ISSN 2079-0961, Arid Ecosystems, 2020, Vol. 10, No. 4, pp. 329–336. © Pleiades Publishing, Ltd., 2020.

SYSTEMATIC STUDY OF ARID TERRITORIES

Evaluation of Estimation Methods for Monthly Reference Evapotranspiration in Arid Climates

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Received January 20, 2020; revised March 1, 2020; accepted March 1, 2020

Abstract– Reference evapotranspiration (ET_0) plays a key role in irrigation system design as well as water management of agricultural ecosystems under irrigated and rainfed conditions. While many methods for estimating the ET_0 have been developed during the past several decades, method selection essentially depends on the availability of measured climatic variables. The FAO-56PM method recommended by experts from Food and Agriculture Organization of the United Nations is widely used in agricultural and environmental research to estimate the ET_0. However, it requires several climatic parameters that are not always available in developing countries, especially in arid regions. Here, we compare and evaluate the performance of 13 widely- and commonly-used equations for estimating ET_0 against that predicted using the FAO-56PM model using climatic data from nine meteorological stations located in arid regions across Iran. On average, the best three methods that could be used as an alternative to the FAO-56PM equation were the Irmak (Irmak et al., 2003), Hargreaves-Samani (Hargreaves and Samani, 1985), and Hargreaves (1975) equations.

Keywords: evapotranspiration, Iran, water availability, water budgets, water management

DOI: 10.1134/S2079096120040150

Limited water availability is a key factor affecting crop production and accurate assessment of crop water needs is critical towards irrigation system design and management in arid and semiarid regions. Accurate estimation of evapotranspiration (ET) is essential in agricultural, climatological, drought monitoring, and hydrological studies for irrigation planning and management (Sentelhas et al., 2010; Attarod et al., 2015a, 2016). ET measurement has always been challenging, especially on the landscape spatial scale with a level of accuracy desired for farm-specific water management planning in regions lacking micrometeorological stations. Unlike directly measurable rainfall and streamflow, ET is usually estimated from mass transfer, energy transfer, or water budget methods (Enku and Melesse, 2013). Traditional measurements of ET using evaporation pan and lysimeter methods are mainly for smaller-scale applications or experimental studies and can be labor and cost intensive. Micrometeorological methods for estimating actual ET, such as energy balance, Bowen ratio, and eddy covariance, have found widespread application and have improved our understanding of the evaporation process (Drexler et al., 2004). More recently developed surface energy renewal methods (McElrone et al., 2013) are gaining greater acceptance, but still require some calibration back to established ET_0 measurements. In developing regions, these methods may be too costly to establish and maintain and necessary data is not available. Some alternative ET estimation methods work well in the area in which they are developed, but when tested in other climatic conditions perform poorly (Enku and Melesse, 2013).

Estimation of crop ET typically requires determination of reference evapotranspiration (ET_0) (Lopez-Urrea et al., 2006). ET_0 has been defined as the rate of ET from an extensive grassed area 12 cm high, with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen et al., 1998). Crop ET is calculated as the product of a crop coefficient (K_c) that depends on the crop type, stage of growth, canopy cover and density as well as soil moisture and ET_0 (Kisi, 2013). Numerous equations, classified as temperature-based, radiation-based, pan evaporation-based, mass transfer-based, and combination type, have been developed for estimating ET_0, but their performance varies from region to region having different environments (Gocic and Trajkovic, 2010). The FAO-56 Penman-Monteith

Table 1. Location and average annual (± SE) information at weather stations across Iran from the period 1987–2016

