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Comparative analysis of 31 reference evapotranspiration methods under humid conditions

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Abstract Evaluation of simple reference evapotranspiration (ET_o) methods has received considerable attention in developing countries where the weather data needed to estimate ET_o by the Penman–Monteith FAO 56 (PMF-56) model are often incomplete and/or not available. In this study, eight pan evaporation-based, seven temperature-based, four radiation-based and ten mass transfer-based methods were evaluated against the PMF-56 model in the humid climate of Iran, and the best and worst methods were selected from each group. In addition, two radiation-based methods for estimating ET_o were derived using air temperature and solar radiation data based on the PMF-56 model as a reference. Among pan evaporation-based and temperature-based methods, the Snyder and Blaney–Criddle methods yielded the best ET_o estimates. The ET_o values obtained from the radiation-based equations developed here were better than those estimated by existing radiation-based methods. The Romanenko equation was the best model in estimating ET_o among the mass transfer-based methods. Cross-comparison of the 31 tested methods showed that the five best methods as compared with the PMF-56 model were: the two radiation-based equations developed here, the temperature-based Blaney–Criddle and Hargreves-M4 equations and the Snyder pan evaporation-based equation.

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Introduction

Evapotranspiration (ET) is the simultaneous process of transfer of water to the atmosphere by transpiration and evaporation in a soil–plant system. ET is an important parameter for climatological and hydrological studies, as well as for irrigation planning and management (Sentelhas et al. 2010). Furthermore, it is necessary to quantify ET for work dealing with water resource management or environmental studies. ET quantification frequently must be preceded by the determination of reference evapotranspiration (ET_o) (Lopez–Urrea et al. 2006). Reference evapotranspiration has been defined as the rate of evapotranspiration from an extensive grassed area of 8–15 cm tall, uniform, actively growing, completely shading the ground and with adequate water (Doorenbos and Pruitt 1977). Subsequently, Allen et al. (1998) elaborated on the concept of ET_o, by referring it to an ideal 12 cm high crop with a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23.

Accurate estimation of ET_o in irrigated lands is necessary for improving the planning and efficient use of water resources. Application of lysimeters is the most common method for estimating ET_o. Unfortunately, lysimeters are unsuitable for monitoring evapotranspiration as compared to direct climate-based measurement at weather stations. This is not only due to their cost and complexity, but also because the limited area of a typical weather station enclosure does not provide sufficient fetch from a representative surface for these measurements to be meaningful

(Sentelhas et al. 2010). In practice, ET_o can be either estimated using available climatic data from a weather station or derived from the pan observation multiplied by a conversion factor (K_{pan}) (Xing et al. 2008). Numerous equations, classified as temperature-based, radiation-based, pan evaporation-based, mass transfer-based and combination-type, have been developed for estimating ET_o, but their performances in different environments vary (Gocic and Trajkovic 2010). The Penman–Monteith FAO 56 (PMF-56) model, which is recommended as the sole method for determining ET_o, has been reported to be able to provide consistent ET_o values in many regions and climates (Allen et al. 2005, 2006), and it has long been accepted worldwide as a good ET_o estimator when compared with others methods (Cai et al. 2007). It is now widely used by agronomists, irrigation engineers and other scientists in field practice and research (Alexandris et al. 2006). The main shortcoming of the PMF-56 equation is that it requires numerous weather data that are not always available for many locations. This is especially true in developing countries where reliable weather data sets of radiation, relative humidity and wind speed are limited (Gocic and Trajkovic 2010; Tabari and Hosseinzadeh Talaee 2011). Furthermore, the installation and maintenance of weather station equipment can be expensive and complicated (Sentelhas et al. 2010).

The application of ET_o equations with fewer meteorological parameters requirements is recommended under situations where more complete weather data is lacking. However, before these equations can be used to estimate ET_o for a given region, they must be evaluated against either lysimeter measurements or the PMF-56 standard model. Although many studies have been conducted for evaluation of ET_o equations under relatively low humidity conditions (semi-arid) throughout the world (e.g., Jensen et al. 1990, 1997; Kashyap and Panda 2001; Irmak et al. 2002, 2003a, b; Grismer et al. 2002; Yoder et al. 2004; Chen et al. 2005; Temesgen et al. 2005; Alkaeed et al. 2006; Trajkovic 2007; Landeras et al. 2008; Xing et al. 2008; Ali and Shui 2009; Trajkovic and Kolakovic 2009; Sentelhas et al. 2010), little such work has been carried out in humid climates of Iran. DehghaniSanij et al. (2004) assessed the estimates of ET_o obtained using the Penman, Penman–Monteith, Wright–Penman, Blaney–Criddle, Radiation balance and Hargreaves models against experimentally determined values in a semi-arid environment. The results indicated that the Penman–Monteith model produced the most reliable estimates compared to lysimeter data. Sabziparvar et al. (2010) examined pan evaporation-based equations for estimating ET_o in cold semi-arid and warm arid climates. They found that the Orang and Snyder models were the best models for estimation of ET_o in cold semi-arid and warm arid environments, respectively. Tabari (2010) evaluated four ET_o models with small weather data requirements (Makkink, Turc, Priestley–Taylor and Hargreaves) in four climates. The results showed that the Turc model was the best-suited model in estimating ET_o for cold humid and arid climates. In addition, the Hargreaves model was the most precise model under warm humid and semi-arid climatic conditions. Sabziparvar and Tabari (2010) prepared the spatially distributed maps of ET_o in the arid and semi-arid regions using the Hargreaves model. The estimated total monthly ET_o revealed a significant variation during the growing seasons (April–September) so that the study region experienced the highest and lowest monthly ET_o values of 250 and 80 mm in July and April, respectively.

