

# Comparison of sum-of-hourly and daily time step standardized ASCE Penman-Monteith reference evapotranspiration

Koffi Djaman<sup>1</sup> · Suat Irmak<sup>2</sup> · Mamadou Sall<sup>3</sup> · Abdoulaye Sow<sup>1</sup> · Isa Kabenge<sup>4</sup>

Received: 21 February 2017 / Accepted: 6 October 2017  
© Springer-Verlag GmbH Austria 2017

**Abstract** The objective of this study was to quantify differences associated with using 24-h time step reference evapotranspiration (ET<sub>o</sub>), as compared with the sum of hourly ET<sub>o</sub> computations with the standardized ASCE Penman-Monteith (ASCE-PM) model for semi-arid dry conditions at Fanaye and Ndiaye (Senegal) and semiarid humid conditions at Sapu (The Gambia) and Kankan (Guinea). The results showed that there was good agreement between the sum of hourly ET<sub>o</sub> and daily time step ET<sub>o</sub> at all four locations. The daily time step overestimated the daily ET<sub>o</sub> relative to the sum of hourly ET<sub>o</sub> by 1.3 to 8% for the whole study periods. However, there is location and monthly dependence of the magnitude of ET<sub>o</sub> values and the ratio of the ET<sub>o</sub> values estimated by both methods. Sum of hourly ET<sub>o</sub> tends to give higher ET<sub>o</sub> during winter time at Fanaye and Sapu, while the daily ET<sub>o</sub> was higher from March to November at the same weather stations. At Ndiaye and Kankan, daily time step estimates of ET<sub>o</sub> were high during the year. The simple linear regression slopes between the sum of 24-h ET<sub>o</sub> and the daily time step ET<sub>o</sub> at all weather stations varied from 1.02 to 1.08 with high coefficient of determination ( $R^2 \geq 0.87$ ). Application of the hourly ET<sub>o</sub>

estimation method might help on accurate ET<sub>o</sub> estimation to meet irrigation requirement under precision agriculture.

## 1 Introduction

Accurate estimation of crop evapotranspiration (ET<sub>c</sub>) in rainfed and irrigated agriculture is becoming increasingly important for better planning and efficient use of water resources, especially in arid or semi-arid environments under changing climate conditions. The most common procedure for computing crop evapotranspiration is to adjust reference evapotranspiration (ET<sub>o</sub>) using a crop coefficient (K<sub>c</sub>, where ET<sub>c</sub> = ET<sub>o</sub> · K<sub>c</sub>). The K<sub>c</sub> represents the integrated effects of changes in leaf area, plant height, crop characteristics, irrigation method, rate of crop development, crop planting or sowing date, degree of canopy cover, canopy resistance, soil and climate conditions, and management practices (Irmak et al. 2013; Djaman and Irmak 2013). Different methods for estimation of reference evapotranspiration exist and range from direct measurement from a reference crop such as a perennial grass (Doorenbos and Pruitt 1977; Watson and Burnett 1995) to computation from weather data using: (a) temperature models (Thornthwaite 1948; Doorenbos and Pruitt 1977), (b) radiation models (Doorenbos and Pruitt 1977; Hargreaves and Samani 1985), and (c) combination-based energy balance models (Allen et al. 1998; ASCE-EWRI 2005). Numerous worldwide studies have shown that the FAO 56 Penman-Monteith (PMF-56) model is the most accurate one under different climatic conditions across the world (Allen et al. 1998; Irmak et al. 2003; Hargreaves and Allen 2003; Garcia et al. 2004; ASCE-EWRI 2005; López-Urrea et al. 2006; Bodner et al. 2007; Irmak et al. 2008; Jabloun and Sahli 2008; Xing et al. 2008; Trajkovic and Kolakovic 2009; Martinez and Thepadia 2010; Tabari et al. 2011; Xystrakis

✉ Koffi Djaman  
k.djaman@cgiar.org

<sup>1</sup> Africa Rice Center (AfricaRice), Regional Sahel Station, Senegal, B.P. 96, St Louis, Senegal

<sup>2</sup> Department of Biological Systems Engineering, University of Nebraska-Lincoln, 241 L.W. Chase Hall, Lincoln, NE 68583-0726, USA

<sup>3</sup> Chargé de recherches Agro-hydrologie /Irrigation ISRA, BP 240 Saint-Louis, Sénégal

<sup>4</sup> Department of Agricultural and Biosystems Engineering, Makerere University, P.O. Box 7062, Kampala, Uganda

and Matzarakis 2011; Azhar and Perera 2011). Mendonça et al. (2003) reported that the PMF-56 method provided the best ETo estimates when compared to lysimeter data. Utset et al. (2004) and Villa Nova et al. (2006) also reported that the PMF-56 method is the most accurate to calculate the ETo compared to other models. However, data requirement for the PMF-56 method is a problem in developing countries, and the procedure developed by Allen et al. (1998) to estimate missing data has showed accuracy of the ETo estimation under different climatic conditions. The Penman-Monteith evapotranspiration model (PM-ETo) applied when only maximum and minimum air temperature in general provided satisfactory ETo estimates as compared to the Penman-Monteith model using full data in various locations in Tunisia under semiarid conditions (Jabloun and Sahli 2008). Sentelhas et al. (2010) reported that the PM-ETo method was still a very good option for estimating ETo for Southern Ontario under missing relative humidity (RH) and wind speed, with root mean squared errors (RMSE) smaller than 0.53 mm/day. Ngongondo et al. (2013) demonstrated good performance of the PM-ETo under limited data conditions in the Southern Malawi. In contrast, when deriving solar radiation from maximum and minimum air temperature, the PM-ETo method consistently overestimated daily ETo as compared to the PM-ETo with full data in Mississippi (Fisher and Pringle 2013).

Moreover, to overcome data non-availability for the use of the PM-ETo method, different simple ETo equations were evaluated across the world for their accuracy. Singh and Xu (1997) reported good performance of evaporation equation after their calibration to the local climatic conditions in north-western Ontario, Canada. Xu and Singh (2000) and Xu and Singh (2001) evaluated some radiation-based evaporation equations (Abtew, Hargreaves, Makkink, Priestley, and Taylor and Turc) at Changins station in Switzerland and had reported that recalibration of the equations improved their performance and concluded that the simple Abtew equation could be used when other meteorological data except radiation are missing. Xu and Singh (2001) demonstrated necessity of recalibration of seven temperature-based equations for evaporation estimation in north-western Ontario, Canada indicating that with proper recalibration, the modified Blaney-Criddle, the Hargreaves, and Thornthwaite methods can be recommended for estimating evaporation in the study region. Martinez and Thepadia (2010) recommended the Turc equation to be used in Florida for estimating ETo when locally calibrated equation is not available. Tabari et al. (2011) reported that the two radiation-based equations developed by the authors, the temperature-based Blaney-Criddle (Blaney and Criddle 1962), and the Hargreaves-M4 equations (Hargreaves and Samani 1985) and the Snyder pan evaporation-based equation (Snyder 1992) were the best performing methods from 31 ETo equations under their

investigation. The Hansen and Turc equations were reported as the most useful with the least average monthly errors in Greece (Xystrakis and Matzarakis 2011). Trajkovic and Kolakovic (2009) indicated that the Turc's equation was the best in the Western Balkans in Europe. López-Urrea et al. (2006) reported that the Hargreaves and Samani (1985) method was the most accurate among five equations for estimating ETo under a semi-arid climate in Spain. Valiantzas (2013a, b, c, d) had developed simplified forms of the PM-ETo equation that estimate daily ETo with accuracy under limited data in Turkey (Kisi 2014), the Senegal River Valley (Djaman et al. 2015), in China (Gao et al. 2015), Iran (Valipour 2015), Australia (Ahooghalandari et al. 2016), and Burkina Faso (Djaman et al. 2016). The applicability of different ETo methods under different climate conditions depends on their complexity and the required climatic variables data and their availability (Droogers and Allen 2002; Xu and Singh 2000; Yoder et al. 2005; Xing et al. 2008; Tabari et al. 2011; Liou and Kar 2014; Valipour 2014, 2015; Tabari et al. 2013; Trajkovic and Kolakovic 2009; Sentelhas et al. 2010; Perera et al. 2015; Djaman et al. 2015; Gao et al. 2015; Arellano and Irmak 2015; Djaman et al. 2016; Almorox and Grieser 2016; Koedyk and Kingston 2016; Ahooghalandari et al. 2016).

