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Sum of Hourly vs. Daily Penman-Monteith Grass-Reference Evapotranspiration under Semiarid and Arid Climate

Koffi Djaman[1]*, Koudahe K[2], Lombard K[1] and O'Neill M[1]

[1]*Department of Plant and Environmental Sciences, Agricultural Science Center at Farmington, New Mexico State University, Farmington, USA*
[2]*ADA Consulting Africa, Lomé, Togo*

Abstract

Under changing climate and the global warming, accurate estimation of crop evapotranspiration might help improving water management and maintaining or improving water productivity. The objective of this study was to compare the sum of hourly ETo with the daily average ETo using the standardized ASCE Penman-Monteith equation under semiarid dry climate. Pair comparison was performed between the sum of hourly reference evapotranspiration (ETo) and the daily average ETo based on the data from four automated weather stations in the State of New Mexico (USA) for the period of 2009-2017. The results showed good agreement between the sum of hourly ETo and daily average ETo with the regression slopes varying from 1.00 to 1.10 and coefficients of determination from 0.63 to 0.97. The least difference between the hourly and daily results was found at Leyendecker. The RMSE values were 0.98, 0.64, 0.21 and 0.35 mm/day at Fabian Garcia, Farmington, Leyendecker and Tucumcari, respectively. The adoption of the hourly ETo estimation method leads to 16.6, 5.5, -0.2, and 4.1% higher annual ETo at Fabian Garcia, Farmington, Leyendecker and Tucumcari respectively, and can help on accurate evapotranspiration estimation to meet crop water requirement under sustainable agriculture.

Keywords: Evapotranspiration; Sum of hourly; Penman-Monteith; Semiarid climate

Introduction

Crop evapotranspiration is the main water losses from the hydrological cycle and is a very important parameter considered for water planning and management under the agricultural and environmental studies. Under global warming the world temperature is rising and the fresh water for crop and fiber production is diminishing [1], agriculture may suffer from drought due to the decreasing trend in annual precipitation with inter-annual variability in most parts of the world [2-9] while abundant precipitation might occur in other parts of the world with increased extreme precipitation events [6,10-13]. The South western United States characterized by the semiarid and arid climate, suffers from drought with increasing temperature, decreasing water availability, high evapotranspiration and percolation losses, and increase in forest woodland mortality [14-16]. In the State of New Mexico particularly, with the ongoing ground water depletion, decreasing trend in precipitation, decreasing stream flow [17], and increasing population, a smart agriculture should be of first choice to cope with the changing climate and maintain and or improve water productivity. Ahadi et al. [18] reported irrigation efficiency varying from 11 to 95% across the lower Rio Grande Basin in New Mexico and that averaged 64%. More effort should be done by irrigation managers to much crop water use to the applied irrigation. Accurate crop evapotranspiration estimation is therefore critical for water management under this arid environment. As most of the irrigation scheduling programs are based on reference evapotranspiration (ETo) and with the tendency of drip irrigation adoption for minimizing water loss and increasing irrigation efficiency, there is a need to investigate the accuracy of using daily average weather variables against the hourly weather variables. Numerous ETo estimation models have been developed in addition to the direct measurement methods [19] and the Penman-Monteith method is worldwide recommended for its accuracy under different climatic conditions [20,21].

Some studies reported uncertainty when applying the Penman Monteith equation using daily, weekly or monthly weather data [22,23], while the distribution of climatic variable during the day time and the night time can be source of error in estimating daily ETo [24] because the nighttime ETo can be non-negligible and equivalent to as high as 30% of the daily ETo [25,26]. Irmak et al. [24] reported 5 to 8% ETo overestimation when using average daily weather data compared to the hourly data from Bushland (Texas), North Platte (Nebraska), Santa Rosa, and Twitchell Island (California) and 3% underestimation at Santa Barbara (california). Djaman et al. [27] reported ETo overestimation range from 4.9 to 8.3% across the semiarid region in Senegal. In contrast, Bakhtiari et al. [28] found ETo overestimation from 7.4 to 47.6% in Iran when using hourly climate variables data. From the non-consistency of the equivalence of the daily ETo estimates using the average daily data and hourly data, it urges to investigate the accuracy of these time steps calculations under the semiarid dry and arid condition where water resources are the main limiting factor for crop production. The objective of this study was to compare the daily ETo estimates using average daily and the hourly climate variables data for the semiarid dry and arid climatic condition in New Mexico.

