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Local and regional calibration of Hargreaves-Samani equations for reference evapotranspiration estimation in a semiarid climate

Abstract

Reference evapotranspiration is estimated by several equations with diverse performance and accuracy. While the Penman-Monteith equation is revealed as the most accurate estimation method, it requires several weather variables that are not measured at most weather stations across the globe. This study aimed to evaluate the Hargreaves evapotranspiration equations and to adjust the parameters or constants within the different equation to improve their performance and accuracy across the State of New Mexico, USA. The results showed that the calibration of the different Hargreaves equations improved equation performance. Calibrated equations' King-Gupta Efficiency (KGE) ranging from 0.73 to 0.97, the Nash-Sutcliffe Efficiency Coefficient (NSE) from 0.84 and 0.88, coefficient of determination (R^2) from 0.76 to 0.93, and the regression slope from 0.97 to 1.04. All equations showed poor performance at the Corona Range which is a hyper arid station without any influence of agricultural irrigation management in the area. The calibrated Equation 11 showed more accuracy and should be recommended for daily reference evapotranspiration across the State of New Mexico.

Keywords: reference evapotranspiration, Hargreaves, calibration/validation, New Mexico

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Introduction

Evapotranspiration is the main source of water losses from the hydrological cycle and one of the most important parameters in hydrological, environmental, and agricultural studies. Evapotranspiration is used as a key parameter in irrigation project design, recreational and tourism, and hydrological projects. While actual crop evapotranspiration estimated by different methods from direct measurements with lysimeters, Bowen ratio energy balance system, Eddy covariance system and scintillometer,[1–6] reference crop evapotranspiration is reasonably estimated from the climatic variables[7–17] and satellite remote sensing models (Lopez et al., 2017).[18,19] Other modeling approaches such as artificial neural network, hybrid modeling and machine leaning are also used to estimate the daily reference evapotranspiration with very good accuracy.[20–23]

Numerous ETo estimation equations have been developed with different performance and adaptability throughout the globe and the Penman-Monteith equation is shown to be the most worldwide accurate under all types of climatic conditions.[16,24–28] Numerous and usually non-available climatic variables required by the Penman-Monteith equation constitute the most limiting constraint for its adoption under limited data conditions. Climatic models with fewer parameters are therefore used throughout the globe.

The Hargreaves reference evapotranspiration equation is a very simple equation that requires air temperature and solar radiation and is one of the most widely used simple reference evapotranspiration equation for daily or monthly ETo estimation with variable degree of performance in Canada,[29] in China,[30,31] in Italy,[32,33] in Spain,[34] in Iran,[35–37] in South Korea,[38] and in Senegal, Kenya, and Tanzania.[39–41] Musa and Elagib[42] reported the calibration of the Hargreaves ETo equation showed latitude dependance of the calibrated constant with is 0.0023 in the original equation, offering interpolation and extrapolation of the constants within the equation across a large study area with limited climate dataset. However, they pointed out that calibrating the constant 0.0023 is more suitable for the hyper-arid and semi-arid zones of Sudan and South-Sudan as well as for the hot and wet seasons. The regionally calibrated Hargreaves ETo equation is a viable alternative for estimating ETo in regions with limited meteorological data compared to the Penman-Monteith equation.[43] Heydari and Heydari[37] 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, while the root mean square error was improved by 40% and the mean bias error was improved by 66%. Aschonitis et al.[44] revised and calibrated the Hargreaves solar radiation equation used into global ETo estimation with improvement of 28% in RMSE. In a hyper-arid and arid Mediterranean region, the Hargreaves ETo equation showed similar performance as the Penman-Monteith equation.[45] Mehdizadeh et al.[46] found the Hargreaves coefficient to be 0.0026 instead of the original value of 0.0023 in the northwest of Iran. The calibrated coefficient for Davis in California is equal to 0.170 (Hargreaves and Samani, 1985) and Salt Lake City in Utah.[47] Feng et al.[48] also reported improvement in ETo estimation with locally calibrated Hargreaves ETo equation in Sichuan basin of southwest China. Almorox and Grieser[49] also found improvement in ETo estimated by the calibrated form of the Hargreaves equation under different Köppen climate using 4,368 weather stations worldwide.

While most of the developed equations are able to predict reference evapotranspiration, their accuracy varies with the climatic zones and the quality of the available meteorological data. Equation calibration to the local climatic conditions usually improves the performance and the accuracy of the equations.[39,50,51] Thus, the objective of this study was to site specific and statewide calibrate the Hargreaves equation for the estimation of the daily reference evapotranspiration across the state of New Mexico, USA.

Material and methods

Study sites

This study was conducted at thirteen (13) weather stations across New Mexico (USA) (Figure 1) for the period of January 2017 to December 2024. The geographical coordinates of the weather stations are presented 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 stations installed by the New Mexico Climate Center. The time series data were checked for quality control following the methodology described by Allen et al.[16] and the abnormal data points were removed before the analysis.

Table 1 The geographical coordinates of the weather stations under the present study

Research Stations	Latitude (degrees)	Longitude (degrees)	Elevation (m)	Tmax (°C)	Tmin (°C)	RHmax (%)	RHmin (%)	U^2 (m/s)	Solar R.s (MJ/m²)
Adams Ranch	34.25	-105.42	1882.4	19.72	3.5	72.91	21.18	2.15	18.4
Alcalde	36.09	-106.06	1734	20.82	1.57	89.9	30.69	2.02	16.61
Artesia	32.75	-104.38	1027	26.12	8.36	72.01	21.42	2.81	18
Clovis	34.6	-103.22	1366	22.97	6.39	77.92	24.83	3.39	19.7
Corona Range	34.27	-105.44	1910	20.05	5.15	69.64	22.05	3.7	19.15
Fabian Garcia	32.28	-106.77	1186	26.35	9.59	64.92	17.73	1.55	20.45
Farmington	36.69	-108.31	1720	19.62	3.75	72.49	22.3	2	18.12
Las Cruces	32.28	-106.76	1185	26.65	10.77	61.36	17.01	1.45	19.52
Leyendecker	32.2	-106.74	1176	26.04	7.37	77.41	18.3	1.58	20.93
Los Lunas	34.77	-106.76	1476	23.47	4.77	75.56	19.3	0.92	17.43
Mora	35.98	-105.35	2213	17.86	0.64	73.08	19.51	1.73	17.56
Sevillata	34.36	-106.69	1595	23.59	7.07	68.83	19.9	2.19	19.87
Tucumcari	35.2	-103.69	1246	23.58	7.56	70.61	22.31	3.06	19.45

Figure 1 Presentation of study location in the United States of America. (Red polygon on the US map) and the weather stations as shown by red arrows (downloaded from Google earth on 17 June 2025).