The standardized Penman-Monteith equation has been adopted and recommended for daily ETo estimation (ASCE-EWRI 2005) among the various methods, and new forms of the equation were developed for ETo estimation at hourly or shorter time steps with different parameters for daily, hourly, or shorter time steps. The standardized ASCE Penman-Monteith (ASCE-PM) equation, based on a surface resistance of  $50 \text{ s m}^{-1}$  during daytime and  $200 \text{ s m}^{-1}$  during nighttime, provided the best agreement with the full form of the ASCE-PM method applied on a daily basis. Numerous comparative studies of the sum of 24-h ETo and daily time step ETo were reported for several parts of the world including the USA (Itenfisu et al. 2003; Irmak et al. 2005, 2011; Jia et al. 2008), Turkey (Yildirim et al. 2004), Australia (Perera et al. 2015), Spain (Gavilán et al. 2008), and Iran (Bakhtiari et al. 2009). Gavilán et al. (2008) showed very small average difference of 2% between the two ETo estimation steps in Andalusia, Southern Spain. Good and consistent agreement between the sum of hourly PM-ETo using 15-min climate data and the daily average ETo in humid climate across the state of Georgia in the USA was reported by Suleiman and Hoogenboom (2009).

While the aforementioned studies provide valuable information on the accuracy of using the ASCE-PM under hourly and daily time steps at several parts of the world, extremely limited data and information is available on the agreement of the evapotranspiration time steps in western part of Africa, particularly in the Senegal River and Gambia River basins where irrigated and rainfed rice productions are predominant beside rainfed sorghum, millet, maize, groundnut, and water

melon. The variations between the hourly and daily time step ETo computations within these basins, especially in semi-arid regions of the Senegal River Basin, are not known. The objective of this study was to quantify differences associated with using 24-h time step ETo, as compared with the sum of hourly ETo computations with the ASCE-PM for semi-arid hot and semiarid humid conditions in the western Africa.

## 2 Materials and methods

### 2.1 Weather stations and data collected

Data under this study were collected from four automated weather stations within three countries: Ndiaye and Fanaye in Senegal, Sapu in The Gambia, and Kankan in Guinea (Fig. 1 and Table 1). The Ndiaye station is located in the Senegal River Delta, 35 km inland, while Fanaye is located in the Senegal River valley, 150 km inland. Both areas for these stations are characterized by a typical Sahelian climate with a short rainy season from July to early October. The Kankan station is located in the East part of Guinea, about 600 km inland and has a tropical wet and dry savanna climate with a pronounced dry season in the low-sun months, and wet season in the high-sun months. The Sapu weather station is

located in the Central River District in The Gambia. The Gambia lies in the Sahelian climatic zone characterized by a short rainy season from June/July to October and a long dry and hot period between November and May. The average daily temperature is 30 °C in the dry season and 27 °C in the wet season.

Daily weather data, including wind speed, maximum and minimum air temperature, maximum and minimum relative humidity, and incoming solar radiation were measured over a well-watered grass surface using automated weather stations. The automatic agro-weather station CimAGRO® is installed in Africa Rice Center experimental fields at Ndiaye and Fanaye. It is an autonomous station powered by solar generator (Tamper-resistant built-in miniature solar panel) and is compliant with WMO recommendations for measurement quality. The incorporated sensors are the following: automatic rain gauge, air temperature and humidity under cover sensor, thermopile pyranometer, and wind sensors. All variables were sampled every 60 s and recorded on an hourly basis. The Sapu and Kankan stations are equipped with the WS-GP1 Automatic Weather Station that has carefully matched high grade sensors as rain gauge RG2, light sensor D-PYRPA-CA, RH, and air temperature sensor RHT3nl-CA able to measure rain, solar radiation, wind speed, wind direction, RH, and air temperature recorded with the GP1 Data Logger.



**Fig. 1** Map of Western Africa showing the weather stations at Ndiaye, Fanaye, Sapu, and Kankan (white big dots). (From Google Earth, accessed on May 14, 2016)

**Table 1** Geographical localization of the weather stations

Name station	Period covered	Latitude degree North	Longitude degree East	Altitude (m)	Country
Fanaye	2/6/2013–12/31/2015	16.53	– 14.8	17	Senegal
Ndiaye	2/6/2013–12/31/2015	16.22	– 16.29	9	Senegal
Sapu	3/7/2013–10/31/2015	13.56	– 14.87	41	The Gambia
Kankan	7/1/2014–12/15/2015	10.53	– 9.32	432	Guinea

## 2.2 Reference evapotranspiration model: Penman-Monteith (ASCE-EWRI 2005)

The ASCE-PM with  $C_n$  and  $C_d$  for daily time steps is exactly the same as the FAO-56-PM equation. However, for hourly time steps, the ASCE-PM uses a smaller value for surface resistance ( $r_s$ ) of vegetation per unit leaf area ( $s\ m^{-1}$ ) during daytime ( $50\ s\ m^{-1}$ ) and a larger value for  $r_s$  during night time ( $200\ s\ m^{-1}$ ). FAO 56-PM presumes constant  $r_s$  of  $70\ s\ m^{-1}$  during all periods (Allen et al. 1998). However, later, in 2005, FAO has recommended applying the FAO-56-PM for hourly or shorter periods using the same  $r_s$  coefficients as for the ASCE-PM (Allen et al. 2006).

The hourly ETo values calculation approach, following the description in the ASCE-EWRI report, was developed by Snyder and Eching (2006). Required data for ETo calculations using ASCE-PM approach included data about site characteristics (latitude and elevation) and weather data, as hourly solar radiation ( $R_s$ ) ( $MJ\ m^{-2}\ h^{-1}$ ), mean air temperature ( $T$ ) ( $^{\circ}C$ ), mean wind speed ( $u_2$ ) ( $m\ s^{-1}$ ), and mean dew point temperature ( $T_d$ ) ( $^{\circ}C$ ).  $T_d$  was calculated as recommended by Allen et al. (1998). Actual vapor pressure ( $ea$ ) (kPa) was calculated from mean saturation vapor pressure ( $es$ ) (kPa) and RH (%).