To our knowledge, there are no reports of studies that have been conducted to evaluate the performance of mass transfer-based methods in Iran. In this study, 29 commonly used ET_o equations that belonged to four groups: (1) pan evaporation-based methods, (2) temperature-based methods, (3) radiation-based methods, and (4) mass transfer-based methods were evaluated against the PMF-56 standard model; and the best and worst equations of each category were determined using climatic data from the Rasht station located in a humid climate near Rash, Iran. In addition, two radiation-based methods for estimating ET_o were derived using air temperature and solar radiation data based on the PMF-56 model as a reference. A cross-comparison of the best equations from each group was also conducted. The assessed methods were: FAO-24 pan table, Cuenca, Allen and Pruitt, Snyder, Modified Snyder, Pereira, Orang, FAO-56 (pan evaporation-based), Thornthwaite, four new types of Hargreaves equation reported by Droogers and Allen (2002) and Trajkovic (2007), Blaney–Criddle and Schendel (temperature-based), Jensen–Haise, Ritchie, McGuinness and Bordne, Irmak and two equations developed here (radiation-based), Dalton, Trabert, Meyer, Rohwer, Penman, Albrecht, Romanenko, Brockamp and Wenner, WMO and Mahringer (mass transfer-based).

Materials and methods

Data set

The data set used in this study was obtained from Rasht station in northern Iran. The station is located between the coast of the Caspian Sea and the slopes of the Alborz mountain (37°15′N, 49°36′E; −6.9 m a.s.l.). Rash city has a mild humid climate with plenty of annual rainfall and is known as the “City of Rain” around Iran. Rasht receives about 1,000–1,400 mm of annual precipitation in the form of rain. The wettest months are October (215 mm) and November (186 mm), respectively. Long-term (41 years) climate data of the experimental area identified January as the coldest month, with a mean temperature of 6.8°C, whereas the hottest month is July, with a mean temperature of 25.2°C. The amount of humidity is truly high throughout the year. The average annual relative humidity is 82%, with an average of 86% during October, November and December, and 75% during July. The average wind speed is 1.3 m/s with an average of 1.6 m/s in January and February, and 1 m/s in July. Climatic variables including mean, maximum and minimum air temperatures, relative humidity, dew point temperature, water vapor pressure, wind speed, atmospheric pressure, precipitation, solar radiation and sunshine hours for the period 1965–2005 and Class A pan evaporation for the period 1993–2005 (period of record) were obtained from IRIMO (2007). The monthly means of the primary climate parameters are summarized in Table 1.

Evapotranspiration estimation methods

The FAO Penman–Monteith method for calculating ET_o can be expressed as (Allen et al. 1998):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a+273} U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

where ET_o is the reference crop evapotranspiration (mm day^{-1}), R_n is the net radiation (MJ m^{-2} day^{-1}), G is the soil heat flux (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa °C^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), and Δ is the slope of the saturation vapor pressure–temperature curve (kPa °C^{-1}), T_a is the average daily air temperature (°C), and U_2 is the mean daily wind speed at 2 m (m s^{-1}). The computation of all data required for calculating ET_o followed the method and procedure given in Chapter 3 of FAO-56 (Allen et al. 1998).

The soil heat flux for monthly periods was estimated as

$$G = 0.14(T_{month2} - T_{month1}) \quad (2)$$

where T_{month2} is the temperature at the end of the period in °C, T_{month1} is the temperature at the beginning of the period in °C, 0.14 is the soil heat capacity coefficient at effective soil depth, typically at 2 m (Allen et al. 1998). Furthermore, the solar radiation gaps were filled using the Angstrom equation (Allen et al. 1998).

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \quad (3)$$

where R_a is the extraterrestrial radiation (MJm^{-2} day^{-1}), n is the actual duration of sunshine (h), N is the maximum possible duration of sunshine or daylight hours (h), a_s is the regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days ($n = 0$) and $a_s + b_s$ is the fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$).

Pan evaporation-based ET_o equations

In many areas, the necessary meteorological data are lacking, and simpler techniques such as pan evaporation-based methods are required. Class A pan evaporation (E_{pan}) data are used for estimating ET_o (Eq. 4) throughout the world because of the simplicity of technique, low cost and ease of application in determining crop water requirements for irrigation scheduling (Singh 1989; Stanhill 2002).

$$ET_o = E_{pan} \cdot K_{pan} \quad (4)$$

where K_{pan} is pan coefficient. In this study, eight methods were applied for estimating ET_o at the humid location. Cuenca (1989):

Table 1 Monthly means of the main climatic variables at Rasht station during 1965–2005

Month	T_{max} (°C)	T_{mean} (°C)	T_{min} (°C)	P (mm)	RH (%)	U (m/s)	R_s (MJ m^{-2} day^{-1})
Jan	11.1	6.8	2.4	133.6	85	1.6	7.0
Feb	11.2	6.9	2.6	119.8	85	1.6	8.4
Mar	13.2	9.2	5.1	117.1	85	1.3	11.7
Apr	19.1	14.3	9.5	63.5	80	1.3	15.1
May	24.1	19.2	14.2	54.3	78	1.2	18.4
Jun	28.0	23.0	18.0	44.7	76	1.1	20.5
Jul	30.3	25.2	20.2	42.0	75	1.0	20.3
Aug	30.1	25.1	20.2	71.4	78	1.1	17.7
Sep	26.7	22.1	17.5	157.4	83	1.1	14.5
Oct	22.0	17.5	13.1	215.4	86	1.1	10.8
Nov	17.4	12.8	8.3	186.0	86	1.2	7.5
Dec	13.5	8.9	4.3	153.8	86	1.4	6.3

