J. Agr. Sci. Tech. (2011) Vol. 13: 223-237

Evaluation of Reference Evapotranspiration Models for a Semiarid Environment Using Lysimeter Measurements

B. Bakhtiari[1], N. Ghahreman[2*], A. M. Liaghat[2], and G. Hoogenboom[3]

ABSTRACT

An accurate determination of evapotranspiration is required for many studies that involve estimation of the water balance. One methodology is the use of lysimeters. Considering the semiarid climate of Kerman Province, in southeastern parts of Iran, the only operating electronic weighing lysimeter in the country was used for calculating daily ET_o from April 2004 to March 2005 in three different periods, i.e. the entire year, and high and low evaporative demands periods. The measured error was equal to 1 kg mass, which is equivalent to 0.14 mm of water in the field. An automated weather station was used that provided 10-min recordings of the weather data to be used for predicting daily ET_o with models. The lysimeter was installed in proximity of the automated weather station and both were located in a field with grass cover. The lysimeteric data were used for the evaluation of six grass evapotranspiration models, including FAO-56 Penman–Monteith, Penman-Kimberly 1996, FAO-24 Blaney-Criddle, FAO-24 Radiation, Makkink, and Hargreaves-Samani. The root mean square error (RMSE) and index of agreement (d) were used for assessing prediction accuracy of different models. Results indicated that for the entire year period, the FAO-24 Radiation equation was the most precise method for calculating ET_o, with a RMSE of 1.63 mm day^{-1} and a d- index of 0.78. During the high evaporative demand period (April to September 2004) the FAO-24 radiation equation was superior compared to the other methods for calculating ET_o with a low RMSE value of 1.86 mm day^{-1} and a d-index of 0.45. During the low evaporative demand period, again, FAO-24 radiation equation was superior compared to the other methods with RMSE of 1.30 mm day^{-1} and d-index of 0.46. In all of the three periods, the Makkink method showed poor performance and can not be recommended for the region.

Keywords: Evapotranspiration, FAO-56 Penman–Monteith, FAO-24 Radiation, Hargreaves-Samani, Lysimeter.

INTRODUCTION

Reliable estimates on evapotranspiration (ET_o) from cropped surfaces are required for efficient irrigation management. With increasing pressure on water resources from competing sectors, great emphasis has been placed on water use efficiency in irrigated fields (Hatfield *et al*., 1996), particularly in semiarid environment irrigation projects. Three terms are normally used in describing evaporation and evapotranspiration: (1) Free water evaporation (E) is used for the amount of evaporation lost from an open water surface (Peterson *et al*., 1995), (2) Actual evapotranspiration (ET_a) describes all the processes by which liquid water at or near the land surface becomes atmospheric water vapor under natural condition (Morton, 1983), (3) Potential evapotranspiration (ET_p) is water loss that will occur if there is no

[1] Department of Water Engineering, College of Agriculture, Shahid Bahonar University, Kerman, Islamic Republic of Iran.
[2] Department of Irrigation and Reclamation, College of Agricultural Engineering and Technology, University of Tehran, Karaj, Islamic Republic of Iran.
[*] Corresponding author, e-mail: nghahreman@ut.ac.ir
[3] AgWeatherNet, Washington State University, Prosser, Washington 99350-8694, USA.

deficiency of water in the soil for use of vegetation at any time (Thornthwaite, 1944). Evapotranspiration (ET), the process by which water in its liquid state evaporates from the soils and plant surfaces to the atmosphere, is an important hydrological process. This term includes evaporation of water stored in the soil surface and plant surfaces, especially from leaves (Jensen *et al*., 1990). Referring to agricultural production, the measurement of ET is very important in arid and semiarid regions, where it is essential for determining crop water demand.

The quantification of ET is normally based on the determination of reference evapotranspiration (ETo). Reference ET is defined as ''the rate of evapotranspiration from an extensive area of 0.08–0.15 m high, uniform, actively growing, green grass that completely shades the soil and is provided with unlimited water and nutrients'' (Allen *et al*., 1994). More recently, Allen *et al*. (1998) elaborated on the concept of ET_o, referring to an ideal 0.12 m high crop with a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23. Since the 1940s, numerous grass (ET_o) or alfalfa reference (ET_r) ET equations have been developed, resulting in confusion as to which equation to select in order to obtain the most accurate ET_o estimates. Adding to the confusion is the fact that there can be subtle differences between multiple versions of the same basic equation, for example, the Penman equation (Itenfisu *et al*. 2000). Grass reference evapotranspiration (ET_o) is widely used to estimate crop water use and water requirements by using appropriate crop coefficients, K_c, The crop coefficient is a dimensionless number that is multiplied by the ET_o value to arrive at a crop ET (ET_c) estimate; $ET_c = K_c\ ET_o$. Crop coefficients depend on several factors, including the crop, development stage, canopy cover and density, and soil moisture. In addition, the K_c is dependent upon the equation that is used to estimate ET_o. Snyder and Pruitt (1992) suggested estimates of K_c for many crops, trees, and vines grown in California,

Table 1. The summary of climatological normals for the period 1951-2003, Kerman station.

T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	RH_{mean} (%)	RH_{max} (%)	RH_{min} (%)	R(mm)	U_{mean} (m s^{-1})	N (hr)
15.8	24.7	6.9	35	51	19	152.9	3	3174.7

T_{mean}: average air temperature, T_{max}: maximum air temperature, T_{min}: minimum air temperature, RH_{mean}: average relative humidity, RH_{max}: maximum relative humidity, RH_{min}: minimum relative humidity, R: total amount of rainfall, U_{mean}: average wind speed,N: total sunshine duration.

USA. The International Commission for Irrigation and Drainage (ICID) and the Food and Agriculture Organization of the United Nations (FAO) Expert Consultation on Revision of FAO methodologies for crop water requirements (Smith *et al*., 1991) recommended that the FAO-56 Penman-Monteith method be used as the standard method for estimating ETo (Allen *et al*., 1998). Jensen *et al*. (1990), Allen *et al*. (1994), and Hargreaves (1994) emphasized the need for a standard method. The FAO-56 Penman-Monteith equation was derived from the ASCE-Penman-Monteith (ASCE-PM) method (Allen, 1986; Allen *et al*., 1994, 1998) by assigning certain parameter values based on a specific reference surface (Itenfisu *et al*., 2000; Allen *et al*, 1998). Suleiman and Hoogenboom (2007) compared the Priestley-Taylor and FAO-56 Penman-Monteith for estimation of daily reference evapotranspiration for a humid climate. Their results showed that the use of FAO-56 Penman-Monteith for estimating ET would improve the irrigation efficiency in Georgia, especially for the mountainous and coastal areas.

