Original Research Article

Evaluation of a Few Evapotranspiration Models using Lysimeteric Measurements in a Semi Arid Climate Region

ABSTRACT

The determination of reference evaporation method in a region with different simple or complex equations requires a wide range of meteorological data. It is difficult task particularly in regions with lacking data collection facilities. One of the common methods for this purpose is the use of lysimeters. In the present study, daily lysimeteric data for two years (2012 to 2013) from April to July in each year were used to evaluate nine different grass evapotranspiration models including FAO-56 Penman–Monteith, Penman-Kimberly 1996, FAO-Penman equation, Blaney–Criddle, FAO-24 Radiation, Makkink, Turc, Priestley–Taylor, and Hargreaves in Kermanshah western part of Iran with semi-arid climate. Finally, the values of RMSE indicate that, the FAO - Penman-Monteith, Makkink and Hargreaves and Samani were found to be the most appropriate models for the studied region. Penman-Kimberly and FAO-Penman methods had the worst results among the studied models. FAO - Penman-Monteith, Makkink and Hargreaves-Samani methods recommended for reference evaporation estimation, irrigation planning and scheduling, dams reservoirs design and different surface or pressurized irrigation projects water requirement application under different crop patterns in Kermanshah region, while weather, radiation and temperature data have been available. Based on RMSE values, the FAO -Penman-Monteith, Makkink and Hargreaves & Samani methods estimated the lysimeter reference evaporation values most closely and Penman-Kimberly and FAO-Penman methods had the worst results in the region.

Keywords: evapotranspiration, ETo equations, Lysimeter, Semi-arid climate.

1. INTRODUCTION

Evapotranspiration (ET), a term to denote evaporation and transpiration together, is the most important component of environmental systems and accomplishes the energy (heat) and mass (water vapor) transfers between atmosphere and land surface (primarily including soils and vegetations) [6]. Reference evaporation (ETo) is defined in as the rate of evapotranspiration from hypothetical crop with as assumed crop height (12cm), an albedo of 0.23, and a fixed canopy resistance (70 Sm^{-1}) which would closely resemble evapotrasnpiration from an extensive surface of the green grass cover of uniform height actively growing, completely shading the ground with no shortage of water [2]. The plant growth and productivity are directly related to the availability of water [30]. ETo can be measured directly by lysimeter. However, it is generally estimated by theoretical or empirical equations, or derived simply by multiplying the standard pan evaporation data by a pan coefficient [13]. Direct measurement of ETo can be difficult and expensive both economically and in time investments while basic measurements of the atmosphere are easy to collect and available at numerous locations. For this reason and to overcome inaccurate ETo estimation, numerous methods have been developed for various types of climatic conditions over the years.

FAO-56 Penman–Monteith (PM) equation is the most commonly used and accurate model to determine the ETo by the United Nations Food and Agriculture Organization (FAO) and by the World Meteorological Organization (WMO) [1]. However, ranking and selecting of the best method to estimate ETo to local conditions is required for water resources and irrigation management and scheduling purposes.

Five ETo estimation methods evaluated by comparing the estimated with results obtained from the PM 56 equation under humid conditions [33]. They showed that Turc's method gave the best ETo estimates and ranking first, and the other equations ranking in a decreasing order were as Priestley–Taylor, Jensen–Haise, Thornthwaite, and Hargreaves. The ETo measured in lysimeter in Campos dos Goytacazes compared with ETo estimated by PM method [25]. The researchers found that PM method satisfactorily estimated ETo values.

Four simpler models based on monthly performance for various climates in Iran evaluated [32]. They reported that the Makkink and Priestley-Taylor models estimated ETo values less accurately than Turc and Hargreaves and Samani models for all climates. The performance of 20 different methods against the lysimeter measuring ETo analyzed for 11 stations located under different climatic conditions around the world [19]. The Penman-Monteith ranked the best method for all climatic condition; however, ranking of the other methods varied depending on their adoption to local calibrations and conditions. The performance of Turk, Priestley–Taylor compared to PM 56 methods to estimate potential evapotranspiration in humid climates in Florida [11]. They concluded that the Priestley–Taylor performance appeared to be superior to the other two methods for a variety of land covers in Florida.