ID#	Station	Lat	Long	Altitude, m	Precipitation, mm	Temperature, °C	Relative humidity, %	Wind speed, m s^{-1}
1	Ahwaz	31.20°	48.40°	23	213.5 ± 15.1	26.3 ± 1.3	41.1 ± 4.3	2.4 ± 0.4
2	Bandar Abass	27.13°	56.22°	10	170.7 ± 12.8	26.8 ± 0.9	64.0 ± 5.5	2.9 ± 0.3
3	Birjand	32.52°	59.12°	1491	166.4 ± 12.1	16.6 ± 1.4	34.6 ± 3.1	2.6 ± 0.5
4	Esfahan	32.37°	51.40°	1550	131.3 ± 10.6	16.0 ± 1.2	38.2 ± 3.6	2.8 ± 0.6
5	Qom	34.42°	50.51°	877	145.1 ± 9.3	18.3 ± 1.0	41.4 ± 4.0	3.1 ± 0.7
6	Kerman	30.15°	56.58°	1754	146.9 ± 11.2	15.8 ± 1.2	32.2 ± 2.8	2.6 ± 0.6
7	Mashhad	36.16°	59.38°	999	248.3 ± 16.1	15.2 ± 0.7	50.2 ± 3.5	2.4 ± 0.6
8	Semnan	35.35°	53.33°	1131	144.1 ± 11.7	18.0 ± 1.0	38.7 ± 2.9	1.7 ± 0.2
9	Yazd	31.54°	54.17°	1237	68.0 ± 7.2	19.9 ± 0.7	28.1 ± 2.3	2.5 ± 0.5

(PM equation (Kisi, 2013) is the only globally accepted method for estimating ET_0, which performs well in different climatic conditions in the world (Allen et al., 2005, 2006; Gocic and Trajkovic, 2010; Enku and Melesse, 2013; Attarod et al., 2015a, 2016). The physically-based FAO-56PM approach requires measurements of several climate parameters that may not be readily available from all stations (Enku and Melesse, 2013), especially in developing countries where reliable weather data sets of radiation, relative humidity, and wind speed are limited and costly (Gocic and Trajkovic, 2010; Tabari et al., 2013). In regions lacking sufficient data to use the PM equation or its equivalent, simpler methods requiring fewer data are important towards estimation of ET_0. However, the applicability of these equations to estimate ET_0 for a given region must first be verified using lysimeter measurements or the FAO-56PM model (Tabari et al., 2013).

Here, we compare and evaluate the performance of 13 widely- and commonly-used equations for estimating ET_0 against that predicted using the FAO-56PM model using climatic data from the 9 meteorological stations located in arid regions across Iran.

MATERIALS AND METHODS

Data and reference *ET* equations. We use monthly climatic data from 9 weather stations operated by the Iran Meteorological Organization (IMO) located across Iran for the period 1987–2016 (see Table 1). We compare the ET_0 predicted from 13 different simpler equations to that estimated using the standard FAO-56PM method for calculating ET_0; the PM equation can be written as (Allen et al., 1998):

$$ET_0 = \frac{0.408(R_n - G) + \gamma(900/(T+273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \quad (1)$$

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation (MJ m^{-2} day^{-1}), G the is soil heat flux density (MJ m^{-2} day^{-1}), γ (kPa $°C^{-1}$) is the psychrometric constant calculated as 0.665×10^{-3} P, T is the mean monthly air temperature (°C), U_2 is the wind speed at a height of 2 m (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is vapor pressure deficit (kPa), and Δ is the slope of the saturation vapor pressure-temperature curve (kPa $°C^{-1}$). We followed the method and procedures given in Chapter 3 of FAO-56PM for computation of ET_0 (Allen et al., 1998). Estimation of ET_0 from several simpler equations requiring less information are summarized below.

The Hargreaves and Samani (1985) equation developed in California can be written:

$$ET_0 = 0.408 \times 0.0023R_a \times \left(\frac{T_{max} + T_{min}}{2} + 17.8\right)(T_{max} + T_{min})^{0.5}, \quad (2)$$

where R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}); T_{max} and T_{min} – daily maximum and minimum air temperature respectively (°C) This method behaves best for weekly or longer predictions, although some accurate daily ET_0 estimations have been reported in the literature. Hargreaves and Allen (2003) and Gao et al. (2017) found that Hargreaves and Samani equation was the best model for estimating ET_0 in semiarid region of China. If air temperatures measured at the station are the only available data, various studies have recommended the use of a Hargreaves and Samani equation to calculate ET_0 (Allen et al., 1998; Sentelhas et al., 2010). The Irmak equation can be written (Irmak et al., 2003):