Penman-Monteith reference evapotranspiration equation

Daily grass-reference ET was computed using the standardized ASCE form of the Penman-Monteith (PM-ETo) equation:[17]

$$ETo = \frac{0.408\Delta\left(Rn - G\right) + \left(900\gamma u2 / \left(T + 273\right)\right)\left(es - ea\right)}{\Delta + \gamma\left(1 + 0.34u2\right)} \quad (1)$$

where: ETo is the reference evapotranspiration (mm day^{-1}), Δ is the slope of saturation vapor pressure versus air temperature curve (kPa °C^{-1}), Rn is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), T is the mean daily air temperature at 1.5 - 2.5 m height (°C), u_2 is the mean daily wind speed at 2 m height (m s^{-1}), es is the saturation vapor pressure at 1.5-2.5 m height (kPa), ea is the actual vapor pressure at 1.5-2.5 m height (kPa), es-ea is the saturation vapor pressure deficit (kPa), γ is the psychrometric constant (kPa °C^{-1}). The procedure developed by Allen et al.[16] was used to compute the needed parameters.

Hargreaves and Samani (1982)

The Hargreaves-Samani[10] reference evapotranspiration equation, when the global solar radiation data is available, is presented as (equation 2):

$$ETo = 0.0135 * Rs * \left(T + 17.8\right) \quad (2)$$

where Rs id the global solar radiation, T is the mean daily temperature. In the case global solar radiation is not available at the site, Hargreaves and Samani[11] and Hargreaves and Allen[13] have developed a formula to estimate the daily solar radiation (equation 3):

$$Rs = Krs * Ra * \left(Tmax - Tmin\right)^{0.5} \quad (3)$$

where Krs is an empirical coefficient, Ra is extra-terrestrial radiation estimated following Allen et al.[16] λ is the latent heat of vaporization, Tmax is maximum temperature, Tmin is minimum temperature. Krs values of 0.16 and 0.19 are recommended for the coastal and inland regions, respectively.[52] Annandale et al.[53] adjusted the Krs equation to account for the elevation of the location and Allen[54] also proposed a new improved equation for Krs estimation accounting for the site altitude.

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$$Krs = Krso\left(\frac{P}{Po}\right)^{0.5} \quad (4)$$

$$Rs = Krso\left(\frac{P}{Po}\right)^{0.5} * Ra * \left(Tmmax - Tmin\right)^{0.5} \quad (5)$$

$$P = Po\left(\frac{293 - 0.0065\,Z}{293}\right)^{5.26} \quad (6)$$

where P is mean atmospheric pressure of the site in kPa,[55] Po is the mean atmospheric pressure at sea level in kPa, Z is the elevation of the site above mean sea level in m, Krso is the empirical coefficient which is equal to 0.17 for coastal regions and 0.20 for inland regions.

The integration of equation 5 into equation 2 results in equation 7:

$$ETo = 0.0135\,Krso\left(\frac{P}{Po}\right)^{0.5} * Ra * \left(T + 17.8\right) * \left(Tmmax - Tmin\right)^{0.5} \quad (7)$$

Hargreaves and Samani (1985)

Equation 7 could be rewritten as equation 8:

$$ETo = KHS * Ra * \left(T + 17.8\right) * \left(Tmax - Tmin\right)^{0.5} \quad (8)$$

where KHS is empirical coefficient; KHS $= 0.0135\,Krso\left(\frac{P}{Po}\right)^{0.5}$. The recommended value of KHS is 0.0023 [11] which gives the equation 9:

$$ETo = 0.0023 * Ra * \left(T + 17.8\right) * \left(Tmax - Tmin\right)^{0.5} \quad (9)$$

Data processing and site-specific and statewide calibration and validation of the Hargreaves-Samani equations

The first step of data processing consisted of daily reference evapotranspiration estimation using the Hargreaves-Samani equations 2 and 9 and which were compared with the Penman-Monteith ETo estimates. In the case of non-measured solar radiation at the site, equation 3 is integrated into equation 2. For the site specific and statewide calibration, the Penman-Monteith ETo estimates were supposed to be the measured or observed data and ETo was estimated using equations 7 and 8 for local and statewide Krs and KHS modeling. Further, different calibrated constants A, B, C, D, E, F, Ko, K1, K2 were determined for each research site and for the State of New Mexico following the equations 10-14.

