

Evaluation of the Penman-Monteith and other 34 reference evapotranspiration equations under limited data in a semiarid dry climate

Koffi Djaman¹  · Michael O'Neill¹ · Lamine Diop² · Ansoumana Bodian² · Samuel Allen¹ · Komlan Koudahe³ · Kevin Lombard¹

Received: 9 January 2018 / Accepted: 2 September 2018

© This is a U.S. Government work and not under copyright protection in the US; foreign copyright protection may apply 2018

Abstract

Reference evapotranspiration (ETo) is an important parameter in hydrological, agricultural, and environmental studies. Accurate estimation of ETo helps to improve water management and increase water productivity and efficiency. While the Penman-Monteith ETo equation enjoys worldwide adoption as the most accurate ETo equation, the number of requested climatic variables makes its application very questionable under limited data conditions. The objective of this study was to evaluate the Penman-Monteith ETo equation under limited climatic data and 34 simple ETo equations that request few climatic variables. Five weather stations were considered under the semiarid and dry climate across New Mexico for the period of 2009–2017. The Penman-Monteith ETo equation showed good performance under missing solar radiation, relative humidity, and wind speed and could still be adapted under limited data conditions across New Mexico. However, it tended to underestimate daily ETo when more than one climatic variable data is missing. Among the simple ETo equations, four of the Valiantzas equations, along with the Makkink, Calibrated Hargreaves, Abtew, Jensen-Haise, and Caprio equations, were the best performing ones compared to the Penman-Monteith equation and could be the best alternative ETo estimation methods. These alternative equations could be used by irrigation managers, producers, engineers, and university researchers to improve water management across the dry semiarid and arid zone across New Mexico, as well as other semiarid areas where water is the most limiting factor to food and fiber production.

1 Introduction

Reference evapotranspiration (ETo) is one of the most important parameters in the hydrological, environmental, and agricultural studies and plays a central key role in designing and managing irrigation project and water management under irrigated and rainfed agriculture. It is estimated by different methods from direct measurements with lysimeters and Eddy covariance system to indirect modeling using local climatic variables (Thorntwaite 1948; Turc 1961;

Penman 1963; Hargreaves and Samani 1985; Abtew 1996; Allen et al. 1998; Irmak et al. 2003; Trajkovic 2007; Valiantzas 2013). Numerous ETo estimations have been developed with different performances and adaptabilities throughout the globe and the Penman-Monteith equation is shown to be the most worldwide accurate under all types of climatic conditions (Allen et al. 1998; ASCE-EWRI, 2005; Lopez-Urrea et al. 2006; Bodner et al. 2007; Jabloun and Sahli 2008; Irmak et al. 2008; Xing et al. 2008; Trajkovic and Kolakovic 2009; Tabari and Talaee, 2011; Xystrakis and Matzarakis 2011). However, climatic variables requirement by the Penman-Monteith equation is the most limiting constraint for its adoption under limited data conditions. Therefore, developed ETo simple equations have been tested, validated, and calibrated to improve their performance under different climatic conditions (Heydari and Heydari 2014; Trajkovic and Kolakovic 2009; Xystrakis and Matzarakis 2011; Todorovic et al. 2013; Tabari et al. 2013, Valipour 2014, Kisi 2014; Djaman et al. 2015, 2016a, b, 2017a, b, c; Ahooghalandari et al. 2017)

✉ Koffi Djaman
kdjaman@nmsu.edu

¹ Department of Plant and Environmental Sciences, New Mexico State University, Agricultural Science Center at Farmington, P.O. Box 1018, Farmington, NM 87499, USA

² Université Gaston Berger (UGB), Saint Louis, Senegal

³ ADA Consulting Africa, 07 BP 14284 Lome, Togo

Tabari and Talaee (2011) evaluated 31 ETo equations and found five ETo models (the two radiation-based equations developed by the authors, the temperature-based Blaney-Criddle and Hargreaves-M4 equations and the Snyder pan evaporation-based equation) as the most accurate with comparison to the Penman-Monteith equation in Iran. The Valiantzas, Trabert, Romanenko, Schendel, and Mahringer equations were shown to be the most accurate among 16 ETo equations evaluated and whose calibration improved their performance in the Senegal river Valley (Djaman et al. 2015, 2016a). Djaman et al. (2017b) evaluated nine Valiantzas' ETo equations across Uganda and other sets of ETo equations across Tanzania and the Western Kenya (Djaman et al. 2017a) and found the Valiantzas equations to overcome the rest of selected ETo equations. Minacapilli et al. (2016) evaluated the Penman-Monteith, Blaney and Criddle, Hargreaves, Priestley-Taylor, Makkink, and Turc ETo equations in against scintillometer measurements and found that the Priestley-Taylor equation can be considered as valid alternative for an accurate estimation ETo in South-West Sicily (Italy). Pandey et al. (2016) reported the Irmak and Turc ETo equations to perform the best among 18 selected equation for ETo estimation in the North East India. In the northeast Louisiana, the radiation-based ETo equations underestimated the growing season ETo by as much as 10%, whereas the temperature-based Hargreaves model overestimated ETo by 8% (Rojas and Sheffield 2013). Bourletsikas et al. (2017) evaluated 24 ETo methods with comparison to the Penman-Monteith equation in a Mediterranean forest environment and found the Copais, original Hargreaves and one of the Valiantzas equation performed well in estimation daily ETo under limited climatic date conditions. Arellano and Irmak (2016) indicated that the FAO24 radiation equation performed the best among selected equations in Davis (California), Clay Center, and Scottsbluff (Nebraska), while it showed poor performance I in Phoenix (Arizona). Ravazzani et al. (2012a, b) calibrated Hargreaves ETo equation to the Upper Po River Basin (Italy) and the Rhone River Basin (Switzerland) with significant improvement in its performance with significant reduction in error.

The Hargreaves ETo equation is one of the most widely used simple ETo equation for daily or monthly ETo estimation with variable degree of performance in Canada (Sentelhas et al. 2010), in Burkina Faso (Ndiaye et al. 2017), in China (Gao et al. 2015; Peng et al. 2017), in Spain (Maestre-Valero et al. 2013), in Italy (Mendicino and Senatore 2013; Berti et al. 2014), in Iran (Fooladmand and Haghighat 2007; Tabari and Talaee 2011; Heydari and Heydari 2014), in South Korea (Jung et al. 2016), and in Senegal, Kenya, and Tanzania (Djaman et al. 2015, 2016a, 2017a). Hargreaves ETo is a very

simple equation that requires only air temperature. Allen et al. (1998) indicated that Hargreaves' equation underestimates ETo under wind speed greater than 3 m/s and overestimated ETo under high relative humidity. Aschonitis et al. (2017) revised and calibrated the annual coefficients for the Hargreaves ETo equation for global ETo estimation and suggested that the database they had developed can support estimations of ETo and solar radiation for locations where climatic data are limited. Trajkovic (2007) calibrated the Hargreaves equation to the humid Balkans regions and found the original exponent 0.5 to be 0.424 with an average overestimation of only 1% as compared to the Penman-Monteith ETo. Heydari and Heydari (2014) calibrated the Hargreaves ETo equation to the semiarid and arid climatic conditions in Iran and found the constant 0.0023 to change to 0.0018 and 0.0037 under semiarid and arid conditions, respectively, with improvement in the root mean square error of 40%.

The non-availability of all climatic variable requirements for accurate estimate of daily ETo by the Penman-Monteith equation encourages development of simple ETo equations and the evaluation, calibration, and validation of the existing simple ETo equations developed under different climatic conditions. In the New Mexico, USA, a semiarid dry and high elevation conditions, climate data are not always available. Thus, it becomes crucial to test ETo methods that estimate ETo by using less climate data. Thus, the objectives of study were to evaluate the P-M ETo equation under limited data conditions and 34 simple ETo equations under the semiarid dry conditions in New Mexico, USA.

2 Materials and methods

This study was conducted at five weather stations across New Mexico (USA) at Alcalde, Fabian-Garcia, Farmington, Leyendecker, and Tucumcari for the period of 2009–2017. The geographical coordinates and the long-term average climatic variables are summarized in Table 1. Minimum temperature (Tmin), maximum temperature (Tmax), minimum relative humidity (RHmin), maximum relative humidity (RHmax), wind speed (u_2), and solar radiation (Rs) were collected on the daily basis from automated weather station installed by the New Mexico Climate Center.

2.1 Reference evapotranspiration estimation methods

The Standardized ASCE form of the Penman-Monteith and 34 simple reference evapotranspiration equations were selected for their simplicity and broad adaptability. The list and data

Table 1 Weather stations with long-term average climatic condition

Parameters	Alcalde	Fabian G.	Farmington	Leyendecker	Tucumcari
Latitude (deg. north)	36.09	32.28	36.69	32.20	35.20
Longitude (deg. west)	-106.06	-106.77	-108.31	-106.74	-103.69
Elevation (m)	1735	1186	1720	1176	1246
Wind speed (m/s)	1.19	1.82	2.45	1.81	3.30
Tmax (°C)	21.09	26.50	20.94	26.12	24.07
Tmin (°C)	2.22	9.82	4.33	7.67	7.52
Tmean (°C)	11.65	18.16	12.63	16.89	15.79
Rhmax (%)	83.86	65.21	68.63	77.34	71.78
Rhmin (%)	22.88	18.60	19.70	19.09	22.29
Rhmean (%)	53.37	41.90	44.17	48.21	47.03
Rs (MJ/m ²)	18.62	21.23	19.84	19.63	19.80

requirements of the 35 reference evapotranspiration equations are summarized in Table 2 (McMahon et al. 2013). The evaluated models were classified in three groups according their data requirement (McMahon et al. 2013). The Penman-Monteith, Valiantzas 4, and Valiantzas 5 are combination models. Berti et al. (2014) and the Dorji et al. (2016) equations are the modified forms of the Hargreaves and Samani (1985) which is temperature-based model as the Romanenko (1961) and the Ahooghalandari et al. (2016) equations. The Caprio (1974), Hargreaves (1975), Irmak et al. (2003), Trajkovic (2007), Droogers and Allen (2002), Jensen and Haise (1963), Tabari and Talaee (2011), Abtew (1996), Makkink (1957), and Valiantzas (2012) equations are grouped as radiation based reference evapotranspiration models. The Albrecht (1950), Brockamp and Wenner (1963), Dalton (1802), Mahringer (1970), Meyer (1926), Penman (1963), Trabert (1896), WMO (1966), and Rohwer (1931) equations are grouped as mass transfer models. The ETo equations are presented as follows:

1. Standardized ASCE form of the Penman-Monteith (ASCE-EWRI 2005) equation:

$$ETo = \frac{0.408\Delta(Rn-G) + \gamma Cn u2/(T+273)(es-ea)}{\Delta + \gamma(1+Cd u2)} \quad (1)$$

2. Caprio (1974):

$$ETo = (0.01092708 T + 0.0060706)Rs \quad (2)$$

3. Hargreaves (1975):

$$ETo = 0.0135 Rs(T + 17.8) \quad (3)$$

4. Hargreaves and Samani (1985):

$$ETo = 0.408$$

$$\times 0.0023Ra (T + 17.8) (T_{max}-T_{min})^{0.5} \quad (4)$$

5. Trajkovic (2007):

$$ETo = 0.408$$

$$\times 0.0025Rs (T + 17.8) (T_{max}-T_{min})^{0.424} \quad (5)$$

6. Droogers and Allen (2002):

$$ETo = 0.00102Rs (T + 16.8) (T_{max}-T_{min})^{0.5} \quad (6)$$

7. Jensen and Haise (1963):

$$ETo = (0.0252 T + 0.078)Rs \quad (7)$$

8. Allen (1993):

$$ETo = 0.408$$

$$\times 0.0029 Rs (T + 20) (T_{max}-T_{min})^{0.4} \quad (8)$$

9. Ahooghalandari et al. (2016): Ahoo 1

$$ETo = 0.252 \times 0.408 Ra$$

$$+ 0.221 T_{mean} \left(1 - \frac{RH}{100} \right) \quad (9)$$

10. Ahooghalandari et al. (2016): Ahoo 2

$$ETo = 0.29 \times 0.408 Ra + 0.15 T_{max} \left(1 - \frac{RH}{100} \right) \quad (10)$$

Table 2 Data requirement of the models used in this study

Models		Latitude	Elevation	Tmax	Tmin	Tmean	RHmax	RHmin	RHmean	Wind Speed	Solar radiation
Authors	Denomination										
Penman-Monteith	FAO-PM	X	X	X	X	X	X	X	X	X	X
Caprio (1974)	Caprio 1974					X					X
Hargreaves (1975)	Harg 75					X					X
Hargreaves and Samani (1985)	HARG			X	X	X					
Allen (1993)	Allen			X	X	X					X
Droogers and Allen (2002)	Droogers			X	X	X					X
Jensen and Haise (1963)	Jesen-Haise					X					X
Irmak et al. (2003)	Irmak					X					X
Trajkovic (2007)	Traj			X	X	X					X
Tabari et al. (2013)	Tabari 1					X					X
Tabari et al. (2013)	Tabari 2			X	X						X
Berti et al. (2014)	Berti 2014			X	X	X					
Ahooghalandari et al. (2016)	Ahoo1					X			X		
Ahooghalandari et al. (2016)	Ahoo2			X					X		
Dorji et al. (2016)	Dorji			X	X	X					
Abtew (1996)-1	Abtew 1			X							X
Abtew (1996)-2	Abtew 2			X							X
Abtew (1996)-simple	Abtew Simple										X
Makkink (1957)	Makkink	X				X					X
Calibrated Hargreaves	Harg Cal			X	X	X					
Romanenko (1961)	Romanenko					X			X		
Valiantzas (2012)	Valiantzas 1	X			X	X					X
Valiantzas (2012)	Valiantzas 2					X			X		X
Valiantzas (2012)	Valiantzas 3					X			X		X
Valiantzas (2013)	Valiantzas 4	X				X			X	X	X
Valiantzas (2013)	Valiantzas 5	X	X	X	X				X	X	X
Albrecht (1950)	Albrecht			X	X		X	X			X
Brockamp and Wenner (1963)	Bro-We			X	X		X	X			X
Dalton (1802)	Dalton			X	X		X	X			X
Mahringer (1970)	Mahringer			X	X		X	X			X
Meyer (1926)	Meyer			X	X		X	X			X
Penman (1963)	Penman 63			X	X		X	X			X
Trabert (1896)	Trabert			X	X		X	X			X
WMO (1966)	WMO			X	X		X	X			X
Rohwer (1931)	Rohwer			X	X		X	X			X

Tmax maximum temperature, *Tmin* minimum temperature, *Tmean* mean temperature, *RHmax* maximum relative humidity, *RHmin* minimum relative humidity, *RHmean* mean relative humidity

11. Irmak et al. (2003)

$$\text{ETo} = -0.611 + 0.149 \text{ Rs} + 0.079 T \quad (11)$$

12. Tabari and Talaee (2011): Tab 1

$$\text{ETo} = -0.642 + 0.174 \text{ Rs} + 0.0353 T \quad (12)$$

13. Tabari and Talaee (2011): Tab 2

$$\text{ETo} = -0.478 + 0.156 \text{ Rs} - 0.0112 \text{ Tmax}$$

$$+ 0.0733 \text{ Tmin} \quad (13)$$

14. Dorji et al. (2016):

$$\text{ETo} = 0.002 \times 0.408 \text{ Ra} (T + 33.9)(\text{Tmax} - \text{Tmin})^{0.296} \quad (14)$$

15. Makkink (1957):

$$\text{ETo} = 0.7 \frac{\Delta}{\Delta + \gamma} \frac{\text{Rs}}{\lambda} \quad (15)$$

16. Berti et al. (2014):

$$\text{ETo} = 0.00193 \text{ Ra} (T + 17.8)(\text{Tmax} - \text{Tmin})^{0.517} \quad (16)$$

17. Calibrated Hargreaves:

$$\text{ETo} = 0.408 K \text{ Ra} (T + b)(\text{Tmax} - \text{Tmin})^c \quad (17)$$

 K, b and c to be determined

18. Abtew (1996)-1

$$\text{ETo} = \frac{\text{Tmax}}{K} \frac{\text{Rs}}{\lambda} \quad (18)$$

19. Abtew (1996)-2

$$\text{ETo} = 0.408 \times 0.01786 \times \text{Rs} \times \text{Tmax} \quad (19)$$

20. Abtew (1996)-simple:

$$\text{ETo} = 0.52 \frac{\text{Rs}}{\lambda} \quad (20)$$

21. Albrecht (1950):

$$\text{ETo} = (1.005 + 2.97 u)(\text{es}-\text{ea}) \quad (21)$$

22. Brockamp and Wenner (1963): Bro-We

$$\text{ETo} = 20.543u^{0.456}(\text{es}-\text{ea}) \quad (22)$$

23. Dalton (1802):

$$\text{ETo} = (3.648 + 0.7223 u)(\text{es}-\text{ea}) \quad (23)$$

24. Romanenko (1961):

$$\text{ETo} = 0.00006 (T + 25)^2 (100 - \text{RH}) \quad (24)$$

25. Mahringer (1970):

$$\text{ETo} = 2.8597 u^{0.5}(\text{es}-\text{ea}) \quad (25)$$

26. Meyer (1926):

$$\text{ETo} = (3.75 + 0.5026 u)(\text{es}-\text{ea}) \quad (26)$$

27. Penman (1963):

$$\text{ETo} = (2.625 + 0.000479/u)(\text{es}-\text{ea}) \quad (27)$$

28. Rohwer (1931):

$$\text{ETo} = (3.3 + 0.89 u)(\text{es}-\text{ea}) \quad (28)$$

29. Trabert (1896):

$$\text{ETo} = 0.408 \times 0.3075 (\text{es}-\text{ea})u^{0.5} \quad (29)$$

30. WMO (1966):

$$\text{ETo} = (1.298 + 0.934 u)(\text{es}-\text{ea}) \quad (30)$$

31. Valiantzas (2012): Valiantzas 1

$$\begin{aligned} \text{ETo} = & 0.0393 \text{ Rs} (\text{Tmean} + 9.5)^{0.5} - 0.19 \text{ Rs}^{0.6} \varphi^{0.15} \\ & + 0.0061(\text{Tmean} + 20)(1.12 \text{ Tmean} - \text{Tmin} - 2)^{0.7} \end{aligned} \quad (31)$$

32. Valiantzas (2012): Valiantzas 2

$$\begin{aligned} \text{ETo} = & 0.0393 \text{ Rs} (\text{Tmean} + 9.5)^{0.5} - 0.19 \text{ Rs}^{0.6} \varphi^{0.15} \\ & + 0.078(\text{Tmean} + 20) \left(1 - \frac{\text{RH}}{100} \right) \end{aligned} \quad (32)$$

33. Valiantzas (2012): Valiantzas 3

$$\text{ETo} = 0.0393 \text{Rs} (\text{Tmean} + 9.5)^{0.5} - 2.4 \left(\frac{\text{Rs}}{\text{Ra}} \right)^2 - (\text{Tmean} + 20) \left(1 - \frac{\text{RH}}{100} \right) (0.024 - 0.1 \text{Waero}) \quad (33)$$

with $\text{RH} > 65\%$, $\text{Waero} = 0.78$; $\text{RH} \leq 65\%$, $\text{Waero} = 1.067$, where Waero is an empirical weighted factor.