Daily grass-reference ET (ETo) was computed using the standardized ASCE form of the Penman-Monteith (ASCE-PM) equation (ASCE-EWRI 2005). The Penman-Monteith reference evapotranspiration equation with fixed stomatal resistance values for grass surface is:

$$E_{To} = \frac{0.408\Delta(R_n - G) + \gamma C_n u_2 / (T + 273)}{\Delta + \gamma(1 + C_d u_2)} (es - ea) \quad (1)$$

where ETo is the reference evapotranspiration (mm/day),  $\Delta$  is the slope of saturation vapor pressure versus air temperature curve ( $kPa\ ^{\circ}C^{-1}$ ),  $R_n$  = net radiation at the crop surface ( $MJ\ m^{-2}\ d^{-1}$ ),  $G$  = soil heat flux density at the soil surface ( $MJ\ m^{-2}\ d^{-1}$ ),  $T$  = mean daily air temperature at 1.5–2.5 m height ( $^{\circ}C$ ),  $u_2$  = mean daily wind speed at 2 m height ( $m\ s^{-1}$ ),  $es$  = the saturation vapor pressure (kPa),  $ea$  = the actual vapor pressure (kPa),  $es - ea$  = saturation vapor pressure deficit (kPa),  $\gamma$  = psychrometric constant ( $kPa\ ^{\circ}C^{-1}$ ),  $C_n$  = numerator constant that changes with reference surface and calculation time step ( $900\ ^{\circ}C\ mm\ s^3\ Mg^{-1}\ d^{-1}$  for 24-h time steps, and  $37\ ^{\circ}C$

$mm\ s^3\ Mg^{-1}\ h^{-1}$  for hourly time steps for the grass-reference surface),  $\gamma$  is the psychrometric constant ( $kPa\ ^{\circ}C^{-1}$ ), and  $\lambda$  is the latent heat of vaporization,  $2.45\ (MJ\ kg^{-1})$ .  $C_d$  = denominator constant that changes with reference surface and calculation time step ( $0.34\ s\ m^{-1}$  for 24-h time steps,  $0.24\ s\ m^{-1}$  for hourly time steps during daytime, and  $0.96\ s\ m^{-1}$  for hourly nighttime for the grass-reference surface). All parameters necessary for computing ETo were computed according to the procedure developed in FAO-56 by Allen et al. (1998).

## 2.3 Evaluation criteria

Comparisons were made using graphics and simple linear regression. The linear regressions were forced through the origin, because ideally, all equations should produce zero ETo when there is no evapotranspiration. Slopes, coefficient of determination ( $R^2$ ), and RMSE were used in comparing ETo and values estimated by the different procedures. The RMSE was estimated as:

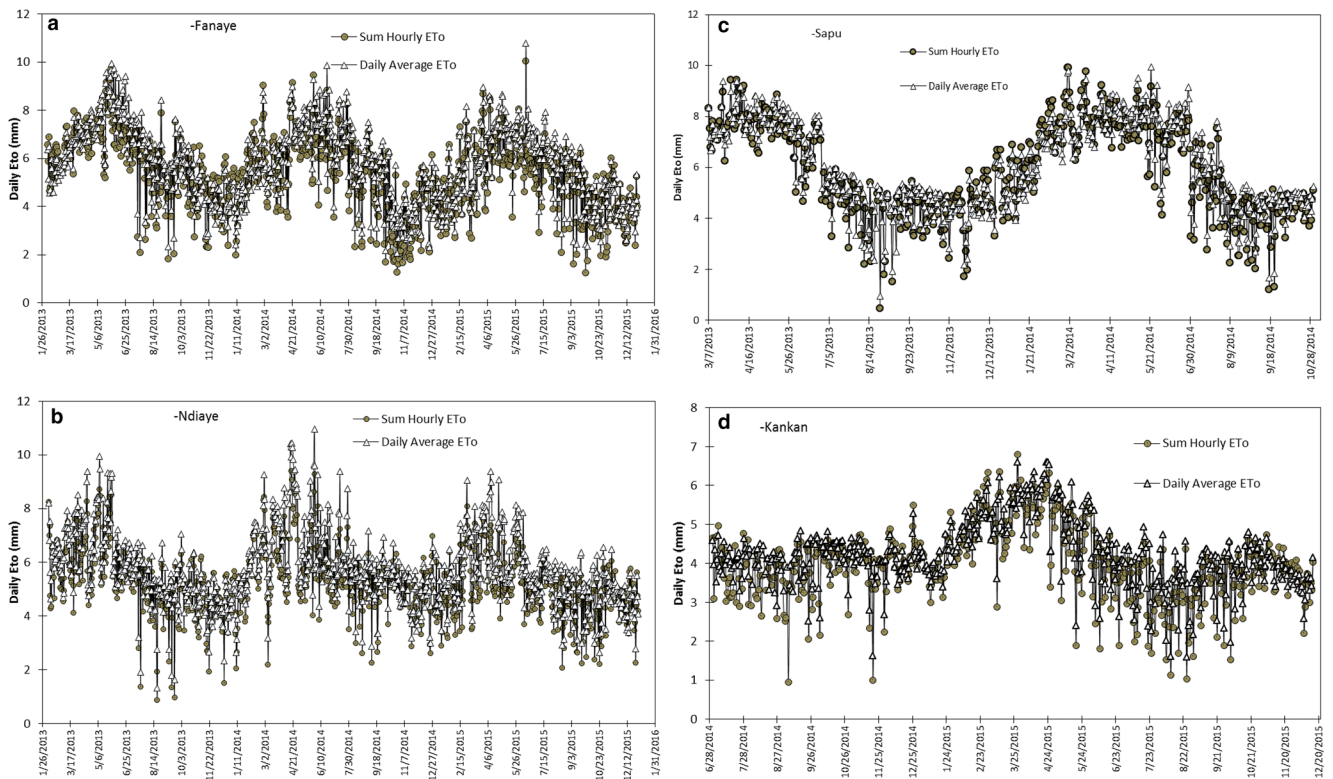
$$RMSE = \sqrt{\frac{\sum_{k=1}^n (Daily\ E_{Toi} - SumHourly\ E_{Toi})^2}{n}} \quad (2)$$

where daily ETo is the ETo calculated at the daily time step, sum hourly ETo is the sum of 24-h ETo calculated at an hourly time step and considered as the standard or measured ETo.