Nine different equation for ETo estimation evaluated by using lysimeter in a semi-arid region in the south of Iran [29]. They concluded that the FAO-Radiation was the most suitable method to estimate ETo for irrigation planning and scheduling in regions where radiation and temperature data are available.

The performance of nine ETo methods with FAO56-PM output data evaluated and compared [28]. The best results after calibration were produced by Blaney-Criddle method while Thornthwaite method had the worst results. Moreover, the determination of evaporation in a region with different simple or complex equations required a wide range of meteorological data. This again proved the difficulty of choosing the most appropriate method.

Moreover, the most common and widely used methods for reference evapotranspiration estimation by local agricultural and water resources organizations and consulting engineers in the region based on climatic availability data was the base reason for different selected method and comparison with lysimetric reading data. Therefore**,** Daily lysimeteric data for two years from April to July were used in the present study to evaluate simple or complex nine ETo models including FAO-56 Penman–Monteith (PM), Penman-Kimberly 1996 (Pk), FAO-Penman equation (PM), Blaney–Criddle (BC), FAO-24 Radiation (FR), Makkink (MA), Turc-radiatoon (TR), Priestley–Taylor (PT), and Hargreaves and Samani (HG) in a region with semi-arid climate. Different methods were compared with experimentally determined values and drainage lysimeters data to find the best and the worst methods in the region for practical irrigation planning purposes.

2. MATERIAL AND METHODS

2.1. EXPERIMENTAL SITE AND WEATHER STATION, SOIL, AND IRRIGATION WATER DETAILS

The Lysimetric experiments were carried out in two years from 2012 to 2013 from April to July at the Irrigation and Water Resources Engineering Research Lysimetric Station No. 3 located at 47°9 ′E and 34°21 ′N, with an elevation of 1319 m (asl), as part of the Campus of Agriculture and Natural Resources of Razi University in Kermanshah, Iran. The region under study has a semi-arid climate. The daily meteorological data were obtained from the regional meteorological station located 100 m off the lysimetric station. (Table 1) shows the average monthly meteorological data during both years of the study. The soil texture in the lysimeters was silty clay composed of different clay, silt, and sand percentages. Tables (2) and (3) show the physical and chemical properties of the soil and the chemical properties of the irrigation water used in this study. The pressure plate and sampling methods were used to determine θ(fc), θ(pwp) and bulk density in different lysimeters soil depths, respectively.

Table 1. Meteorological Data for growing period 2012-2013

Year	Month	Mean temperature (C°)	Mean relative humidity (%)	Mean wind speed (m/s)	Mean monthly sunshine (h)	Total precipitation (mm)
2012	April	11.8	53.9	7.1	6.9	45.7
	May	18.4	36.5	7.7	8.3	0.0
	June	24.8	21.4	7.9	9.7	0.0
	July	28.1	19.6	7.6	10.2	0.0
2013	April	13.4	42.5	7.3	7.3	10.7
	May	15.1	54.2	8.4	5.3	63.3
	June	23.3	27.4	7.4	9.2	0.0
	July	29.1	14.7	7.4	11.6	0.0

Table 2. Physical and Chemical Properties of Soil

Soil Texture	Sand (%)	Silt (%)	Clay (%)	Ec (dS/m)	Θ(Fc) (%)	Θ(PWP) (%)	pH	Bulk density (g/cm^3)	Soil depth (cm)
Silty Clay				0.61			7.63	1.3	0-30
	54	42.3	3.7	0.61	27.6	17.2	7.61		30-60
				0.59			7.73		60-90
				0.58			7.73		90-120

Table 3. Physical and Chemical Properties of Irrigation Water

SO_2^- (Meq/L)	CL^- (Meq/L)	HCO_3^- (Meq/L)	CO_3^{2-} (Meq/L)	TDS (Meq/L)	pH	EC (dS/m)	Anions (Meq/L)	Mg^{2+} (Meq/L)	Na+ (Meq/L)	Ca^{2+} (Meq/L)	Cations (Meq/L)
1.25	1.90	6.15	0	390	7.2	0.61	9.30	3.1	1.15	5.05	9.30