Taking into account the semiarid climate of Kerman (southeast of Iran) and lack of adequate water resources, the objective of this study was to use average daily ETo values measured with an electronic weighing lysimeter to evaluate various equations being used to calculate reference evapotranspiration and select suitable models to estimate ET_o in the study region.

MATERIALS AND METHODS

This study was conducted in the Iranian Academic Center for Education, Culture and Research (ACECR) Experimental Farm located at the University of Kerman (Latitude 30° 15' N; Longitude 56° 58' E; Elevation 1753.8 m above sea level). The climate is characterized as continental, with average temperatures of 5–6 °C during the coldest month (January) and 30.2 °C during the hottest month (July). The local climate can be characterized as semiarid based on Extended-DeMartonne climatic classification (Khalili, 1997). The summary of climatological normals for the period 1951-2003 is shown in Table 1.

The mean monthly air temperature and relative humidity, solar radiation measurements (R_s), and the computed clear sky (R_{so}) values are shown in Figure 1.

The experimental plot soil texture is sandy clay loam, with 55% sand, 24% silt and 23% clay. The soil has a pH of 7.8 and is poor in organic matter and total nitrogen. An automated meteorological station was

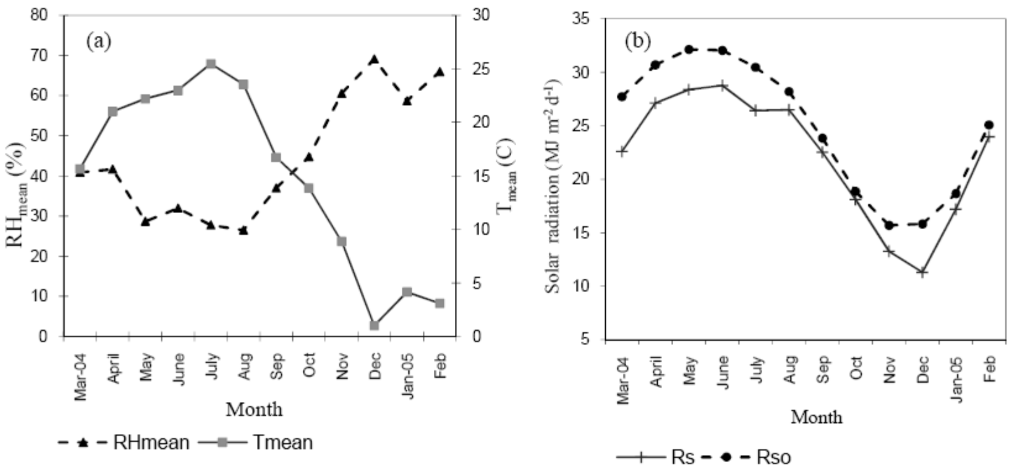

Figure1. a: Mean monthly air temperature (T_{mean}) and mean monthly relative humidity (RH_{mean}), b: solar radiation (R_s) and computed clear sky radiation (R_{so}) during the study period.

installed next to the lysimeter equipped with necessary sensors to measure the variables required for calculating reference evapotranspiration (ET_o):

Air temperature at 2 m: Sensor specifications ranged from -30 to 80 ºC; precision ±0.1 ºC. Relative air humidity at 2 m: Sensor specifications ranged from 0 to 100%; ±0.5% precision. Net short wave radiation at 2 m: a pyranometer (Lambrecht GmbH, 16131 model) was installed. Sensor specifications are: Spectral range 0.305–2.8 µm; irradiation of 0-2000 W m^{-2} and sensitivity 9-15 µV W^{-1} m^{-2}. Wind velocity at 2 m was measured by a very sensitive, cup anemometer designed for measuring very light wind of up to only 0.2 m s^{-1}. Sensor specifications are: 0-40 m s^{-1} range and ±0.2m s^{-1} precision. Atmospheric pressure (P) and soil heat flux (G) were estimated using the methods recommended by Allen *et al*. (1998). From April 2004 to March 2005, daily average of air temperature, relative humidity, wind speed, and sunshine hours were calculated based on 10 minutes records.

In this region, accurate estimation of ET_o and conservation of water is of prime importance for irrigation of agricultural lands. Therefore, a large electronic wieghing lysimeter was built for estimating crop water requirement and for evaluation of the available equations for calculation of ET_o. The lysimeter includes two tanks of 3.00 m in diameter, 1.75 m deep and 12.4 m^3 volume with approximate soil capacity of 19.5 metric tons each. The weighing mechanism for each tank is a set of three compression strain gage load cells (C_3H_2), which are fixed on 1.20 m height column above the floor. According to the specification of the load cells, the maximum possible weighing error may be about 0.01 percent of total mass, but the measured error was equal to 1 kg mass, which is equivalent to 0.14 mm of water (Barani and Khanjani, 2002). A cone shaped drainage system, filled with gravel and connected to a 100 mm pipe was mounted at the bottom of the tank. The depth of drained water was measured using volumetric method. The lysimeter was installed in the center of a 26 m × 26 m plot, which was uniformly covered with fescue (*Festuca Lollium perenne*) and surrounded by well watered clipped alfalfa. Fescue grown in the lysimeter was kept at a height of 0.10 to 0.15 m by weekly mowing. The experimental plot was irrigated by a sprinkler system. The continuous weighing lysimeter was connected to an electronic data recorder. Thus, a comparison could be made with the data obtained by using 10 minutes changes of the lysimeter weights. The data generated by the lysimeter were displayed on the screen and also stored in the data logger. A personal computer, located in the control room of the lysimeter station, was connected to the data acquisition unit. Software was installed for communication with the data logger for programming and data downloading. Those measurements of the lysimeter that were affected by irrigation, precipitation, and mowing were eliminated from the records. In this study, six ET_o computing methods, which use grass as a reference crop, were evaluated. These methods include: FAO-56 Penman–Monteith, Penman-Kimberly 1996, FAO-24 Blaney–Criddle, FAO-24 Radiation, Makkink, and Hargreaves-Samani. Equations and are described as follows:

FAO-56 Penman–Monteith

The Penman–Monteith (PM) method is considered to be ‘physically based’, since it incorporates the effects of physiological and aerodynamic characteristics of the reference surface (Allen, *et al*., 1998). Several studies have shown the superiority of the PM method for a wide range of climatic conditions (Jensen *et al*., 1990; Irmak *et al*., 2003; Itenfisu *et al*., 2000). Therefore, the recent version of the FAO methodology for estimating crop water requirements (Allen *et al*., 1998) FAO-56, recommends the sole use of the PM method for ET_o estimation for all climates. The FAO-56 approach defines the reference crop evapotranspiration for a hypothetical crop with an assumed height of 0.12 m that has a surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen *et al*., 1998). This closely resembles the evapotranspiration of an extended green grass surface with a uniform height that grows actively and is adequately watered (Allen *et al*., 1998). It is defined as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1$$

Where ET_o is the reference evapotranspiration (mm day^{-1}), R_n: the net radiation at the crop surface (MJ m^{-2} day^{-1}), G: the soil heat flux density (MJ m^{-2} day^{-1}), T: the mean daily air temperature at a 2-m height ($^\circ C$), u_2: the wind speed at a 2-m height (m s^{-1}), e_s: the saturation vapour pressure (kPa), e_a: the actual vapour pressure (kPa), e_s-e_a: the saturation vapour pressure deficit (kPa), Δ: the slope of the vapour pressure curve ($kPa^\circ C^{-1}$) and γ: the psychrometric constant ($kPa^\circ C^{-1}$).

This equation uses standard climatologic records of solar radiation (net, short wave, or sunshine duration), minimum and maximum air temperature, humidity (preferably minimum and maximum relative humidity), and wind speed. To ensure the integrity of computations, the weather measurements should be made at 2 m (or converted to that height) above an extensive surface of green grass, shading the ground and not short of water. Standard methods are proposed by Allen *et al*. (1998) to compute the parameters of the FAO-PM equation (1) from the observed climatic variables.

Penman-Kimberly 1996

In 1996, Wright presented a variable wind function to use with the Penman-Kimberly equation for predicting ET_o. This form of the Penman-Kimberly 1982 with grass wind function is referred to as the Penman-Kimberly 1996. The Penman-Kimberly 1996 combination equation for daily values in MJ m^{-2} is:

$$\lambda ET_O = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma} 6.43(e_s - e_a)W_f \quad (2$$

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n: the net radiation at the crop surface (MJ m^{-2} day^{-1}), G: the soil heat flux density (MJ m^{-2} day^{-1}), e_s: the saturation vapour pressure (kPa), e_a: the actual vapour pressure (kPa), e_s-e_a: the saturation vapour pressure deficit (kPa), Δ: the slope of the vapour pressure curve ($kPa^\circ C^{-1}$), γ: the psychrometric constant ($kPa^\circ C^{-1}$), and W_f is the wind function. The Penman-Kimberly 1996 ET_o values were calculated using the wind function (Wright, 1996):

$$W_f = a_w + b_w u_2 \quad (3)$$

where u_2 is the wind speed at a height of 2 m (m s^{-1}), a_w and b_w are:

$$a_w = 0.3 + 0.58 \exp\left\{-\left[\frac{(J-170)}{45}\right]^2\right\} \quad (4$$

$$b_w = 0.32 + 0.54 \exp\left\{-\left[\frac{(J-220)}{67}\right]^2\right\} \quad (5$$

where J is the day of year.

FAO-24 Blaney–Criddle

The original Blaney–Criddle method (Blaney and Criddle, 1950) was modified by Doorenbos and Pruitt (1977) to improve the effect of climate on crop water requirements. This method for calculating ET_o considers general levels of minimum relative humidity, wind speed and sunshine. The Blaney–Criddle method modified by FAO is as follows:

$$ET_o = a_a + b_b f \quad (6$$

where ET_o is reference evapotranspiration (mm day^{-1}); a_a and b_b are coefficients of the linear equation that relate ET_o and f. In this study the expressions proposed by Frevert *et al*., (1983) are used for calculating coefficients a_b and b_b; to obtain a better precision in predicting ET_o , f is the Blaney–

Criddle factor (mm day^{-1}), which is expressed as:

$$f = p(0.46T + 8.13) \qquad (7$$

where p is the mean daily percentage of total annual daytime hours for given months and latitude; T is mean air temperature ($^{\circ}$C).

FAO-24 Radiation

The FAO-24 Radiation method was first introduced by Doorenbos and Pruitt (1977) as amodification of the Makkink (1957) method (Doorenbos and Pruitt 1977; Jensen *et al*., 1990). Originally it was recommended for this model to be used as a replacement for the Penman method (Jensen *et al*., 1990) when measured air temperature and solar radiation were available but wind and humidity data were unavailable or were of questionable quality (Doorenbos and Pruitt 1977; Jensen *et al*., 1990). However, this model performs much better with measured data (Jensen *et al*., 1990). The form of FAO-24 Radiation as defined by Jensen *et al*. (1990) is described as:

$$ET_o = a + b\left(\frac{\Delta}{\Delta+\gamma}.R_s\right) \qquad (8$$

where ET_o is reference evapotranspiration (mm day^{-1}); a is -0.3 (mm day^{-1}); b is an adjustment factor that varies with the mean relative humidity and daytime wind speed calculated by equation 9 ; Δ is the slope of the vapour pressure curve (kPa$^{\circ}$C^{-1}), γ is the psychrometric constant (kPa$^{\circ}$C^{-1}) and R_s is solar radiation (MJ m^{-2} day^{-1}).

$$b = 1.066 - 0.13\times10^{-2} RH_{mean} + 0.045U_d - 0.20\times10^{-3} RH_{mean}U_d - 0.315\times10^{-4} RH_{mean}^2 - 0.11\times10^{-2} U_d^2 \qquad (9$$

Where RH_{mean} is the daily mean relative humidity (percent) and U_d is the mean daytime wind speed (m s^{-1}) (Jensen *et al*., 1990).

Makkink model

The Makkink model was developed in the Netherlands as a modification of the Penman equation (Makkink, 1957) and has been used successfully in the US (Amatya *et al*., 1995). It can be considered as a simplified Priestley-Taylor formula, requiring, similar to Priestley-Taylor, only radiation and temperature as inputs. The difference is that, instead of using net radiation (R_n) and temperature, the Makkink formula uses incoming short-wave radiation (R_s) and temperature. Short-wave radiation can be easily obtained as, on the average, there is a constant ratio ($\cong$ 40%) between R_n and R_s. The Makkink formula is expressed as:

$$ET_o = 0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\frac{R_S}{2.45} - 0.12 \qquad (10$$

where ET_o is reference evapotranspiration (mm day^{-1}), Δ is the slope of the vapour pressure curve (kPa$^{\circ}$C^{-1}), γ is the psychrometric constant (kPa$^{\circ}$C^{-1}), R_s is solar radiation (MJ m^{-2} day^{-1}) and constant 2.45 is latent heat of vaporization at approximately 20 $^{\circ}C$.