## 3 Results and discussion

### 3.1 Comparison of the sum of 24-h ETo and the average daily ETo at daily time step

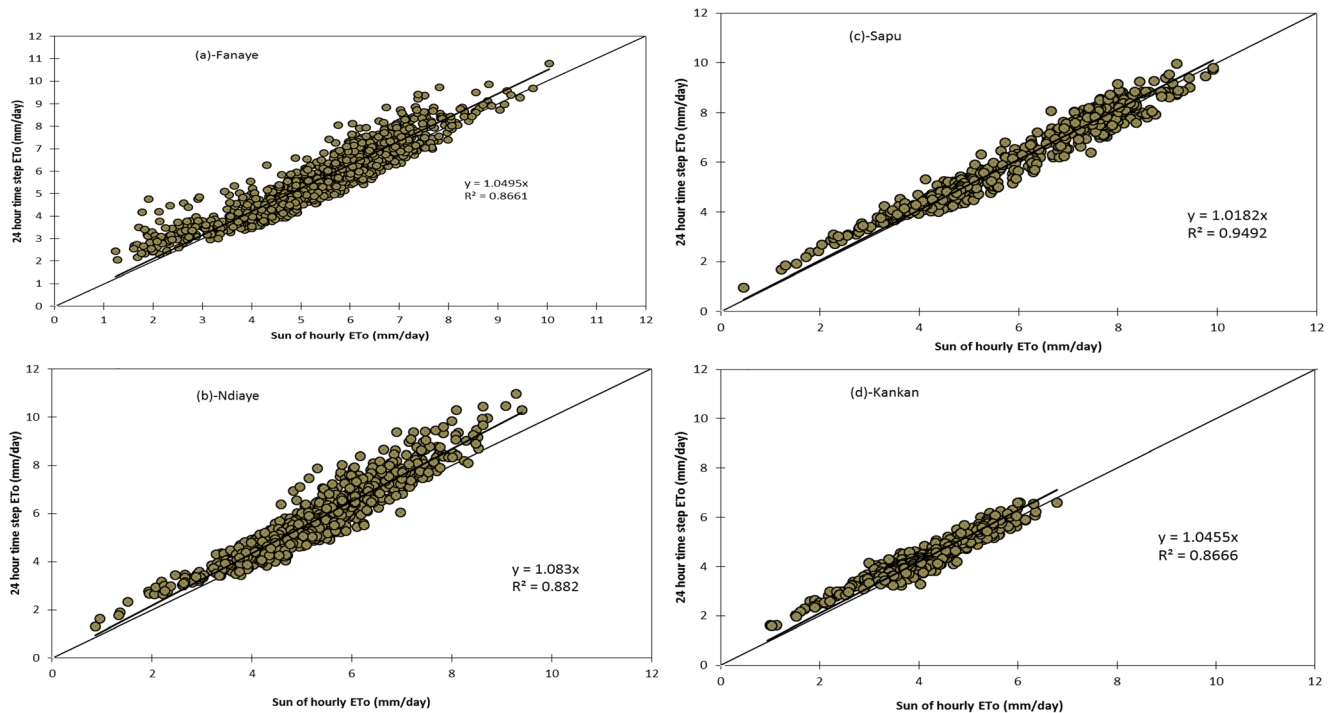
There was slight difference between the sum of 24-h ASCE-PM ETo and the daily ASCE-PM ETo at all four weather stations. The comparison of the sum of hourly ETo and daily time step ETo for the Fanaye, Ndiaye, Sapu, and Kankan weather stations and respective study period is shown in Fig. 2, and the relationships between the sum of hourly ETo and daily time step ETo are presented in Fig. 3. The regression slopes were 1.05, 1.08, 1.02, and 1.05 for the Fanaye, Ndiaye, Sapu, and Kankan stations, respectively, and coefficients of



**Fig. 2** Comparison of the sum of hourly ETo and daily time step ETo at **a** Fanaye, **b** Ndiaye, **c** Sapu, and **d** Kankan weather stations

determination of the relationships were as high as 0.87, 0.88, 0.95, and 0.87 for the respective stations (Fig. 3). The magnitude of the slopes which are close to unity and the high coefficients of determination ( $R^2 \geq 0.87$ ) showed the good

correlation between the sum of hourly ETo and daily time step ETo estimations at all four locations. The highest  $R^2$  value was obtained at Sapu in The Gambia. The sum of 24-h ASCE-PM ETo estimates were lower than the daily ASCE-PM ETo



**Fig. 3** Relationship between the sum of hourly ETo and daily time step ETo at **a** Fanaye, **b** Ndiaye, **c** Sapu, and **d** Kankan weather stations

estimates as presented in Table 2. On the study periods basis, there were overestimation of ETo by 5.4, 8.3, 1.3, and 5.6% when using daily average climatic data compared to the hourly data at Fanaye, Ndiaye, Sapu, and Kankan stations, respectively. The rates of lower estimation on the hourly basis are in agreement with those reported by ASCE-EWRI (2004) and Irmak et al. (2005). Irmak et al. (2005) indicated higher estimation of daily PM-ETo using daily average climatic data compared to the sum of hourly ETo across the humid coastal region, semiarid temperate regions, two Mediterranean-type regions along the west coast of California in the USA. The ratios of ETo at daily time step to ETo as sum of 24 h were reported as 1.07 at Bushland and 1.04 at Champion (ASCE-EWRI 2004) and 1.08 at North Platte and 1.05 at Bushland (Irmak et al. 2005) under semiarid climate. The average ratio of the daily time step ASCE-PM ETo to the sum of 24-h ASCE-PM ETo for the pooled four sites in this study is 1.05 and provides a strong agreement between the two methods with 5% ETo overestimation by the daily time step ASCE-PM method. The overestimation by the daily time step ASCE-PM ETo method was due to the higher value for  $r_s$  (200 s m<sup>-1</sup>) used by the hourly ASCE-PM during nighttime which tends to lower nighttime ETo estimates and therefore counters some of the increase in daytime estimates (Irmak et al. 2005). The results of this study are also in agreement with Perera et al. (2015) who reported a very strong correlation between the hourly and daily results for the ASCE-PM version in the tropical and arid climates. In Spain, comparisons made between daily ETo obtained by summing hourly ASCE-PM estimations and daily ETo estimated on a daily basis showed lower differences between the two computational time steps (2% on the average) (Gavilán et al. 2008). Jia et al. (2008) reported that comparison of the daily to the sum of 24-h reference ET provided a good assessment on the highest amount of water that could be potentially used by agricultural crops in the Devils Lake area in northeastern North Dakota. They indicated that across the USA, the daily ETo estimated higher than hourly ETo at all locations except one, and agreement between the computational time steps was best in humid regions.

At Ndiaye and Fanaye, air temperature reaches its lowest value about 10 °C in January–February and can change in a very short time mostly during the night (Djaman et al. 2015). Therefore, the hourly estimates of ETo were able to capture the abrupt changes in climate variables, while the daily ETo does not capture the abrupt changes within a day (Irmak et al. 2005). Gebler et al. (2015) reported strong agreement between the hourly ETo from lysimeter and hourly estimates by the PM-ETo method, while the daily PM-ETo values were greater using the average daily climatic variables than hourly climatic variables data. López-Urrea et al. (2006) and Vaughan et al. (2007) also found a good agreement between hourly PM-ETo values and hourly lysimeter data. From a comparative study of the hourly PM-ETo and lysimeter measurement in California

**Table 2** Comparison for the sum of hourly ETo and daily ETo at Fanaye, Ndiaye, Sapu, and Kankan weather stations

Months	Fanaye			Ndiaye			Sapu			Kankan		
	Sum hourly ETo (mm)	Daily ETo (mm)	Variation (%)	Sum hourly ETo (mm)	Daily ETo (mm)	Variation (%)	Sum hourly ETo (mm)	Daily ETo (mm)	Variation (%)	Sum hourly ETo (mm)	Daily ETo (mm)	Variation (%)
January	4.6	4.5	-2.7	4.8	5.1	5.4	5.9	5.6	-5.6	4.01	4.1	1.5
February	5.9	5.6	-5.0	6.0	6.3	6.5	7.8	7.4	-5.1	4.86	4.9	1.7
March	5.9	5.9	0.0	6.0	6.7	11.8	7.8	7.6	-1.7	5.26	5.4	2.1
April	6.6	7.0	5.8	6.2	7.2	16.0	7.9	8.2	3.0	5.33	5.8	8.2
May	6.8	7.5	9.9	6.1	6.9	13.3	7.7	8.0	4.4	4.66	5.0	7.7
June	6.4	7.3	14.9	5.3	5.8	9.1	6.8	7.2	5.7	3.70	4.1	10.0
July	6.0	6.6	9.8	5.3	5.8	10.2	5.1	5.5	7.2	3.54	3.9	9.5
August	5.2	5.6	7.4	4.7	5.1	8.1	4.0	4.3	9.5	3.23	3.6	12.9
September	4.9	5.2	7.3	4.5	4.9	8.5	4.2	4.4	6.1	3.47	3.9	11.2
October	4.0	4.5	14.1	4.8	5.1	6.0	4.4	4.6	4.5	3.92	4.1	5.1
November	3.8	4.0	3.1	4.5	4.6	0.5	4.3	4.1	-3.5	3.92	3.9	-0.1
December	4.2	4.1	-2.2	4.6	4.5	-0.4	5.0	4.8	-4.1	3.78	3.8	0.3
Mean	5.4	5.7	5.4	5.2	5.7	8.3	5.9	6.0	1.3	4.1	4.4	5.6

and Italy, Ventura et al. (1999) reported a RMSE of 0.26 mm/day found between the hourly Penman-Monteith and lysimeter-measured ETo values. Yildirim et al. (2004) reported higher values of daily ETo at daily time step than at hourly time step in Turkey. Van Bavel (1966) indicated that the PM-ETo method was only valid for instantaneous or hourly data with a better impact of the effect of weather conditions on daily ETo estimates.