34. Valiantzas (2013): Valiantzas 4

$$\begin{aligned} \text{ETo} = & 0.051(1-\alpha)\text{Rs}(\text{Tmean} + 9.5)^{0.5} - 2.4 \left(\frac{\text{Rs}}{\text{Ra}} \right)^2 \\ & + 0.048(\text{Tmean} + 20) \left(1 - \frac{\text{RH}}{100} \right) (0.5 + 0.536 u2) \\ & + 0.00012 z \end{aligned} \quad (34)$$

35. Valiantzas (2013): Valiantzas 5

$$\begin{aligned} \text{ETo} = & 0.051(1-\alpha)\text{Rs} (\text{Tmean} + 9.5)^{0.5} \\ & - 0.188(\text{Tmean} + 13)(\text{Rs}/\text{Ra} - 0.194) \left(1 - 0.00015(\text{Tmean} + 45)^2 \left(\frac{\text{RH}}{100} \right)^{0.5} \right. \\ & \left. - 0.0165\text{Rs} u^{0.7} + 0.0585(\text{Tmean} + 17)u^{0.75} \left(\left(1 + 0.00043(\text{Tmax} - \text{Tmin})^2 \right)^2 \right. \right. \\ & \left. \left. - \text{RH}/100 \right) / (1 + 0.00043(\text{Tmax} - \text{Tmin})^2 \right) \\ & + 0.0001z \end{aligned} \quad (35)$$

where ETo is reference evapotranspiration (mm/day), Δ is the slope of saturation vapor pressure versus air temperature curve ($\text{kPa}/^\circ\text{C}$), R_n = net radiation at the crop surface ($\text{MJ/m}^2/\text{day}$), G = soil heat flux density at the soil surface ($\text{MJ/m}^2/\text{day}$), Tmax and Tmin are maximum and minimum temperature ($^\circ\text{C}$), T = mean daily air temperature at 1.5–2.5 m height ($^\circ\text{C}$), $u2$ = mean daily wind speed at 2 m height (m/s), es = the saturation vapor pressure (kPa), ea = the actual vapor pressure (kPa), $es - ea$ = saturation vapor pressure deficit (kPa), γ = psychrometric constant ($\text{kPa}/^\circ\text{C}$), C_n = numerator constant that changes with reference surface and calculation time step (900 $^\circ\text{C mm s}^3/\text{Mg/day}$ for 24 h time steps for the grass-reference surface), γ is the psychrometric constant ($\text{kPa}/^\circ\text{C}$), C_d = denominator constant that changes with reference surface and calculation time step (0.34 s/m for 24 h time steps), Rs = solar radiation ($\text{MJ/m}^2/\text{day}$), and RH = relative humidity (%). All parameters necessary for computing ETo were computed according to the procedure developed in FAO-56 by Allen et al. (1998).

According to their mathematical structure and their parameterization, the ETo equations could be grouped into height different classes or basic mathematical models such as [Hargreaves and Samani (1985), Trajkovic (2007), Droogers and Allen (2002), Allen (1993), Calibrated Hargreaves, Berti et al. (2014) Dorji et al. (2016)], [Caprio (1974), Jensen and Haise (1963)], [Irmak et al. (2003), Tabari and Talaee (2011) Tab 1, Tabari and Talaee (2011), Tab 2], [Makkink (1957), Abtew (1996)-1-2-simple], [Albrecht (1950), Brockamp and Wenner (1963); Bro-We, Dalton (1802), Romanenko (1961), Mahringer (1970), Meyer (1926), Penman (1963), Rohwer

(1931), Trabert (1896), WMO (1966)], [Ahooghalandari et al. (2016): Ahoo 1 and Ahoo 2], [Valiantzas (2012), Valiantzas 1, 2, 3], and [Valiantzas (2013), Valiantzas 4, 5]. Each group represents different parameterizations of the same ETo basic model.

The 34 ETo equations tested against the Penman-Monteith reference evapotranspiration can be classify in 5 groups considering the parameterization approaches used by the equation developers. The five parameterization approaches differ in several respects: input datasets and need different degrees of calibration. The characteristics of each approach are summarized as:

- Percentage of net radiation: [$\text{ETo} = p \text{Rs}$]
- Linear function of mean temperature: [$\text{ETo}/\text{Rs} = aT + b$]
- Linear function of mean temperature with offset temperature ($\text{Tmax} - \text{Tmin}$) included the following: [$\text{ETo}/\text{Rs} = (aT + b)(\text{Tmax} - \text{Tmin})$]
- Linear function of (u^c): [$\text{ETo}/(es - ea) = a u^c + b$]
- Simple measurement which is not a truly parameterization approach use by Valiantzas

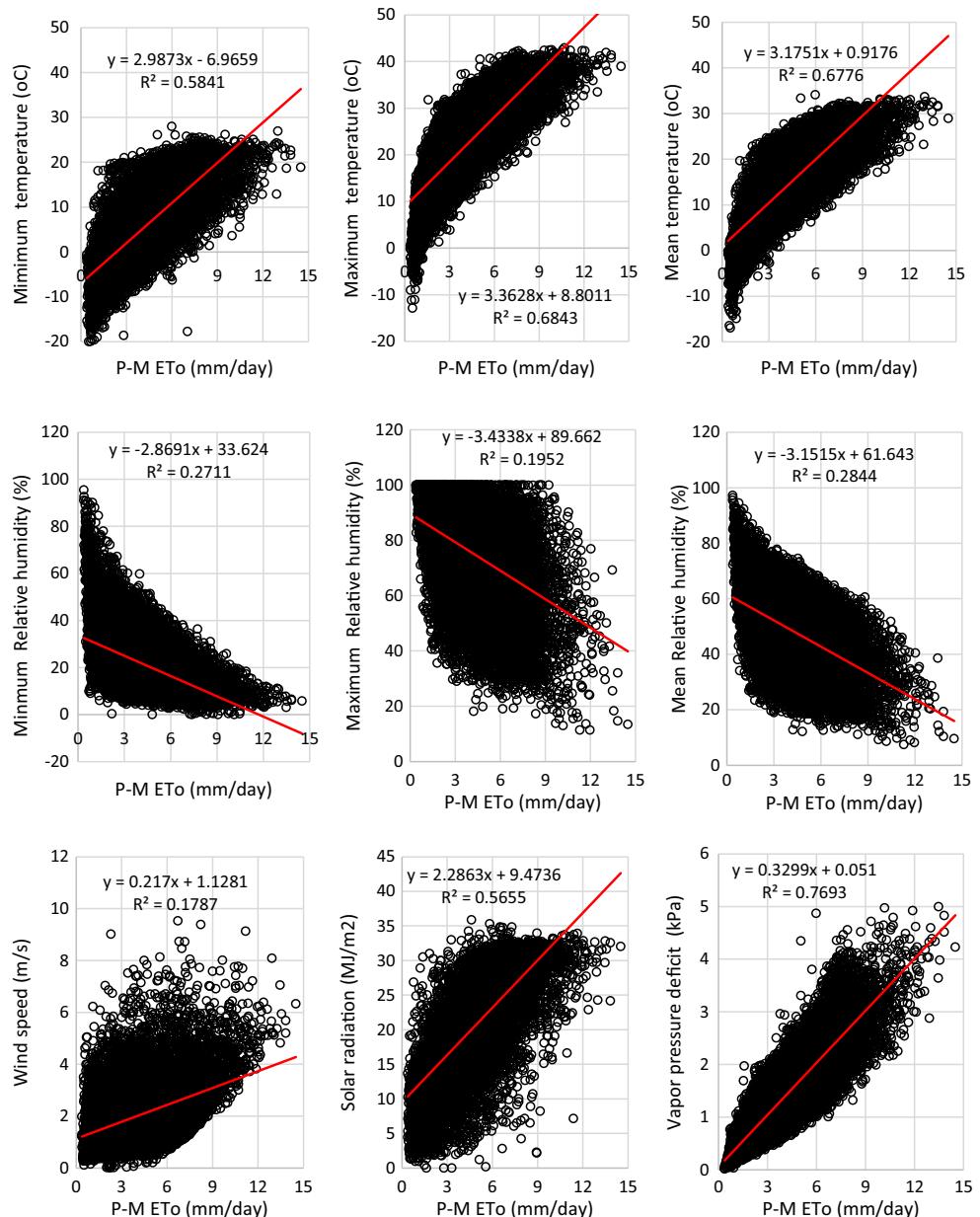
2.2 Evaluation of P-M ETo equation under limited data conditions

Under missing Rs , RH , and or $u2$, as it always occurs in most of the weather stations, the PM ETo model was evaluated using limited data. Under missing solar radiation data, daily Rs was estimated from Hargreaves

radiation formula (Hargreaves and Samani 1982; Allen et al. 1998). In the conditions of missing relative humidity, actual vapor pressure ea was estimated using the method proposed by Allen et al. (1998), assuming that dew point temperature (T_{dew}) is close to daily T_{min} , which is usually experienced at sunrise in reference weather stations (Allen et al. 1998).

Under missing wind speed data, daily ETo was also estimated using the global average wind speed value of 2 m/s. Under more than one climatic variable, missing condition daily ETo was estimated by combining the abovementioned assumptions and acronyms were selected as summarized in Table 2 by Djaman et al. (2017a).

Fig. 1 Relationship between the daily Penman-Monteith reference evapotranspiration estimates (P-M ETo) and the climatic variables (pooled data of all five locations)



2.3 Calibration of ETo-Rs-RH-um and Hargreaves' equations

The original Hargreaves, Abtew, and Makkink equations were calibrated to the local semiarid and dry climatic conditions of each location under this study. These equations (Eqs 15, 17, and 18) were calibrated using the experimental data and the generalized reduced gradient method. This procedure allows iterations by changing the constants in the equations to create new equations for each location. The solver add-in is a tool that was used to fit the original equations by minimizing the sum of the squared residuals. Multiple initial values were

tested to ensure that the global minimum of the errors was found (Bogawski and Bednorz 2014).

