany and measured class A pan evaporation (E_p) are compared with reference to the empirical formula released by the Food and Agricultural Organization Penman-Monteith (FAO56-PM) method of estimation of reference evapotranspiration (ET_o). The class A evaporimeter (evaporation pan) is the World Meteorological Organization's (WMO's) standard device for manual as well as automatic measurement of evaporation. E_p is taken as a measured value. Because E_p is directly obtained from the difference in water levels of class A evaporimeter which are measurement values ([3] p.2). In this study, ET_o, which is globally the sole standard reference method of estimation of evapotranspiration in all climates ([4] p.2; [5] p.65), is used as a reference method.

In another scenario, 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. Pan coefficient is used to convert E_p to ET_o, i.e., $ET_o = K_p \times E_p$. ET_o is important component in water management practices of irrigated crops.

The scientific rigor of this study relies on the calculation of class A pan evaporation (E_p) and the merits of the study is generally for water conservation development practices. Particularly, the need and significance of this study is to support and strengthen the provision of a reliable climate water balance (precipitation minus evaporation) information of a place which in turn is useful for efficient water management practices in agriculture, water, engineering, and forest developmental sectors. The methods used in this study can be used in other parts of the world with a different or similar climate condition with Tharandt site after proper validation. Therefore, this study can be a useful information input for local community of a place, researchers, and policymakers. However, care has to be given because the driving power/capability of the evaporation deriving meteorological parameters vary from region to region and sometimes within a region, i.e., from site to site [6]. Note that gauge as well as grid and satellite precipitation (rainfall) data can be easily obtained from different providers such as Meteorological and Hydrological offices across the world.

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. Climate data from 2004 to 2013 obtained from Tharandt Meteorology Office were used for the study as described in [6] p.184 Table 1 and [8] p.210–211. However, in this article, only the summer half-year (SHY), i.e., the time from April to September is considered.

For the calculation of evapotranspiration, two methods (Haude and Wendling) are selected based on their particular suitability for the climate condition of Germany. Note that Tharandt has a very humid climate based on De Martonne's aridity index (AI); $AI = \frac{P}{10+T}$, (as cited in [9] p.76) 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. Another two methods (Penman [10] 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) ([11] p. 233), Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliffe [12]; as cited in [13] p.887), mean absolute error (MAE), mean square error (MSE), root mean square error (RMSE), RMSE-observations standard deviation ratio (RSR) ([13] p.888), and mean percent of error (MPE) (in %) ([14] p.155 & 157). The model evaluation statistics were applied by considering reference methods as measured (observed) values (x) while the rest values were taken as estimated (simulated) values (y). In the linear regression equation ("$y = ax + b$"), the y-intercept (b) and slope (a) indicate how well "y" relate or match with "x." The y-intercept indicates presence of a lead or lag, or that the data sets are not perfectly aligned while the slope indicates the degree or magnitude of relationship between model predictions and measured data ([13] p.887).

The methods are compared using a combination of graphical methods (box plot and trend check) and model evaluation statistics such as R^2, RMSE, MPE, NSE, MAE, RSR, and p value.

This study is a good work for agriculture, forest, and water sectors particularly in warm and arid or semi-arid climate as well as for local community. Therefore, the methods used in this study can also be used for local community studies in various sites across the world.

Class A Pan Evaporation

Class A pan evaporation (E_p) is used as calculated and described in Antensay et al. [3].

Table 1 f [mm day^{-1} hPa^{-1}] for short grass (source: as cited in [7] p.28)

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

Potential Evapotranspiration According to Haude

Haude's approach for the estimation of PET is originally developed for the climate conditions of Germany. It uses water vapor pressure deficit measured or estimated at 2 p.m. at 2 m above ground in mbar (hPa) and a calibrated factor (f) referring to the plant cover. In arid climates, f which is calibrated for mid-latitudes has also been successfully applied (as cited in [15] p.76).

$$\text{PETHaude}=\boldsymbol{f}\cdot(\boldsymbol{e_s}-\boldsymbol{e_a}), \tag{1}$$

(as cited in Weiβ [16] p.97)

where PET_{Haude} is potential evapotranspiration (in mm day^{-1}), f is a calibrated factor (see Table 1) and e_s and e_a are saturated and actual water vapor pressure (in hPa), respectively.

Saturation vapor pressure (e_s) in kPa is calculated as defined in Allen et al. [5].

$$\text{es}\ (T) = 0.6108\cdot\exp\left[\frac{17.27\times T}{(T+237.3)}\right], (\text{Allen et al.1998 p.36}) \tag{2}$$

where T is air temperature (in °C).