$$ET_0 = -0.611 + 0.149R_s + 0.079T, \quad (3)$$

where R_s is solar radiation (MJ m^{-2} day^{-1}); T is the average daily air temperature (°C). Iramk equation has been proposed for estimating ET_0 in a humid climate. The Hargreaves formula can be written as (Hargreaves, 1975):

$$ET_0 = 0.0135 + 0.408R_s(T + 17.8). \quad (4)$$

This method is applicable when only R_s and T were available. Several studies showed that the accuracy of the Hargreaves equation for estimating ET_0 under humid (Jensen et al., 1990; Bautista et al., 2009) and semiarid (Bautista et al., 2009) climates. The Copais formula developed by Alexandris et al. (2006); hereafter referred to as Copais uses three meteorological variables can be written:

$$ET_0 = m_1 + m_2C_2 + m_3C_1 + m_4C_1, \tag{5}$$

where m_1 = 0.057, m_2 = 0.277, m_3 = 0.643, m_4 = 0.0124, and

$$C_1 = 0.6416 - 0.00784RH + 0.372R_s - 0.00264(R_sRH), \tag{6}$$

$$C_2 = -0.0033 + 0.00812T + 0.101R_s + 0.00584(R_sT), \tag{7}$$

where RH is the daily average relative humidity (%). An application of Copais method approved under humid climate (Alexnadris et al., 2006). Valiantzas (2013) developed the ET_0 equation for arid and humid climates that can be written:

$$ET_0 = 0.0393R_s\sqrt{T+9.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.048(T+20)\left(1-\frac{RH}{100}\right)u^{0.7}, \tag{8}$$

where φ is latitude (rad), and u is average 24 h wind speed at 2 m height (m s^{-1}). Turc (1961) developed an equation under humid (Jensen et al., 1990) and semiarid (Attarod et al., 2015b) climates that can be written:

$$ET_0 = (23.89R_s + 50)\frac{0.013T}{T+15} \times [1 + W_{RH}(0.71 - 1.43RH/100)], \tag{9}$$

where W_{RH} = 1 when RH < 50% and W_{RH} = 0 when RH > 50%. Trajkovic and Stojnic (2007) reported that the performance of the Turc method depends on the wind speed and that this method over predicted ET_0 estimates at windless locations.

Droogers and Allen (2002) reported three new types of the Hargreaves-Samani (1985) equation for arid regions that can be written as follows:

$$ET_0 = 0.408 \times 0.0030(T_a + 20)(T_{\max} - T_{\min})^{0.4} R_a, \tag{10}$$

$$ET_0 = 0.408 \times 0.0025(T_a + 16.8)(T_{\max} - T_{\min})^{0.5} R_a, \tag{11}$$

$$ET_0 = 0.408 \times 0.0013(T_a + 17) \times (T_{\max} - T_{\min} - 0.0123)^{0.76} R_a, \tag{12}$$

where T_a is the average daily air temperature (°C). The Jensen and Haise (1963) equation was developed in Colorado for application in the western USA and proposed for arid climates (Salih and Sendil, 1984) and can be written:

$$ET_0 = \frac{C_T(T_a - T_s)R_s}{\lambda}, \tag{13}$$

where λ is latent heat of vaporization (cal g^{-1}); C_T (temperature constant) = 0.025, and T_x = –3°C and T_a is the mean air temperature (°C). Trajkovic (2007) adjusted the Hargreaves equation for humid climates as follows:

$$ET_0 = 0.0023(T_a + 17.8)(T_{\max} - T_{\min})^{0.424} R_a. \tag{14}$$

While Ravazzani et al. (2012) developed an ET_0 equation for the humid climate that can be written:

$$ET_0 = (0.817 + 0.00022Z) \times 0.0023R_a(T_{\text{mean}} + 17.8)(T_{\max} - T_{\min})^{0.5}, \tag{15}$$

where T_{mean} – average daily air temperature (°C).