2.4 Evaluation criteria for the P-M ETo equations under limited data and the selected ETo equations

Simple linear regression was used for the Penman-Monteith ETo estimates under full dataset and the Penman-Monteith ETo estimates under limited data. The same method was used to compare simple ETo equations with the Penman-Monteith ETo equation with full dataset. The intercept of the regression line was forced to be zero. The more accurate the ETo equation is, the more the regression slope and the coefficient of determination are close to unity. Root mean square error (RMSE), percent error (PE), mean bias error (MBE),

and the mean absolute error (MAE) were also used for model evaluation and calculated as follows:

$$\text{RMSE} = \sqrt{\sum_{i=0}^n \frac{(Ei - Oi)^2}{n}} \quad (36)$$

$$\text{PE} = \frac{\text{RMSE}}{\text{ETo mean}} \times 100 \quad (37)$$

$$\text{MBE} = n^{-1} \sum_1^n (Ei - Oi) \quad (38)$$

$$\text{MAE} = n^{-1} \sum_1^n |Ei - Oi| \quad (39)$$

where Ei is the estimated ETo with FAO-PM under limited data and the selected ETo equations and Oi is ETo estimated with FAO-PM model with full dataset at the i th data point and n is the total number of data points.

Table 3 Comparison between daily Penman-Monteith ETo under full and limited dataset

Indices	Location	ETo-Rs	ETo-RH	ETo-umean	ETo-um	ETo-Rs-um	ETo-Rs-RH	ETo-RH-um	ETo-Rs-RH-um
R^2	Alcalde	1.030	0.961	0.988	1.140	1.167	0.993	1.075	1.104
	Fabian G.	0.973	0.899	0.983	1.014	0.987	0.863	0.916	0.879
	Farmington	0.990	0.877	0.992	0.925	0.915	0.864	0.839	0.826
	Leyendecker	1.013	0.917	0.999	1.032	1.045	0.932	0.948	0.962
	Tucumcari	0.988	0.847	0.973	0.811	0.797	0.830	0.742	0.723
	Alcalde	0.97	0.99	0.94	0.91	0.88	0.95	0.88	0.84
	Fabian G.	0.97	0.96	0.88	0.88	0.83	0.92	0.85	0.77
	Farmington	0.99	0.97	0.93	0.93	0.92	0.95	0.90	0.89
	Leyendecker	0.98	0.97	0.87	0.86	0.82	0.93	0.82	0.76
	Tucumcari	0.99	0.96	0.90	0.89	0.86	0.93	0.86	0.82
RMSE (mm/day)	Alcalde	0.33	0.25	0.44	0.79	0.94	0.42	0.69	0.85
	Fabian G.	0.35	0.66	0.66	0.69	0.80	0.89	0.85	1.06
	Farmington	0.24	0.73	0.63	0.70	0.74	0.82	1.03	1.10
	Leyendecker	0.27	0.53	0.68	0.73	0.84	0.60	0.80	0.90
	Tucumcari	0.27	1.05	0.82	1.35	1.46	1.19	1.74	1.88
PE (%)	Alcalde	9.9	7.4	13.1	23.4	28.1	12.4	20.6	25.4
	Fabian G.	7.4	13.7	13.9	14.5	16.7	18.7	17.8	22.2
	Farmington	5.3	16.1	13.8	15.4	16.4	18.2	22.7	24.2
	Leyendecker	6.0	11.8	15.1	16.2	18.8	13.3	17.9	20.1
	Tucumcari	4.9	19.4	15.3	25.1	27.0	22.2	32.3	34.9
MBE (mm/day)	Alcalde	0.11	-0.13	0.03	0.60	0.70	-0.01	0.38	0.49
	Fabian G.	-0.11	-0.48	0.03	0.19	0.08	-0.62	-0.31	-0.46
	Farmington	-0.03	-0.53	0.04	-0.27	-0.31	-0.58	-0.67	-0.72
	Leyendecker	0.08	-0.36	0.09	0.25	0.33	-0.27	-0.13	-0.05
	Tucumcari	-0.04	-0.78	-0.01	-0.92	-0.97	-0.84	-1.31	-1.38
MAE (mm/day)	Alcalde	0.21	0.14	0.32	0.66	0.79	0.27	0.57	0.70
	Fabian G.	0.22	0.49	0.50	0.54	0.61	0.67	0.63	0.78
	Farmington	0.16	0.54	0.44	0.44	0.49	0.62	0.71	0.78
	Leyendecker	0.18	0.37	0.53	0.58	0.67	0.39	0.61	0.69
	Tucumcari	0.17	0.79	0.61	0.97	1.05	0.89	1.33	1.43

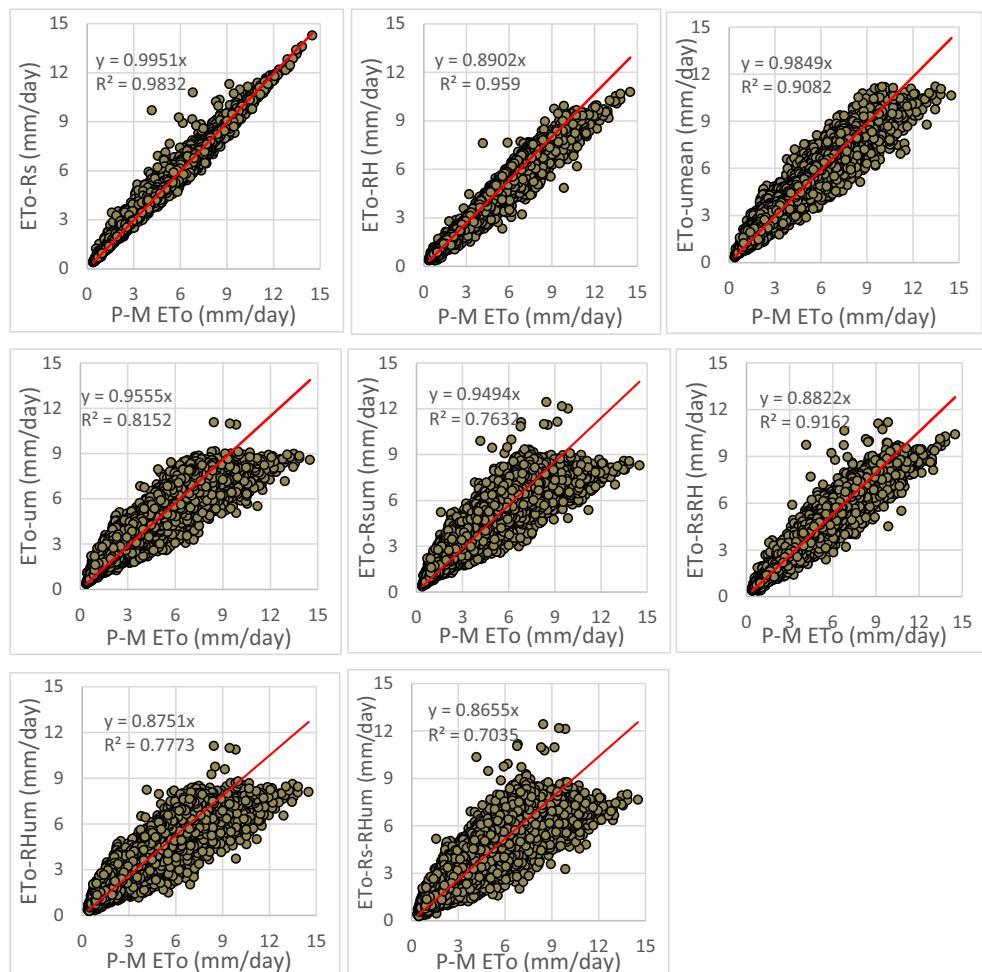
3 Results and discussion

3.1 Evaluation of the Penman-Monteith equation under missing data

The relationship between the Penman-Monteith ETo estimates and the climatic variables are presented in Fig. 1. Daily ETo showed the strongest correlation with the vapor pressure deficit ($R^2 = 0.77$), followed by maximum and mean temperature ($R^2 = 0.68$), minimum temperature ($R^2 = 0.58$), and solar radiation ($R^2 = 0.57$) (Fig. 1). Daily ETo was poorly related to relative humidity and wind speed (Fig. 1). These relationships might help understanding the behavior the Penman-Monteith ETo equation under missing climatic variable data as investigated under this study. The Penman-Monteith ETo equation showed good performance under limited data conditions across the New Mexico State. When solar radiation was estimated by the Hargreaves equation (Allen et al. 1998), the Penman-Monteith ETo was estimated with PE lower than 10% and RMSE lower than 0.40 mm/day and MAE lower than 0.25 mm/day with linear regression slope varying from 0.973 to 1.030 and R^2 from 0.97 to 0.99 (Table 3). The

methodology proposed by Hargreaves for estimating solar radiation is therefore applicable with a precision range of 97–99% under the semiarid and dry condition across New Mexico. Under missing relative humidity data, the Penman-Monteith generally performed well with regression slope that varied from 0.847 to 0.961 and R^2 from 0.96 to 0.99 and RMSE from 0.25 to 1.05 mm/day (Table 3). The best performance was shown at Alcalde and the poorest one at Tucumcari and Fabian-Garcia. Using the long-term average wind speed at each weather station, the Penman-Monteith performed very well with regression slope between 0.973 and 0.999 and coefficient of determination higher than 0.86, PE lower than 16%, and very low MBE varying from –0.01 to 0.09 mm/day (Table 3). When the global average wind speed of 2 m/s was considered in the case of missing wind speed data, the Penman-Monteith equation overestimated daily ETo at Alcalde where the long-term average wind speed was lower and averaged 1.19 m/s. ETo underestimation was observed at Farmington and Tucumcari where the average wind sped was greater than 2 m/s (Table 1). Under missing more than one climatic variable, Penman-Monteith only showed relatively good performance as shown by the