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

$$\text{es}\ (\text{T2pm}) = 6.108\cdot\exp\left[\frac{17.27\times \text{T}_{2\ \text{pm}}}{(\text{T}_{2\ \text{pm}}+237.3)}\right] \tag{3}$$

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 [16] used Eq. 1 for the calculation of PET, where e_s is used as given in the equations below:

$$\text{es} = 6.11\cdot e^{\left(\frac{17.62\cdot \text{T2pm}}{243.12+\text{T2pm}}\right)}\ \text{if T2pm} > 0, \tag{4}$$

(Weiβ [16] p.97)

$$\text{es} = 6.11\cdot e^{\left(\frac{22.64\cdot \text{T2pm}}{272.62+\text{T2pm}}\right)}\ \text{if T2pm} < 0, \tag{5}$$

(Weiβ [16] p.97)

Whereas, Seiler and Gat [15] used Eq. 6 for the calculation of PET and Eq. 7 and Eq. 8 for the calculation of e_s as given below:

$$\text{PETHaude}=\sum_1^{i\text{–days}}0.75\cdot f\cdot(e_s-e_a)[\text{mm/i–days}], (\text{Seiler and Gat 2007 p.75}) \tag{6}$$

$$es = 6.11\cdot 10^{\left(\frac{17.62\cdot T2\text{pm}}{243.12+\text{T2pm}}\right)}\text{if T2 pm} > 0, (\text{Seiler and Gat 2007 p.75}) \tag{7}$$

$$es = 6.11\cdot 10^{\left(\frac{22.64\cdot \text{T2pm}}{272.62+\text{T2pm}}\right)}\text{if T2 pm} < 0, (\text{Seiler and Gat 2007 p.75}) \tag{8}$$

In another literature, Wittenberg [7] used Eq. 1 for the calculation of PET; where e_s is calculated as follows:

$$es = 6.11\cdot 10^{\left(\frac{7.48\cdot \text{T}_{2\ \text{pm}}}{237+\text{T}_{2\ \text{pm}}}\right)}, (\text{Wittenberg 2011 p.28}) \tag{9}$$

In this article, Eq. 3 is used for calculation of e_s because it had resulted in more acceptable values (0–7.2 mm day^{-1}) of PET_{Haude} in Eq. 1.

Relative humidity in % (RH) 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 ([5] p.35 Eq.10). Rearranging the equation of RH and replacing RH with RH at 2 p.m. (RH_{2pm}), e_a is calculated as given below.

$$ea = 100\cdot\frac{\text{RH}_{2\text{pm}}}{e_s} \tag{10}$$

Potential Evapotranspiration According to Wendling

PET from a well-watered plant stand is dependent on radiation, air temperature, humidity, and wind velocity ([17] p. 253) as given below:

$$\text{PET} = \text{g}\cdot\left[\frac{G}{410}+(0.5+0.54+\text{u2})\cdot(100\text{–RH})\cdot\frac{N}{905}\right], \quad (\text{Wendling 1991 p.253}) \tag{11}$$

where PET is potential evapotranspiration in mm day^{-1}, RH is relative humidity in %, G is daily sum of global radiation in J cm^{-2}; G in $Jcm^{-2} = 8.4 \times R_s$ in W m^{-2} day^{-1}, N is day length (the daylight hour) in h.; see [5] p.48, g is a function which depends on air temperature in °C (see Eq. 12), and u_2 is wind speed at 2 m above ground in m s^{-1} (see Eq. 13).

$$g = 2.4\frac{(\text{T}+22)}{(\text{T}+123)}, (\text{Wendling 1991 p.253}) \tag{12}$$

$$u2 = \frac{u_z\times 4.2}{(3.5+\ln(z))}, (\text{Wendling 1991 p.253}) \tag{13}$$

where u_z is the wind speed at height z above ground in m s^{-1} and z is the height above ground in m. Except for PET according to Wendling, for all other cases, u_2 is calculated using the equation of [5] p.56.

Potential Evapotranspiration According to Penman [10]

Penman was the first to calculate evaporation by combining the mass-transfer and energy-balance approaches; without using surface temperature data ([18] p.285). The classical form of the Penman equation (Penman [19, 20, 10]) is as formulated below.

$$\mathrm{PET} = \left(\frac{\Delta}{\Delta+\Upsilon}(\mathrm{Rn{-}G}) + \mathrm{Kw}\cdot\frac{\Upsilon}{\Upsilon+\Delta}\ (\mathrm{aw}+\mathrm{bw}\cdot\mathrm{u2})\ (\mathrm{es{-}ea})\right) /\lambda, \text{(ASCE−EWRI 2002 p.B−12)} \tag{14}$$

where,

Δ slope of vapor pressure curve (in kPa °C^{-1}), see [5] p.53;

γ psychrometric constant (γ) (in kPa °C^{-1}), see [5] p.31;

K_w a unit constant,

a_w and b_w wind function coefficients,

R_n net radiation (in MJ m^{-2}day^{-1}); see [5] p.53,

G daily soil heat flux density (in MJ m^{-2}d^{-1}); see [5] p.54,

u_2 wind speed at 2 m above ground (in m s^{-1}); see [5] p.56,

e_s and e_a saturated & actual vapor pressure (in kPa); see [5] p.36,

λ latent heat of vaporization (in MJ kg^{-1}); see [21] p.B-7,

The value of λ varies only slightly over normal temperature ranges; $\lambda = 2.45$ MJ kg^{-1} for standardized calculations. For PET in mm day^{-1}, $K_w = 6.43$. For wind speed in m s^{-1}, e_s - e_a in kPa and ET_o in mm day^{-1}, $a_w = 1.0$ and $b_w = 0.537$ ([21] p.B-12). Penman (1948) was first applied to open water and implicitly to grass, and later (in 1963) to clipped grass. In this study, the 1963 Penman method is used for the calculation of PET according to Penman. In the case of PET according to Penman (1963), e_s is based on mean daily air temperature (T ≈ 8.92 °C). Also, for the calculation of e_a, daily RH is used rather than RH_{max} and RH_{min}.