T_{max}, T_{min} and T_{mean} are maximum, minimum and mean air temperatures, respectively; P is precipitation; RH is relative humidity; U is wind speed; R_s is solar radiation

$$K_{pan} = 0.475 - (0.245 \times 10^{-3} U_2) + (0.516 \times 10^{-2} \mathrm{RH}) + (0.118 \times 10^{-2} F) - (0.16 \times 10^{-4} \mathrm{RH}^2) - (0.101 \times 10^{-5} F^2) - (0.8 \times 10^{-8} \mathrm{RH}^2 U_2) - (0.1 \times 10^{-7} \mathrm{RH}^2 F) \quad (5)$$

Allen and Pruitt (1991):

$$K_{pan} = 0.108 - (3.31 \times 10^{-4} U_2) + (0.0422 \ln(F)) + (0.1434 \ln(\mathrm{RH})) - [6.31 \times 10^{-4} ((\ln(F))^2 \ln(\mathrm{RH}))] \quad (6)$$

Snyder (1992):

$$K_{pan} = 0.482 + [0.24 \ln(F)] - (3.76 \times 10^{-4} U_2) + (0.0045\,\mathrm{RH}) \quad (7)$$

Modified Snyder:

$$K_{pan} = 0.5321 - (3 \times 10^{-4} U_2) + (0.0249 \ln(F)) + (0.0025\,\mathrm{RH}) \quad (8)$$

Pereira (Pereira et al. 1995):

$$K_{pan} = 0.85 \times (\Delta + \gamma)/[\Delta + \gamma(1 + 0.33\,U_2)] \quad (9)$$

Orang (1998):

$$K_{pan} = 0.51206 - (0.000321 \cdot U_2) + (0.002889 \cdot \mathrm{RH}) + (0.03188 \cdot \ln(F)) - (0.000107 \cdot \mathrm{RH} \cdot \ln(F)) \quad (10)$$

FAO-56 (Allen et al. 1998):

$$K_{pan} = 0.108 - 0.0286\,U_2 + 0.0422 \ln(F) + 0.1434 \ln(\mathrm{RH}) - 0.000631\,[\ln(F)]^2 \ln(\mathrm{RH}). \quad (11)$$

In the above pan evaporation-based equations, U_2 is the mean daily wind speed measured at 2 m height (km day^{-1}), RH is the mean daily relative humidity (%), F is the upwind fetch distance of low-growing vegetation (m), Δ is the slope of the vapor pressure curve (kPa °C^{-1}) and γ is the psychrometric constant (kPa °C^{-1}). In the FAO-56 pan equation, U_2 is in m s^{-1}. In addition to the above mentioned equation, the K_{pan} values obtained from the FAO-24 pan table (Doorenbos and Pruitt 1977) were also evaluated.

Temperature-based ET$_o$ equations

The temperature-based ET$_o$ models are some of the earliest methods for estimating ET (Xu and Singh 2002). According to Jensen et al. (1990), the relation of ET to air temperature dated back to the 1920s. In this study, seven temperature-based methods were used. In the following equations, T_a, T_{max} and T_{min} are the mean, maximum and minimum air temperatures, respectively (°C), RH is the relative humidity (%) and R_a is the extraterrestrial radiation (MJ m^{-2} day^{-1}).

Thornthwaite (1948):

$$\mathrm{ET}_o = 16\left(10\frac{T_a}{I}\right)^a \quad (12)$$

$$I = \sum_{n=1}^{12} (0.2T_a)^{1.514} \quad (13)$$

$$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.7912 \times 10^{-2} I + 0.49239. \quad (14)$$

Where ET$_o$ is in mm month^{-1}. I is a thermal index imposed by the local normal climatic temperature regime, and the exponent a is a function of I. In order to convert the estimates from a standard monthly (mm month^{-1}) to a daily time scale (mm day^{-1}), the following correction factor (C) was used:

$$C = \frac{N}{360}. \quad (15)$$

Where N is the photoperiod (h) for a given day.Blaney and Criddle (1950):

$$\mathrm{ET}_o = a + b[P(0.46T_a + 8.13)] \quad (16)$$

where ET$_o$ is in mm day^{-1}, P is the mean annual percentage of daytime hours that can be obtained from Doorenbos and Pruitt (1977), and a and b are the parameters of the equation. The a and b coefficients were computed using regression equations developed by Allen and Pruitt (1991). Schendel (1967):

$$\mathrm{ET}_o = 16 \cdot \frac{T_a}{\mathrm{RH}} \quad (17)$$

where ET$_o$ is in mm day^{-1}. Droogers and Allen (2002) reported three new types of the Hargreaves equation (Hargreaves and Samani 1985) as follows:

$$\mathrm{ET}_o = 0.408 \times 0.0030 \times (T_a + 20) \times (T_{max} - T_{min})^{0.4} \times R_a \quad (18)$$

$$\mathrm{ET}_o = 0.408 \times 0.0025 \times (T_a + 16.8) \times (T_{max} - T_{min})^{0.5} \times R_a \quad (19)$$

$$\mathrm{ET}_o = 0.408 \times 0.0013 \times (T_a + 17) \times (T_{max} - T_{min} - 0.0123P)^{0.76} \times R_a \quad (20)$$

where ET$_o$ is in mm day^{-1} and P is monthly rainfall (mm). The coefficient of 0.408 is for converting MJ m^{-2} day^{-1} into mm day^{-1} (Allen et al. 1998). The Eqs. 18, 19 and 20 are defined hereafter as Hargreaves-M1, Hargreaves-M2 and Hargreaves-M3, respectively. Trajkovic (2007) adjusted the Hargreaves equation for the humid climate of Western Balkans region (hereafter as Hargreaves-M4) as follows:

$$ET_o = 0.408 \times 0.0023 \times (T_a + 17.8) \times (T_{max} - T_{min})^{0.424} \times R_a. \quad (21)$$