Fig. 2 Relationship between Penman-Monteith ETo model (P-M ETo) with full data and Penman-Monteith ETo with missing climatic data (pooled data)



regression slopes, R^2 , RMSE, MBE, and MAE (Table 3). Overall, the Penman-Monteith equation could be used under missing climatic data as shown by the Fig. 2. However, Penman-Monteith equation tended to underestimate daily ETo at values greater than 8 mm/day under missing wind speed and when more than one climate variable are missing (Fig. 2). Under missing solar radiation, the results are in agreement with those of Djaman et al. (2016b) who reported that when solar radiation was estimated from air temperatures, ETo was accurately estimated with regression slope that varied from 0.98 to 1.04, RMSE less than 0.60 mm/day, and MBE that ranged from –0.18 to 0.02 mm/day while relatively poor to acceptable results were obtained in the case of missing relative humidity and wind speed data in the semiarid climatic condition across Burkina Faso. Córdova et al. (2015) reported 24% error under missing solar radiation, 14% error under missing relative humidity, and 30% error when only temperature data is available using the Penman-Monteith equation for ETo estimation in the high Andes of southern Ecuador. Tomas-Burguera et al. (2017) reported the applicability of the Penman-Monteith equation under limited data at monthly scale in the Iberian Peninsula. Hsin-Fu (2017) showed that ETo was slightly overestimated by the Penman-Monteith equation under missing solar radiation and wind speed in Taiwan while it was underestimated under missing RH and when only temperature data is available. Similar results were obtained by Jabloun and Sahli (2008) who reported large discrepancies when ETo was estimated by the Penman-Monteith equation with limited data under semiarid climate conditions in Tunisia. The results of the present study are in agreement with Popova et al. (2006) who reported that the Penman-Monteith accurately estimated ETo under missing solar radiation, relative humidity and wind speed (adopting the global average wind speed of 2 m/s) and when only temperature data is available in Bulgaria. Sentelhas et al. (2010) reported ETo overestimation under missing relative humidity and solar radiation in Canada using the Penman-Monteith equation. Stöckle et al. (2004) reported that under missing solar radiation and relative humidity, the Penman-Monteith equation performed from poor to acceptable in the arid and semiarid locations; however, it acceptably performed at weekly scale. Similar results were obtained by Djaman et al. (2017a) who found that the Penman-Monteith equation reasonably estimated the daily ETo under missing solar radiation, relative humidity, and wind speed data with regression slopes varying from 0.68 to 0.89, from 0.79 to 1.00, and from 0.79 to 0.96, respectively, and root mean squared error (RMSE) lower than 0.63, 0.53, and 0.44 mm/day under the respective conditions under humidity climate in Tanzania and Western Kenya. They indicated that when more than one climatic variable is missing, the Penman-Monteith poorly estimated the daily ETo similar to the results of the present study.

3.2 Performance of the selected ETo equations and the calibrated Hargreaves ETo equation

The selected ETo equations showed different performance at the five weather stations under this study. Among the 34 ETo equations under this study, the Valiantzas 5 showed the best performance at all locations with regression slope almost unity and R^2 of 1, RMSE varying from 0.12 and 0.17 mm/day, PE averaging 3.2% and MBE from –0.04 to 0.04 mm/day. With a precision of 100% and high accuracy, the Valiantzas 5 is a good alternative the Penman-Monteith equation across the study area. The Valiantzas 4 also showed good performance at all locations (Figs. 3, 4, and 5). Figures 3, 4, and 5 summarize the performance statistics of the models showing the best-performing models in terms of R^2 , regression slope, RMSE, MBE, and MAE. The Allen, Droogres, Jensen-Haise, Ahoo1, Abtew, Makkink, Abrecht, Bro-We, and WMO equations

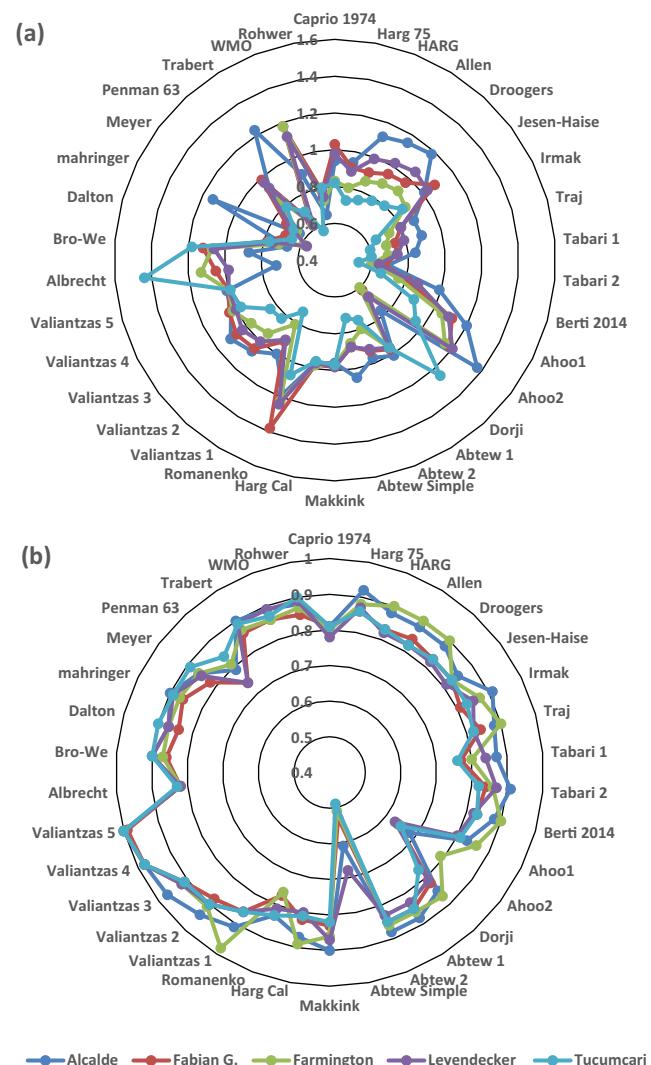


Fig. 3 Regression slope (a) and coefficient of determination (b) between Penman-Monteith and the selected ETo equation at Alcalde, Fabian Garcia, Farmington, Leyendecker, and Tucumcari

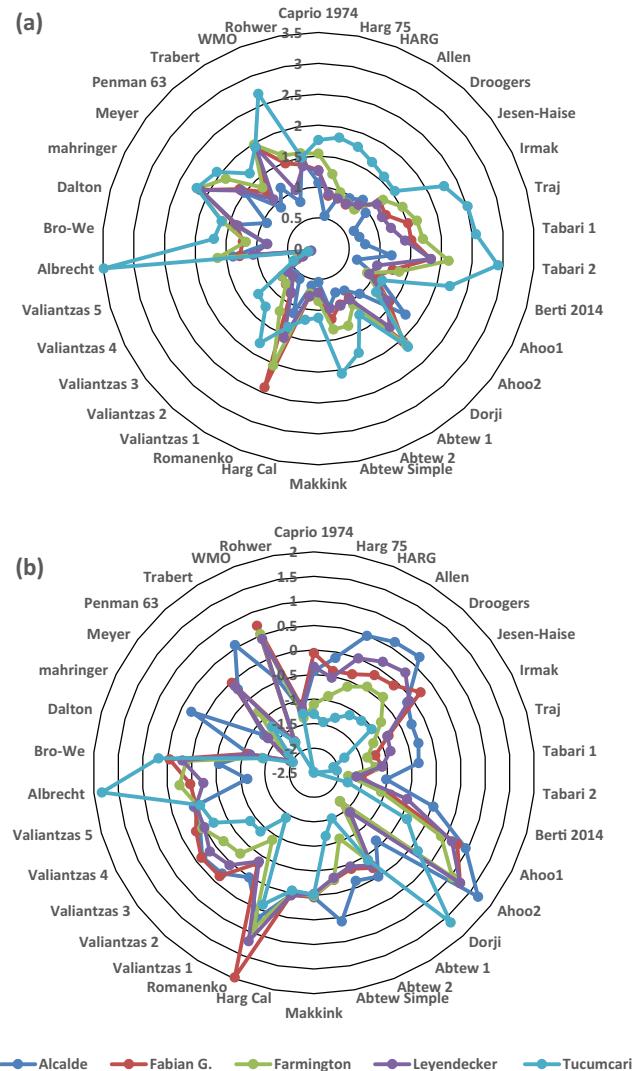


Fig. 4 Root mean square error (a) and percent error (b) between Penman-Monteith and the selected ETo equation at Alcalde, Fabian Garcia, Farmington, Leyendecker, and Tucumcari

performed very well compared to the Penman-Monteith equations with simple linear regression slope close to unity (Fig. 3a) and precision greater than 80% (Fig. 3b). However, the RMSE and PE obtained were relatively high and negative MBE synonym of low accuracy of ETo estimation by these equations. The Mahringer equation showed the poorest performance overall with RMSE as high as 2.18 mm/day (Fig. 4a), PE as high as 48% (Fig. 4b), and MBE as high as 2 mm/day (Fig. 5a). The calibration of Hargreaves equation improved its performance with 25% reduction in the RMSE, 103% reduction in the MBE (Fig. 5a), and 25% reduction in MAE (Fig. 5b). The Abtew and the calibrated Abtew equations showed similar performance indicating the great performance of the Abtew equation under the semiarid dry climate across New Mexico whenever this equation was developed under humid climate in Florida. However, the simple Abtew equation underestimated daily ETo by 29% on average. The