Berti et al. (2014) modified the Hargreaves-Samani (1985) equation for sub-humid climate as follows:

$$ET_0 = 0.00193R_a + (T_{\text{mean}} + 17.8)(T_{\max} - T_{\min})^{0.517}. \tag{16}$$

Performance evaluation criteria. We use the root mean square error ($RMSE$), the model efficiency metric (CE; Nash and Sutcliffe, 1970), and Akaike's Information Criterion (AIC; Akaike, 1974) to evaluate how predictions from the simplified ET_0 equations compare with those from the FAO-56PM equation.

$$RMSE = \left[N^{-1}\sum_{i=1}^{N}(P_i - O_i)^2\right]^{0.5}, \tag{17}$$

$$CE = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2}, \tag{18}$$

$$AIC = N\ln(RMSE) + 2t, \tag{19}$$

where N = total number of observation pairs; P_i = predicted value; O_i = an observed value; $\overline{O}$ = average of the observed values, $\overline{P}$ = average of predicted values, and t is the number of parameters in each model. $RMSE$ showed agreement between the observed and modeled datasets and is a non-negative metric that has no upper bound and for a perfect model, the result would be zero (Sadeghi et al., 2015, 2017). CE is intended to range from –∞ to one, and the maximum positive score of one represents a perfect model fit. The model with the lowest AIC is the best model among all models specified for the data at hand.

RESULTS AND DISCUSSION

We list in Table 2 the mean daily ET_0 values for each month calculated using FAO-56PM and data from the nine stations. For the year, the mean daily ET_0 in arid regions across Iran was 4.53 mm/day with

Table 2. Mean daily ET_0 (mm) each month calculated using FAO-56PM method at the nine arid stations. across Iran

Month	Station ID no.									Mean
	1*	2	3	4	5	6	7	8	9	
Jan	1.71	2.72	1.68	1.63	1.83	2.07	1.27	1.01	1.94	**1.76**
Feb	2.60	3.33	2.28	2.59	2.81	2.99	1.86	1.72	2.88	**2.56**
March	3.88	4.34	3.40	3.77	4.08	4.13	2.96	2.90	3.91	**3.71**
April	5.30	5.72	4.50	4.87	5.07	5.14	4.3	4.33	5.00	**4.91**
May	6.75	7.08	5.80	6.11	6.31	6.26	5.62	5.47	6.32	**6.19**
June	8.49	7.33	7.10	7.15	7.67	6.85	7.13	6.66	7.12	**7.28**
July	8.21	6.78	7.60	7.13	7.94	7.25	7.47	6.74	7.37	**7.39**
Aug	7.73	6.53	6.70	6.53	7.08	6.61	6.78	6.11	6.78	**6.76**
Sept	6.09	6.04	5.06	5.34	5.57	5.32	5.25	4.86	5.43	**5.44**
Oct	4.19	5.07	3.53	3.85	3.96	3.88	3.57	3.32	4.04	**3.93**
Nov	2.87	3.89	2.33	2.34	2.51	2.59	1.98	1.80	2.65	**2.55**
Dec	1.86	3.21	1.69	1.55	1.7	1.98	1.32	1.00	1.99	**1.81**
Mean	**4.97**	**5.17**	**4.31**	**4.41**	**4.71**	**4.59**	**4.13**	**3.83**	**4.62**	**4.53**

* 1 to 9 refers Stations Ahwaz, Bandar Abass, Birjand, Esfahan, Qom, Kerman, Mashhad, Semnan, and Yazd stations, respectively, see Table 1.

a coefficient of variation of 9.1% for values that range from 3.83 to nearly 5.17 mm/day across all 9 stations. During the maximum ET_0 month of July, the mean ET_0 was 7.39 mm/day with the smallest coefficient of variation of 6.6%; while the greater coefficient of variation (33.9%) occurred in December. Amongst the nine stations, the greatest and least monthly mean daily ET_0 occurred at the Ahwaz and Semnan stations, respectively (Table 2). From a water resources planning perspective, more than 60% of the annual ET_0 occurs in the months of May through September when ET_0 variability between stations is also the least, hence we consider ET_0 estimation method performance for this period separately.