Hargreaves-Samani model

The Hargreaves-Samani model is a representative version of one of the older evapotranspiration models (Hargreaves and Allen, 2003). The model used in this study has similar conceptual versions (Hargreaves and Samani, 1985), which intend to be computationally simple and applicable to a variety of climates using only commonly available meteorological data. The creation of the Hargreaves-Samani method was intended to simplify the previous version of Hargreaves (1975) further by using only air temperature and extraterrestrial radiation (Ra) as a substitute for measured sunshine or radiation data (Hargreaves and Allen, 2003). This model was later adopted for use by the FAO for areas where air temperature is the only available variable (Allen *et al*. 1998, Hargreaves and Allen, 2003). The form of the Hargreaves-Samani equation presented in FAO- 56 by Allen *et al*. (1998) is:

$$ET_o = 0.0023 \times (T_{max} - T_{min})^{0.5} (T_{mean} + 17.8) R_a \quad (11$$

where ET_o is reference evapotranspiration (mm day^{-1}); T_{mean} is the daily mean air temperature ($^\circ$C); T_{max} is the daily maximum air temperature ($^\circ$C); T_{min} is the daily minimum air temperature ($^\circ$C); R_a is the extraterrestrial radiation (mm day^{-1}) (R_a in mm day^{-1} = R_a in MJ m^{-2} day^{-1}/2.45).

2-7 Statistical analysis

ET_o was measured with the lysimeter and computed through various methods as defined in the previous section. Both the measured ET_o and calculated values were then compared using simple regression analysis and a series of statistics proposed by Willmott (1982). The Root Mean Square Error (RMSE; mm day^{-1}) was calculated as:

$$\mathrm{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N} (P_i - O_i)^2 \right]^{\frac{1}{2}} \quad (12$$

where N is the number of observations; P_i is estimated or calculated ET_o (mm day^{-1}); O_i is ET_o values observed with the lysimeter (mm day^{-1}). The mean square error expressed as a percentage of the mean values of ET_o measured in the lysimeter (O_{avg}) was used as a measure of relative error (RelRMSE = RMSE/O_{avg}) from April 2004 to March 2005 for 333 observations (Table 2). The index of agreement (d) was also used as a relative measure of the difference among variables, defined as:

$$d = 1 - \left[\frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} [(P_i - O_{avg}) + (O_i - O_{avg})]^2} \right] \quad (13$$

where O_{avg} is the mean value of the observed variable for the given study periods (entire year, high evaporative demand period, low evaporative demand period). Perfect agreement would exist between P_i and O_i, if d = 1.

Table 2. Comparison of the measured and calculated daily ET_o for the entire year.

Method	P_{avg} (mm day^{-1})	P_{avg}/ O_{avg} (%)	$ET_{o\,Est}$ = A+B ($ET_{o\,Lys}$) A (mm day^{-1})	B	R	RMSE (mm day^{-1})	Rel RMSE (%)	d
FAO-56 Penman- Monteith	5.16	73.14	1.13	0.57	0.75	2.27	32.19	0.63
FAO-24 Radiation	6.08	86.21	1.75	0.61	0.79	1.63	23.14	0.78
FAO-24 Blaney– Criddle	5.04	71.54	0.71	0.61	0.74	2.43	34.46	0.62
Makkink	3.49	49.46	1.21	0.32	0.66	3.87	54.91	0.26
Hargreaves-Samani	4.89	69.42	0.54	0.62	0.79	2.48	35.22	0.60
Penman-Kimberly 1996	5.48	77.64	0.13	0.76	0.78	1.94	27.64	0.73

Regression analysis of the calculated values over those measured in the lysimeter. Number of observations: 333; P_{avg}: mean of the values calculated by various methods; O_{avg}: mean of the values measured in the lysimeter (7.05 mm day^{-1}); A: ordinate at the origin; B: regression coefficient; R: coefficient of regression, RMSE: root mean squared error; RelRMSE: relative error; d: index of agreement.

RESULTS AND DISCUSSION

Evaluation of ET_o estimation methods during the entire year

Daily ET_o values measured in the lysimeter were compared with the calculated values obtained from the various equations used in this study. This comparison was conducted for 333 observations, starting in April 2004 and ending in March 2005. The result of simple regression analysis, RMSE and index of agreement between the values calculated by various methods and lysimeter measurements are shown in Table 2.

For statistical analysis, it was assumed that the best methods were those that had the lowest RMSE, the highest R and the highest d. The methods were ranked from the best to the worst as follows. The FAO-24 Radiation method provided the best performance with a RMSE of 1.63 mm day^{-1}, equivalent to a relative error of 23.14 %, a coefficient of regression (R) equal to 0.79 and a d value of 0.78. Next to that equation, the best performance was shown by the Penman-Kimberly 1996, which had RMSE value of 1.94 mm day^{-1}, corresponding to a relative error of approximately 28% and a coefficient of regression equal to 0.78. The FAO-56 Penman–Monteith method, ranked as the third one, again presenting underestimation, with a RMSE of 2.27 mm day^{-1}, equivalent to a relative error close to 32%. The index of agreement of the method was 0.63. The Hargreaves-Samani method underestimated lysimeter measurements, with the slope of the straight regression line being 0.62 and noticeably coinciding with the intercept; but, a high value of RMSE (2.48 mm day^{-1}) and an index of agreement equal to 0.60 indicated the unsatisfactory performance of the method. The FAO-24 Blaney-Criddle method, too, showed underestimation with a slope of 0.61 for the regression line. The respective coefficient of regression was 0.74, but, a RMSE value as high as 2.43 and a relative error of approximately 35% indicated the unacceptability of the results of the model. The Makkink method was the one that demonstrated the worst performance due to the significant underestimations, with RMSE of 3.87 mm day^{-1}, equivalent to a relative error of about 55% and the lowest d index of 0.26. Figure 2 shows graphs of the regressions of the six methods. The intercept and the slope of each regression line are also shown for comparing the measured and the estimated values.

Evaluation of ET_o estimation methods during the periods of high and low evaporative demands

The relationship between the lysimeter measurements and the calculated values obtained from different methods for estimating daily ET_o was also evaluated during two different periods of the year: one for high evaporative demand between the months of April and September 2004, and the other between October 2004 and March 2005 (s 3 and 4).