Radiation-based ET_o equations

Four commonly used radiation-based equations including Jensen–Haise, Ritchie, McGuinness and Bordne and Irmak were evaluated and compared in this study. Selection of the equations was carried out by taking into account the equations (Makkink 1957; Turc 1961, Priestley and Taylor 1972) used in the previous study carried out in the region (Tabari 2010). In the following equations, T_a, Δ, γ and R_n have the same meaning as those defined in the PMF-56 model, R_s is the solar radiation, T_{max} and T_{min} are the maximum and minimum air temperatures, respectively and λ is the latent heat.

Jensen and Haise (1963):

$$ET_o = \frac{C_T(T_a - T_x) \times R_s}{\lambda} \quad (22)$$

where ET_o is in mm day^{-1}, λ is in cal gr^{-1}, R_s is in mm day^{-1}, C_T (temperature constant) = 0.025, and $T_x = -3$ when T_a is in degrees Celsius. These coefficients were considered to be constant for a given area (Xu and Singh 2000).

McGuinness and Bordne (1972):

$$ET_o = \left\{(0.0082 \times T_a - 0.19)\left(\frac{R_s}{1500}\right)\right\} \times 2.54 \quad (23)$$

where ET_o is in cm day^{-1} for a monthly period, T_a is in degrees Fahrenheit, R_s is in cal/cm^2/day. Ritchie (1972) method as described by Jones and Ritchie (1990):

$$ET_o = \alpha_1[3.87 \times 10^{-3} \cdot R_s(0.6T_{max} + 0.4T_{min} + 29)] \quad (24)$$

where T_{max} and T_{min} are in °C and the ET_o units are the same as those of R_s. When

$$5 < T_{max} 35°C \quad \alpha = 1.1$$

$$T_{max} > 35°C \quad \alpha = 1.1 + 0.05 \cdot (T_{max} - 35) \quad (25)$$

$$T_{max} < 5°C \quad \alpha = 0.1 \exp[0.18 \cdot (T_{max} + 20)] \quad (26)$$

Irmak (Irmak et al. 2003b):

$$ET_o = -0.611 + 0.149 \times R_s + 0.079 \times T_a \quad (27)$$

where the units of ET_o, R_s and T_a are same as those defined in the PMF-56 model.

Similar to the study of Irmak et al. (2003b), two radiation-based equations were developed in this study using multiple linear regressions. In the multiple linear regressions, the PMF-56 ET_o values were used as the dependent variable and T_{max} and T_{min} or T_a and R_s were the independent variables. The developed radiation-based equations are as follows:

$$ET_o = -0.642 + 0.174\,R_s + 0.0353\,T_a \quad (28)$$

$$ET_o = -0.478 + 0.156\,R_s - 0.0112\,T_{max} + 0.0733\,T_{min} \quad (29)$$

where ET_o, R_s, T_a, T_{max} and T_{min} have the same meaning as before, ET_o is in mm day^{-1}. It should be noted that 65% of the data (1965–1990) were used for development of the equations and the rest of data (1991–2005) were applied for validation.

Mass transfer-based ET_o equations

The mass transfer-based methods utilize the concept of eddy transfer of water vapor from an evaporating surface to the atmosphere. All such methods are fundamentally based on Dalton's gas law. The mass transfer-based methods give satisfactory results in many cases and normally use easily measurable variables and have simple model forms (Singh and Xu 1997). Ten mass transfer-based equations were used in this study.

Dalton (1802):

$$ET_o = (0.3648 + 0.07223u) \cdot (e_s - e_a) \quad (30)$$

Trabert (1896):

$$ET_o = 0.3075 \cdot \sqrt{u} \cdot (e_s - e_a) \quad (31)$$

Meyer (1926):

$$ET_o = (0.375 + 0.05026u) \cdot (e_s - e_a) \quad (32)$$

Rohwer (1931):

$$ET_o = 0.44(1 + 0.27u) \cdot (e_s - e_a) \quad (33)$$

Penman (1948):

$$ET_o = 0.35(1 + 0.98/100u) \cdot (e_s - e_a) \quad (34)$$

Albrecht (1950):

$$ET_o = (0.1005 + 0.297u) \cdot (e_s - e_a) \quad (35)$$

Romanenko (1961):

$$ET_o = 0.0018(T_a + 25)^2 \cdot (100 - RH) \quad (36)$$

Brockamp and Wenner (1963):

$$ET_o = 0.543 \cdot u^{0.456} \cdot (e_s - e_a) \quad (37)$$

WMO (1966):

$$\mathrm{ET}_o = (0.1298 + 0.0934u) \cdot (e_s - e_a) \quad (38)$$

Mahringer (1970):

$$\mathrm{ET}_o = 0.15072 \cdot \sqrt{3.6u} \cdot (e_s - e_a). \quad (39)$$

In the above equations, e_s and e_a are the saturation and actual vapor pressure, respectively, u is the wind speed, RH is the relative humidity (%) and T_a is the mean air temperature (°C). e_s and e_a are in hPa in all the equations except Rohwer and Penman models, e_s and e_a are in mmHg in Rohwer and Penman models, u is in m s^{-1} in all the equations except Penman model, u is in miles day^{-1} in Penman model, ET_o is in mm day^{-1} in all the equations except Romanenko model where ET_o is in cm $month^{-1}$.