Materials and Methods

This study was conducted at four weather stations across New Mexico (USA) at 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), average tempetrature (Tmean), minimum relative humidity (RHmin), maximum relative humidity (RHmax), average relative humidity (RHmean), average wind speed (u_2), and solar radiation (Rs) were collected on the hourly basis and averaged over daily time step from

***Corresponding author:** Koffi Djaman, Department of Plant and Environmental Sciences, Agricultural Science Center at Farmington, New Mexico State University, Farmington, USA, Tel: +1505 960 7757; E-mail: kdjaman@nmsu.edu

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Parameters	Fabian Garcia	Farmington	Leyendecker	Tucumcari
Latitude (Deg. North)	32.28	36.69	32.20	35.20
Longitude (Deg. West)	-106.77	-108.31	-106.74	-103.69
Elevation (m)	1186	1720	1176	1246
Wind speed (m/s)	1.82	2.45	1.81	3.30
Tmax (°C)	26.50	20.94	26.12	24.07
Tmin (°C)	9.82	4.33	7.67	7.52
Tmean (°C)	18.16	12.63	16.89	15.79
Rhmax (%)	65.21	68.63	77.34	71.78
Rhmin (%)	18.60	19.70	19.09	22.29
Rhmean (%)	41.90	44.17	48.21	47.03
Rs (MJ m^{-2})	21.23	19.84	19.63	19.80

Tmin: Minimum temperature; Tmax: Maximum temperature; Tmean: Average Tempetrature; Rhmin: Minimum Relative Humidity; Rhmax: Maximum Relative Humidity; Rhmean: Average Relative Humidity and Rs: Solar Radiation.

Table 1: Weather stations with long term average climatic condition.

automated weather stations installed by the New Mexico Climate Center.

Penman-Monteith reference evapotranspiration model: (ASCE-EWRI, 2005)

The hourly ETo values calculation approach was developed by Snyder and Eching [29], following the description in the ASCE-EWRI report [21]. Required data for ETo calculations using ASCE-PM approach included data about site characteristics (latitude and elevation) and weather data, as hourly solar radiation (Rs) (MJ m^{-2} h^{-1}), mean air temperature (T) (°C), mean wind speed (u_2) (m s^{-1}) and mean dew point temperature (Td) (°C). Td was calculated as recommended by Allen et al. [20]. 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 [21]. The Penman-Monteith reference evapotranspiration equation with fixed stomatal resistance values for grass surface is:

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

Where: ETo is the reference evapotranspiration (mm/day);

Δ=The slope of saturation vapor pressure versus air temperature curve (kPa°C^{-1});

Rn=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 (°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);

γ=Psychrometric constant (kPa °C^{-1});

Cn=Numerator constant that changes with reference surface and calculation time step (900°C mm s^3 Mg^{-1} d^{-1} for 24 h time steps, and 37°C mm s^3 Mg^{-1} h^{-1} for hourly time steps for the grass-reference surface);

Cd=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. [20].

Evaluation criteria

Comparisons were made using the *t*-test, graphics and simple linear regression. A paired sample *t*-test (two-sample for means) was performed to identify any significant difference between the sum of hourly ETo and the daily average ETo estimates at 5% significance level. The null hypothesis was that the daily average ETo estimates and the sum of hourly ETo estimates came from the same population and that mean difference between ETo estimates was zero. The linear regressions were forced through the origin because ideally all equations should produce zero ETo when there is no evapotranspiration. The regression slopes, coefficient of determination (R^2), Root mean squared error (RMSE), Percent error (PE), mean bias error (MBE), and absolute mean error (MAE) were also used and the RMSE, PE were calculated as follow:

$$RMSE = \sqrt{\sum_{i=0}^{n} \frac{(\text{Daily EToi} - \text{Sum of hourly EToi})^2}{n}} \quad (2)$$

$$PE = \frac{RMSE}{Sum\ of\ hourly\ ETo\ mean} 100 \quad (3)$$

$$MBE = n^{-1} \sum_{1}^{n} (Daily\ EToi - Sum\ of\ hourly\ EToi) \quad (4)$$

$$MAE = n^{-1} \sum_{1}^{n} |Daily\ EToi - Sum\ of\ hourly\ EToi| \quad (5)$$

Where:

daily ETo=ETo calculated at the daily time step;

Sum of hourly ETo=sum of 24 hour ETo calculated at an hourly time step and considered as the standard or measured ETo at the *ith* data point and *n* is the total number of data points.