We summarize the performance criteria values associated with the use of each of the simplified ET_0 equations to estimate daily ET_0 as they compare to that from the FAO-56PM method in Table 3 considering all 12 months and in Table 4 considering the high ET_0, low variability months of May through September. At the Ahwaz, Bandar Abass, Qom, and Semnan stations, the simplified ET_0 equation that had the least *RMSE* and *AIC*, as well as greatest *CE* is equation (3) from Irmak et al. (2003). At the Birjand, Kerman, and Mashhad stations, the best simplified ET_0 estimation method by these performance criteria is equation (10) from Droogers and Allen (2003), and the best method for estimating ET_0 in Esfahan is equation (12) proposed by Droogers and Allen (Droogers and Allen, 2002). For the last station, Yazd, the best method is the equation (14) proposed by Trajkovich (2007). Overall, the simplified ET_0 equation that had the least *RMSE* and *AIC*, as well as greatest efficiency across all stations for estimating daily ET_0 on a monthly basis is equation (3) from Irmak et al. (2003).

For the high ET period (Table 4), Irmak equation (Eq. (3); Irmak et al., 2003) is the best at 4 stations, namely: Ahwaz, Bandar Abbas, Qom, and Semnan (Table 4). Hargreaves equation (Eq. (4); Hargreaves, 1975) is the best method for estimating ET_0 in Birjand and Mashhad stations. The best method to estimate ET_0 in Esfahan, Kerman and Yazd stations were equations (12) (Droogers and Allen, 2002), (6) (Alexandris et al., 2006), and (9) (Turc, 1961), respectively. Overall, the simplified ET_0 equation that had the least *RMSE* and *AIC*, as well as greatest efficiency across all stations for estimating daily ET_0 on a monthly basis during the high *ET* period is equation (3) from Irmak et al. (2003). Estimation of *ET* for less instrumented areas where continuous meteorological data are not available has been a challenge. Simplified methods for estimating daily ET_0 rely on empirically derived equations that employ local daily temperature, radiation, and relative humidity data and are typically assumed to apply only in narrow geographically defined regions. Most ET_0 estimations developed in arid and semi-arid climates because of the need for more information as water resources related projects were developed. Here, we found for arid regions of Iran, as indi-

Table 3. Summary of performance criteria values of each method at each station considering all 12 months