2.2. DETAIL OF DRIANABLE LYSIMETERS

In this study three drainable lysimeter with depth of 1.40 m and internal diameter of 1.20 m were used. The lysimeters were constructed with 3-mm-thick mild steel. To prevent rusting phenomenon both inside and outside parts of lysimeters were painted with epoxy material. By using tarry material all parts of lysimeters were also isolated carefully. For extra drainable water collection, the bottom of each lysimeter was inclined towards the center. In the bottom of each lysimeter an stainless steel screen was used with mesh size of 0.2 mm. In the above of stainless steel screen, 10-cm layer of gravel and a 10-cm layer of sand were used. In each lysimeter to measure of extra drained water collection by a graded container a steel pipe with diameter of 2.50 cm fixed with a control gate valve was used. In all lysimeters a silty clay soil consisting of 54, 42.3, and 3.7% clay, silt, and sand was used. All lysimeters were filled with air-dried soil and compacted manually to reach a bulk density of 1.30 gcm^{-3} according to [26] method. Soil moisture characteristic curves was determined by using [20] method. Lawn grass with 12 cm height inside and also in an area of (50×50m) was planted around the lysimeters respectively.

2.3. SOIL MOISTURE MEASUREMENT

A TDR system (Trime-Fm with P2G probes) was used to measure soil moisture.TDR probes were 0.60 cm in diameter and 16 cm long and were installed in all lysimeters at 6 different depths of 20, 40, 60, 80, 100, and 120 cm. The irrigation was carried out in all lysimeters after 20% depletion of available soil moisture in order to avoid any water stress during grass growing period.

2.4. LYSIMETER MEASUREMENT

Three lysimeters were used to estimate grass evapotranspiration; also, potential evapotranspiration (ETo) was calculated using Equation (1) as follows:

$$ETo = P + I - D - R + \Delta s \tag{1}$$

Where, ETo = reference evapotranspiration (mm); P = precipitation (mm); I = irrigation (mm); D = amount of drained water (mm); R = runoff (mm); and ΔS = changes in soil water storage during the period for which ETo was computed (mm). The precipitation was measured with a rain gauge *in situ*. The irrigation (I), D, and R for the lysimeters were measured with a precession graded container and rain gauge. The changes in soil moisture were obtained from soil moisture readings at different depths. Daily meteorological data including minimum and maximum temperatures, sunshine hours, wind speed, and average relative humidity were also collected from a regional meteorological station. Different equations for estimation of ETo were as follows:

2.5. METHODS OF COMPUTING (ETo)

Different nine methods were chosen to estimate ETo for the study area as follows:

2.5.1. FAO-PENMAN METHOD, Doorenboss [8,9, 10]

$$ETo = c\left[\left(\frac{\Delta}{\Delta+\gamma}\right)\left(R_n\right)+\left(\frac{\gamma}{\Delta+\gamma}\right)(2.7)\left(W_f\right)\left(e_z^{\circ}-e_z\right)\right] \qquad (2)$$

Where, ETo, (e^0_z –e_z), Y, Δ , R_n , W_f and c are reference evapotranspiration (mm day^{-1}), vapor pressure deficit at height z (kPa), psychometric constant (kPa ºC^{-1}), slope vapor pressure curve (kPa ℃$^{-1}$), net radiation (MJ m^{-2} per day), the wind function and adjustment factor which is equal to 1 respectively.

2.5.2. PENMAN-KIMBERLY METHOD , Wright [35]

$$ETo = \frac{1}{\lambda}\left[\left(\frac{\Delta}{\Delta+\gamma}\right)\left(R_n-G\right)+\left(\frac{\gamma}{\Delta+\gamma}\right)(6.43)\left(W_f\right)\left(e_z^{\circ}-e_z\right)\right] \qquad (3)$$

where, G and λ are soil heat flux density (MJ m^{-2} day^{-1}) and latent heat of vaporization in (MJ kg^{-1}).

2.5.3. FAO-PENMAN-MONTEITH METHOD , Allen [1,2]

$$ETo = \frac{0.408\Delta\left(R_n-G\right)+\gamma\frac{900}{T+273}u_2\left(e_s-e_a\right)}{\Delta+\gamma\left(1+.034u_2\right)} \qquad (4)$$

where, u_2 and (e_s - e_a) are wind speed at 2 m height (m s^{-1}) and saturation vapor pressure deficit (kPa).