Reference Evapotranspiration

The Food and Agricultural Organization (FAO) Penman-Monteith method (FAO56-PM) ([5] p.65 Eq.6) has been the sole standard method for the computation of ET_o from meteorological data ([5] p.65). For the calculation of grass reference evapotranspiration (ET_o) refer Allen et al. [5].

Calibration of a_s and b_s

The actual duration of sunshine in hours is derived from Angstrom formula (Eq. 15).

$$R_s = \left(a_s + b_s\ \frac{n}{N}\right) R_a, \text{(Allen et al.1998 p.50)} \tag{15}$$

where,

R_s solar or shortwave radiation (in MJ m^{-2} day^{-1}),

n actual duration of sunshine (in h),

N maximum possible duration of daylight (in hours); see [5] p.48,

$\frac{n}{N}$ relative sunshine duration (no unit),

R_a extraterrestrial radiation (in MJ m^{-2} day^{-1}); see [5] p.46,

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 Eq. 15 for n and b_s while using measured R_s, we get:

$$n = \frac{N}{b_s}\left(\frac{R_s}{R_a}\text{–as}\right) \tag{16}$$

$$bs = \frac{N}{n}\left(\frac{R_s}{R_a}\text{–}as\right) \tag{17}$$

Calibration of a_s is needed if Eq. 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 $\frac{R_s}{}\ R_a$.

Daily Soil Heat Flux

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

$$G = 0.1\ R_n \tag{18}$$

Soil heat flux density (G) is formulated as follows:

$$G = C_s\ \mathrm{d_s}\ (T_i\text{–}T_D), \text{(as cited in Irmak et al.2002 p.155)} \tag{19}$$

where G = soil heat flux density (MJ m^{-2} day^{-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 3 days (°C) (as cited in [14] p.155).

According to Allen et al. [5], daily soil heat flux density can be assumed to be zero.

$$G\text{day} \approx 0, \text{(Allen et al.1998 p.54)} \tag{20}$$

Class A Pan Coefficient

From Snyder's [22] equation for the relation of ET_o and E_{pan} (see [5] p.79), 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.

$$Kp = \frac{ET_o}{E_p} \tag{21}$$

where ET_o is reference evapotranspiration (in mm day^{-1}), K_p is pan coefficient from class A pan (dimensionless), and E_p is pan evaporation from class A pan (in mm day^{-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 day^{-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 et al. [23] developed a polynomial equation where the coefficients of the equation were later rounded off by Cuenca [24] as given below (as cited in [14] p.154).

$$\mathrm{Kp} = 0.475-\left(0.24\cdot10^{-3}u_2\right) + \left(0.516\cdot10^{-2}\,\mathrm{RH}\right) + \left(0.118\cdot10^{-2}\,\mathrm{F}\right)-\left(0.16\cdot10^{-4}\mathrm{RH}^2\right)-\left(0.101\cdot10^{-5}\,\mathrm{F}^2\right) -\left(0.8\cdot10^{-8}\mathrm{RH}^2u_2\right)-\left(0.1\cdot10^{-7}\mathrm{RH}^2\,\mathrm{F}\right), \text{(as cited in Irmak et al.2002 p.154)} \tag{22}$$

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

As cited in [14] p.154, Snyder (1992) also proposed a simpler logarithmic equation to calculate daily K_p as a function of F, RH, and u_2 as follows:

$$\mathrm{Kp} = 0.482 + [0.24\ln(\mathrm{F})]-(0.000376\,u_2) + (0.0045\,\mathrm{RH}) \tag{23}$$

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} day^{-1}, maximum air temperature ($T_{\max}$) in °C, and minimum relative air humidity ($\mathrm{RH}_{\min}$) in % as in the "trial" equation given below ([6] p.190) (Fig. 1).

$$\mathrm{Kp} = 1.44-0.2(0.372\,R_s + 0.1312\,T_{\max}-0.028\,\mathrm{RH}_{\min} + 1.4866)/3.24 \tag{24}$$

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, 514.8, 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. At Tharandt, the SHY total amount of evaporation is assumed not to exceed the precipitation (A.-S. [25] p. 187–188). 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 ([26] p.v, [18] p.272–273, and Baumgartner and Reichel [27] TABLE12 as cited in [1] p.1331).