$$ETo = A * Rs * \left(T + 17.8\right) \quad (10)$$

$$ETo = B * Rs * \left(T + C\right) \quad (11)$$

$$ETo = Ko * Ra * \left(T + 17.8\right) * \left(Tmax - Tmin\right)^{0.5} \quad (12)$$

$$ETo = K1 * Ra * \left(T + D\right) * \left(Tmax - Tmin\right)^{0.5} \quad (13)$$

$$ETo = K2 * Ra * \left(T + E\right) * \left(Tmax - Tmin\right)^{F} \quad (14)$$

The generalized reduced gradient method was used for model calibration for the January 2017-March 2020 period. This procedure allows iterations by changing the constants in the equations to create new equations for each location and for all 13 stations pooled together. The solver add-in Excel is a tool that was used to fit the original equations by minimizing the sum of the squared residuals between the Penman-Monteith ETo estimates and the ETo estimates by the equation to be calibrated. The Penman-Monteith equation was recommended as the standard reference evapotranspiration method by the Agriculture Organization (FAO) and the World Meteorological Organization (WMO).[16] Multiple initial values were tested to ensure that the global minimum of the errors was found[56] and maximum value of the Kling-Gupta efficiency (KGE)[57] was reached. For model evaluation, simple linear regression was used to compare the daily ETo estimates by the Hargreaves-Samani equations and the Penman-Monteith equation at each weather station and all 13 stations pooled together. The intercept of the regression line was forced to be zero. The more accurate the reference evapotranspiration is the more the regression slope and the coefficient of determination are close to unity. The Kling-Gupta efficiency (KGE),[57,58] Nash-Sutcliffe model efficiency coefficient (NSE), the coefficient of determination R^2, and the mean absolute error (MAE)[59] were also used for model evaluation. The KGE is a statistical approach proposed to overcome the limitations of other statistical model performance evaluation such as the NSE and R^2. The KGE measures not only the accuracy of the model predictions but also it has the ability to reproduce the variability and timing of the observed data. The objective function was to maximize KGE (KGE varies between – infinite and 1 and the higher KGE is, the better the simulation process is). The calibrated equations were validated for the April 2020-December 2024 period.

Results and discussion

Model performance evaluation

The adjustment of different parameters of equations 10, 11, 12, 13 and 14 was great overall when the estimated daily reference evapotranspiration values were compared to the estimated by the Penman-Monteith equation. For the equation 10, 11, 12, 13 and 14, all statistics evaluation criteria varied with stations across the State of New Mexico. KGE varied from 0.73 to 0.93 for equation 10, from 0.73 to 0.97 for equation 11, from 0.77 to 0.94 for equation 12, from 0.88 to 0.96 for equation 13 and from 0.88 to 0.96 for equation 14, and averaged 0.85, 0.92, 0.88, 0.92 and 0.92 for the respective equations (Table 2). All KGE values are greater than 0.5, indicating that all models' performance is good.[60] The calibration of the Hargreaves ETo equations significantly improved the performance achieving validation values of NSE ranging from 0.67 to 0.94 while the NSE values of the original equations ranged from −0.57 to 0.87 in the Peruvian Altiplano.[43] The performance of all models was the poorest at the Corona Range which is hyper arid area while the best model performance occurred at Alcalde and Las Cruces. Model calibration might be focused on the monthly and or seasonal basis to account for the abrupt changes in the weather parameters patterns in the temperate hyper-arid locations. Model performance at all stations is confirmed by the Nash-Sutcliffe model efficiency coefficient which averaged between 0.84 and 0.88 for the five equations all stations combined and from 0.80 to 0.91 all equations together. The greatest NSE value was obtained at Alcalde while the lowest value was registered at Corona Range like for the KGE.

The coefficient of determination of the linear regression between the daily reference evapotranspiration estimated by the Penman-Monteith and the different models represented by equations 10, 11, 12, 13, and 14, varied from 0.84 to 0.93, 0.81 to 0.93, 0.78 to 0.93, 0.76 to 0.93, and from 0.76 to 0.93 and averaged 0.88, 0.87, 0.85, 0.85 and 0.85 for the respective equations (Table 2). The highest R^2 was obtained at Alcalde while the lowest R^2 was obtained at Corona Range. The regression slopes of the linear regression between the daily reference evapotranspiration estimated by the Penman-Monteith and the different models varied from 1.00 to 1.04, 0.98 to 1.00, 0.98 to 1.02, 0.97 to 0.99, and from 0.97 to 0.99 for the equation 10, 11, 12, 13, and 14, respectively, and averaged 1.01, 0.99, 1.00, 0.98 and 0.98 for the respective equations (Table 2). The average regression slopes varied from 0.99 to 1.00 for the different stations, showing the good performance of different equations with only 1% of evapotranspiration overestimation or 2% of evapotranspiration underestimation. The equation 10 overestimated daily reference evapotranspiration from 1 to 4% at 77% of the stations. The equations 11, 13, and 14 underestimated daily reference evapotranspiration up to 3% compared to the Penman-Monteith equation. Higher daily reference evapotranspiration overestimation and underestimation were observed at the Corona Range station.

Table 2 Summary of the calibration evaluation criteria

Evaluation criteria	Weather Location	Equation 10	Equation 11	Equation 12	Equation 13	Equation 14
KGE	Adams Ranch	0.83	0.94	0.83	0.89	0.89
	Alcalde	0.92	0.97	0.93	0.95	0.95
	Artesia	0.84	0.91	0.92	0.92	0.92
	Clovis	0.75	0.92	0.78	0.89	0.89
	Corona Range	0.73	0.73	0.82	0.88	0.88
	Fabian Garcia	0.92	0.95	0.93	0.93	0.93
	Farmington	0.88	0.96	0.91	0.96	0.96
	Las Cruces	0.93	0.95	0.93	0.93	0.94
	Leyendecker	0.82	0.92	0.89	0.92	0.93
	Los Lunas	0.88	0.95	0.93	0.94	0.94
	Mora	0.76	0.93	0.77	0.9	0.9
	Sevilleta	0.9	0.94	0.94	0.94	0.95
	Tucumcari	0.86	0.93	0.89	0.92	0.92
NSE	Adams Ranch	0.88	0.87	0.81	0.79	0.79
	Alcalde	0.93	0.93	0.9	0.9	0.9
	Artesia	0.84	0.82	0.84	0.84	0.85
	Clovis	0.86	0.85	0.79	0.78	0.79
	Corona Range	0.84	0.84	0.78	0.76	0.76
	Fabian Garcia	0.9	0.89	0.86	0.86	0.86
	Farmington	0.92	0.92	0.93	0.93	0.93
	Las Cruces	0.91	0.9	0.87	0.87	0.89
	Leyendecker	0.85	0.84	0.84	0.84	0.85
	Los Lunas	0.9	0.91	0.88	0.88	0.89
	Mora	0.88	0.87	0.8	0.79	0.8
	Sevilleta	0.89	0.88	0.89	0.89	0.89
	Tucumcari	0.87	0.86	0.86	0.85	0.85
R2	Adams Ranch	0.88	0.87	0.81	0.79	0.79
	Alcalde	0.93	0.93	0.9	0.9	0.9
	Artesia	0.84	0.83	0.85	0.84	0.85
	Clovis	0.87	0.85	0.79	0.78	0.79
	Corona Range	0.85	0.81	0.78	0.76	0.76
	Fabian Garcia	0.9	0.9	0.86	0.86	0.87
	Farmington	0.92	0.92	0.93	0.93	0.93
	Las Cruces	0.91	0.9	0.87	0.87	0.89
	Leyendecker	0.85	0.84	0.84	0.84	0.85
	Los Lunas	0.9	0.91	0.88	0.88	0.89
	Mora	0.88	0.87	0.8	0.8	0.8
	Sevilleta	0.89	0.88	0.89	0.89	0.89
	Tucumcari	0.87	0.86	0.86	0.85	0.85
Regression slope	Adams Ranch	1.02	0.99	1	0.98	0.98
	Alcalde	1.01	1	1	0.99	0.99
	Artesia	1.01	0.98	0.98	0.98	0.98
	Clovis	1.03	0.99	1.01	0.98	0.98
	Corona Range	1.04	0.98	1	0.97	0.97
	Fabian Garcia	1	0.99	0.99	0.99	0.99
	Farmington	1.02	0.99	1.01	0.99	0.99