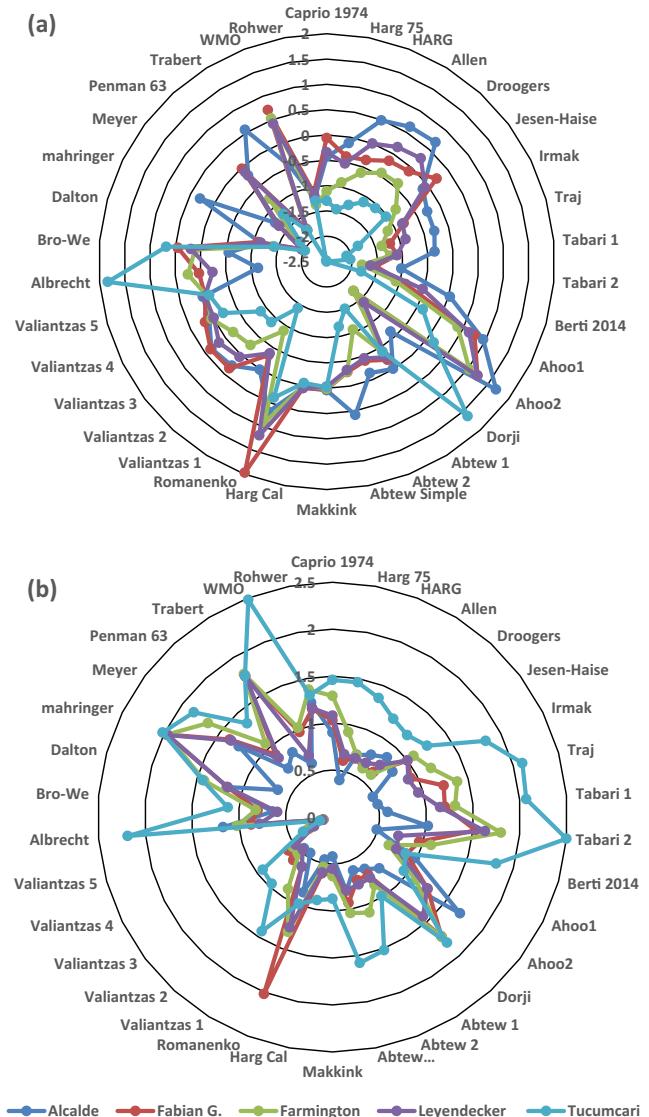


Fig. 5 Mean bias error (a) and mean absolute error (b) between Penman-Monteith and the selected ETo equation at Alcalde, Fabian Garcia, Farmington, Leyendecker, and Tucumcari

best ETo equations using the criteria of regression slope greater than 0.90 and a precision greater than 80% with comparison to the Penman-Monteith equation were Valiantzas 5, Valiantzas 4, Valiantzas 3, Makkink, Calibrated Harvreibes, Abtew, Jensen-Haise, Valiantzas 2, and Caprio equations (Fig. 6). The constant of the Abtew equation during the calibration was 53.7794242 at Alcalde, Fabian-Garcia, and Leyendecker, 47.0270716 at Farmington, and 43.677216 at Tucumcari. The calibrated constants K , b , and c as shown in Eq. 17 for the Hargreaves ETo equation were 0.00202, 27.758, 0.40879 at Alcalde; 0.00346, 32.108, 0.26937 at Fabian-Garcia; 0.00234, 28.069, 0.45067 at Farmington; 0.00289, 38.254, 0.26935 at Leyendecker; and 0.00241, 26.120, 0.50136 at Tucumcari, respectively. Most of the ETo equations performed with PE greater than the suggested upper

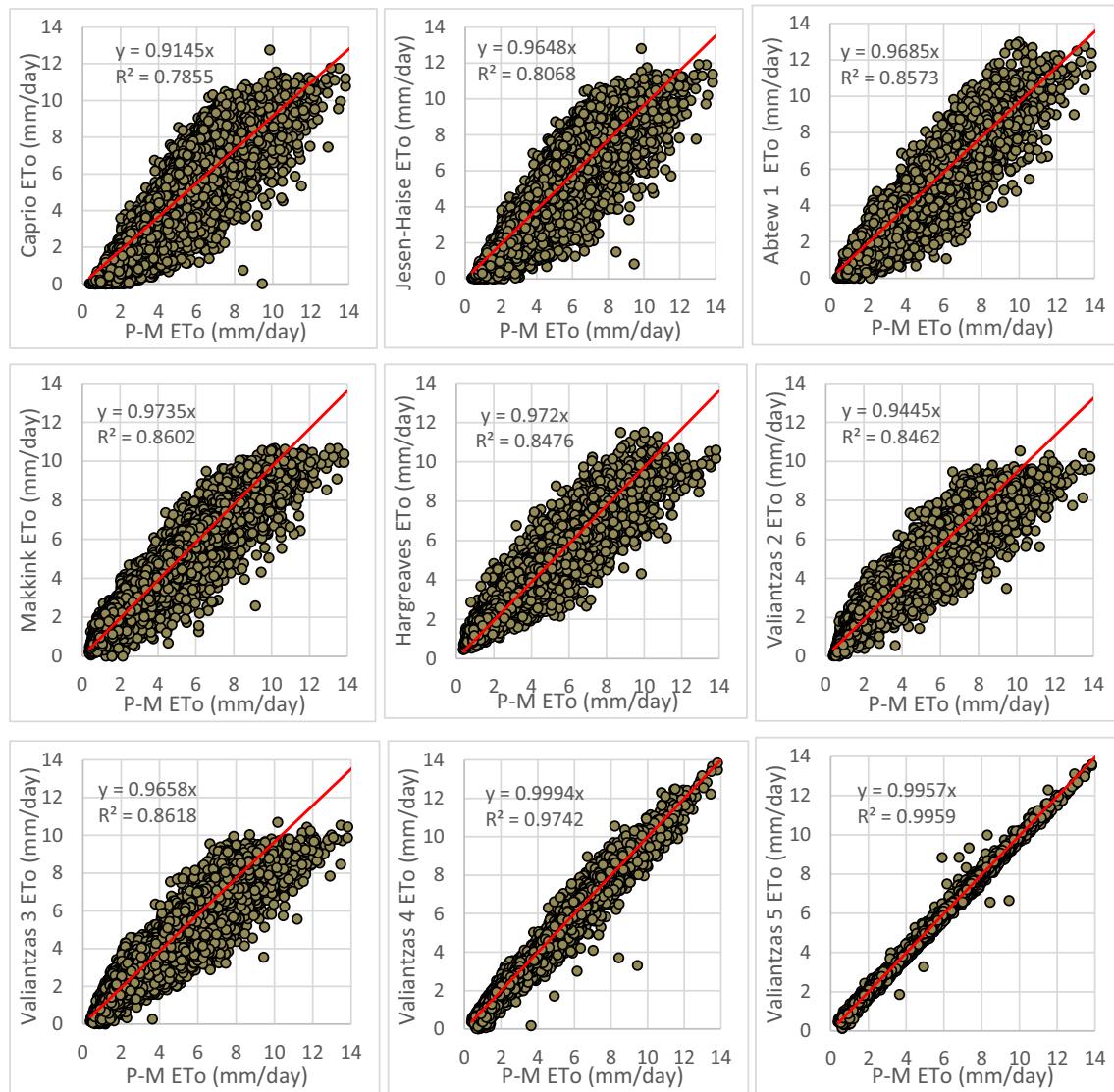


Fig. 6 Comparison of daily ETo estimated by methods versus Penman-Monteith model (P-M ETo) and the best simple ETo equations with regression slope greater than 0.90 and R^2 greater than 0.80 (pooled data)

limit of 15% Allen (1993). Gao et al. (2017) reported that the Priestly-Taylor and 1985 Hargreaves equations performed best in the arid and semiarid regions, while the 1957 Makkink was more adapted to the humid region in China. The Tur and Makkink equations were found to work the best for crop evapotranspiration estimation in the prairie region of Canada (Martel et al. 2018). The Abtew ETo equation performed the best among 11 selected ETo equation in the semiarid climate in Mali (Djaman et al. 2017c) while Xu and Singh (2000) reported the adaptability of the simple Abtew equation to the state of Vaud in Switzerland when only solar radiation data are available. ETo estimates by the Romanenko ETo equation showed 59% of error in Greece (Bourletsikas et al. 2017). The Jansen and Haise equation showed the best performance among six ETo equations with PE as low as 2% at Yaoude in Cameroun (Tellen 2017), and the Berti ETo

equation was selected the best alternative of the Penman-Monteith equation in the mainland China (Peng et al. 2017). Xu et al. (2016) selected the Hargreaves equation as the best alternative of the Penman-Monteith equation in the arid China. The results of this study are in agreement with Morales-Salinas et al. (2017) who reported that after calibration, Hargreaves ETo equation showed only 5% error with comparison the Penman-Monteith equation in the central-southern Chile. Čadro et al. (2017) indicated that the calibrated Trajkovic and Hargreaves equations to the local climate showed best performance among 33 ETo equations as compared to the Penman-Monteith in Bosnia and Herzegovina. Hargreaves equation was used to estimate daily ETo under hyper arid to sub-humid environment in the Mongolia (China) with RMSE lower than 1 mm/day (Ren et al. 2016). Feng et al. (2017) reported that the original and the calibrated

Hargreaves ETo equations overestimated ETo in Sichuan basin of southwest China. However, they indicated that the Hargreaves ETo equation estimated ETo value closer to the Penman-Monteith equation and proposed the adoption of the calibrated Hargreaves equation for ETo estimation Sichuan basin of southwest China when only temperature data is available. The Berti ETo equation (Berti et al. 2014) is one form of the Hargreaves' equation, as the best alternative to the Penman-Monteith with good spatial accuracy in the mainland China (Peng et al. 2017). Hargreaves equation tended to overestimate ETo in Burgaria (Popova et al. 2006). The Hargreaves and Trajkovic equations systematically overestimated daily ETo by 20–93% under semiarid condition in the Northern Senegal (Djaman et al. 2015). Heydari and Heydari (2014) reported relatively poor performance of the Hargreaves equation with RMSE as high as 5.38 mm/day and MBE as low as –5.35 mm/day, respectively, in the semiarid arid climate in Iran. They reported that the calibration of Hargreaves ETo equation improved the RMSE and MBE values by 40% and 66%, respectively. Fooladmand and Haghigat (2007) reported that different Hargreaves coefficients should be used for each month of year and yearly time step instead of the original coefficient of 0.0023 in the Hargreaves equation and recommended calibration of the Hargreaves equation to the local climate before its adoption for ETo estimation. Tabari and Talaee (2011) indicated the need to calibrate the Hargreaves equation to the arid climate in Iran and changed the Hargreaves coefficient from 0.0023 to 0.0031. The Hargreaves and the Droogers and Allen (2002) equations showed poor estimation on the daily ETo with RMSE range that varied from 1.39 to 3.21 mm/day in the semiarid regions and 2.56 to 4.83 mm/day in the arid region of Jordan (Mohawesh 2011).