However, at Tharandt, this was maintained only in the case of ET_o and E_p which had SHY total amounts of 476.4 and 459.1 mm, respectively. Because in most countries ET_o is taken as the sole standard reference method for the estimation of evapotranspiration, 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 (see Fig. 2). However, from the visualization of the box plot alone, it was not possible to compare the methods.

Hence, model evaluation statistics are used for the comparison of the evaporation schemes with respect to ET_o using linear regression model. A first check for using the linear regression model is to check whether a systematic trend exists or not. Generally, the existence of an increasing trend of PET according to Wendling and Penman and a decreasing trend of E_p and PET according to Haude were observed for increasing values of ET_o (see Fig. 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 ($R^2 \leq$

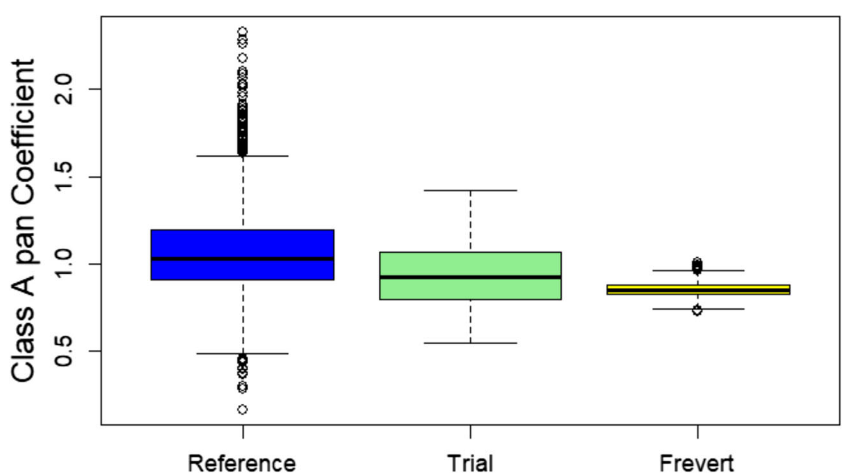
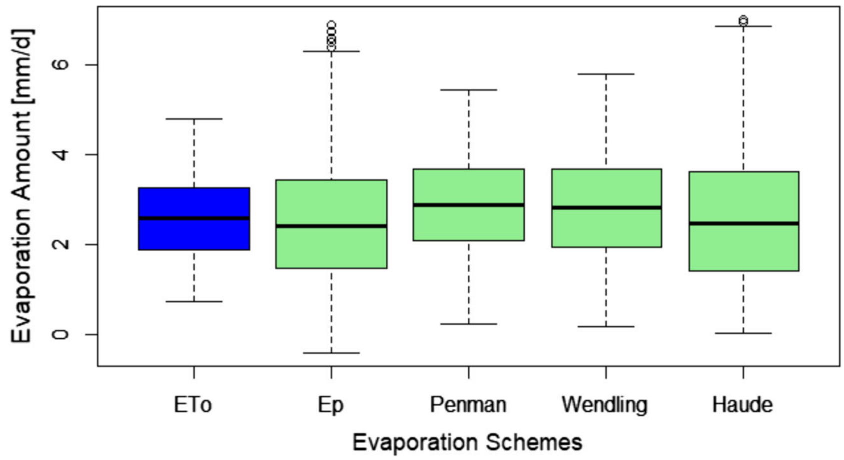


Fig. 1 Box plots of K_p from the reference, "trial," and Frevert et al. methods at Tharandt

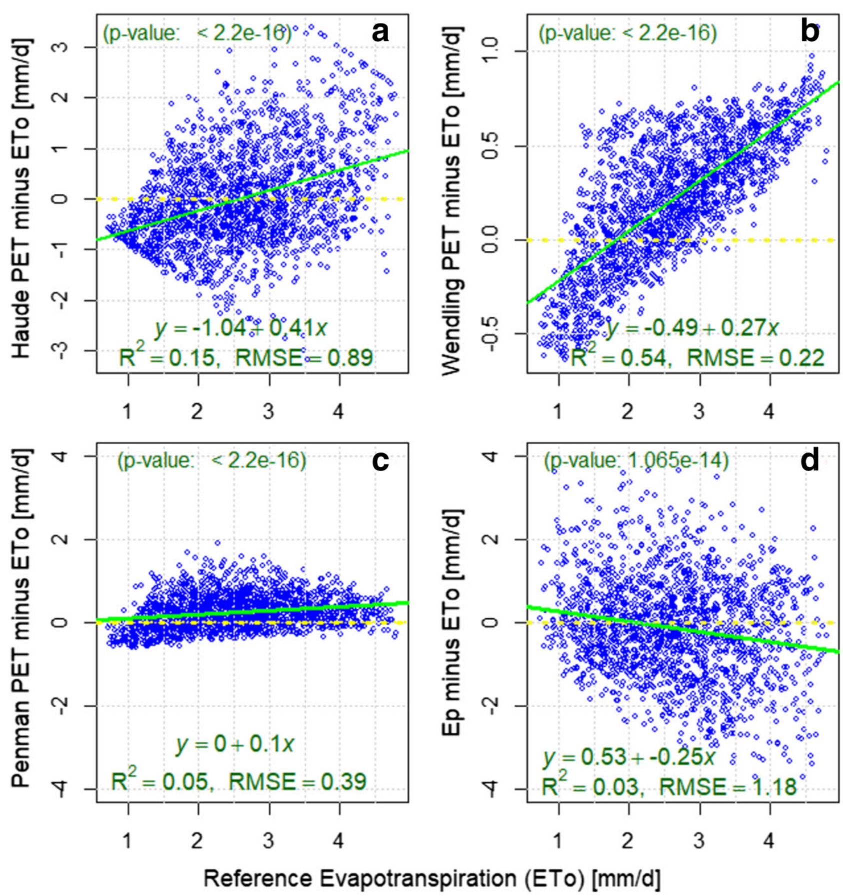
Fig. 2 Comparison of summer half-year E_p and PET estimated according to Haude, Wendling, and Penman with ET_o