Table 1 Continued...

	Las Cruces	1	0.99	0.99	0.99	0.99
	Leyendecker	1.01	0.99	1	0.99	0.99
	Los Lunas	1.01	0.99	1	0.99	0.99
	Mora	1.03	0.99	1.02	0.98	0.98
	Sevilleta	1	0.99	0.99	0.99	0.99
	Tucumcari	1.01	0.99	1	0.98	0.98
RMSE	Adams Ranch	0.87	0.78	1.09	1.01	1.01
	Alcalde	0.51	0.48	0.62	0.59	0.58
	Artesia	1.18	1.09	1.03	1.02	1
	Clovis	0.79	0.69	0.95	0.82	0.81
	Corona Range	1.13	1.13	1.2	1.12	1.12
	Fabian Garcia	0.7	0.68	0.79	0.79	0.77
	Farmington	0.71	0.65	0.65	0.6	0.6
	Las Cruces	0.65	0.64	0.75	0.75	0.7
	Leyendecker	0.89	0.8	0.86	0.81	0.77
	Los Lunas	0.6	0.53	0.62	0.59	0.58
	Mora	0.75	0.64	0.94	0.8	0.79
	Sevilleta	0.93	0.91	0.89	0.89	0.87
	Tucumcari	1.07	1.01	1.07	0.92	1.03
MAE	Adams Ranch	0.66	0.61	0.85	0.79	0.79
	Alcalde	0.39	0.36	0.45	0.43	0.43
	Artesia	0.89	0.82	0.77	0.77	0.74
	Clovis	0.58	0.51	0.72	0.62	0.6
	Corona Range	0.89	0.89	0.94	0.89	0.89
	Fabian Garcia	0.54	0.51	0.58	0.57	0.57
	Farmington	0.54	0.49	0.48	0.44	0.44
	Las Cruces	0.5	0.49	0.55	0.55	0.52
	Leyendecker	0.7	0.62	0.64	0.61	0.59
	Los Lunas	0.47	0.41	0.45	0.43	0.43
	Mora	0.55	0.48	0.72	0.6	0.59
	Sevilleta	0.71	0.7	0.68	0.68	0.66
	Tucumcari	0.82	0.79	0.83	0.8	0.8

The RMSE varied with locations and reference evapotranspiration models. It varied from 0.51 to 1.18 mm/day, 0.48 to 1.13 mm/day, 0.62 to 1.2 mm/day, 0.59 to 1.12 mm/day, and from 0.58 to 1.12 mm/day and averaged 0.83, 0.77, 0.88, 0.82 and 0.82 for the equations 10, 11, 12, 13, and 14 (Table 2). The RMSE was at the highest values at the Corona Range station while the lowest RMSE values were observed at Alcalde and Los Lunas. The Mean absolute error also varied with locations and evapotranspiration models. It varied from 0.39 to 0.89 mm/day, 0.36 to 0.89 mm/day, 0.45 to 0.94 mm/day, 0.43 to 0.89 mm/day, and from 0.43 to 0.89 mm/day for the equations 10, 11, 12, 13, and 14, respectively, and averaged 0.63, 0.59, 0.67, 0.63 mm/day for the respective equations (Table 2). The lowest MAE values were obtained at Alcalde station for all equations while the highest MAE values were obtained at Corona Range due to the differences in model performance at these locations.

Adjusted Krs values at each location

Krs values varied from 0.1371 to 0.2409 and averaged 0.1877. The most arid location Corona Range showed the highest Krs value, and the lowest value was obtained at Los Lunas. Krs value when all the stations were pooled together is 0.1850, which is 1.4% lower than the average Krs value. Hargreaves and Samani[11] set the initial Krs to 0.17 for arid and semiarid regions and Hargreaves[52] recommended 0.16 for interior regions and 0.19 for coastal regions[16] and which are similar to the reported values in the present study. Krs values of 0.17-0.18 and 0.10-0.22 were reported for the semiarid and arid-hyper arid area respectively in Inner Mongolia, Iran, Portugal, and Spain.[61] Lujano et al.[62] reported a range of Krs values from 0.150 to 0.209 in the Peruvian Lake Titicaca basin, Peru. Krs values from 0.157 and 0.165 were found in the Évora district in the Alentejo region, Southern Portugal.[63] Tabari et al.[64] found the Krs of the Hargreaves-Samani model of 0.14 for the semi-arid climate of Iran. Krs was empirically developed to estimate solar radiation based solely on the air temperature. However, solar radiation is influenced by other factors such as cloud cover, air relative humidity and wind speed which are not incorporated into the Krs estimation method, and which might explain the differences in Krs values across different environments López-Urrea et al.[65]