2.5.4. TURC-RADIATION METHOD ,Turc [34]

$$ETo = a_T (0.013) \frac{T_{mean}}{T_{mean} + 15} \left(\frac{23.8856 R_s + 50}{\lambda} \right) \quad (5)$$

where, Tmean and Rs are mean daily air temperature (℃), and solar radiation (MJ m^{-2} d^{-1}), a_T is equal 1.0 for $RH_{mean} \geq 50\%$ and it is equal $1+(50-RH_{mean})/70$ for $RH_{mean} < 50\%$.

2.5.5. HARGREAVES AND SAMANI METHOD, Hargreaves [14, 15]

$$ETo = \frac{1}{\lambda} (0.0023) R_A TD^{1/2} (T + 17.8) \quad (6)$$

where, R_A, TD and T are extra-terrestrial solar radiation received on earth's surface (MJ m^{-2} d^{-1}), difference of mean maximum and mean minimum air temperatures (Cº) and mean daily air temperature at 2 m height (℃) respectively.

2.5.6. MAKKINK METHOD [23]

$$ETo = 0.61 \frac{\Delta}{\Delta + \gamma} \frac{R_s}{2.45} - 0.12 \quad (7)$$

2.5.7. FAO-RADIATION METHOD, Doorenboss [9, 10]

$$ETo = b \left[\frac{\Delta}{\Delta + \gamma} \frac{R_s}{\lambda} \right] - 0.3 \quad (8)$$

$$b = 1.066 - 0.13 \times 10^{-2} RH + 0.045 U_d - 0.2 \times 10^{-2} RHU_d - 0.315 \times 10^{-4} RH^2 - 0.11 \times 10^{-2} U_d^2 \quad (9)$$

where, RH is mean relative humidity (%).

2.5.8. PRIESTLEY AND TAYLOR METHOD [27]

$$ETo = \frac{1}{\lambda} \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (10)$$

where, α is a constant (α = 1.26).

2.5.9. BLANEY-CRIDDLE METHOD , Blaney [4, 5], Doorenboss [9, 10]

$$ETo = a + bf \tag{11}$$

$$a = 0.0043 RH_{\min} - \frac{n}{N} - 1.41$$

$$b = 0.82 - 0.41 \times 10^{-2} RH_{\min} + 1.07 \times \frac{n}{N} + 0.066 U_d - 0.6 \times 10^{-2} RH_{\min} \times \frac{n}{N} - 0.60 \times 103 RH_{\min} \times U_d$$

$$f = p(0.46T + 8.13)$$

where, RH_{min}, n,N, p and U_d are minimum relative humidity (%), actual daily sunshine hours (h), maximum possible daily sunshine hours (h), monthly percentage of daytime hours and daytime wind speed (ms^{-1}) respectively.

2.6. DATA ANALYSES

The method suggested by [17,18] were used for statistical analyses. The following equations were used to compute the regression coefficients (r), root mean square error (RMSE), mean bias error (MBE) and t-statistic test (t).

$$r = \frac{\sum_{i=1}^{n} (x - \bar{x})(y - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x - \bar{x})^2 \sum_{i=1}^{n} (y - \bar{y})^2}} \qquad -1 \leq r \leq 1 \tag{12}$$

$$MBE = \sum_{i=1}^{n} \frac{d_i}{n} \tag{13}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \tag{14}$$

$$t = \sqrt{\frac{(n-1)\,MBE^2}{RMSE^2 - MBE^2}} \tag{15}$$

where, x = the measurement value, $\bar{x}$ = the mean measurement value, y = the predicted value, $\bar{y}$ = the mean predict value, di = difference between ith predicted and ith measured values, n = number of data pairs i.

The regression equations computed from below formula:

$$Y = mX + C \quad (16)$$

where, Y represents the daily ETo measured; X is the daily ETo estimated from each of the other nine methods; and m (slope) and C (intercept) are the regression constants.

3. RESULTS AND DISCUSSION

The daily evapotranspiration was computed based on water-balance data collected from lysimeters using Equation (1) the computed ETo values from the lysimeter data for grass which was the reference crop, from the months of April to July and were compared to the ETo values computed by nine different methods. The average ETo values of lysimeter were obtained as 73,122,173 and 222 mm per month for April, May, June and July during 2012 and 2013, respectively. The values of monthly measured ETo, the total values of ETo for lysimeter data and the predicted values from each of the nine methods are presented in (Table 4). As shown in (Figure 1), the ETo increased from April to July for both lysimeters and other chosen methods.