0.15) except for PET according to Wendling. Generally, from Fig. 2 and Fig. 3, it was clear that PET estimated according to Wendling and Penman methods had overestimated ET_o for more days; this was true particularly for larger values of ET_o (see Fig. 3 "B" and "C"). Hence, first rank of "1" was given for E_p and PET according to Haude while second rank of "2" was given to PET according to Wendling and Penman (see Table 3).

In addition to the comparison of the methods using box plot and trend check (Fig. 2 and Fig. 3), linear regression model together with the model evaluation statistics described before were also used to compare the methods as presented in Fig. 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

Fig. 3 Checking trends of summer half-year PET according to Haude, Wendling, and Penman (figure panels "**A**", "**B**," "**C**") and E_p (figure panel "**D**") with respect to ET_o



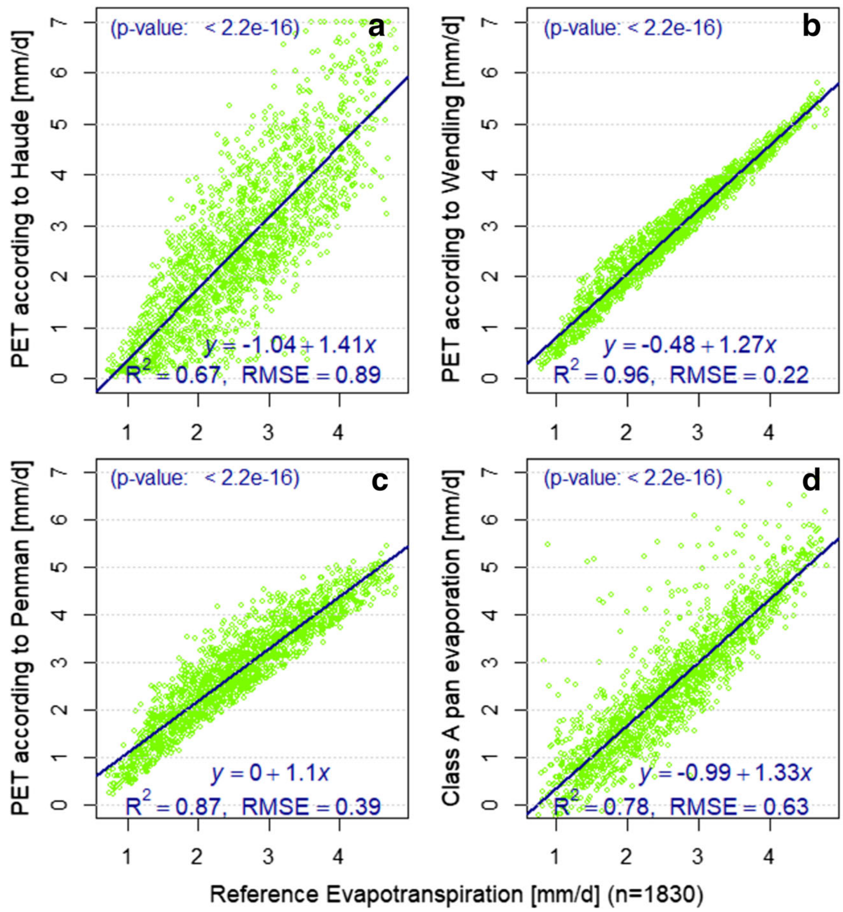


Fig. 4 Comparison of summer half-year PET according to Haude, Wendling, and Penman (figure panels "**A**", "**B**," "**C**") and E_p (figure panel "**D**") with ET_o using a linear regression model

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 (see 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 $\underline{a_s}$ value is used for the calculation of ET_o. Eq. 16 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 h, respectively when recommended values of $a_s = 0.25$ and $b_s = 0.50$ ([5] p.50) were used. 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, 0.001, and 5.320 h, respectively; which is in the range of n (see Fig. 5). Therefore, for Tharandt, $a_s \approx 0.014$ and $b_s = 0.50$ are recommended.