Equation#	Criteria	Station ID no.								
		1	2	3	4	5	6	7	8	9
2	*RMSE*	1.38	1.63	1.34	1.89	2.14	1.05	1.14	1.15	1.29
	CE	0.69	0.05	0.62	0.13	0.04	0.69	0.74	0.72	0.57
	AIC	103.6	139.4	86.9	182.1	216.2	21.1	42.3	44.1	82.9
3	*RMSE*	0.71	1.14	1.62	1.78	1.89	1.17	1.32	0.80	0.93
	CE	0.92	0.53	0.44	0.23	0.25	0.61	0.66	0.86	0.78
	AIC	–100.1	39.5	137.9	162.5	180.0	51.9	80.6	–57.9	–15.3
4	*RMSE*	2.11	2.47	1.63	2.06	2.23	1.14	1.38	1.57	1.76
	CE	0.27	–1.20	0.43	–0.03	–0.04	0.63	0.62	0.47	0.20
	AIC	228.5	253.4	138.4	203.1	224.8	42.0	93.5	128.3	160.3
5	*RMSE*	2.18	1.60	1.42	1.99	2.16	1.55	1.33	1.95	2.17
	CE	0.22	0.07	0.57	0.04	0.02	0.32	0.65	0.19	–0.21
	AIC	239.3	136.0	103.5	195.8	218.9	137.0	85.1	189.7	237.9
8	*RMSE*	3.16	2.01	1.68	1.79	1.96	1.30	1.54	2.08	2.51
	CE	–0.64	–0.47	0.39	0.22	0.19	0.52	0.53	0.08	–0.63
	AIC	355.4	203.2	12.08	171.0	196.1	89.4	128.6	211.5	286.1
9	*RMSE*	2.52	1.59	1.72	2.07	2.23	1.77	1.42	2.09	1.36
	CE	–0.04	0.08	0.37	–0.05	–0.04	0.11	0.60	0.07	0.53
	AIC	285.3	136.7	157.4	208.9	229.8	178.5	104.9	211.2	99.1
10	*RMSE*	1.31	1.98	1.32	1.89	2.12	0.97	1.13	1.15	1.28
	CE	0.72	–0.42	0.63	0.13	0.06	0.73	0.75	0.72	0.58
	AIC	89.2	197.1	83.9	183.3	215.1	–1.1	41.1	46.9	80.8
11	*RMSE*	1.73	1.69	1.45	1.95	2.24	1.37	1.26	1.37	1.47
	CE	0.51	–0.03	0.55	0.07	–0.05	0.47	0.69	0.60	0.44
	AIC	172.8	152.6	110.2	192.3	230.7	102.8	71.3	95.7	123.6
12	*RMSE*	3.02	1.98	2.28	0.42	2.98	2.86	9.12	2.15	2.29
	CE	–0.49	–0.42	–0.11	0.96	–0.87	–1.32	–15.49	0.02	–0.35
	AIC	341.1	199.1	237.3	–227.2	311.7	325.1	620.4	220.6	258.3
13	*RMSE*	4.38	4.24	1.93	2.36	2.66	1.71	1.85	2.76	2.88
	CE	–2.15	–5.47	0.20	–0.36	–0.48	0.17	0.32	–0.63	–1.14
	AIC	449.3	404.1	188.0	242.9	275.7	163.2	176.3	286.0	323.7
14	*RMSE*	7.13	5.35	4.99	4.94	5.65	6.23	4.88	6.83	0.45
	CE	–7.33	–9.33	–4.33	–4.94	–5.69	–10.07	–3.71	–8.98	0.95
	AIC	597.0	470.7	451.6	448.7	486.1	557.0	445.5	538.1	–230.5
15	*RMSE*	7.73	5.55	9.40	9.06	8.51	11.12	7.88	8.92	9.59
	CE	–8.80	–10.16	–17.90	–18.99	–14.41	–34.30	–11.29	–16.04	–22.69
	AIC	623.5	483.2	628.2	618.2	600.9	675.2	579.8	613.9	688.2
16	*RMSE*	8.75	6.31	6.30	6.28	6.99	7.19	6.11	6.14	6.93
	CE	–11.56	–13.40	–7.51	–8.61	–9.23	–13.73	–6.38	–7.07	–11.37
	AIC	658.7	516.4	516.0	515.2	544.7	552.6	507.4	508.8	542.3

Table 4. Summary of performance criteria values of each method at each station considering 5-month period of May through September