The RMSE between sum of 24-h ASCE-PM ETo and the daily time step ASCE-PM ETo values were 0.84, 0.70, 0.41, and 0.36 mm/day at the Fanaye, Ndiaye, Sapu, and Kankan stations, respectively. The study period average hourly temperature and RH were 25.6, 27.8, 28.1, and 26.2 °C and 63.8, 46.7, 56.9, and 64.8%, respectively at Ndiaye, Fanaye, Sapu, and Kankan. The equivalent values using daily average data were 27.0, 28.3, 29, and 26.8 °C and 59.9, 45.5, 52.6, and 64.0% for the respective variables and at the respective stations. Air temperature and relative humidity are the driving forces of evapotranspiration through their implicit effect on vapor pressure deficit (Djaman et al. 2015), and the observed RH differences between daily average and hourly average ranged from 0.7 to 4.3% and could have contributed to the discrepancies in the daily ETo average at both time step calculations. The humid location Kankan had the lowest value of RMSE of 0.36 mm/day, and the highest RMSE value was observed under the semiarid and hot conditions at Fanaye in Senegal. Similar results were obtained by Irmak et al. (2005) who reported low RMSE as low as 0.26 and 0.31 mm/day under humid conditions and RMSE as high as 0.57 under semiarid conditions. Perera et al. (2015) reported RMSE values that ranged from 0.19 to 0.34 mm/day depending on locations in Australia. However, values obtained under the Senegal and The Gambia semiarid conditions were much higher. Daily average temperature and relative humidity from meteorological weather stations are not representative in the extreme environment similar to Fanaye where  $T_{max}$  varied from 23 °C (early January) to 46 °C (late May);  $T_{min}$  varied from 8 to 33 °C with generally hot daytime temperature and cool night time temperatures (Djaman et al. 2015). Therefore, hourly variation in temperature and relative humidity are not captured when using daily average climate variables for ETo estimation.

In the Devils Lake basin in northeastern North Dakota, Jia et al. (2008) showed that the daily and sum of 24-h ETo were comparable and provided good assessment on the potential irrigation requirement. Hourly ETo estimation improves the accuracy in locations with large diurnal variation in wind speed and direction, and the dynamics in cloudiness contrary to the location where the day step ETo methods have been developed (Allen et al. 2000). Irmak (2011) reported that the percent ratio of the daily ETo to the sum of 24-h ETo was more than 80–85% with the night time sum ETo of 5% of the sum of 24-h ETo. However, the daily average ETo calculation is

considered to be sufficiently accurate for planning and designing irrigation and drainage infrastructure, irrigation scheduling, and other applications (Irmak et al. 2005). Unlike Perera et al. (2015) who reported geographical dependence of the correlation between the two methods, our study results show no correlation between methods agreement and the geographical positions of the weather stations. However, the best correlation was observed at Sapu in The Gambia (slope = 1.02), while the lowest RMSE of 0.36 was obtained at Kankan in Guinea under humid climate with less variation hourly climatic variables compared to the other stations. Fanaye is reputed hot and dry compared to other stations, and Sapu and Kankan are located in the humid regions. These results are not in agreement with Irmak et al. (2005) who reported that the greatest differences between daily ET and hourly ETo were in locations where strong, dry, hot winds cause advective increases in ETo, and the daily average ETo did not account for abrupt diurnal changes in wind speed, air temperature, and vapor pressure deficit. The daily time step ETo estimation ignores any evapotranspiration occurring during nighttime, and the soil heat flux is assumed null overnight for the 24-h time step. However, Tolck et al. (2006) reported that the nighttime ETo can be considerable up to 15% of the daily ETo in semiarid and arid climates. Caird et al. (2007) indicated that nighttime transpiration rates are typically 5–15% of the daily ETo and could sometimes be as high as 30% of the daily ETo. Irmak (2011) reported that seasonal average nighttime evaporative losses were 0.11 and 0.19 mm/night in Nebraska during 2 years with maximum of 0.50 mm/night. While Jarvis and Mansfield (1981) considered the nighttime ETo negligible assuming that stomata are closed at night, significant stomatal conductance and transpiration for 11 of 17 plant species was observed by Snyder et al. (2003). Mutibwa and Irmak (2010) reported that maize stomata were still opened during the night. At the light of the results of this study, the hourly estimates of ETo could be used for crop water requirement estimation for precision irrigation management under the semiarid and water scarcity conditions. However, hourly climatic data are not usually available at most of weather station in the developing countries similar to the Western African countries and due to the relatively low percent error between both time step ETo estimates, the daily time step ETo estimation using average daily weather data should be recommended for ETo estimation under the Western Africa climatic conditions.

### 3.2 Comparison of the sum of 24-h ETo and the average daily ETo at monthly time step

Monthly average of the sum of 24-h ETo, the daily time step ETo, and variations (percent difference relative to the sum of 24-h ETo) are presented in Table 2. The magnitude of monthly average ETo (using the daily time step ETo data) is presented in Fig. 4. The daily ETo increased at all weather stations from