The adjusted parameters in equations 10, 11, 12, 13, and 14

The adjustment of equation 10 at each station revealed variation of A values from 0.0135 to 0.0204 and average 0.0167 while it was 0.0164 when all stations were pooled together. The lowest value was obtained Los Lunas in the central region of New Mexico while the highest value was obtained at Corona Range in the highly arid area without active farm irrigation system. The parameters B and C within equation 11 varied from 0.0082 to 0.143 and from 23.610 to 62.531 and averaged 0.0111 and 35.846, respectively. With all the stations pooled together, the adjusted B and C values were 0.0148 and 21.507, respectively. Ko values varied with locations and ranged from 0.0019 to 0.0033 and averaged 0.0025, Ko value obtained when all the weather stations' data were pooled together during the calibration phase was 0.0025 (Table 3). The highest value is recorded at Corona Range in the desert area while the lowest value was recorded at Alcade and Los Lunas research centers. The relatively lower values at the other stations compared to Corona range might be the impact of agricultural irrigation not too far from the stations and which increases air relative humidity, temperature, and vapor pressure deficit. In arid and semiarid region in Iran, Heydari and Heydari[37] found the Ko values of the calibrated Hargreaves and Samani[11] (equation 12) to range from 0.0018 to 0.0037 while a range of 0.0025-0.0186 was found in the Amu Darya River Basin, Central Asia, due to the hyper aridity conditions in the study area.[66] Azzam et al.[66] reported a very high value of 0.0047 in a very dry windy and high vapor pressure region and 0.0033 at an area toward humid region of the study area. Gavilan et al.[67] showed that calibration was not necessary for some locations because the new coefficients were 0.00234 and 0.00241 while new values were 0.00209, 0.0021, 0.0026, 0.00273, and 0.0029 for other locations with an improvement of the MBE of 54%. Vanderlinden et al.[47] reported an average value of 0.0029 at the coastal area and 0.0022 at inland area in Spain. In recent study, Musa and Elagib[42] found Ko to increase to 0.00238 and 0.00247 at Port Sudan and Dongola in the northern Sudan, respectively, while it was within the range from 0.00176 to 0.00226 elsewhere in Soudan. Very high values within the range of 0.0025-0.0067 were recorded across different agricultural climatic zones in India.[68] A large range of Ko values was reported by Gavilan et al.[67] with averages of 0.00209, 0.00235, 0.00241, 0.00271, and 0.0029 for difference regions and three values such as 0.0021, 0.00273, and 0.0026 were proposed for different regions in Andalusia (Spain) instead of 0.0023. Tabari and Talaee[36] and Ndiaye et al.[69] reported ko value of 0.0031 in the arid and cold climates of Iran and Senegal.

Table 3 Summary of the calibrated parameters

Stations	Calibrated parameters (constants)									
	Krs	A	B	C	Ko	K1	D	K2	E	F
Adams Ranch	0.2208	0.0189	0.012	36.049	0.003	0.0021	30.9095	0.0026	28.7823	0.4413
Alcalde	0.1441	0.0143	0.0117	24.649	0.0019	0.0017	22.647	0.0021	21.4894	0.4414
Artesia	0.2103	0.0196	0.0132	35.308	0.0028	0.0028	18.7703	0.0018	20.6695	0.6405
Clovis	0.1811	0.0172	0.0082	49.7	0.0024	0.0015	35.5847	0.0007	44.3733	0.6953
Corona Range	0.2409	0.0204	0.0083	62.531	0.0033	0.0024	29.0366	0.0028	27.6314	0.454
Fabian Garcia	0.1675	0.0142	0.0118	25.249	0.0023	0.0022	18.6407	0.0037	16.3314	0.3394
Farmington	0.1899	0.0161	0.0119	29.437	0.0026	0.0021	24.8319	0.0025	23.8291	0.4432
Las Cruces	0.1625	0.0142	0.0123	23.61	0.0022	0.0022	18.4559	0.005	14.9871	0.2346
Leyendecker	0.172	0.0159	0.0096	40.946	0.0023	0.0019	25.636	0.0037	21.9163	0.2976
Los Lunas	0.1371	0.0135	0.0098	30.596	0.0019	0.0017	21.6686	0.0027	19.8895	0.3558
Mora	0.1831	0.0172	0.0083	48.29	0.0025	0.0014	39.2594	0.0007	48.4587	0.6752
Sevilleta	0.2103	0.0181	0.0143	27.187	0.0028	0.0027	19.5117	0.004	17.9041	0.3777
Tucumcari	0.2201	0.0177	0.0126	32.445	0.003	0.0025	24.9393	0.0023	25.259	0.5179
Average	0.1877	0.0167	0.0111	35.846	0.0025	0.0021	25.3763	0.0027	25.5016	0.4549
Pooled data	0.185	0.0164	0.0148	21.507	0.0025	0.0031	11.2629	0.0023	11.7155	0.6023