Daily Soil Heat Flux

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

Table 2 Comparison of summer half-year class A pan evaporation (E_p) and PET according to Haude, Wendling, and Penman with ET_o

	R^2	RMSE (in mm day^{-1})	MPE	NSE	MAE (in mm day^{-1})	RSR
Haude	0.67	0.89	− 4.8%	− 0.19	0.77	1.09
Wendling	0.96	0.22	5.1%	0.81	0.33	0.44
Penman	0.87	0.39	8.6%	0.73	0.36	0.52
E_p	0.78	0.63	− 1.4%	− 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 and trend check	R^2	RMSE	MPE	NSE	MAE	RSR	Average	Rank
Haude	1	4	4	2	3	4	3	3.00	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

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 et al. (1983) and K_p calculated from the equation of Snyder (1992) were compared with each other and with the reference method using box plot (see Fig. 6).

The box plot shows that K_p from the equation of Frevert et al. [23] and K_p from the equation of Snyder under and overestimated the reference K_p, respectively. 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 in Fig. 6). This result also agrees with the finding of Irmak et al. [14]. On the other hand, for fetch distances of 500 m and 1000 m, K_p calculated from the equation of Snyder (1992) 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 et al. [23] method gave an average value of $K_p = 0.85$ (between 0.70 and 0.88).

Eq. 24 which is a trial method for calculation of K_p gave better estimates as compared to K_p calculated from the equation of Frevert et al. [23] 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 (see Fig. 1).

Generally, K_p increases with increasing relative humidity and with decreasing wind speed ([5] p. 81). For a very humid climate, the average value of K_p is between 0.70 and 0.88 (FAO24-Doorenbos and Fruitt 1977 p.34 as cited in [9] p.81); note that for the summer half-year, the range may differ. At 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.

Conclusions

Suitable methods for estimation of evaporation schemes and class A pan coefficient for a very humid climate site (Tharandt, Germany) were compared using a very good quality climate data of more than ten meteorological parameters found from Technische Universität Dresden, Faculty of Environmental Sciences, Institute of Hydrology and Meteorology, Chair of Meteorology for the summer half-year from 2004 to 2013.

The selected evaporation schemes were class A pan evaporation (E_p) and potential evapotranspiration (PET) according to Haude, Wendling, and Penman. These evaporation schemes were compared with respect to the FAO56-PM method of estimation of reference evapotranspiration (ET_o). The result of the comparison showed that all the evaporation schemes had a very good correlation with the reference