Evaluation criteria

In this study, the root mean square error (RMSE), percentage error of estimate (PE), mean bias error (MBE) and coefficient of determination (R^2) were used for the evaluation of the simplified ET_o equations. The RMSE, PE, MBE and R^2 are defined as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (40)$$

$$\mathrm{PE} = \left|\frac{\bar{P} - \bar{O}}{\bar{O}}\right| \times 100\% \quad (41)$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}(P_i - O_i)}{n} \quad (42)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(P_i - \bar{P})(O_i - \bar{O})\right]^2}{\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (43)$$

where P_i and O_i are the predicted and observed values, respectively; $\bar{P}$ and $\bar{O}$ are the average of P_i and O_i, and n is the total number of data.

Results and discussion

Pan evaporation-based ET_o equations

First, we calculated K_{pan} values using the pan evaporation-based methods and then evaluated their relative performance with respect to PMF-56 ET_o estimates in the study area. The comparisons of calculated mean monthly K_{pan} values using the pan evaporation-based methods are given in Fig. 1. In the K_{pan} calculations, the upwind fetch of low-growing vegetation (F) was taken as 1,000 m since the weather station was surrounded by irrigated agricultural crops. The highest K_{pan} values were obtained by the Snyder and Cuenca equations, respectively. The K_{pan} values generated by the Snyder equation varied from 0.99 in November to 0.89 in July, with an average of 0.97. Moreover, the K_{pan} values calculated from Cuenca equation ranged from 0.91 in November to 0.88 in July, with an average of 0.89. The K_{pan} values determined by the Snyder and Cuenca equations in this study are higher than those reported by Irmak et al. (2002) who obtained average K_{pan} values of 0.93 and 0.85 by the Snyder and Cuenca equations at a humid location in Florida, USA. This is due to the higher relative humidity at Rasht station (82%) as compared with that at the Green Acres Agricultural Research Center weather station in Florida (73%). The average K_{pan} values generated by Allen and Pruitt, Orang, Modified Snyder, FAO-24 pan table, FAO-56 pan and Pereira methods were 0.89, 0.86, 0.86, 0.83, 0.82 and 0.73, respectively.

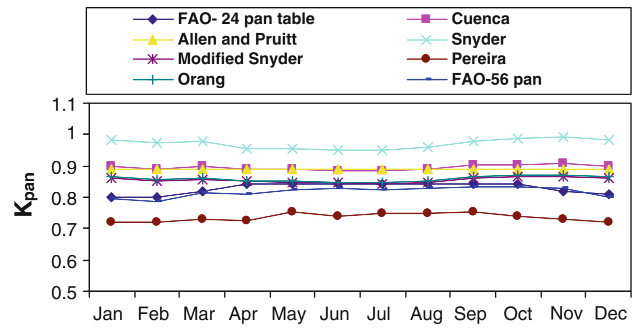

Fig. 1 Mean monthly K_{pan} obtained from the pan evaporation-based methods

The mean monthly of ET_o values calculated from the PMF-56 model and the pan evaporation-based methods were plotted in Fig. 2. As shown, all of the pan evaporation-based methods underestimated PMF-56 ET_o at the Rasht study site. The underestimation of ET_o values by the pan evaporation-based equations was also found in the United States (Grismer et al. 2002) and Canada (Xing et al. 2008). The Snyder equation provided the least underestimate average of 0.11 mm/day, while the Pereira equation

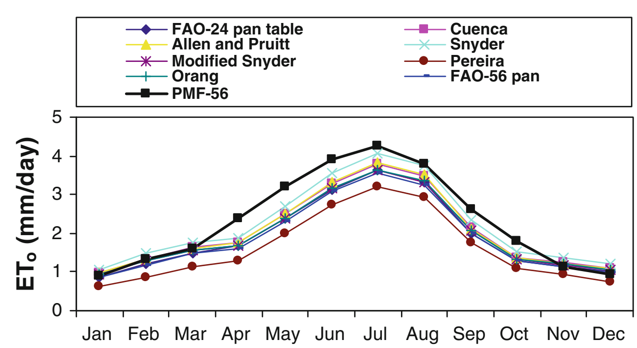

Fig. 2 Comparison of 13-year mean monthly ET_o calculated from the PMF-56 model and the pan evaporation-based methods

Table 2 Statistical performance of the pan evaporation-based methods versus the PMF-56 model for estimating monthly ET_o during the study period (1993–2005)