4 Conclusion

The Penman-Monteith and 34 simple reference evapotranspiration equations were evaluated under limited climatic data conditions at five weather stations in New Mexico, USA. The Penman-Monteith ETo equation performed well under missing solar radiation, relative humidity, and wind speed. The Penman-Monteith ETo was estimated with PE lower than 10% and RMSE lower than 0.40 mm/day and MAE lower than 0.25 mm/day with linear regression slope varying from 0.973 to 1.030 and a precision from 97 to 99%. Under missing relative humidity data, the Penman-Monteith generally performed well with regression slope that varied from 0.847 to 0.961 and R^2 from 0.96 to 0.99 and RMSE from 0.25 to 1.05 mm/day. The best performance was shown at Alcalde and the poorest one at Tucumcari. Using the long-term average wind sped at each weather

station, the Penman-Monteith equation performed very well with regression slope between 0.973 and 0.999 and coefficient of determination R^2 as higher than 0.86, PE lower than 16%, and very low MBE varying from –0.01 to 0.09 mm/day. However, Penman-Monteith equation tended to underestimate daily ETo at values greater than 8 mm/day under missing wind speed and when more than one climate variable are missing. The best simple ETo equations that showed good ETo estimation accuracy with regression slope greater than 0.90 and precision greater than 80% were four of the Valiantzas combination equations, the Makkink, Calibrated Harvreaves, Abtew, Jensen-Haise, and Caprio temperature or radiation-based equations and could be considered as the best alternative ETo estimation methods under the semiarid dry climate across New Mexico.

References

- Abtew W (1996) Evapotranspiration measurements and modelling for three wetland systems in South Florida. *J Am Water Resour Assoc* 32:465–473
- Ahooghalandari M, Khiadani M, Jahromi ME (2016) Developing equations for estimating reference evapotranspiration in Australia. *Water Resour Manag* 30(11):3815–3828
- Ahooghalandari M, Khiadani M, Jahromi ME (2017) Calibration of Valiantzas' reference evapotranspiration equations for the Pilbara region, Western Australia. *Theor Appl Climatol* 128:845–856
- Albrecht F (1950) DieMethoden zur Bestimmung Verdunstung der Natürlichen Erdoberfläche. *Archives Meteorological Geophysics B2*:1–38
- Allen RG (1993) Evaluation of a temperature difference method for computing grass reference evapotranspiration. Technical report, Water Resources Development and Management Service, and Water Development Division, FAO, Rome
- Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-guidelines for computing crop water requirements—FAO irrigation and drainage paper 56. FAO, Rome
- Arellano GM, Irmak S (2016) Reference (potential) evapotranspiration: Part I. Comparison of temperature, radiation, and combination-based energy balance equations in humid, subhumid, arid, semiarid and Mediterranean-type climates. *J Irrig Drain Eng* 142(4): 04015065
- ASCE-EWRI (2005) The ASCE standardized reference evapotranspiration equation. In: Allen RG, Walter IA, Elliot RL, et al. (eds.) Environmental and Water Resources Institute (EWRI) of the American Society of Civil Engineers, ASCE, Standardization of Reference Evapotranspiration Task Committee Final Report, 213pp. Reston, VA: American Society of Civil Engineers (ASCE)
- Aschonitis VG, Papamichail D, Demertzis K, Colombani N, Mastrocicco M, Ghirardini A, Castaldelli G, Fano EA (2017) High resolution global grids of revised Priestley-Taylor and Hargreaves-Samani coefficients for assessing ASCE-standardized reference crop evapotranspiration and solar radiation. *Earth Syst Sci Data* 9:615–638
- Berti A, Tardivo G, Chiaudani A, Rech F, Borin M (2014) Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy. *Agric Water Manag* 140:20–25

- Bodner G, Loiskandl W, Kaulm H (2007) Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agric Water Manag* 93:85–98
- Bogawski P, Bednorz E (2014) Comparison and validation of selected evapotranspiration models for conditions in Poland (Central Europe). *Water Resour Manag* 28(14):5021–5038
- Bourletsikas A, Argyrokastritis I, Proutsos N (2017) Comparative evaluation of 24 reference evapotranspiration equations applied on an evergreen-broadleaved forest. *Hydrology Research*, nh2017232; DOI: 10.2166/nh.2017.23
- Brockamp B, Wenner H (1963) Verdunstungsmessungen auf den Steiner See bei Munster. *Dt Gewa sserkundl Mitt* 7:149–154
- Čadro S, Uzunović M, Žurovec J, Žurovec O (2017) Validation and calibration of various reference evapotranspiration alternative methods under the climate conditions of Bosnia and Herzegovina. *Inter Soil Water Conservation Res* 5:309–324. <https://doi.org/10.1016/j.iswcr.2017.07.002>
- Caprio JM (1974) The solar thermal unit concept in problems related to plant development and potential evapotranspiration. H. Lieth (Ed.), *Phenology and seasonality modeling*. Ecological Studies, Springer Verlag, New York (1974), pp. 353–364
- Córdova M, Carrillo-Rojas G, Crespo P, Wilcox B, Céller R (2015) Evaluation of the Penman-Monteith (FAO 56 PM) method for calculating reference evapotranspiration using limited data. *Mt Res Dev* 35(3):230–239
- Dalton J (1802) Experimental essays on the constitution of mixed gases; on the force of steam of vapour from waters and other liquids in different temperatures, both in a torricellian vacuum and in air on evaporation and on the expansion of gases by heat. *Mem Manch Lit Philos Soc* 5:535–602
- Djaman K, Balde AB, Sow A, Muller B, Irmak S, N'Diaye MK, Manneh B, Moukoumbi YD, Futakuchi K, Saito K (2015) Evaluation of sixteen reference evapotranspiration methods under sahelian conditions in the Senegal River Valley. *J Hydrology: Regional Studies* 3: 139–159
- Djaman K, Tabari H, Balde AB, Diop L, Futakuchi K, Irmak S (2016a) Analyses, calibration and validation of evapotranspiration models to predict grass reference evapotranspiration in the Senegal River Delta. *J Hydrology: Regional Studies* 8:82–94
- Djaman K, Irmak S, Kabenge I, Futakuchi K (2016b) Evaluation of the FAO-56 Penman-Monteith model with limited data and the Valiantzas models for estimating reference evapotranspiration in the Sahelian conditions. *J Irrig Drain Eng* 142(11):04016044
- Djaman K, Irmak S, Futakuchi K (2017a) Daily reference evapotranspiration estimation under limited data in Eastern Africa. *J Irrig Drain Eng* 143(4):0001154
- Djaman K, Rudnick D, Mel VC, Mutiibwa D, Diop L, Sall M, Kabenge I, Bodian A, Tabari H, Irmak S (2017b) Evaluation of the Valiantzas' simplified forms of the FAO-56 Penman-Monteith reference evapotranspiration model under humid climate. *J Irrig Drain Eng* 133(8): 0001191
- Djaman K, Koudahe K, Allen S, O'Neill M, Irmak S (2017c) Validation of Valiantzas' reference evapotranspiration equation under different climatic conditions. *J Irrig Drain Eng* 6:3. <https://doi.org/10.4172/2168-9768.1000196>
- Dorji U, Olesen JE, Seidenkrantz MS (2016) Water balance in the complex mountainous terrain of Bhutan and linkages to land use. *J Hydrology: Regional Studies* 7:55–68
- Droogers P, Allen RG (2002) Estimating reference evapotranspiration under inaccurate data conditions. *Irrig Drain Syst* 16:33–45
- Feng Y, Jia Y, Cui N, Zhao L, Li C, Gong D (2017) Calibration of Hargreaves model for reference evapotranspiration estimation in Sichuan basin of southwest China. *Agric Water Manag* 181:1–9
- Fooladmand HR, Haghhighat M (2007) Spatial and temporal calibration of Hargreaves equation for calculating monthly ETo based on Penman-Monteith method. *Irrig Drain* 56:39–449
- Gao X, Peng S, Xu J, Yang S, Wang W (2015) Proper methods and its calibration for estimating reference evapotranspiration using limited climatic data in Southwestern China. *Arch Agron Soil Sci* 61:415–426
- Gao F, Feng G, Ouyang Y, Wang H, Fisher D, Adeli A, Jenkins J (2017) Evaluation of reference evapotranspiration methods in arid, semiarid, and humid regions. *J Am Water Resour Assoc* 53(4):791–808
- Hargreaves GH (1975) Moisture availability and crop production. *Trans ASAE* 18:980–984
- Hargreaves GH, Samani ZA (1982) Estimating potential evapotranspiration. *J Irrig Drain Engr ASCE* 108(IR3):223–230
- Hargreaves GH, Samani Z (1985) Reference crop evapotranspiration from temperature. *Appl Eng Agric* 1(2):96–99
- Heydari MM, Heydari M (2014) Calibration of Hargreaves-Samani equation for estimating reference evapotranspiration in semiarid and arid regions. *Arch Agron Soil Sci* 60:695–713
- Hsin-Fu Yeh (2017) Comparison of evapotranspiration methods under limited data. DOI: 10.5772/intechopen.68495. Chapter from the book Current perspective to predict actual evapotranspiration. Downloaded from: <http://www.intechopen.com/books/current-perspective-to-predict-actual-evapotranspiration> Accessed 20 Dec 2017
- Irmak S, Irmak A, Allen R, Jones J (2003) Solar and net radiation-based equations to estimate reference evapotranspiration in humid climates. *J Irrig Drain Eng* 129:336–347
- Irmak S, Irmak A, Howell TA, Martin DL, Payero JO, Copeland KS (2008) Variability analyses of alfalfa-reference to grass-reference evapotranspiration ratios in growing and dormant seasons. *J Irrig Drain Eng ASCE* 134(2):147–159
- Jabloun M, Sahli A (2008) Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data: application to Tunisia. *Agric Water Manag* 95(6):707–715
- Jensen ME, Haise HR (1963) Estimating evapotranspiration from solar radiation. *Proceedings Am Soc Civil Engineers, J Irrig Drain Div* 89:15–41
- Jung CG, Lee DR, Moon JW (2016) Comparison of the Penman-Monteith method and regional calibration of the Hargreaves equation for actual evapotranspiration using SWAT-simulated results in the Seolma-cheon basin, South Korea. *Hydrol Sci J* 61:793–800
- Kisi O (2014) Comparison of different empirical methods for estimating daily reference evapotranspiration in Mediterranean climate. *J Irrig Drain Eng -ASCE* 140:04013002
- Lopez-Urrea R, Santa Olalla F, Fabeiro C, Moratalla A (2006) Testing evapotranspiration equations using lysimeter observations in a semiarid climate. *Agric Water Manag* 85:15–26
- Maestre-Valero JF, Martínez-Álvarez V, González-Real MM (2013) Regionalization of the Hargreaves coefficient to estimate long-term reference evapotranspiration series in SE Spain. *Span J Agric Res* 11(4):1137–1152
- Mahringer W (1970) Verdunstungsstudien am Neusiedler See. *Arch Met Geoph Biokl Ser B* 18:1–20
- Makkink GF (1957) Testing the Penman formula by means of lysimeters. *J Int Water Eng* 11:277–288
- Martel M, Glenn A, Wilson H, Kröbel R (2018) Simulation of actual evapotranspiration from agricultural landscapes in the Canadian Prairies. *J Hydrology: Regional Studies* 15:105–118
- 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 Sc* 17:1331–1363. <https://doi.org/10.5194/hess-17:1331-2013>
- Mendicino G, Senatore A (2013) Regionalization of the Hargreaves coefficient for the assessment of distributed reference evapotranspiration in southern Italy. *J Irrig Drain Eng* 139(5):349–362
- Meyer A (1926) Über einige Zusammenhänge zwischen Klima und Boden in Europa. *Chem Erde* 2:209–347