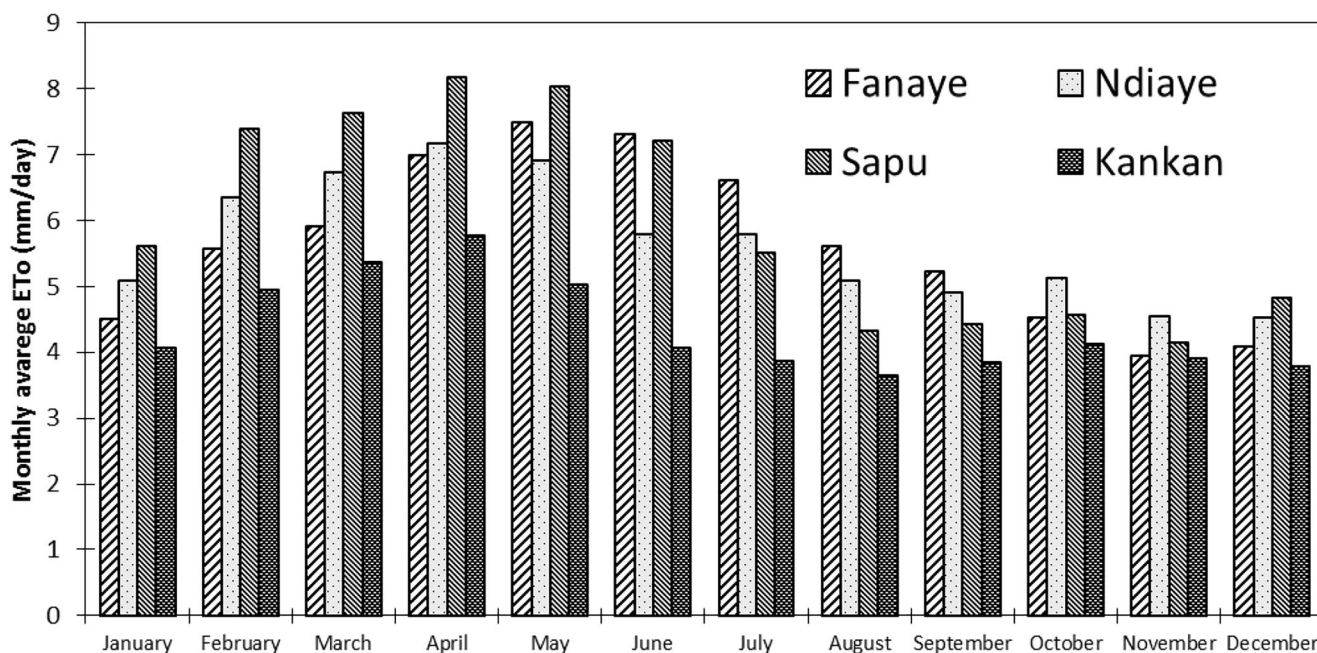


Fig. 4 Comparison of the monthly average ETo at Fanaye, Ndiaye, Sapu, and Kankan weather stations

January to April–May and decreased thereafter until December. The monthly average of the daily time step ETo values were higher than the monthly average of the sum of 24-h ETo values, and there was good agreement between the two methods with a regression slope of 1.05 and a very high coefficient of determination  $R^2$  of 0.94 (Fig. 5). There is monthly variability in the difference between the two time step estimations. The sum of

24-h ETo values were greater than the daily time step ETo from December to March at Fanaye in Senegal and from November to March at Sapu in The Gambia, showing percent differences that varied from 0 to 5% at Fanaye and from -5.6 to -1.6% at Sapu. The sum of 24-h ETo only showed lower ETo about 0.4% in December at Ndiaye in Senegal and 0.1% in November at Kankan in Guinea (Table 2).

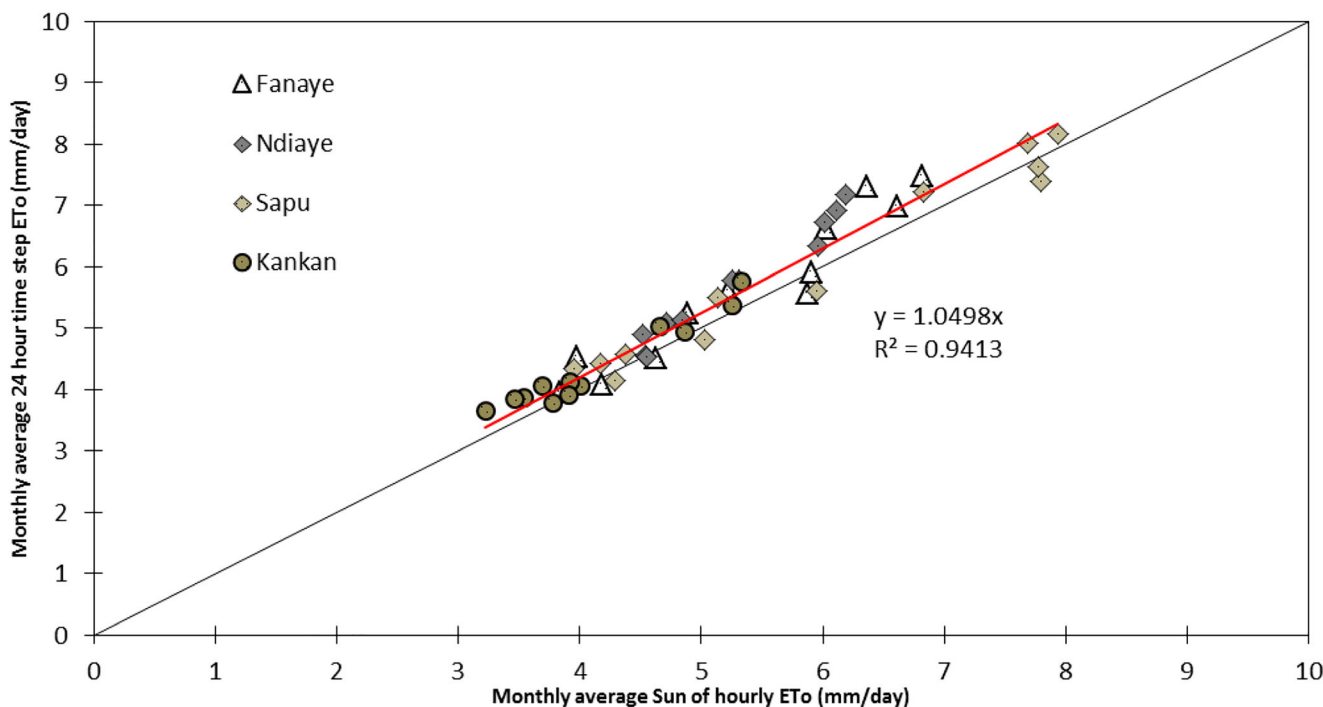


Fig. 5 Relationship between the monthly average sum of hourly ETo and daily time step ETo at Fanaye, Ndiaye, Sapu, and Kankan weather stations pooled together

The overestimation by the daily time step ETo method ranged from 5.8 to 15% at Fanaye, from 0.5 to 16% at Ndiaye, from 3 to 9.5% at Sapu, and from 1.5 to 13% at Kankan (Table 2). The highest percent variation was observed in June, April, August, and August at Fanaye, Ndiaye, Sapu, and Kankan, respectively. In the Senegal River Delta and Valley, the period of April–June corresponds to the peak of evaporative demand of the atmosphere (Figs. 2 and 4). Seasonal variability in agreement between the sum of hourly ETo and the daily time step ETo methods was reported by Perera et al. (2015) in the tropical and arid climates in Australia. These results are not in agreement with Bakhtiari et al. (2009) who reported ETo overestimation at hourly summation time step from 7.4 to 47.6% using ASCE-PM equation in Iran. The comparison of the sum of daily ETo for crop growing season and for a year might have some implications on water management in agricultural, hydrological, and environmental studies. The differences in time step ETo values during the period for March to November is extremely critical for agricultural water management mostly in Senegal and The Gambia where rainfed crop production and double irrigated rice cropping are adopted. Assuming the sum of hourly ETo is the true estimate of reference evapotranspiration, the adoption of the daily average ETo estimation method should overestimate seasonal ETo of hot and dry season from February to July by 61, 92, 25, and 39 mm at Fanaye, Ndiaye, Sapu, and Kankan, respectively. During the wet season from August to November, ETo overestimation should be 44, 33, 21, and 31 mm at the respective weather stations. For both growing seasons combined, ETo overestimations are 104, 124, 46, and 69 mm at Fanaye, Ndiaye, Sapu, and Kankan, respectively. The differences between the two ETo time steps showed significant variations from one location to another. For example, at Sapu and Kankan, the differences on seasonal basis were 46 and 69 mm for the March–November period, respectively, while at Fanaye and Ndiaye, the differences were 104 and 124 mm. The Fanaye and Ndiaye stations resulted in high seasonal differences, and the Sapu and Kankan stations resulted in small difference between the two ETo computation procedures on a seasonal basis. The Fanaye and Ndiaye stations are further north and further west under more pronounced semi-arid conditions than the Sapu and Kankan stations (Fig. 2, Table 1). Differences as high as 124 mm of ETo will make a considerable difference in terms of designing and planning of irrigation and drainage systems and other water storage infrastructure (Irmak et al. 2005).