The calibrated parameters K1 and D varied from 0.0014 to 0.0028 and from 18.46 to 39.26, respectively. There is a decreasing trend in parameter K1 with increasing D values. With all data pooled together, the parameter K1 was 0.0032 and the D was 11.26 while the parameters K1 and D averaged 0.0021 and 25.38, respectively. The lowest values of K1 were obtained at Mora and Clovis with the corresponding highest values of D at the same locations. Adversely the highest value of K1 was obtained at Artesia in the southeastern New Mexico. The parameters K_2, E, and F of the equation 14 varied with locations and ranged from 0.0007 to 0.0050, 14.99 to 48.46, and from 0.2346 to 0.6953 and averaged 0.0027, 25.50, and 0.4549, respectively. Using all stations data pooled together, the respective parameters were 0.0023, 11.7155, and 0.6023. The parameters at each single station are quite different from the 0.0023, 17.8, and 0.5 within the original equation. These parameters differ from the reported values in other studies. Calibration of the Hargreaves' equation 14 in Sichuan basin of southwest China revealed that parameter K2, E, and F were within the rages of 0.00213 – 0,00217, 16.19 – 16.58, and 0.40 – 0.46, and averaged 0002166, 16.40105, and 0.4353, respectively.[31] Feng et al.[31] reported no clear change trend of these parameters, however their reported values were lower than the original values within equation 9. In Jordan, Mohawest and Talozi[70] reported values of 0.6957, 0.58 and 16.6 for the K2, E, and F respectively, while Droogers and Allen[71] reported 0.0030, 0.4, and 20.0 worldwide, and Smith[72] reported 0.0030, 0.4, and 20.0 for the respective parameters in California, USA. Ranges of parameters K2, E, and F of 0.0011-0.0013, 1.1669-15.5731, and 0.6128-0.8312 were reported for the respective parameters in Brazil.[73] The calibration parameters K, E, and F across the Han-River basin in South Korea were within the ranges of 0.0015–0.0028, 19.3–36, and 0.25–0.49, respectively.[74] The locally recalibrated equations effectively reduced the systematic bias associated with the use of the original equations.[42,66,74,68,31,40,70,72]

Adjusted equations with the pooled dataset

The adjustment of different parameters with the pooled data calibration showed nonconsistency across the models. The comparison of the Hargreaves-Samani[10] (equation 7) and the adjusted equation 9 to the Penman-Monteith equation showed an improvement of the regression slope from 0.823 showing 17.7 % of ETo underestimation to 0.983 with only 1.7% of ETo underestimation. However, the RMSE was only reduced by 3.6% and the MAE was reduced by 2.8%. With the original Hargreaves-Samani[10] and the equation 10 adjusted, the regression slope was improved from 0.823 to 1.0026 decreasing ETo underestimation of 17.7 to ETo overestimation of only 0.26% with 15.08% decrease in RMSE and 14.08% of the MAE and showing the great opportunity to adopt the adjusted equation 10 for ETo estimation across the State of New Mexico. Similarly, the adjusted equation 11 showed improvement of the regression slope from 0.823 to 0.994 with the greatest improvement of RMSE by 17.79% and the MAE by 16.98%. Therefore, the adjusted equation 11 is the best performing ETo model across New Mexico. The comparison of the Hargreaves[11] and the adjusted equation 12 to the Penman-Monteith showed an increase in regression slope from 0.904 to 0.9882 equivalent to a decrease of ETo underestimation of 9.6% to 1.83%. The RMSE was reduced by 0.42% while the MAE was increased by 0.37%. The adjusted equation 13 increased the regression slope from 0.904 to 1.003, equivalent to only 0.3% of ETo overestimation compared to the Penman-Monteith model. However, the adjusted equation 13 increased the RMSE by 8.02% and the MAE by 11.69%. Consequently, the adjusted equation 13 may lead to some misleading daily irrigation water requirement estimation, jeopardizing crop growth and development, and probably crop yield and should not be used while the adjusted equations 10 and 11 showed better performance than the adjusted equation 13. Like the adjusted equation 13, the adjusted equation 14 showed only 0.39% ETo overestimation compared to the original Hargreaves 1985 model but it induced 8.02% increase in RMSE and 11.69% increase in MAE. The results shown in Figure 2 and Figure 3 for the calibration phase are confirmed with the validation phase shown in Figure 4. Çıtakoglu et al.[75] reported that reference evapotranspiration estimates by using calibrated Hargreaves and Samani (HS) equations are close to those calculated by Penman-Monteith equation in Marmara Region of Turkey. Overall, the combination of model evaluation criteria, the adjusted equation 11 should be the first choice from the Hargreaves' reference evapotranspiration estimation model at the location with only temperature and/or solar radiation data available. Adjusted equation 10 should be the second choice under the same limited weather dataset across the State of New Mexico.