Results and Discussion

Maximum hourly wind speed, temperature, relative humidity and solar radiation were 11.2 m/s, 41.7°C, 89.7% and 4.22 Mj/m^2, respectively, at Fabian Garcia, 14.7 m/s, 37.7°C, 100%, and 3.92 Mj/m^2, respectively, at Farmington, 11.3 m/s 40.9°C, 97.7% and 3.95 Mj/m^2, respectively, at Leyendecker, and 15.3 m/s, 41.9°C, 97.7% and 4.09 Mj/m^2 at Tucumcari. Daily average values were 5.3 m/s, 34.2°C, 89.6%, 32.3 Mj/m^2 for the hourly wind speed, temperature, relative humidity and solar radiation, respectively, at Fabian Garcia, 8.2 m/s, 29.7°C, 96.3% and 33.20 Mj/m^2 at Farmington, 6.1 m/s, 31.2°C, 87.6% and 32.31 Mj/m^2 for the respective variables at Leyendecker, and 9.7 m/s, 33.0°C, 97.3% and 33.9 Mj/m^2 for the respective variables at Tucumcari. It can be drawn that the daily average approach does not account for the hourly abrupt changes in the climate variables.

The sum of hourly ETo showed good agreement with the daily average ETo (Figures 1-3). The regression slope between the sum of hourly ETo and the daily average ETo and the coefficient of determination were 1.104 and 0.63 at Fabian Garcia, 1.091 and 0.92 at Farmington, 1.002 and 0.97 at Leyendecker and 1.028 and 0.97 at Tucumcari. Overall, error related to the ETo estimates using daily average weather data is 10, 9, 0.2 and 3% at Fabian Garcia, Farmington, Leyendecker and Tucumcari, respectively. The data showed ETo slight underestimation during the year at Fabian Garcia (Figures 1 and 2), and from April to August in Farmington (Figure 2). However, the peak

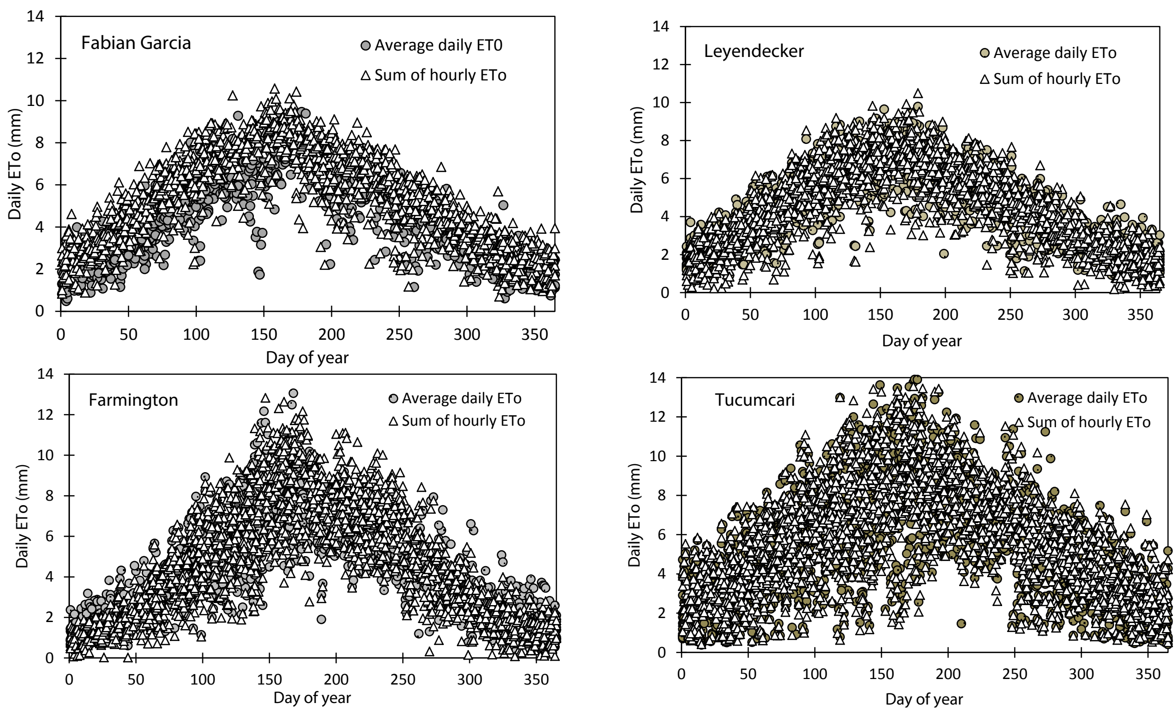

Figure 1: Comparison of the sum of hourly ETo and the average daily ETo at Fabian Garcia, Farmington, Leyendecker and Tucumcari weather stations.