These two periods of the year were separated to determine the best equation for each period. Table 3 shows the results of comparing the six evaluated methods of calculation with lysimeter measurements in the period from April to September 2004. The calculated values were taken as dependent variables and the lysimeter measurements as the independent variable.

The FAO-24 Radiation equation showed its superiority over the other methods studied, with a low RMSE value (1.86 mm day^{-1}), equivalent to a relative error (RelRMSE) of approximately 22 %. Besides, its index of agreement was over 0.41, the highest value among all the methods evaluated. However, similar to the other methods, the corresponding regression line fitted on the calculated values showed some underestimation. Next to this method, the Penman–Kimberly 1996 equation ranked as the second method with RMSE of 2.13 mm day^{-1}, equivalent to relative errors and

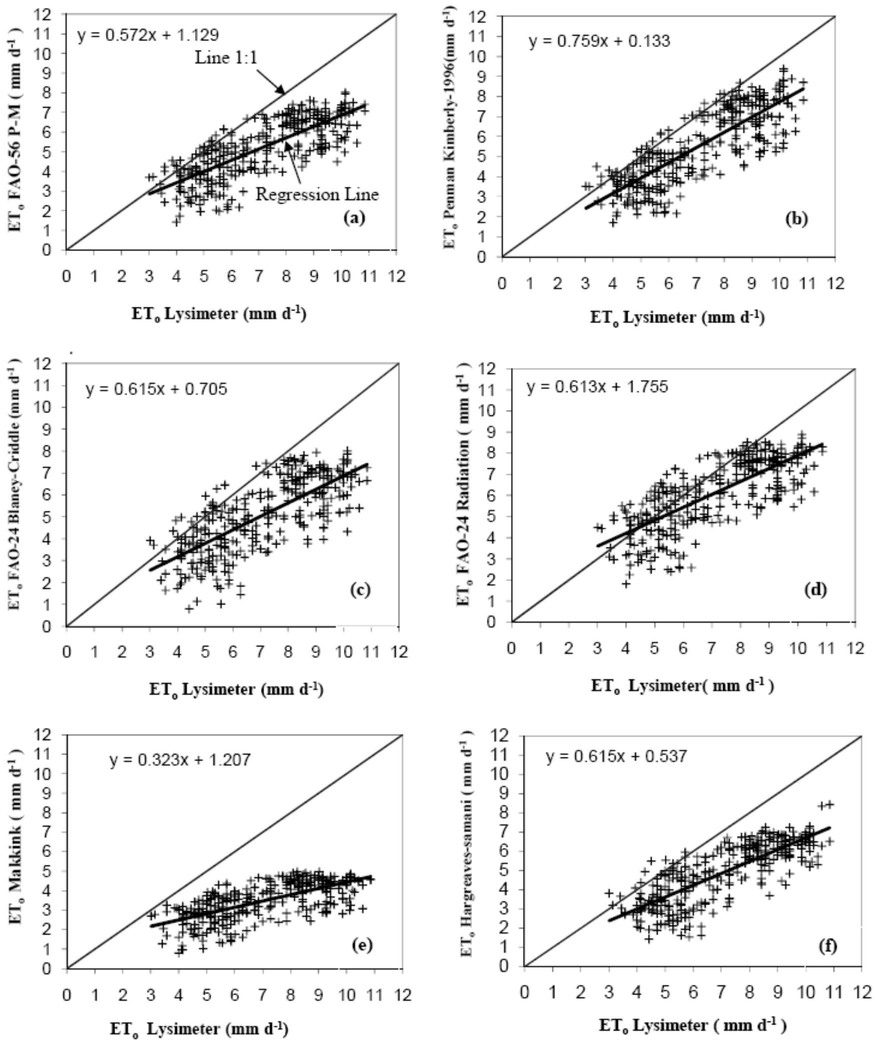

Figure 2. Comparison between ET_o values measured in the lysimeter and those calculated, for the six methods during the entire year.

index of agreement of 24.8% and 0.42, respectively. Based on similar criteria, the remaining equations were ranked as follows: FAO-56 Penman–Monteith, FAO-24 Blaney-Criddle, Hargreaves-Samani and Makkink methods (Table 3).

Similarly all equations showed underestimation. Besides, based on the RMSE of 4.69 mm day^{-1} and index of agreement equal to 0.06, Makkink method can not be recommended at all. In all cases, the coefficient of regression (R) decreased with regard to the comparison carried out for the whole year, due to an increase in dispersion. The same thing happened in a similar study conducted in Cordoba (Mantovani, 1993), when dividing the year into three periods of high, medium, and low evaporative demand. Figure 3 shows graphically the relationship between the measurements made on the lysimeter and the six ET_o methods of calculation in the period of high evaporative demand. The FAO-24 Radiation method (Fig. 3d) generated an underestimation for values between 6.6 and 10 mm day^{-1}. For values less than 6 mm day^{-1} the overestimation was more. In the Penman–Kimberly 1996 method (Fig. 3b), a similar trend was seen. Figure 3a shows the regression line of the calculated values by

Table 3. Average daily ET_o in the period of high evaporative demand (from April to September 2004).

Method	P_{avg} (*mm day*$^{-1}$)	P_{avg}/ O_{avg} (%)	$ET_{o\,Est} = A+B\,(ET_{o\,Lys})$ A (*mm day*$^{-1}$)	B	R	RMSE (*mm day*$^{-1}$)	RelRMSE (%)	d
FAO-56 Penman- Monteith	6.15	71.72	3.04	0.36	0.49	2.71	31.12	0.24
FAO-24 Radiation	7.14	83.27	3.81	0.39	0.44	1.86	21.79	0.41
FAO-24 Blaney– Criddle	6.08	70.91	1.86	0.49	0.46	2.79	32.55	0.29
Makkink	4.03	46.99	2.06	0.23	0.38	4.69	54.69	0.06
Hargreaves-Samani	5.99	69.92	2.53	0.40	0.43	2.81	33.68	0.24
Penman-Kimberly 1996	6.82	74.14	2.52	0.50	0.51	2.13	24.85	0.42

Regression analysis of the calculated values over those measured in the lysimeter. Number of observations: 181; P_{avg}: mean of the values calculated by various methods; O_{avg}: mean of the values measured in the lysimeter (8.57 mm day^{-1}); A: ordinate at the origin; B: regression coefficient; R: coefficient of regression; RMSE: root mean squared error; RelRMSE: relative error; d: index of agreement.

Table 4. Average daily ET_o in the period of low evaporative demand (from October 2004 to March 2005).