Equation#	Criteria	Station ID no.								
		1	2	3	4	5	6	7	8	9
2	*RMSE*	1.84	1.27	1.33	2.70	3.04	1.51	1.21	1.54	1.42
	CE	–1.57	–2.15	0.42	–11.55	–3.74	–2.64	0.49	–0.85	–1.50
	AIC	82.4	33.61	38.5	120.4	133.9	57.6	27.7	55.8	50.3
3	*RMSE*	0.73	0.78	1.50	2.17	2.38	0.89	1.25	1.03	0.69
	CE	0.60	0.46	0.07	–7.08	0.06	–0.08	0.40	0.29	0.48
	AIC	–36.1	–25.14	50.4	93.03	103.5	–10.1	29.3	6.81	–42.1
4	*RMSE*	3.05	3.14	1.27	2.67	2.92	0.76	1.19	2.11	1.90
	CE	–6.05	–23.31	0.52	–11.17	–3.04	0.31	0.52	–2.63	–3.58
	AIC	143.5	135.5	31.8	116.6	127.6	–31.0	24.2	89.7	84.2
5	*RMSE*	3.17	1.40	1.68	2.83	3.03	2.24	1.48	2.88	3.10
	CE	–6.59	–3.03	–0.34	–12.72	–3.70	–7.36	–0.17	–5.98	–11.33
	AIC	150.2	44.5	65.3	125.5	133.6	106.8	51.0	127.8	147.3
8	*RMSE*	4.72	1.62	2.38	2.59	2.85	0.65	2.14	3.13	3.78
	CE	–15.86	–4.73	–2.40	–10.54	–2.55	0.58	–2.32	–7.28	–17.43
	AIC	204.0	65.3	109.5	119.5	130.3	–44.9	97.4	141.3	176.3
9	*RMSE*	3.74	1.38	1.87	2.78	3.01	2.30	1.47	3.06	0.94
	CE	–9.56	–2.87	–0.85	–12.27	–3.55	–7.85	–0.14	–6.87	–0.03
	AIC	172.8	44.7	80.1	125.6	134.7	112.2	52.0	136.6	–0.40
10	*RMSE*	1.73	2.37	1.27	2.70	3.01	1.38	1.18	1.56	1.39
	CE	–1.26	–12.40	0.50	–11.52	–3.56	–2.00	0.54	–0.89	–1.41
	AIC	76.4	107.1	35.2	122.25	134.9	48.6	27.1	59.08	49.4
11	*RMSE*	2.39	1.58	1.61	2.79	3.18	1.98	1.48	1.93	1.84
	CE	–3.33	–5.42	–0.19	–12.39	–4.66	–5.45	–0.17	–2.00	–3.26
	AIC	117.1	60.7	62.9	126.1	141.0	93.2	53.0	83.4	83.9
12	*RMSE*	4.27	2.37	3.18	0.49	4.17	4.02	13.21	2.51	3.27
	CE	–12.76	–12.39	–5.67	0.60	–12.30	–26.56	–155.4	–4.22	–12.77
	AIC	191.3	109.1	143.1	–73.0	174.1	183.8	306.8	115.6	158.2
13	*RMSE*	6.60	6.19	2.02	3.15	3.64	1.96	2.24	4.08	4.03
	CE	–31.92	–96.50	–1.27	–15.98	–12.95	–5.36	–2.70	–13.18	–19.92
	AIC	241.9	215.7	86.8	137.8	154.5	90.4	106.7	167.7	180.1
14	*RMSE*	10.10	7.77	7.36	6.86	7.79	8.16	7.16	9.07	0.54
	CE	–76.16	–153.1	–37.76	–79.86	–57.89	–126.7	–44.57	–69.80	0.73
	AIC	297.1	243.8	237.6	229.5	244.0	279.2	234.4	261.5	–69.5
15	*RMSE*	10.94	8.06	13.85	12.42	11.62	11.91	11.54	12.94	13.98
	CE	–89.55	–164.1	–135.4	–264.0	–136.2	–243.8	–118.1	–143.1	–252.0
	AIC	309.1	249.9	312.2	299.8	292.0	319.7	291.2	304.4	339.7
16	*RMSE*	12.38	9.15	9.30	7.37	9.57	7.34	8.94	5.93	10.15
	CE	–114.7	–213.3	–61.17	–92.11	–90.49	–91.66	–70.18	–29.14	–132.4
	AIC	322.5	262.6	264.4	237.6	267.7	257.1	259.9	212.7	297.7

cated by ten different meteorological stations across the country, that the Irmak equation best predicted daily ET_0 on a monthly basis for the year and during the high ET period (May to September).

CONCLUSIONS

This study evaluated the performance of 13 reference evapotranspiration equations against the FAO-56PM equation under the arid condition across Iran. On average, the best three methods that could be used as an alternative to the FAO-56PM equation were the Irmak (Irmak et al., 2003), Hargreaves-Samani (Hargreaves and Samani, 1985), and Hargreaves (Hargreaves, 1975) equations. However, these equations must be calibrated for the local conditions and the tested using a broad number of weather stations data covering several years to account for changes in climate variables. The results of this research should provide invaluable data and information to the water management agencies, irrigators, and university researchers in terms of which method to select for more accurate ET_0 estimations in the arid regions of Iran for irrigation and water management and for water analyses that can aid in more efficient and sustainable use of water resources.

COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflict of interest.

Statement on the welfare of animals. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

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