The cross correlation (R^2), slope, intercept and RMSE, MBE and t-test statistical methods were used to compare the lysimeter ETo values with the ETo values by nine other methods. According to the [18], the performance of each method in the present study was based on t values. Lower t-values showed a better performance of the method indicating that the differences between the measure and the estimated values were lower. Also, the negative sign of the MBE indicates that the computed ETo values were lower than ETo values measured by the lysimeter while positive MBE shows overestimation of the lysimeter ETo values; the absolute value is also an indicator of method performance. The slope near to unity indicates a parallelism of the measured and the calculated ETo curves, while the lower intercept of the regression equation indicates proportionality between the two methods. For statistical analysis, it was assumed that the best methods were those with the lowest RMSE. The results of these comparisons for the above parameters are shown in (Table 5). The methods in (Table 5) are ranked according to RMSE. The estimated ETo values by the PF, PK, PM, TR, HG, MA, FR, PT and BC methods were evaluated with lysimeter ETo values having RMSE values as 12.96, 8.74, 1.34, 2.67, 2.03, 1.48, 3.55, 2.34, 2.58 mm/day, respectively. Based on RMSE and MBE values presented in (Table 5) and also as shown in Figure 2, the PM, MA and HG methods estimated the lysimeter ETo values most closely and PK and PF methods did not show any close agreement with the lysimeter values and had the worst results. Other methods (including PT, BC, TR, and FR) showed reasonable agreement with the lysimeter values.

A comparison of the results show that the PK, PF, HG and FR methods overestimated while PM, TR and MA equation underestimated potential evapotranspiration compared to lysimetric estimation method**.**

Table 4. Lysimeteric and different estimating potential evapotranspiration methods

Methods	ETo (mm)				
	Month				Total
	April	May	June	July	
Lysimeteric measurement	73.0	122.1	173.4	222.7	591.2
FAO-Penman (PF)	365.8	469.3	583.4	669.1	2087.6
Penman-Kimberly(PK)	469.8	269.9	293.7	345.1	1378.6
FAO - Penman-Monteith(PM)	57.5	90.3	154.6	213.4	515.8
Turc-Radiation (TR)	40.0	53.2	89.6	115.7	298.5
Hargreaves & Samani (HG)	123.1	170.4	233.9	277.4	804.9
Makkink (MA)	87.1	107.1	143.6	170.4	508.2
FAO-Radiation (FR)	153.8	192.9	281.3	338.2	933.3
Priestley and Taylor (PT)	141.2	173.2	231.8	275.2	821.3
Blaney-Criddle (BC)	112.2	156.2	251.2	316.6	836.2

Table 5. The comparing of different methods with Lysimetic measurement in daily scale

Methods	Lysimeter measurement							Ranking
	Performance Indicator							
	Slope of the regression line	**Intercept of the regression line**	**R^2**	**RMSE (mm)**	**MBE**	t	R/t	
Lysimeteric measurement	1	0	1	-	-	-	-	-
FAO - Penman-Monteith(PM)	1.045	-0.933	0.841	1.34	-0.66	6.27	0.14	1
Makkink (MA)	0.534	1.531	0.701	1.48	-0.74	6.42	0.12	2
Hargreaves & Samani (HG)	0.985	1.726	0.843	2.03	1.77	19.87	0.04	3
Priestley and Taylor (PT)	0.86	2.489	0.710	2.34	1.79	13.16	0.06	4
Blaney-Criddle (BC)	1.361	0.130	0.853	2.58	1.96	13.01	0.07	5
Turc-Radiation (TR)	0.504	-0.045	0.836	2.67	-2.42	23.85	0.04	6
FAO-Radiation (FR)	1.206	1.968	0.757	3.55	2.98	17.24	0.05	7
Penman-Kimberly(PK)	-0.607	14.27	0.080	8.74	6.57	12.67	-0.03	8
FAO-Penman (PF)	1.846	7.997	0.473	12.96	11.77	24.06	0.03	9