#### 4 Conclusions

In this study, the standardized daily and hourly ASCE-PM models were evaluated to assess differences between using a daily computation time step of ETo and the sum-of-hourly

ETo at four sites under humid climate at Kankan in Guinea and semiarid climates at Sapu in The Gambia, Fanaye, and Ndiaye in Senegal. There was good agreement between the sum of hourly ETo and daily time step ETo at all four locations with the simple linear regression slope varying from 1.02 to 1.08 with high coefficient of determination  $R^2$  that varied from 0.86 and 0.95. The RMSE varied from 0.36 to 0.84 mm/day and increased with aridity. The daily time step method overestimated the daily ETo relative to the sum of hourly ETo by 1.3 to 8%, depending on locations for the whole study periods. However, there is location and monthly dependence of the magnitude of ETo values and the ratio of the ETo values estimated by both methods. Application of the hourly ETo estimation method helps to improve the accuracy of estimated reference evapotranspiration and better planning of rainfall and irrigation water management under precision agriculture. Thus, to ensure reliable and adequate availability of the required weather data at the hourly time step, it is imperative to invest in automated weather stations and human resource for optimum maintenance throughout the Western Africa and other regions. The results of this study are of significant practical use by crop producers, crop consultants, and university researchers for better management of water resources under rainfed and irrigated precision agriculture under humid and semiarid climates in Western Africa.

#### References

- Ahooghalandari M, Khiadani M, Jahromi WE (2016) Calibration of Valiantzas' reference evapotranspiration equations for the Pilbara region. *Western Australia Theor Appl Climatol*. <https://doi.org/10.1007/s00704-016-1744-7>
- Allen RG, Pereira LS, Raes D, Smith M (1998) *Crop evapotranspiration: guidelines for computing crop water requirements*. FAO Irrigation and Drainage Paper No. 56, FAO, Rome
- Allen RG, Walter IA, Elliott R, Mecham B, Jensen ME, Itenfisu D, Howell TA., Snyder R, Brown P, Eching S, Spofford T, Hattendorf M, Cuenca RH, Wright JL, Martin D (2000) Issues, requirements and challenges in selecting and specifying a standardized ET equation. *Proc., 4<sup>th</sup> National Irrig. Symp., ASAE, Phoenix*
- Allen RG, Pruitt WO, Wright JL, Howell TA, Ventura F, Snyder R, Itenfisu D, Steduto P, Berengena J, Yrisary JB, Smith M, Pereira LS, Raes D, Perrier A, Alves A, Walter I, Elliot R (2006) A recommendation on standardized surface resistance for hourly calculation of reference ETo by the FAO56 Penman-Monteith method. *Agric Water Manag* 81(1–2):1–22
- Almorox J, Grieser J (2016) Calibration of the Hargreaves-Samani method for the calculation of reference evapotranspiration in different Köppen climate classes. *Hydrol Res*. <https://doi.org/10.2166/nh.2015.091> in press
- Arellano G, Irmak S (2015) Reference (potential) evapotranspiration. i: comparison of temperature, radiation, and combination-based energy balance equations in humid, subhumid, arid, semiarid, and mediterranean-type climates. *J Irrig Drain Eng*. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000978](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000978) 04015065

- ASCE-EWRI (2004) The ASCE standardized reference evapotranspiration equation. Standardization of Reference Evapotranspiration Task Committee Final Report. Reston, Va.: ASCE Environmental and Water Resources Institute
- 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. American Society of Civil Engineers (ASCE), Reston, 213pp
- Azhar AH, Perera BJC (2011) Evaluation of reference evapotranspiration estimation methods under southeast Australian conditions. *J Irrig Drain Eng* 137(5):268–279
- Bakhtiari B, Khalili A, Liaghat AAM, Khanjani J (2009) Comparison of daily with sum-of-hourly reference evapotranspiration in Kerman reference weather station. *J Water Soil (Agric Sci Technol)* 23(1): 45–56
- Blaney HF, Criddle WD (1962) Determining consumptive use and irrigation water requirements. USDA Technical Bulletin 1275, US Department of Agriculture, Beltsville
- Bodner G, Loiskand W, Kaulm H (2007) Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agric Water Manage* 93(3):85–98
- Caird MA, Richards JH, Donovan LA (2007) Nighttime stomatal conductance and transpiration in C3 and C4 plants. *Plant Physiol* 143(4):4–10
- Djaman K, Irmak S (2013) Actual crop evapotranspiration and alfalfa- and grass-reference crop coefficients of maize under full and limited irrigation and rainfed conditions. *J Irrig Drain Eng ASCE* 139(6): 433–446
- Djaman K, Balde AB, Sow A, Muller B, Irmak S, Ndiaye MK, Manneh B, Moukoubi YD, Futakuchi K, Saito K (2015) Evaluation of sixteen reference evapotranspiration methods under sahelian conditions in the Senegal River Valley. *J Hydrol: Reg Stud* 3:139–159
- Djaman K, Irmak S, Kabenge I, Futakuchi K (2016) 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*. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0001070](https://doi.org/10.1061/(ASCE)IR.1943-4774.0001070)
- Doorenbos J, Pruitt WO (1977) Guidelines for predicting crop water requirements. FAO Irrigation and Drainage, Paper, 24. FAO, Rome
- Droogers P, Allen RG (2002) Estimating reference evapotranspiration under inaccurate data conditions. *Irrig Drain Syst* 16(1):33–45
- Fisher D, Pringle H III (2013) Evaluation of alternative methods for estimating reference evapotranspiration. *Agric Sci* 4:51–60
- Gao X, Shizhang P, Junzeng X, Shihong Y, Weiguang W (2015) Arch *Agron Soil Sci* 61(3):415–426. [Proper methods and its calibration for estimating reference evapotranspiration using limited climatic data in Southwestern China](#)
- Garcia M, Raes D, Allen R, Herbas C (2004) Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). *Agric Forest Meteorol* 125:67–82
- Gavilán P, Estévez J, Berengena J (2008) Comparison of standardized reference evapotranspiration equations in southern Spain. *J Irrig Drain Eng* 134(1):1–12
- Gebler S, Hendricks Franssen HJ, Pütz T, Post H, Schmidt M, Vereecken H (2015) Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket. *Hydrol Earth Syst Sci* 19:2145–2161
- Hargreaves GH, Allen RG (2003) History and evaluation of Hargreaves evapotranspiration equation. *J Irrig Drain Eng ASCE* 129(1):53–63
- Hargreaves GH, Samani ZA (1985) Reference crop evapotranspiration from temperature. *Appl Eng Agric* 1:96–99
- Irmak S (2011) Dynamics of nocturnal, daytime, and sum-of-hourly evapotranspiration and other surface energy fluxes over nonstressed maize canopy. *J Irrig Drain Eng*. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000360](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000360)
- Irmak S, Irmak A, Jones JW (2003) Solar and net radiation-based equations to estimate reference evapotranspiration in humid climates. *J Irrig Drain Eng ASCE* 129(5):336–347
- Irmak S, Howell TA, Payero JO, Martin DL (2005) Standardized ASCE-Penman-Monteith: impact of sum-of-hourly vs. 24-hr-time step computations at reference weather station sites. *Trans ASAE* 48(3):1063–1077
- 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
- Irmak S, Odhiambo LO, Mutiibwa D (2011) Assessing the impact of daily net radiation models on grass and alfalfa-reference evapotranspiration estimated using Penman-Monteith equation in a sub-humid and arid climate. *J Irrig Drain Eng* 137(2):59–72
- Irmak S, Odhiambo LO, Specht JE, Djaman K (2013) Hourly and daily single and basal evapotranspiration crop coefficients as a function of growing degree days, days after emergence, leaf area index, fractional green canopy cover, and plant phenology for soybean. *Trans ASABE* 56(5):1785–1803
- Itenfisu D, Elliot RL, Allen RG, Walter IA (2003) Comparison of reference evapotranspiration calculations as part of the ASCE standardization effort. *J Irrig Drain Eng* 129(6):440–448
- Jabloun M, Sahli A (2008) Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data application to Tunisia. *Agric Water Manage* 95:707–715
- Jarvis PG, Mansfield TA (1981) Stomatal physiology. Cambridge University Press, Cambridge, p 295
- Jia X, Steele D, Hopkins D (2008) Hourly reference evapotranspiration estimates for alfalfa in North Dakota. *World Environ Water Resour Congr* 2008:1–10. [https://doi.org/10.1061/40976\(316\)89](https://doi.org/10.1061/40976(316)89)
- Kisi O (2014) Closure to “Comparison of different empirical methods for estimating daily reference evapotranspiration in Mediterranean climate” by Ozgur Kisi. *J Irrig Drain Eng*. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000817](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000817) 07014045
- Koedyk LP, Kingston DG (2016) Potential evapotranspiration method influence on climate change impacts on river flow: a mid-latitude case study. *Hydrol Res*, in press. <https://doi.org/10.2166/nh.2016.152>
- Liou YA, Kar SK (2014) Evapotranspiration estimation with remote sensing and various surface energy balance algorithms. *A Review. Energies* 7:2821–2849
- López-Urrea R, Martín de Santa Olalla F, Fabeiro C, Moratalla A (2006) Testing evapotranspiration equations using lysimeter observations in a semiarid climate. *Agric Water Manage* 85:15–26
- Martinez CJ, Thepadia M (2010) Estimating reference evapotranspiration with minimum data in Florida. *USA J Irrig Drain Eng* 136(7):494–501
- Mendonça JC, Sousa EF, de Bernardo S, Dias GP, Grippa S (2003) Comparison of estimation methods of reference crop evapotranspiration (ET<sub>0</sub>) for Northern Region of Rio de Janeiro State, Brazil. *Revista Brasileira de Engenharia Agrícola e Ambiental* 7:275–279
- Mutiibwa D, Irmak S (2010) On the scaling up soybean leaf level stomatal resistance to canopy resistance for one-step estimation of actual evapotranspiration. *Trans ASABE* 54(1):141–154
- Ngongondo C, Xu CY, Tallaksen LM, Alemaw B (2013) Evaluation of the FAO Penman-Monteith, Priestly-Taylor and Hargreaves models for estimating reference evapotranspiration in southern Malawi. *Hydrol Res* 44(4):706–722
- Perera K, Western A, Nawarathna B, George B (2015) Comparison of hourly and daily reference crop evapotranspiration equations across seasons and climate zones in Australia. *Agric Water Manage* 148: 84–96