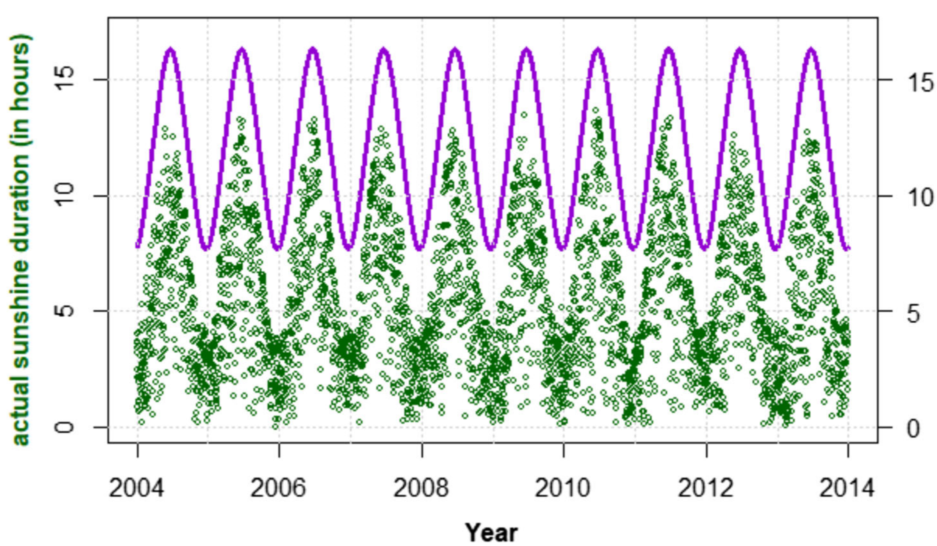


Fig. 5 Actual sunshine duration (n) and daylight hours (N) at Tharandt

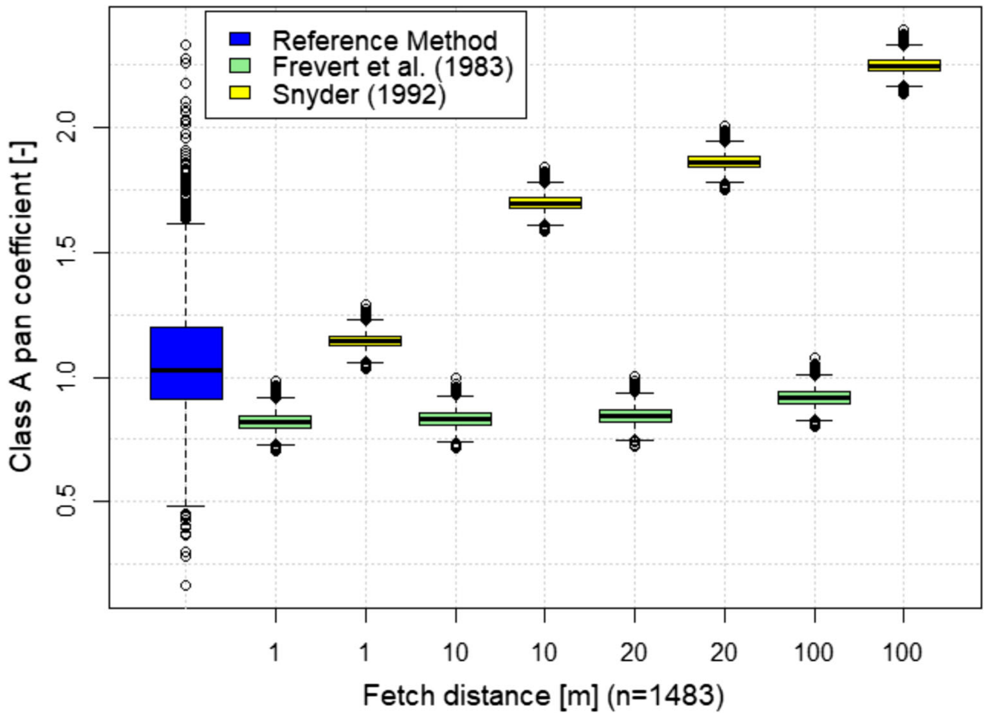


Fig. 6 Box plots of summer half-year K_p calculated from the equation of Frevert et al. [23] and Snyder (1992) and reference K_p for different fetch distances at Tharandt

method and all were considered suitable methods for estimation of evaporation or evapotranspiration. 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 evapotranspiration 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 day^{-1} can be maintained by replacing values of PET ≥ 7 mm day^{-1} with 7 mm day^{-1}.

K_p calculated from the equation of Frevert et al. [23] and Snyder (1992), 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. [23] gave better estimates than that of Snyder (1992). Note however that the trial method needs validation before being 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, − 36, and − 43.5 mm) while for ET_o and E_p it was positive (2.4 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 evapotranspiration 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. After applying the proper validation, this study can be used as a very useful information input for a local community of a place, development workers, researchers, and policy makers across the globe. Applying these and other suitable methods the future research may bring more reliable and easy methods of estimation of evaporation particularly for warm and arid sites across the world.

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Data Availability 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.

Compliance with Ethical Standards

Conflict of Interest The author declares that they have no conflict of interest.