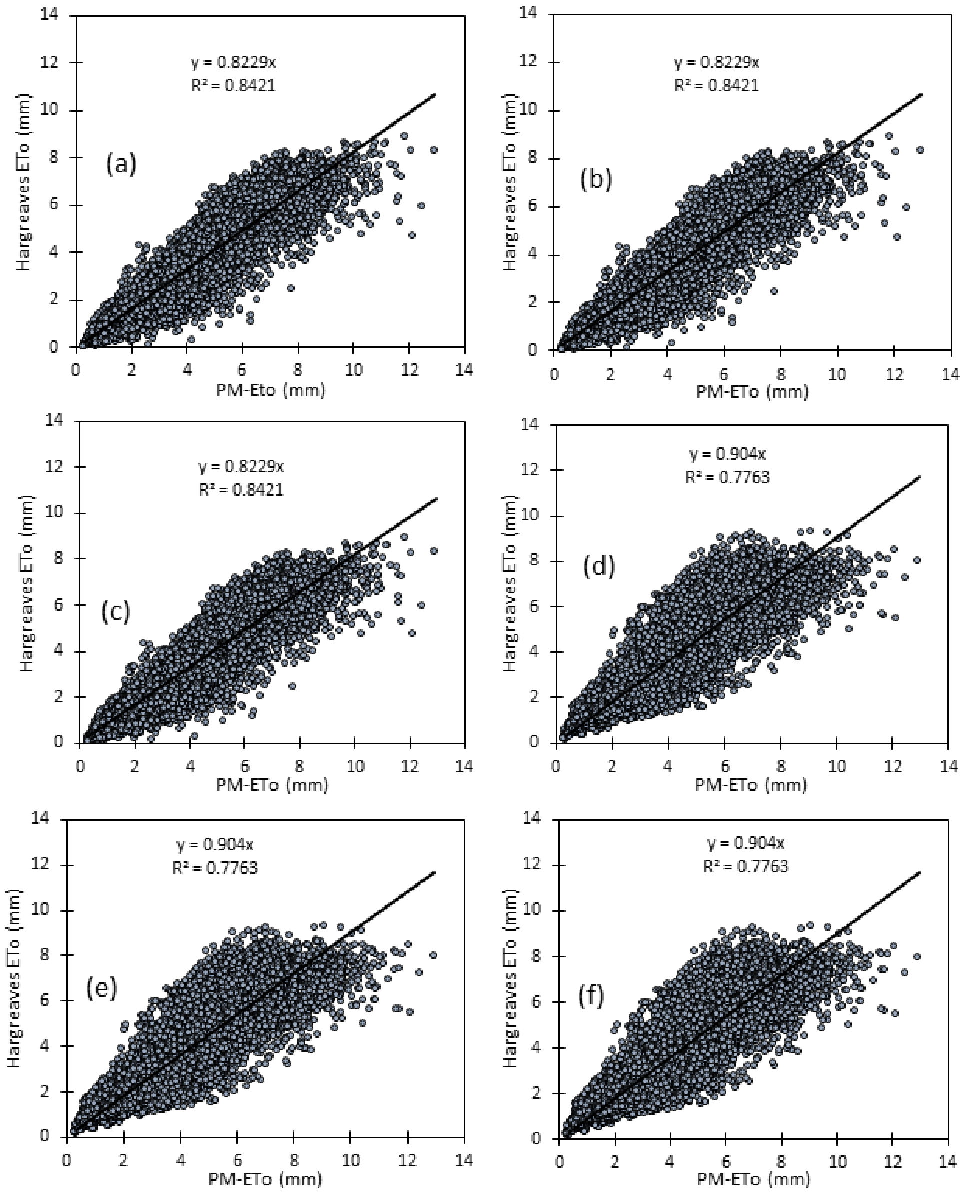

Figure 2 Comparison of the Penman-Monteith ETo estimates to the original Hargreaves and Samani ETo estimates (a) Equation 9 (b) equation 10, (c) equation 11, (d) equation 12), (e) equation 13, (f) equation 14 (all 13 weather stations pooled together) for the January 2017-March 2020 period.

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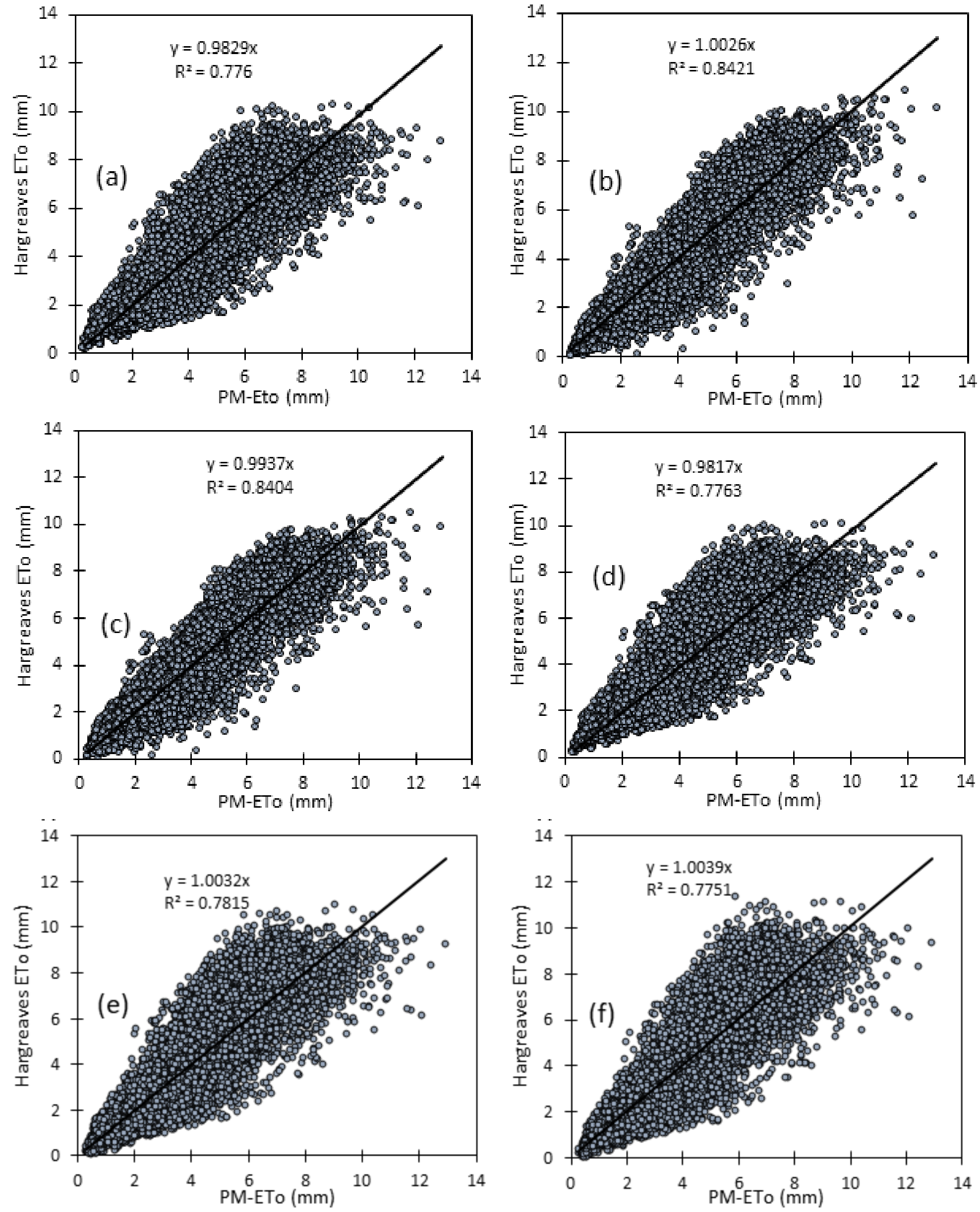
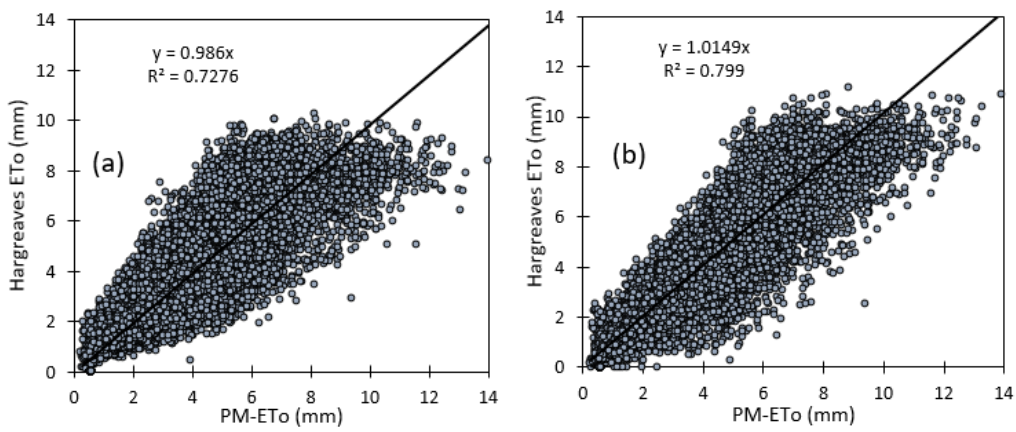