Method	P_{avg} (*mm day*$^{-1}$)	P_{avg} / O_{avg} (%)	$ET_{o\,Est} = A+B\,(ET_{o\,Lys})$ A (*mm day*$^{-1}$)	B	R	RMSE (*mm day*$^{-1}$)	RelRMSE (%)	d
FAO-56 Penman- Monteith	3.98	75.73	1.92	0.39	0.34	1.70	32.61	0.30
FAO-24 Radiation	4.82	91.76	2.41	0.46	0.37	1.30	24.74	0.46
FAO-24 Blaney– Criddle	3.81	72.61	1.86	0.37	0.28	1.92	36.60	0.24
Makkink	2.84	54.14	1.38	0.28	0.32	2.59	49.42	0.12
Hargreaves-Samani	3.58	68.30	1.78	0.34	0.28	2.04	38.93	0.21
Penman-Kimberly 1996	3.89	74.14	1.77	0.40	0.34	1.68	32.06	0.30

Regression analysis of the calculated values over those measured in the lysimeter. Number of observations: 152; P_{avg}: mean of the values calculated by various methods; O_{avg}: mean of the values measured in the lysimeter (5.25 mm day^{-1}); A: ordinate at the origin; B: regression coefficient; R: coefficient of regression; RMSE: root mean squared error; RelRMSE: relative error; d: index of agreement.

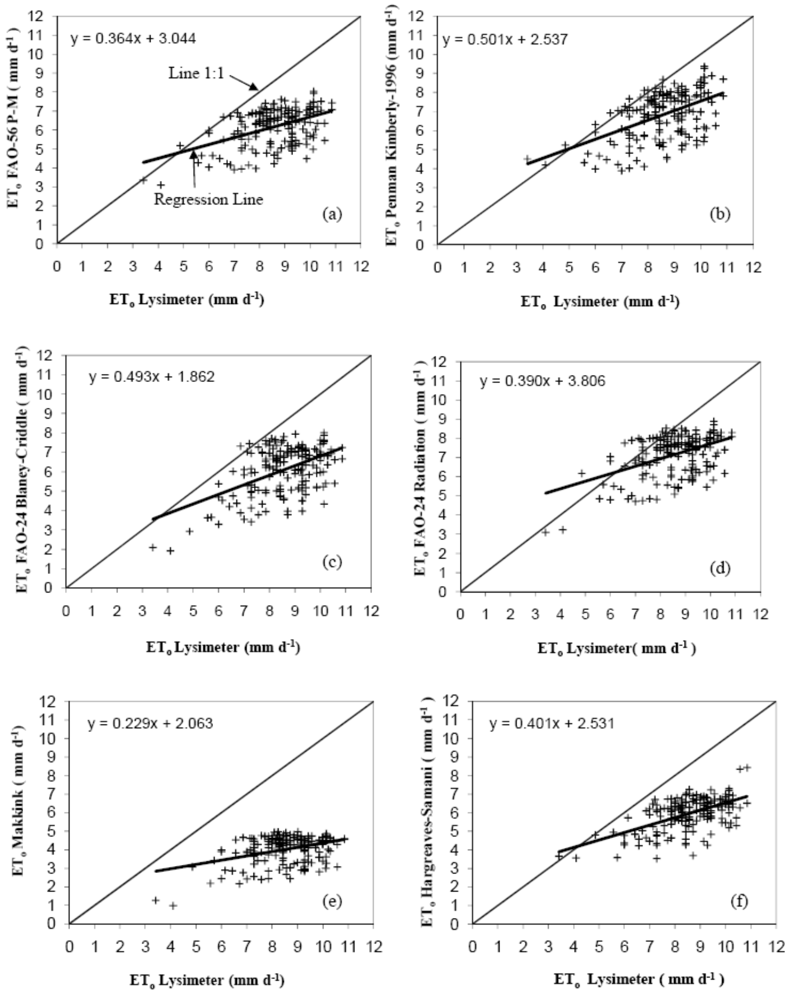

Figure 3. Comparison between ET_o values measured in the lysimeter and those calculated, for the six methods in the period of April to September, 2004.

the FAO-56 Penman–Monteith method versus lysimeteric measurements.

Table 4 shows the result of the evaluation of these same methods for calculating the average daily ET_o with lysimeter measurements in the period of low evaporative demand during October 2004 to March 2005 that the experimental work lasted. The various calculation methods were taken as independent variables and the lysimeter measurements as dependent variable.

The best performance corresponded to the FAO-24 Radiation method. It presented the lowest RMSE value (1.30 mm day^{-1}) and the highest index of agreement equal to 0.46. Also, the Penman–Kimberly 1996 and FAO-56 Penman–Monteith methods ranked as the second and the third equations, respectively (Table 4 for details). Once again the Makkink method performed the worst in this period, due to significant underestimations, with a RMSE value of 2.59 mm day^{-1}, equivalent to a relative error of over 49%. Similarly in low evaporative demand, the values of regression coefficients were low due to increased dispersion.

Figure 4 presents the graphs where the measurements conducted in the lysimeter are compared to the six methods of calculation in the period of low evaporative demand. The FAO-24 Radiation method (Fig. 4d) underestimated the values of ET_o between 4.5 and 7.5 mm day^{-1} and overestimated