References

1. McMahon TA, Peel MC, Lowe L, Srikanthan R, McVicar TR (2013) Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis. Hydrol Earth Syst Sci 17:1331–1363
2. Ghumman AR, Ghazaw YM, Alodah A, Rauf A, Shafiquzzaman and Haider H (2020) Identification of parameters of evaporation equations using an optimization technique based on pan evaporation https://doi.org/10.3390/w12010228 (www.mdpi.com/journal/water)
3. Antensay M, Christian B, Moderow U (2019) Estimation of evaporation using daily and ten-minute class-a pan data from automatic measuring pressure sensor instrument at Tharandt, Germany. Int J Environ Sci Nat Res 19(1):556003. https://doi.org/10.19080/IJESNR.2019.19.556003 The pdf document can be download at https://juniperpublishers.com/ijesnr/pdf/IJESNR.MS.ID.556003.pdf
4. Tellen VA (2017) A comparative analysis of reference evapotranspiration from the surface of rainfed grass in Yaounde, calculated by six empirical methods against the Penman Monteith formula Springer Open: Earth Perspectives 4:4 https://doi.org/10.1186/s40322-017-0039-1
5. Allen RG, Pereira LS, Raes D, and Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper No. 56, Food and Agricultural Organization of the United Nations, Rome
6. Antensay M (2020a) Dependency of evaporation and class a pan coefficient on meteorological parameters. Int J Environ Sci Nat Res 24(2):556134. https://doi.org/10.19080/IJESNR.2020.23.556134
7. Wittenberg H (2011) Praktische Hydrologie: Grundlagen und Übungen. [Prof. Dr.-Ing. Hartmut Wittenberg]. Accessed online on 9th of February, 2017 at https://books.google.co.uk/books?id=Xb0kBAAAQBAJ&pg=PA28&dq=DVWK+1996+f+January+0.22+February+0.22&hl=en&sa=X&ved=0ah1UKEwjYirP7g4PSAhXEFZoKHSIbDg8Q6AEIHDAA#v=onepage&q=DVWK%201996%20f%20January%200.22%20February%200.22&f=false
8. Antensay M (2020b) Evaluation of evaporation paradox at Tharandt. Int J Environ Sci Nat Res 24(4):556142. https://doi.org/10.19080/IJESNR.2020.24.556142
9. Mohammadi M, Ghahraman B, Davary K, Liaghat AM, Bannaya M (2012) Pan coefficient (K_p) estimation under uncertainty on fetch. Meteorog Atmos Phys 117:73–83. https://doi.org/10.1007/s00703-012-0186-8
10. Penman HL (1963) Vegetation and hydrology. Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England p125. https://doi.org/10.1002/qj.49708938220
11. Legates DR, McCabe GJ Jr (1999) Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water Resour Res 35(1):233–241
12. Nash JE, Sutcliffe JV (1970) River Flow Forecasting through Conceptual Model. Part 1—A Discussion of Principles. Journal of Hydrology, 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6
13. Moriasi DN, Arnold GJ, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulation. Am Soc Agric Biol Eng 50(3):885–900
14. Irmak S, Haman DZ, Jones JW (2002) Evaluation of class A pan coefficients for estimating reference evapotranspiration in humid location. J Irrig Drain Eng ASCE 128(3):153–159
15. Seiler K-P, and Gat JR (2007) Groundwater recharge from run-off, infiltration, and percolation. Accessed (in a read-only format) online on 9th of February, 2017: https://books.google.co.uk/books?id=er2yibHEdAgC&pg=PA11&lpg=PA11&dq=Evaporation+Haude+1955&source=bl&ots=64i2sNK49i&sig=9jJm35I4w7c974uWznZ3jFJpv40&hl=en&sa=X&ved=0ahUKEwixuOno1oLSAhXnQJoKHcULCfoQ6AEIHzAB#v=onepage&q=Evaporation%20Haude%201955&f=false
16. Weiss A (2009) Beitrag unterschiedlicher Bodenbearbeitungsverfahren und Bewirtschaftungsformen der Landwirtschaft zur Reduzierung des Hochwasserabflusses." ['Kasseler Wasserbau-Mitteilungen Fachgebiet Wasserbau und Wasserwirtschaft Universität Kassel.' Univ.-Prof. Dr.-Ing. Stephan Theobald (Hrsg.)]. Accessed online at https://books.google.co.uk/books?id=pCerIlfC_yAC&pg=PA97&lpg=PA97&dq=Haude+f+Jan+0,22&source=bl&ots=H5mORomg8Z&sig=EiZwWDNZMOr8JTQSQuBaIDmZaf4&hl=en&sa=X&ved=0ahUKEwib87DXgIPSAhWBJZoKHdk4BgsQ6AEIODAF#v=onepage&q=Haude%20f%20Jan%200%2C22&f=false on 9th of February, 2017
17. Wendling U (1991) Schätzmethoden der Verdunstung landwirtschaftlicher Bestände nach den Ansätzen von Penman und Turc. = 'Estimating evaporation in crop stands according to Penman and Turc formulas.' (in German, with English summary). Arch.Acker- Pflanzenbau Bodenkd 35, 251–257
18. Dingman SL (2002) Physical hydrology, 2nd edn. Prentice Hall, Upper Saddle River
19. Penman HL (1948) Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond. Ser. A, 193: 120–145. https://doi.org/10.1098/rspa.1948.0037
20. Penman HL (1956) Estimating evaporation. Trans. Am. Geophysical Union, 37: 43–50. https://doi.org/10.1029/TR037i001p00043
21. ASCE-EWRI (2002) The ASCE standardized reference evapotranspiration equation appendix A-F. Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) Standardized Reference Evapotranspiration Task Committee (TC)
22. Snyder RL (1992) Equation for evaporation pan to evapotranspiration conversions. Journal of Irrigation and Drainage Engineering,

118, 977–980. https://doi.org/10.1061/(ASCE)0733-9437(1992)118:6(977)

23. Frevert DK, RW, Hill BC, Braaten (1983) Estimation of FAO evapotranspiration coefficients. J. Irrig. Drain. Engrg., 109, 265–270. https://doi.org/10.1061/(ASCE)0733-9437(1983)109:2(265)
24. Cuenca RH (1989) Irrigation System Design: An Engineering Approach. 1st Edn., Prentice-Hall, Englewood Cliffs, N.J., pp 552
25. Smedman A-S, Gryningz S-E, Bumke K, Högstro U, Rutgerssony A, Batchvarovaz E, Peters G, Hennemuth B, Tammelin B, Hyvönen R, Omstedtk A, Michelson D, Andersson T, Clemens M (2005) Precipitation and evaporation budgets over the Baltic Proper: observations and modeling. J Atmos Ocean Sci 10(3): 163–191. https://doi.org/10.1080/17417530500513756
26. Nova'k V (2012) Evapotranspiration in the soil-plant-atmosphere system. ISBN 978-94-007-3839-3 ISBN 978-94-007-3840-9 (eBook) https://doi.org/10.1007/978-94-007-3840-9 Library of Congress Control Number: 2012942176 (www.springer.com)
27. Baumgartner A, Reichel E (1975) The world water balance, mean annual global, continental and maritime precipitation, evaporation and runoff. Oldenbourg Verlag GmbH, Munchen. Agric Water Manag 1(1):100–101. https://doi.org/10.1016/0378-3774(76)90012-3