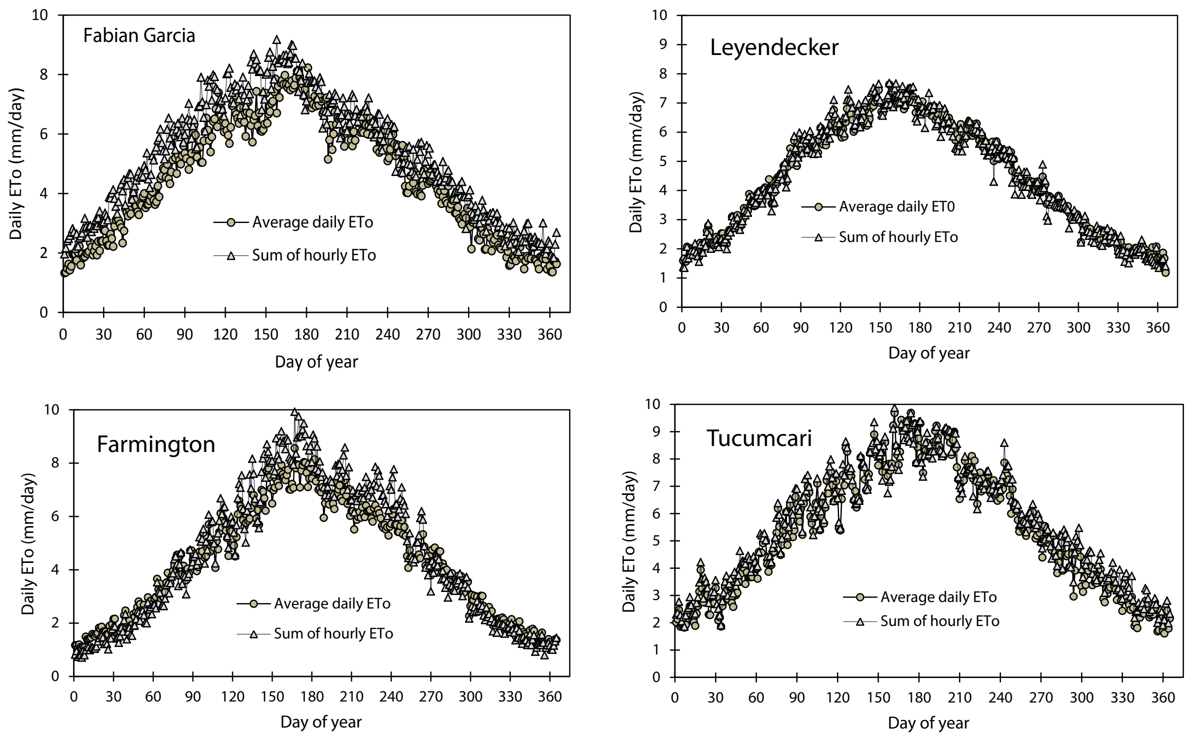

Figure 2: Comparison of the mean of the sum of hourly ETo and the mean of the average daily ETo at Fabian Garcia, Farmington, Leyendecker and Tucumcari weather stations.

ETo month is June at all four locations and the sum of hourly showed higher peak ETo values of 9.2 and 9.3 mm/day at Fabian Garcia and Farmington, respectively, while the daily average ETo peak values were 8.0 and 8.5 mm/day at the respective locations. The annual mean ETo using the hourly and the daily average climatic variables was 1938.8 and 1662.1 mm at Fabian Garcia, 1647.0 and 1561.3 mm at Farmington, 1626.4 and 1629.9 mm at Leyendecker and 2043.9 and 1960 mm at Tucumcari. Using hourly data leads to 16.6, 5.5, -0.2, and 4.1% higher annual ETo compared to the daily average approach. The t-test showed significant difference between the annual mean daily average ETo and the annual mean sum of hourly ETo at Fabien Garcia, Farminton and Tucumcari (Table 2). No significant difference between the annual mean daily average ETo and the annual mean sum of hourly ETo at Legendeccker (Table 2). For practical irrigation water requirement estimation and irrigation management the hourly data should be preferred to the daily average mean to avoid putting crop under water stress that will impact the yield if the data is available at Farmington. The RMSE values were 0.98, 0.64, 0.21 and 0.35 mm/day and were equivalent to PE values of 18.5, 14.2, 4.8 and 6.3% at Fabian Garcia, Farmington, Leyendecker and Tucumcari, respectively (Table 3). The lowest MBE and MAE were obtained at Leyendecker and the greatest values were observed at Fabian Garcia (Table 3). The application of the hourly ETo approach considers the diurnal abrupt changes in the climate variables and should be of first choice up to the availability of the data [24-30]. However, the Hourly and daily ETo estimation approach could be interchangeable at Leyendecker, Tucumcari and Farmington due to the small differences between daily ETo values revealed by this study at these weather stations.