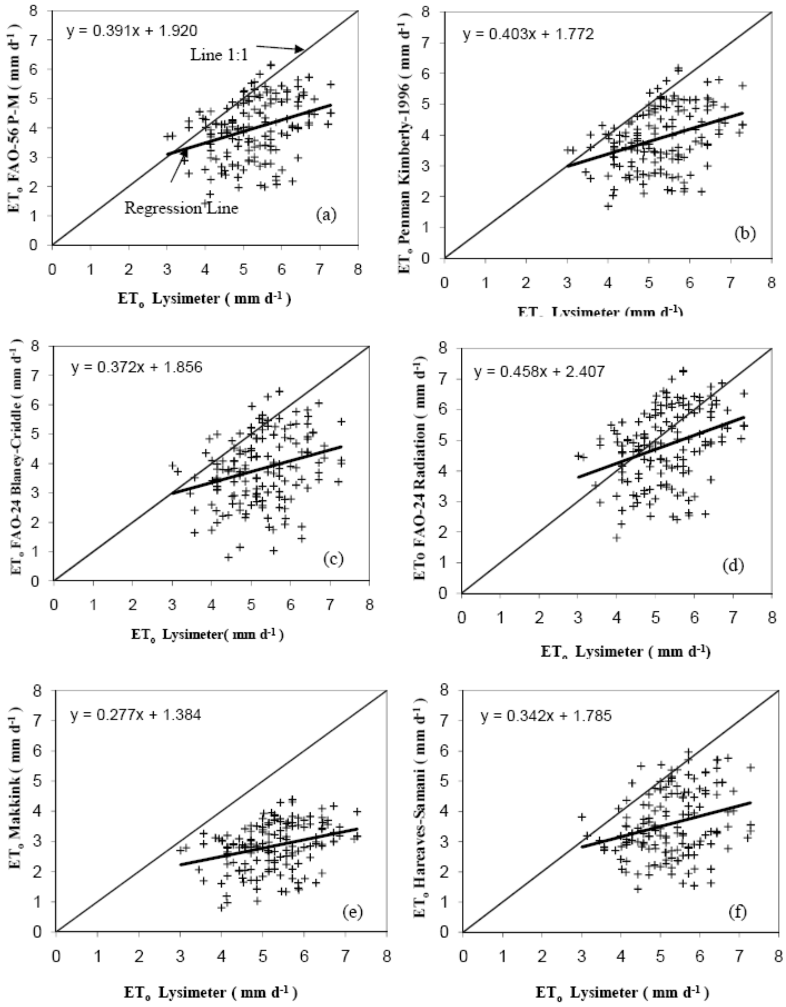

Figure 4. Comparison between ET_0 values measured in the lysimeter and those calculated, for the six methods in the period of October, 2004 to March, 2005.

them below 4.5 mm day^{-1}. The FAO-56 Penman–Monteith method (Fig. 4a) overerestimated below values of approximately 3 mm day^{-1} and underestimated above 3.2 mm day^{-1}. The Penman–Kimberly 1996 method (Fig. 4b) overestimated for values less than about 3 mm day^{-1} and above this value it underestimated lysimeter measurements. The results of evaluating the six methods studied demonstrate the superiority of the FAO-24 Radiation method over the others in the study area. The results do not agree with a similar study performed by Lopez-Urrea *et al*. (2006) carried out in semiarid climate of Albacete, Spain, in which the FAO-56 Penman–Monteith equation turned out to be the most accurate method in both low and high evaporative demand periods of the year. This might be because of differences in lysimeteric measurements error and local climatic conditions. Several studies have shown that the Penman-Kimberly method performs very well in semi-arid and arid regions, where there is considerable sensible heat advection, because the method incorporates a region-specific wind-function (Ervin and Koski, 1997; Wright 1982; Jensen *et al*., 1990). As the results show, there are almost large deviations (lysimeter

ET_o vs. calculated ET_o) compared to other studies. This could be attributed to the dry climate of the region in which advective transport added energy to increase the ET_o in the reference grass plot.

CONCLUSION

Six methods of calculating ETo including FAO-56 Penman–Monteith, Penman-Kimberly 1996, FAO-24 Blaney–Criddle, FAO-24 Radiation, Makkink, and Hargreaves-Samani were assessed during three different time periods in Kerman region. For the entire year period, FAO-24 Radiation was the best method for calculating daily ET_o, when compared to the lysimeter measurements. During the high evaporative demand period, the FAO-24 Radiation method showed the best performance, although it mostly underestimated the ET_o values. Finally, during the low evaporative demand period, again, the FAO-24 Radiation turned out as the best method when compared with the lysimeter measurements. Among these six methods, FAO-24 Blaney–Criddle, Hargreaves-Samani, and Makkink ranked as the last three, of which Makkink cannot be recommended in this region due to its poor performance. The results of this research can be recommended for semiarid environments outside the ambit where the experiment was conducted for irrigation scheduling, selection of cropping pattern, optimum allocation of water resources, and efficient use of water.

REFERENCES

1. Allen, R. G. 1986. A Penman for All Seasons. *J. Irrig. Drain. Eng.*, **112(4):** 348–368.
2. Allen, R. G., Smith, M., Pereira, L. S. and A. Perrier. 1994. An Update for the Calculation of Reference Evapotranspiration. *ICID Bulletin*, **43(2):** 35–92.
3. Allen, R. G., Pereira, L. S., Raes, D. and M. Smith. 1998. Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage, Paper No. 56, FAO, Rome.
4. Amatya, D. M, R.W. Skaggs, and J. D., Gregory. 1995. Comparison of Methods for Estimating REF-ET. *J. Irrig. Drain. Eng.*, **121(6):** 427-435.
5. Barani, G. A. and Khanjani, M. J. 2002. A Large Electronic Weighing Lysimeter System: Design and Installation, *J. Am. Water Res. Assoc.* **38(4)**: 1053–1060.
6. Blaney, H. F. and W. D. Criddle. 1950. Determining Water Requirements in Irrigated Areas from Climatological and Irrigation Data. In: USDA Soil Conserv. Serv., SCS-TP-96, 44 p.
7. Doorenbos, J. and W. O. Pruitt. 1977. Crop Water Requirements. FAO Irrigation and Drainage, Paper No. 24, FAO, Rome.
8. Ervin, E. H. and A. J. Koski. 1997. Comparison of Modified Atmometer Estimates of Turf Grass Evapotranspiration with Kimberly-Penman Alfalfa Reference Evapotranspiration. *Int. Turfgrass Soc. Res. J.*, **8**: 663-670.
9. Frevert, D. K., Hill, R. W. and B. C. Braaten. 1983. Estimation of FAO Evapotranspiration Coefficients. *J. Irrig. Drain. Eng.*, ASCE. **109**: 265–270.
10. Hargreaves, G. H. 1975. Moisture Availability and Crop Production. *Trans. Am. Soc. Agric. Eng*. **18(5)**: 980-984.
11. Hargreaves, G. H. 1994. Defining and Using Reference Evapotranspiration. *J. Irrig. Drain. Eng.*, **120(6):** 1132–1139.
12. Hargreaves, G. H. and Z. A. Samani. 1985. Reference Crop Evapotranspiration from Temperature. *Appl. Eng. Agric.* **1(2)**: 96–99.
13. Hargreaves, G. H. and R. G. Allen. 2003. History and Evaluation of Hargreaves Evapotranspiration Equation. *J. Irrig. Drain. Eng.*, **129(1):** 53-63
14. Hatfield, J. L., Prueger, J. H., Reicosky, D. C., 1996. Evapotranspiration Effects on Water Quality. In: Proceeding of the ASAE International Conference on Evapotranspiration and Irrigation Scheduling, 3–6 November, San Antonio, TX, pp. 536–546.
15. Irmak, S., Allen, R. G. and E. B. Whitty. 2003. Daily Grass and Alfalfa-reference Evapotranspiration Estimates and Alfalfa-to-grass Evapotranspiration Ratios in Florida. *J. Irrig. Drain. Eng.,* **129 (5):** 360-370.