R = regression coefficients

RMSE= root mean square error

MBE= mean bias error

t = t-statistic test

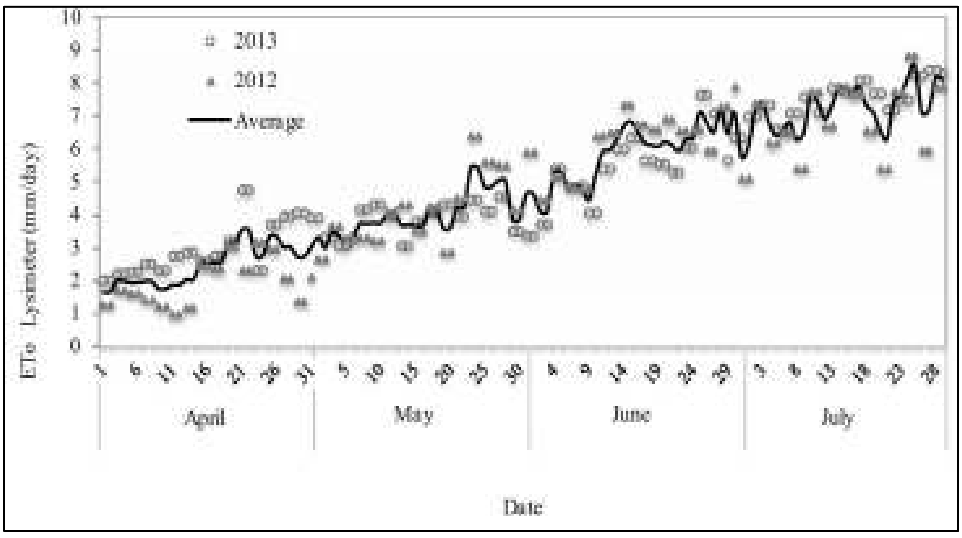
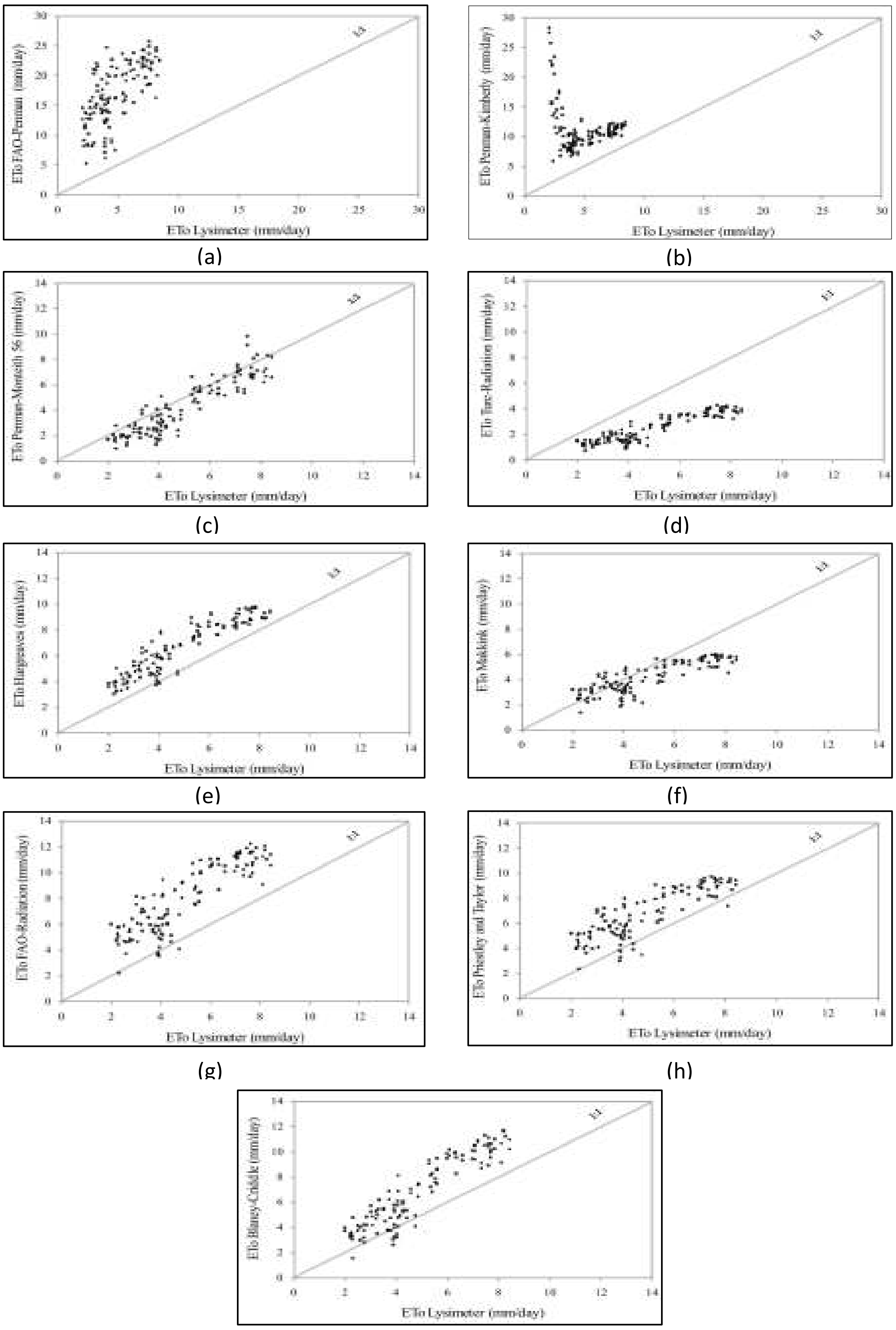