Djaman et al. [27] reported good agreement between the daily and hourly time steps ETo with regression slope from 1.02 to 1.08 and R^2 greater than 0.87. The daily time step ETo showed ETo overestimation from 1.3 to 8% as compared to the sum of hourly ETo across the semiarid and humid region of West Africa [27]. Similar results were reported in the Southern Spain by Gavilan et al. [30] and in the state of Georgia (USA) by Suleiman and Hoogenboom [31]. The hourly ETo over 24 hours was 5.8 to 47.6% higher than daily ETo using average daily weather data in Iran [28]. Jia et al. [32] also found that the daily showed good agreement with the sum of 24-hour reference ETo under the sub-humid continental climate in North Dakotas (USA). Allen et al. [33] indicated that estimating ETo at hour time step improves the accuracy of ETo estimation under very variable and dynamics environment in locations with large variation in wind speed and cloud

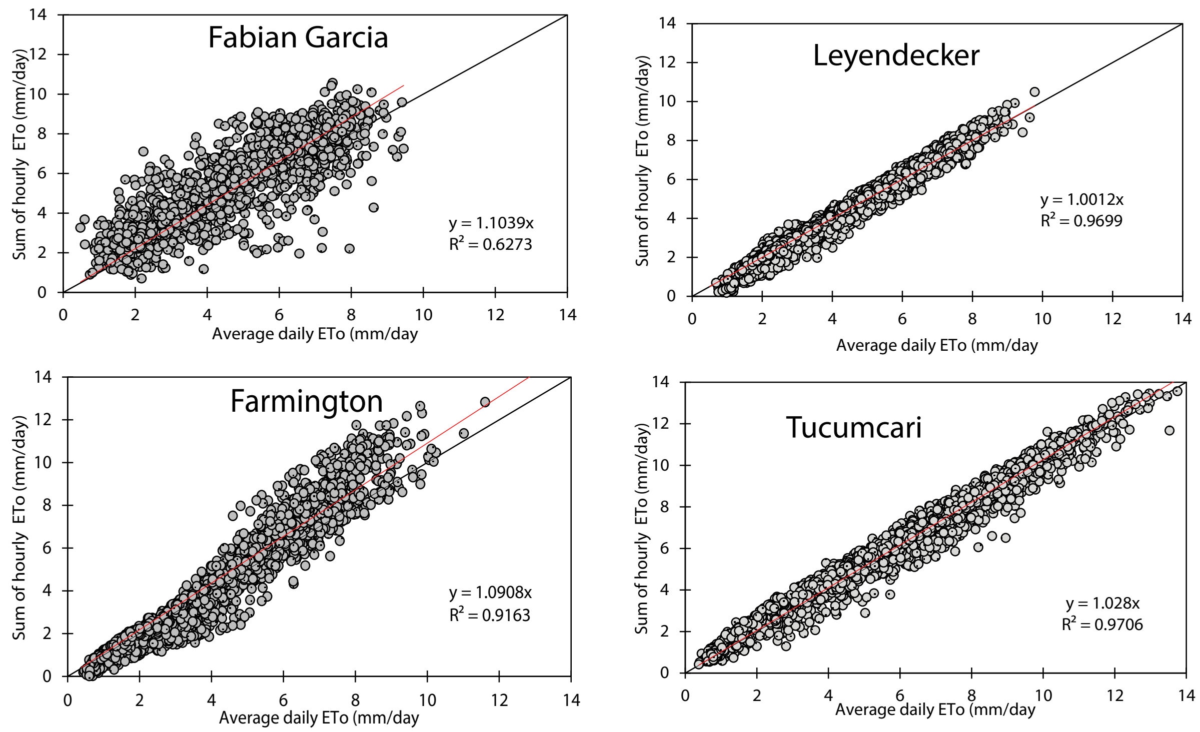

Figure 3: Relationship between the sum of hourly ETo and average daily ETo at Fabian Garcia, Farmington, Leyendecker and Tucumcari weather stations.