16. Itenfisu, D., Elliot, R. L., Allen, R. G. and I. A. Walter. 2000. Comparison of Reference Evapotranspiration Calculations Across a Range of Climates. Proc., 4th National Irrigation Symp., Am. Soc. of Agric. Eng., St. Joseph, Mich.
17. Jensen, M. E., Burman, R. D. and R. G. Allen (Eds.). 1990. Evapotranspiration and Irrigation Water Requirements. Committee on Irrigation Water Requirements, Irrigation and Drainage Division of ASCE, Manual No. 70. Am. Soc. Civil Eng., New York, 332 p.
18. Khalili, A. 1997. Integrated Water Plan of Iran. Vol. 4: Meteorological studies, Ministry of Power, Iran.
19. Lopez-Urrea, R., Martın de Santa Olalla, F., Fabeiro, C. and A. Moratalla. 2006. Testing Evapotranspiration Equations Using Lysimeter Observations in a Semiarid Climate. *J. Agric. Water Manag.*, **85:**15 – 26.
20. Makkink, G. F. 1957. Testing the Penman Formula by Means of Lysimeters. *Int. J. Water Eng.*, **11**: 277-288.
21. Mantovani, E. C. 1993. Desarrollo y Evaluacio´n de Modelos Para el Manejo del Riego; Estimacio´n de la Evapotranspiracio´n y Efectos de la Uniformidad de Aplicacio´n Del Riego Sobre la Produccio´n de Cultivos. Ph. D. Thesis, Cordoba University, Spain.
22. Morton, F. I. 1983. Operational Estimates of Areal Evapotranspiration and their Significance to the Science and Practice of Hydrology. *J. Hydrol.*, **66:** 1–76.
23. Peterson, T. C., Golubev, V. S. and P. Groisman. 1995. Evaporation Losing Its Strength. *Nature,* **377**: 687–688.
24. Smith, M., Allen, R. G., Monteith, J. L., Perrier, A., Pereira, L., and A. Segeren. 1991. Report of the Expert Consultation on Procedures for Revision of FAO Guidelines for Prediction of Crop Water Requirements. UN-FAO, Rome, Italy, 54 p.
25. Snyder, R. L. and W. O. Pruitt. 1992. Evapotranspiration Data Management in California. ASCE Water Forum “92,” Baltimore, Md.
26. Suleiman**,** A. and G. Hoogenboom. 2007. Comparison of Priestley-Taylor and FAO-56 Penman-Monteith for Daily Reference Evapotranspiration Estimation in Georgia. *J. Irrig. and Drain. Eng.*, **133(2)**: 175.
27. Thornthwaite, C. W. 1944. Report of the Committee on Transpiration and Evaporation. Transaction of the American Geophysical Union, **25(5):** 683–693.
28. Willmott, C. J. 1982. Some Comments on the Evaluation of Model Performance. *Bull. Am. Meteorol. Soc.*, **63 (11):** 1309–1313.
29. Wright, J. L. 1982. New Evapotranspiration Crop Coefficients. *J. Irrig. and Drain. Div.*, ASCE, **108**: 57-74.
30. Wright, J. L. 1996. Derivation of Alfalfa and Grass Reference Evapotranspiration. In: “*Evapotranspiration and Irrigation Scheduling*”. (Eds): C. R. Camp, E. J. Sadler, and R. E. Yoder. Proc. Int. Conf., ASAE, San Antonio, TX. p. 133-140.

ارزیابی مدلهای تبخیرتعرق مرجع با استفاده از اندازه‌گیری‌های لایسیمتری در یک اقلیم نیمه خشک

ب. بختیاری، ن. قهرمان، ع. م. لیاقت و گ. هوگنبوم

چکیده

تعیین دقیق مقدار تبخیرتعرق در بسیاری از مطالعات بیلان آبی مورد نیاز است. یکی از روش‌های موجود در این زمینه استفاده از لایسیمترها می‌باشد. با توجه به اقلیم نیمه خشک استان کرمان در جنوب شرق

ایران، تنها لایسیمتر عملیاتی وزنی- الکترونیکی کشور جهت محاسبه تبخیر تعرق روزانه طی ماه فروردین ۱۳۸۳ تا اردیبهشت ۱۳۸۴ در سه دوره مختلف (کل سال، دوره نیاز تبخیری زیاد و دوره نیاز تبخیری کم) مورد استفاده قرار گرفت. خطای اندازه‌گیری معادل ۱ کیلوگرم جرم آب یا ۰/۱۴ میلی‌متر آب در مزرعه بوده است. داده های هواشناسی مورد نیاز برای محاسبه تبخیرتعرق روزانه با گام زمانی ۱۰ دقیقه ای از یک ایستگاه هواشناسی خودکار در مجاورت محل لایسیمتر جمع آوری گردید. ایستگاه خودکار و لایسیمتر در داخل مزرعه ای از چمن قرار داشتند. از داده های لایسیمتری جهت ارزیابی ۶ معادله تبخیرتعرق چمن شامل پنمن-مانتیث فائو- ۵۶، پنمن-کیمبرلی ۱۹۹۶، بلانی کریدل فائو-۲۴، ماکینک، تشعشع فائو-۲۴ و هارگریوز- سامانی استفاده شد. آماره های جذر مربعات میانگین خطا (RMSE)و نمایه توافق (d) برای انجام تحلیل های آماری و مقایسه ها مورد استفاده قرار گرفت. نتایج نشان داد برای کل دوره سال، معادله FAO-24 تابش با داشتن $RMSE = ۱/۶۳\ mmd^{-1}$ دقیق‌ترین روش بوده است. در دوره نیاز تبخیری زیاد، معادله FAO-24 تابش با مقادیر $RMSE = ۱/۸۶\ mmd^{-1}$ و $d = ۰/۴۵$ معادله ارجح برای محاسبه ET_o می‌باشد. همچنین در طی دوره نیاز تبخیری کم (شهریور ۱۳۸۳ تا اردیبهشت ۱۳۸۴) نیز همین معادله در مقایسه با سایر معادلات با داشتن آماره‌های $RMSE = ۱/۳\ mmd^{-1}$ و $d = ۰/۴۶$ در مقایسه با سایر روشهای برتری داشته است. در هر سه مقطع زمانی، معادله ماکینک عملکردی ضعیف داشته و برای این منطقه قابل توصیه نیست.