Figure 1. Daily ETo measurement values



(a) (b)

(c) (d)

(e) (f)

(g) (h)

(o)

Figure 2. Comparison of ETo measurement with different estimation methods

The capabilities of models found in this study, while reported by others, were different. Although, for daily, smoothed daily, mean 10-day and mean monthly ETo were estimated by Penman-Monteith, Hargreaves-Samani, Jensen- Haise, Turc, Priestley-Taylor, FAO-Blaney-Criddle, FAO-Radiation and Pan Evaporation equations and a linear regression equation was obtained for the estimated and measured values [29]. They compared the results of the equations with ETo data from a weighing type lysimeter and ranked results of different methods according to statistical and error analysis. The results indicated that the FAO-Radiation and Hargreaves-Samani were the most appropriate methods while the Priestley-Taylor method was the least appropriate. The Penman-Monteith ranked in third to fifth on the list according to the duration of mean values.

The estimated ETo by Hargreaves-Samani method was more appropriate than those obtained by the Penman-Montheith method while the FAO-Radiation method showed the best results [21]. The slope of linear relationships between ETo estimated by the Hargreaves-Samani and Penman- Monteith methods and measured ETo by lysimeter were close to 1.0 [16].

Hourly ETo estimations obtained by Penman-Montheith under the semiarid climate of Kerman, Iran. Hourly ETo estimations obtained from the proposed method were compared with measured ETo values by using a large weighing electronic lysimeter during the months of April to September, 2005. The results showed that FAO-56 Penman-Monteith underestimated ETo values by 18.4, 19.3, 26.3, 20.4, 21.4 and 22.1% for the months of April to September, respectively [3].

ETo calculation by seven different equations and comparison with lysimeter data in a semi-arid climate and that the PM method obtained the best and most accurate equation [24]. The same results also were reported by [1]; [31] and [7]. They reported that the PM performed much better in humid regions. Although, the PM has a weakness of meteorological data as compared to input demands among the other models, particularly in the developing countries with the shortage of sufficient data. The results of this study and their comparison with those of other researches showed that the perfect selection of simple and complex methods in a region based on available meteorological data needs to consider results and calibrations either by lysimetric or by PM method for precise regional practical purposes because, as suggested by [22] human activity and natural factors have a certain influence on the spatial variation of ETo, and a decisive role in the spatial variation character of reference evapotranspiration in an investigated area.

4. CONCLUSIONS

The performance of nine ETo methods were evaluated and compared with Lysimeter measurement data to choose the appropriate methods with the best results to estimate and project ETo in a semi-arid climate area. The Lysimetric experiments were carried out in two years from 2012 to 2013 from months of April to July. The cross correlation (R^2), slope, intercept and RMSE, MBE and t-test statistical methods were used to compare the lysimeter ETo values with the ETo values computed by nine different methods. The methods were ranked according to RMSE. Based on RMSE values, the PM, MA and HG methods estimated the lysimeter ETo values most closely and PK and PF methods had the worst results. The use of PM, MA and HG methods for ETo estimation, irrigation planning and scheduling, dams reservoirs design and different surface or pressurized irrigation can help project water requirement application under different crop pattern conditions in the semi-arid region under study where complete weather data and only radiation and temperature records are available.

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