Weather station	Mean ETo		Variance ETo		t-test (one tail)		P-value	Significance
	Daily Average	Sum of hourly	Daily Average	Sum of hourly	t-computed	t-critical		
Fabien Garcia	4.55	5.31	3.84	3.98	-23.27	1.649	3E-74	*
Farmington	4.28	4.51	4.37	6.70	-7.53	1.649	2E-13	*
Leyendecker	4.46	4.45	3.34	3.63	0.91	1.649	0.181	n.s.
Tucumcari	5.37	5.60	4.98	4.52	-16.20	1.649	4E-45	*

*Significant at the 5% significance level.

n.s.=non-significant at the 5% significance level.

Table 2: Summary of the paired sample *t*-test (two-sample for means) statistics for the daily average ETo versus the sum of hourly ETo (α=0.05).

Indices	Fabian Garcia	Farmington	Leyendecker	Tucumcari
Regresion slope	1.1	1.09	1.001	1.03
R^2	0.63	0.92	0.97	0.97
RMSE (mm/day)	0.98	0.64	0.21	0.35
PE (%)	18.5	14.2	4.8	6.3
MBE (mm/day)	0.76	0.23	-0.01	0.29
MAE (mm/day)	0.82	0.5	0.16	0.23

R^2: Coefficient of Determination; RMSE: Root Mean Squared Error; PE: Percent Error; MBE: Mean Bias Error and MAE: Absolute Mean Error.

Table 3: Statistics summary of the comparison between the sum of hourly and daily Penman-Monteith ETo.

cover. Perera et al. [34] found the best agreement between the hourly and daily results for the FAO-Penman-Monteith version in temperate climates and the ASCE-Penman-Monteith version in the tropical and arid climates while Berengena and Gavilan [35] reported daily ETo underestimation of 3% and 2% by the FAO-Penman-Monteith version ASCE-Penman-Monteith versions in Cordoba (Spain), respectively. Irmak et al. [24] indicated that differences between daily average ETo and sum of hourly ETo were shown under strong, dry, hot winds with advective increases in hourly ETo while the daily average ETo did not account for abrupt changes in wind speed, air temperature, and vapor pressure deficit during the day. Moreover, the night time ETo can be equivalent to 15% of the daily ETo in semiarid and arid environment as reported by Tolk et al. [25]. Caird et al. [26] reported the nighttime transpiration rates of 5-30% of the daily ETo. Seasonal variability in the ratio of the sum of hourly ETo and daily ETo at Fabian Garcia and Farmington is in agreement with the results of Perera et al. [34] in the tropical and arid climates in Australia.

The finding of this study might be useful to crop growers, irrigation managers and environmentalists for water management and planning to optimized crop actual water vs. potential irrigation requirement across the State of New Mexico. With the development of irrigation management technology, producers are encouraged to go for high irrigation frequency especially under the coarse sandy soils with small water holding capacity and the extremely high air temperature during the crop growth and development period similar to New Mexico for effective water and nutrient management [36,37]. The hourly actual evapotranspiration base irrigation might be more efficient due to the slight variability of the surface resistance, and crop coefficient during daytime [38] and the hourly ETo might be much more useful for crop irrigation water requirement for a short period, growth stage or the growing period [24,27,39]. Locally developed hourly and daily crop coefficients data [36,40,41] could be used to improve water management at field, scheme and watershed levels. ETo underestimation might conduct to crop under irrigation that might reduce crop yield and its overestimation will lead to crop fading over irrigation with negative impact on crop yield and promote nutrient leaching.

Conclusion

Comparison between the sum of hourly reference evapotranspiration and the daily average evapotranspiration was performed at four automated weather stations in the State of New Mexico (USA) for the period of 2009-2017 using the standardized Penman-Monteith reference evapotranspiration equation. The results showed good agreement between the sum of hourly ETo and daily average ETo with the regression slopes varying from 1.00 to 1.10, the coefficient of determination from 0.63 to 0.97 and the RMSE values varied from 0.21 to 0.98 mm/day. ETo estimation at hourly basis that accounts for the abrupt changes in the weather variables, improves ETo estimation and might help estimating accurate crop water requirement and improving water management and water productivity under semiarid dry climate in the State of New Mexico and the neighboring States under similar climatic conditions with water resources as the most limiting factor for food and fiber production.

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