Pan evaporation-based methods	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
FAO-24 pan table	0.91	0.57	0.41	17.41
Cuenca	0.87	0.59	0.27	11.63
Allen and Pruitt	0.88	0.56	0.26	11.25
Snyder	0.86	0.53	0.11	4.91
Modified Snyder	0.87	0.65	0.36	15.56
Pereira	0.88	0.82	0.67	30.16
Orang	0.87	0.65	0.35	15.19
FAO-56 pan	0.86	0.72	0.45	19.41

yielded the greatest underestimate average of 0.67 mm/day (Table 2). The ET_o calculated by the Snyder equation best matched the ET_o estimates by the PMF-56 equation with the lowest errors rates (RMSE = 0.53 mm/day and PE = 4.91%). Xing et al. (2008) evaluated the Snyder and Cuenca equations to estimate ET_o in Maritime region of Canada and found that the Snyder equation generally performed better than the Cuenca equation. According to the results (Table 2), the Allen and Pruitt equation can be selected as the second best method with the R^2 value of 0.88, the RMSE value of 0.56 mm/day and an underestimation of 11.25%. Overall performances suggest that the FAO-24 pan table and Cuenca methods can be more reliable than the Orang, Modified Snyder, FAO-56 pan and Pereira methods for estimating ET_o for the study area. Grismer et al. (2002) found that pan evaporation-based estimates of ET_o using both K_{pan} tables and equations were generally within an error of approximately 10% for humid regions of California.

Temperature-based ET_o equations

Table 3 summarizes the results of the application of the temperature-based methods for the Rasht humid site, when compared with the full-data PMF-56 method. Consideration of all the results from the analysis indicated that the Blaney–Criddle equation had the best performance (R^2 = 99, RMSE = 0.33 mm/day and PE = 1.17%) among the temperature-based methods, followed by the Hargreaves-M4 (R^2 = 95, RMSE = 0.34 mm/day and PE = 7.87%) and Thornthwaite equations (R^2 = 82, RMSE = 0.64 mm/day and PE = 10.30%). Good performance of the Blaney–Criddle equation may stem from its original development for humid areas where the advective effect is usually negligible and has been reported by several researchers (Irmak et al. 2003b; Ali and Shui 2009). The Blaney–Criddle and Hargreaves-M4 equations overestimated PMF-56 ET_o by 0.03 and 0.182 mm/day, respectively, while the Thornthwaite equation underestimated it by 0.24 mm/day (Fig. 3). Jensen et al. (1990), Alkaeed et al. (2006), Trajkovic and Kolakovic (2009) and Sentelhas et al. (2010) found that the Thornthwaite equation underestimated ET_o in relation to the PMF-56 method at humid locations.

The Hargreaves-M1, Hargreaves-M2 and Hargreaves-M3 equations performed relatively well with a R^2 higher than 0.90. The results indicated that the new version of the Hargreaves equation that contains the rainfall parameter provided closer ET_o estimates than the other new types of the Hargreaves equation developed by Droogers and Allen (2002). In addition, the performance of the Hargreaves-M3 model was better than that (RMSE = 0.70 mm/day and MBE = −0.62 mm/day) for the original Hargreaves equation reported by Tabari (2010) at Rasht station. The overestimation of the Hargreaves-M1, Hargreaves-M2 and Hargreaves-M3 equations varied from 0.32 mm/day (14.21%) to 0.96 mm/day (41.57%). The overestimation of the Hargreaves equation under humid conditions were found by Jensen et al. (1997); Kashyap and Panda (2001); Yoder et al. (2004); Trajkovic (2007) and Landeras et al. (2008). Furthermore, according to Temesgen et al. (2005), higher wind speed combined with lower humidity resulted in lower values of Hargreaves ET_o compared to PMF-56 ET_o. Also, lower wind speed combined with higher

Table 3 Statistical performance of the temperature-based methods versus the PMF-56 model for estimating monthly ET_o during the study period (1965–2005)

Temperature-based methods	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Thornthwaite	0.82	0.64	0.24	10.30
Blaney–Criddle	0.99	0.33	−0.03	1.17
Schendel	0.87	1.03	−0.86	37.32
Hargreaves-M1	0.95	1.08	−0.96	41.57
Hargreaves-M2	0.95	0.94	−0.81	35.06
Hargreaves-M3	0.90	0.67	−0.32	14.21
Hargreaves-M4	0.95	0.34	−0.18	7.87

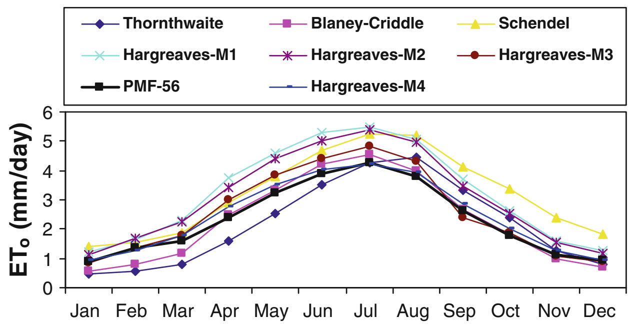

Fig. 3 Comparison of 41-year mean monthly ET_o calculated from the PMF-56 model and the temperature-based methods

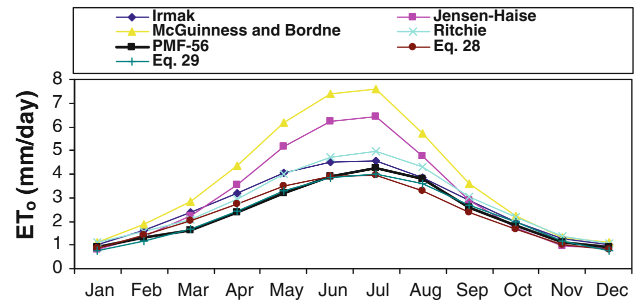

Fig. 4 Comparison of 41-year mean monthly ET_o calculated from the PMF-56 model and the radiation-based methods

humidity resulted in higher values of Hargreaves ET_o compared to PMF-56 ET_o. This is probably due to the lack of explicit wind speed and humidity terms in the Hargreaves equation. The Schendel equation was not a suitable method for estimation of ET_o at the humid location due to the high overestimations (37.32%) it presented, with a RMSE of more than 1 mm day^{-1}.