- Sentelhas PC, Gillespie TJ, Santos EA (2010) Evaluation of FAO Penman-Monteith and alternative methods for estimating reference evapotranspiration with missing data in Southern Ontario, Canada. *Agric Water Manag* 97:635–644
- Singh VP, Xu CY (1997) Evaluation and generalization of 13 mass-transfer equations for determining free water evaporation. *Hydrol Process* 11:311–323
- Snyder RL (1992) Equation for evaporation pan to evapotranspiration conversions. *J Irrig Drain Eng* 118:977–980
- Snyder RL, Eching S (2006) PMhr Penman-Monteith Hourly ETref for short and tall canopies. University of California, Davis
- Snyder KA, Richards JH, Donovan LA (2003) Nighttime conductance in C3 and C4 species: do plants lose water at night? *J Exp Bot* 54(383): 861–865
- Suleiman AA, Hoogenboom G (2009) A comparison of ASCE and FAO-56 reference evapotranspiration for a 15-min time step in humid climate conditions. *J Hydrol* 375:326–333. <https://doi.org/10.1016/j.jhydrol.2009.06.020>
- Tabari H, Grismer M, Trajkovic S (2011) Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrig Sci* 31(2):107–117
- Tabari H, Grismer ME, Trajkovic S (2013) Comparative analysis of 31 reference evapotranspiration methods under humid conditions. *Irrig Sci* 31:107–117
- Thornthwaite CW (1948) An approach towards a rational classification of climate. *Geogr Rev* 38(1):55–94
- Tolk JA, Howell TA, Evett SR (2006) Nighttime evapotranspiration from alfalfa and cotton in a semiarid climate. *Agron J* 98(3):730–736
- Trajkovic S, Kolakovic S (2009) Evaluation of reference evapotranspiration equations under humid conditions. *Water Resour Manage* 23: 3057–3067
- Utset A, Farre I, Martinez-Cob A, Cavero J (2004) Comparing Penman-Monteith and Priestley-Taylor approaches as reference evapotranspiration inputs for modeling maize water use under Mediterranean conditions. *Agric Water Manag* 66:205–219
- Valiantzas JD (2013a) Simplified forms for the standardized FAO-56 Penman-Monteith reference evapotranspiration using limited data. *J Hydrol* 505:13–23
- Valiantzas JD (2013b) Simplified reference evapotranspiration formula using an empirical impact factor for penman's aerodynamic term. *J Irrig Drain Eng* 139(1):108–114
- Valiantzas JD (2013c) Simple ETo forms of Penman's equation without wind and/or humidity data I theoretical development. *J Irrig Drain Eng* 139(1):1–8
- Valiantzas JD (2013d) Simple ETo forms of penman's equation without wind and/or humidity data II: comparisons with reduced set-FAO and other methodologies. *J Irrig Drain Eng* 139(1):9–19
- Valipour M (2014) Investigation of Valiantzas' evapotranspiration equation in Iran. *Theor Appl Climatol* 121:1–2. <https://doi.org/10.1007/s00704-014-1240-x>
- Valipour M (2015) Importance of solar radiation, temperature, relative humidity, and wind speed for calculation of reference. *Arch Agron Soil Sci* 6:239–255
- Van Bavel CHM (1966) Potential evaporation: the combination concept and its experimental verification. *Water Resour Res* 2(3):455–467
- Vaughan DA, Balazs E, Heslop-Harrison JS (2007) From crop domestication to super-domestication. *Ann Bot (Lond)* 100:893–901
- Ventura F, Spano D, Duce P, Snyder RL (1999) An evaluation of common evapotranspiration equations. *Irrig Sci* 18(4):163–170
- Villa Nova NA, Miranda JH, Pereira AB, Oliveira K (2006) Estimation of the potential evapotranspiration by a simplified Penman method. *Eng Agric* 26:713–721
- Watson I, Burnett AD (1995) *Hydrology: an environmental approach*. CRC Press, Boca Raton
- 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 generalisation of radiation-based equations for calculating evaporation. *Hydrol Process* 14: 339–349
- Xu CY, Singh VP (2001) Evaluation and generalisation of temperature-based equations for calculating evaporation. *Hydrol Process* 15: 305–319
- Xystrakis 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
- Yildirim E, Cakmak B, Kose T (2004) Comparison of hourly and daily reference evapotranspiration values for GAP project area. *J Appl Sci* 4(1):53–57
- Yoder RE, Odhiambo LO, Wright WC (2005) Evaluation of methods for estimating daily reference crop evapotranspiration at a site in the humid southeast United States. *Appl Eng Agric* 21:197–202