Figure 3 Comparison of the Penman-Monteith ETo estimates to the calibrated Hargreaves and Samani ETo estimates (a) Equation 9 (b) equation 10, (c) equation 11, (d) equation 12), (e) equation 13, (f) equation 14 (all 13 weather stations pooled together) for the January 2017-March 2020 period.



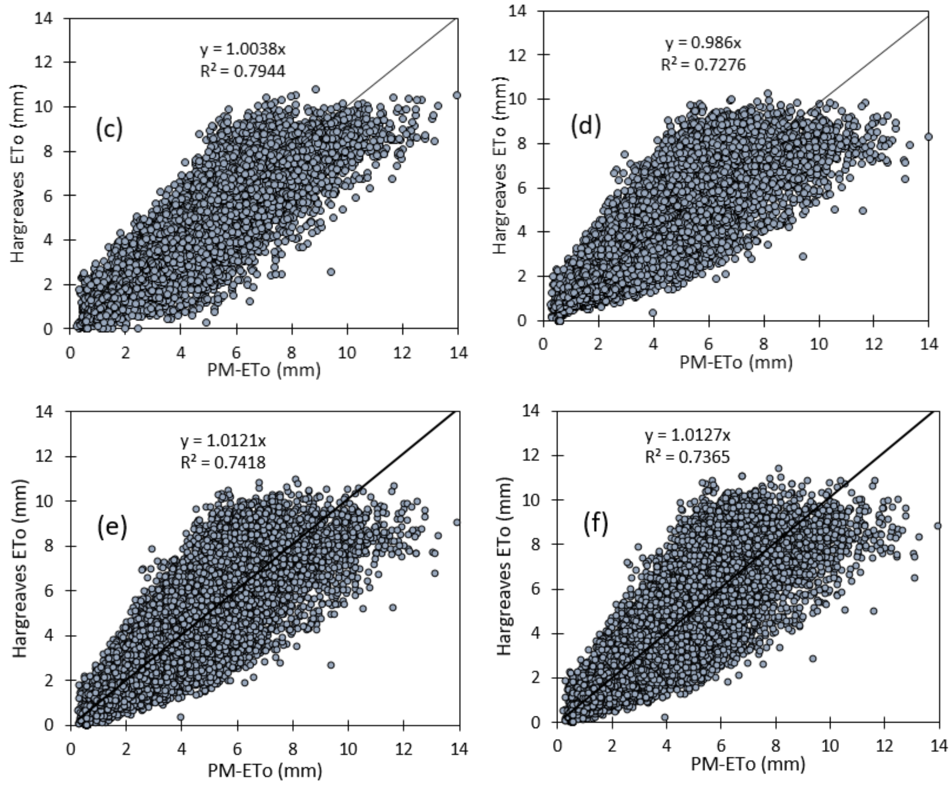


Figure 4 Validation of the calibrated equations for the April 2000 - December 2024 period: the calibrated Hargreaves and Samani ETo estimates (a) Equation 9 (b) equation 10, (c) equation 11, (d) equation 12), (e) equation 13, (f) equation 14 (11 weather stations pooled together).

The calibrated Hargreaves-Samani model showed a good performance within acceptable ranges of accuracy in the Free State, South Africa.[76] The calibration of reference evapotranspiration using the Solver tool from Microsoft Excel was successfully used by Ferreira et al.[63] who concluded less uncertainty using solver to optimize the solution. In contrast, Gharehbaghi et al.[77] used three different model calibration methods and found that the regression analysis and traditional methods demonstrated a higher level of accuracy. For future work we recommend testing different model calibrations methods and evaluating their performance accuracy.[78,79]

Conclusion

The Hargreaves reference evapotranspiration equations were evaluated across the State of New Mexico (USA) after adjustment of the equations' constants. The performance of different equations varies with locations with the poorest performance at Corona Range, the hyper arid. Overall, equation calibration improved the performance of all equations which showed good agreement with the Penman-Monteith equation. The correlation between the reference evapotranspiration estimates by the equation 11 and the Penman-Monteith equation showed a coefficient of determination varying from 0.81 to 0.94 and the regression slope from 0.98 to 1.00 with the calibration KEG varying from 0.92 to 0.97 besides the KEG value of 0.73 at the Farmington station, and the NSE varying from 0.82 to 0.93. The adjusted equation 11 requiring only the daily solar radiation and air temperature, is the best performing one and should be considered as the alternative reference evapotranspiration estimation method under limited weather variables under the semiarid dry climate across New Mexico.

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Conflicts of interest

The authors declare no conflict of interest exists.

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