Radiation-based ET_o equations

The results of the statistical analysis of the radiation-based methods versus the PMF-56 model are given in Table 4. As listed, good coefficients of determination were obtained for all the radiation-based equations, with values greater than 0.93. The derived equations (Eqs. 28, 29), Irmak and Ritchie models were the best options to estimate ET_o in the study area. Eq. 29 slightly overestimated PMF-56 ET_o by 0.22% with a R^2 value of 0.98 and RMSE of 0.18 mm/day (Fig. 4). Equation 28 had a lower R^2 (0.94) and higher error (RMSE = 0.26 mm/day, MBE = −0.02 mm/day and PE = 0.26%) than Eq. 29 for the study site. It means that the inclusion of maximum and minimum air temperatures instead of mean air temperature resulted in better ET_o estimates. The Irmak model overestimated PMF-56 ET_o by 18.10% with a R^2 value of 0.93 and RMSE of 0.54 mm/day. The overestimation of the Irmak equation was also reported by Irmak et al. (2003b) under humid conditions of Florida. The Ritchie equation overestimated ET_o as compared to the PMF-56 model (MBE = −0.50 mm/day), with a R^2 value of 0.98 and RMSE of 0.57 mm/day. The Ritchie equation is a modification of the Priestley–Taylor equation. A slightly better ET_o estimates (R^2 = 0.98, RMSE = 0.44 mm/day and MBE = −0.25 mm/day) were obtained by the Priestley–Taylor model (Tabari 2010) compared with the Ritchie equation at the Rasht station. The Jensen–Haise and McGuinness and Bordne models demonstrated the worst performances among the radiation-based methods with the RMSE of 1.18 and 1.87 mm/day, respectively. The poor performance of the Jensen–Haise equation obtained in this study is in good agreement with the results found in humid climates of Serbia (Trajkovic and Kolakovic 2009) and Florida (Irmak et al. 2003a, b). The Jensen–Haise and McGuinness and Bordne models greatly overestimated PMF-56 ET_o by 30.24 and 59.79%, respectively. Analyses by Jensen et al. (1990) showed the Jensen–Haise equation had a tendency to overestimate ET_o in humid climates.

Mass transfer-based ET_o equations

Table 5 summarizes the results from comparing the ten evaluated mass transfer-based estimates to that from the PMF-56 model. According to the MBE values, all of the mass transfer-based equations underestimated PMF-56 ET_o except Rohwer, Albrecht and Brockamp and Wenner. The Romanenko (R^2 = 0.92, RMSE = 0.66 mm/day and PE = 11.99%), Dalton (R^2 = 0.81, RMSE = 0.79 mm/day and PE = 13.92%) and Meyer (R^2 = 0.84, RMSE = 0.80 mm/day and PE = 14.36%) equations yielded the best ET_o

Table 4 Statistical performance of the radiation-based methods versus the PMF-56 model for estimating monthly ET_o during the study period (1965–2005)

Radiation-based methods	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Jensen–Haise	0.94	1.18	−0.73	30.24
McGuinness and Bordne	0.94	1.87	−1.41	59.79
Ritchie	0.98	0.57	−0.50	21.75
Irmak	0.93	0.54	−0.41	18.10
Eq. 28	0.94	0.26	−0.02	0.26
Eq. 29	0.98	0.18	0.01	0.22

Table 5 Statistical performance of the mass transfer-based methods versus the PMF-56 model for estimating monthly ET_o during the study period (1965–2005)

Mass transfer-based methods	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Dalton	0.81	0.79	0.32	13.92
Trabert	0.75	0.96	0.60	25.99
Meyer	0.84	0.80	0.33	14.36
Rohwer	0.79	0.80	−0.36	15.38
Penman	0.80	0.81	0.41	17.59
Albrecht	0.65	1.73	−0.56	25.89
Romanenko	0.92	0.66	0.28	11.99
Brockamp and Wenner	0.76	1.42	−0.60	26.09
WMO	0.70	1.28	1.03	44.41
Mahringer	0.75	1.03	0.72	31.18

estimations as compared to that from the PMF-56 method. Furthermore, the Rohwer and Penman equations provided satisfactory estimations of ET_o in the study area. The WMO, Mahringer and Trabert equations with average underestimations of 44.41, 31.18 and 25.99% and the Brockamp and Wenner with an average overestimation of 26.09% showed the worst performances among the mass transfer-based methods for estimating ET_o in the humid area. The mean monthly ET_o estimated by the mass transfer-based methods and the PMF-56 model is plotted in Fig. 5.