- Minacapilli M, Consoli S, Vanella D, Ciraolo G, Motisi A (2016) A time domain triangle method approach to estimate actual evapotranspiration: application in a Mediterranean region using MODIS and MSG-SEVIRI products. *Remote Sens Environ* 174:10–23
- Mohawesh OE (2011) Evaluation of evapotranspiration models for estimating daily reference evapotranspiration in arid and semiarid environments. *Plant Soil Environ* 57(4):145–152
- Morales-Salinas L, Ortega-Farías S, Riveros-Burgos C, Neira-Román J, Carrasco-Benavides M, López-Olivari R (2017) Monthly calibration of Hargreaves–Samani equation using remote sensing and Topoclimatology in central-southern Chile. *Int J Remote Sens* 38:7497–7513
- Ndiaye PM, Bodian A, Diop L, Djaman K (2017) Evaluation de vingt méthodes d'estimation de l'évapotranspiration journalière de référence au Burkina Faso. *Physio-Geo* 11-1:129–146
- Ortega-Farías S, Riveros-Burgos C, Neira-Román J, Carrasco-Benavides M, López-Olivari R (2017) Monthly calibration of Hargreaves–Samani equation using remote sensing and topoclimatology in central-southern Chile. *Int J Remote Sens* 38(24):7497–7513
- Pandey PK, Dabral PP, Pandey V (2016) Evaluation of reference evapotranspiration methods for the northeastern region of India. *Int Soil Water Conservation Res* 4:52–63
- Peng L, Li Y, Feng H (2017) The best alternative for estimating reference crop evapotranspiration in different sub-regions of mainland China. *Scientific Reports* 7, Article number: 5458 (2017). doi:10.1038/s41598-017-05660-y
- Penman LH (1963) Vegetation and hydrology. Tech. Comm. No. 53, Commonwealth Bureau of Soils, Harpenden, England, 125
- Popova Z, Kercheva M, Pereira LS (2006) Validation of the FAO methodology for computing ET with limited data application to south Bulgaria. *J Irrig Drain Eng* 55:201–215
- Ravazzani G, Corbari C, Morella S, Gianoli P (2012a) Modified Hargreaves–Samani equation for the assessment of reference evapotranspiration in Alpine River basins. *J Irrig Drain Eng* 148(7). [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000453](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000453)
- Ravazzani G, Corbari C, Morella S, Gianoli P, Mancini M (2012b) Modified Hargreaves–Samani equation for the assessment of reference evapotranspiration in Alpine River Basins. *J Irrig Drain Eng ASCE* 138(7):592–599
- Ren X, Qu Z, Martins DS, Parades P, Pereira LS (2016) Daily reference evapotranspiration for hyper-arid to moist sub-humid climates in inner Mongolia, China: I. Assessing temperature methods and spatial variability. *Water Res Management* 30:3769–3791
- Rohwer C (1931) Evaporation from free water surface. USDA Tech Null 217:1–96
- Rojas JP, Sheffield RE (2013) Evaluation of daily reference evapotranspiration methods as compared with the ASCE-EWRI Penman–Monteith equation using limited weather data in northeast Louisiana. *J Irrig Drain Eng* 139:285–292
- Romanenko VA (1961) Computation of the autumn soil moisture using a universal relationship for a large area. Proceedings, Ukrainian Hydrometeorological Research Institute, No. 3 Kiev (1961)
- Sentelhas P, Gillespie T, Santos E (2010) Evaluation of FAO Penman–Monteith and alternative methods for estimating reference evapotranspiration with missing data in southern Ontario, Canada. *Agric Water Manag* 97(5):635–644
- Stöckle C, Kjelgaard J, Bellocchi G (2004) Evaluation of estimated weather data for calculating Penman–Monteith reference crop evapotranspiration. *Irrig Sci* 23(1):39–46
- Tabari H, Talaee PH (2011) Local calibration of the Hargreaves and Priestley–Taylor equations for estimating reference evapotranspiration in arid and cold climates of Iran based on the Penman–Monteith model. *J Hydrol Eng* 16:837–845
- Tabari H, Grismer ME, Trajkovic S (2013) Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrig Sci* 31:107–117
- 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. *Earth Perspectives Transdisciplinarity Enabled* 2017 4:4. <https://doi.org/10.1186/s40322-017-0039-1>
- Thorntwaite CW (1948) An approach toward a rational classification of climate. *Geogr Rev* 38:55–94
- Todorovic M, Karic B, Pereira LS (2013) Reference evapotranspiration estimate with limited weather data across a range of Mediterranean climates. *J Hydrol* 481:166–176
- Tomas-Burguera M, Vicente-Serrano SM, Grimalt M, Beguería S (2017) Accuracy of reference evapotranspiration (ET_0) estimates under data scarcity scenarios in the Iberian Peninsula. *Agric Water Manag* 182: 103–116
- Trabert W (1896) Neue Beobachtungen über Verdampfungsgeschwindigkeiten. *Meteorol Z* 13:261–263
- Trajkovic S (2007) Hargreaves versus Penman–Monteith under humid conditions. *J Irrig Drain Eng* 133:38–42
- Trajkovic S, Kolakovic S (2009) Evaluation of reference evapotranspiration equations under humid conditions. *Water Resour Manag* 23(14):3057–3067
- Turc L (1961) Water requirements assessment of irrigation, potential evapotranspiration: simplified and updated climatic formula. *Annales Agronomiques* 12:13–49
- Valiantzas JD (2012) Simple ET forms of Penman's equation without wind and/or humidity data. I: theoretical development. *J Irrig Drain Eng* 10.1061/(ASCE)IR.1943-4774.0000520, 1–8
- Valiantzas JD (2013) Simplified reference evapotranspiration formula using an empirical impact factor for Penman's aerodynamic term. *J Irrig Drain Eng* 18(1):108–114
- Valipour M (2014) Investigation of Valiantzas' evapotranspiration equation in Iran. *Theor Appl Climatol* 121(1-2):267–278. <https://doi.org/10.1007/s00704-014-1240-x>
- WMO (1966) Measurement and estimation of evaporation and evapotranspiration. Tech. Pap. (CIMO-Rep) 83. Genf
- Xing Z, Chow L, Meng F, Rees HW, Monteith J, Lionel S (2008) Testing reference evapotranspiration estimation methods using evaporation pan and modeling in maritime region of Canada. *J Irrig Drain Eng* 134(4):417–424
- Xu CY, Singh VP (2000) Evaluation and generalization of radiation-based methods for calculating evaporation. *Hydro Process* 14: 339–349
- Xu J, Wang J, Wei Q, Wang Y (2016) Symbolic regression equations for calculating daily reference evapotranspiration with the same input to Hargreaves–Samani in arid China. *Water Resour Management* 30: 2055–2073
- Ystrakis F, Matzarakis A (2011) Evaluation of 13 empirical reference potential evapotranspiration equations on the island of Crete in southern Greece. *J Irrig Drain Eng* 137(4):211–222