Cross-comparison of the ET_o methods

According to the RMSE values, the 10 best methods were selected among the 31 considered ET_o methods (Fig. 6). Equation 29 (radiation-based) ranked first with a RMSE of 0.18 mm/day. Equation 28 (radiation-based) ranked second with a RMSE of 0.26 mm/day. The temperature-based Blaney–Criddle and Hargreaves-M4 equations can be considered as the third and fourth best methods with RMSE values of 0.33 and 0.34 mm/day, respectively. The fifth was the Snyder radiation-based equation with a RMSE of 0.53 mm/day. The Irmak, Ritchie, Allen and Pruitt, FAO-24 pan table and Cuenca methods ranked sixth place to tenth, respectively. In general, the comparative results showed that the mass transfer-based equations had the worst performances among the ET_o methods evaluated. The radiation-based and temperature-based models were the best-suited equations for the humid climate. Furthermore, the pan evaporation-based methods performed well in the study area, indicating that the pan measurement simulates the change in all relevant climatic conditions fairly well. This may not be surprising as pan evaporation provides an integrated measurement of the effects of solar radiation, wind speed, air temperature and relative humidity (Chen et al. 2005). To evaluate the best ET_o equations obtained, the Eqs. 29, 28, Blaney–Criddle and Hargreaves-M4 were tested at another humid site (Bandar–Anzali). The equations with the R^2 values higher than 0.94 and the RMSE values lower than 0.7 mm/day presented the good performances at Bandar–Anzali station (Table 6).

Summary and conclusions

In this study, 29 commonly used ET_o equations that developed from four different approaches (1) pan evaporation-based, (2) temperature-based, (3) radiation-based, and (4) mass transfer-based were tested against the PMF-56 standard

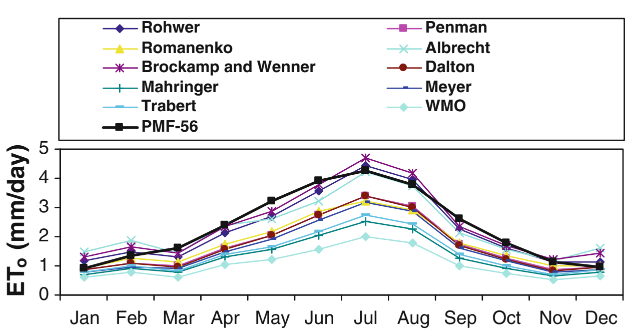

Fig. 5 Comparison of 41-year mean monthly ET_o calculated from the PMF-56 model and the mass transfer-based methods

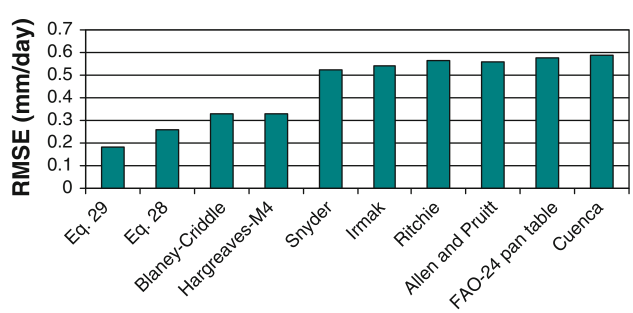

Fig. 6 The RMSE values for the 10 best methods among the 31 considered ET_o methods

Table 6 Performance evaluation of the four best ET_o equations at Bandar–Anzali station

Methods	R^2	RMSE (mm/day)	MBE (mm/day)	PE (%)
Eq. 29	0.97	0.24	−0.04	1.77
Eq. 28	0.94	0.32	0.13	5.30
Blaney–Criddle	0.99	0.26	0.02	0.73
Hargreaves-M4	0.97	0.64	0.48	20.31

model. The best and worst equations of each group were determined using climatic data from Rasht station located in a humid climate of northern Iran. In addition, two radiation-based methods for estimating ET_o were derived using air temperature and solar radiation data based on the PMF-56 model as a reference. The results indicated that all of the pan evaporation-based methods had a tendency to underestimate PMF-56 ET_o. Similarly, the majority of the mass transfer-based equations underestimated PMF-56 ET_o in the humid environment. Among the pan evaporation-based methods, the ET_o calculated by the Snyder equation best matched the ET_o estimates from the PMF-56 equation with the lowest errors rates (RMSE = 0.53 mm/day and PE = 4.91%). The Romanenko ($R^2 = 0.92$, RMSE = 0.66 mm/day and PE = 11.99%), Dalton ($R^2 = 0.81$, RMSE = 0.79 mm/day and PE = 13.92%) and Meyer ($R^2 = 0.84$, RMSE = 0.80 mm/day and PE = 14.36%) equations gave the best ET_o estimations among the mass transfer-based methods.

In contrast with the pan evaporation-based and mass transfer-based methods, the temperature-based and radiation-based equations overestimated PMF-56 ET_o. The analysis also showed that the Blaney–Criddle equation had the best performance ($R^2 = 99$, RMSE = 0.33 mm/day and PE = 1.17%) among the temperature-based methods, followed by the Hargreaves-M4 ($R^2 = 95$, RMSE = 0.34 mm/day and PE = 7.87%). Furthermore, the ET_o values estimated by the two radiation-based equations developed in this study were superior to the corresponding values obtained from the existing radiation-based methods. Comparison of the 31 considered ET_o methods showed that the two developed radiation-based equations yielded ET_o values most similar to those from the PMF-56 model, and the Blaney–Criddle, Hargreaves-M4, Snyder, Irmak, Ritchie, Allen and Pruitt, FAO-24 pan table and Cuenca methods were the third to tenth best methods, respectively. In general, the comparative results showed that the mass transfer-based equations had the worst performances, while the radiation-based and temperature-based models were the best-suited equations for estimating ET_o in this humid climate of Iran. Considering the unavailability of full weather data for applying the PMF-56 model for estimation of ET_o in many regions of the world, especially in developing countries, the results will be useful for choosing the simpler ET_o methods in humid climates. Such comprehensive studies as that conducted here are recommended for evaluation of the simpler ET_o methods in other climatic conditions.

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