Performance of Some Evapotranspiration Equations in an Arid Region

Mohammad Mehdi HEYDARI¹, *, Ali ABBASI¹ and Morteza HEYDARI²

¹Young Researchers and Elite Club, Kashan Branch, Islamic Azad University, Kashan, Iran
²Department of Computer Engineering, Ashtian Branch, Islamic Azad University, Ashtian, Iran

(* Corresponding author's e-mail: mehdiheydari2010@yahoo.com)

Received: 30 August 2013, Revised: 23 October 2013, Accepted: 22 November 2013

Abstract

Estimation of evapotranspiration is necessary for planning, design and irrigation design and water resources management. In order to determine the best method to estimate evapotranspiration using data of Qom synoptic meteorological stations during the years 1987 to 2007 was statistically significant. The FAO Penman Monteith (FAO-56 PM) method has been accepted by many researchers and international institutes as the reference and standard method. Accurate difference methods include Blaney-Criddle, Hargreaves-Samani, Jensen-Haise, Linacre, Rn-based method, Thornthwaite and Turc were applied and then their results were compared with the FAO-56 PM method. In this study, using statistical indicators, the best method to estimate ET₀ in Qom province was selected and found to be Blaney-Criddle (RSME = 0.690 mmd⁻¹, MAE = 0.545 mmd⁻¹, D = 0.998). The results indicate that ET₀ increases from north to south, west to east in the province. The regression relationship between the mean temperature and FAO-56 PM method and evaporation from the pan were determined. Also comparison of the pan evaporation and monthly values of FAO-56 PM method, coefficient pan (Kp = 0.583) is calculated.

Keywords: Qom province, evapotranspiration, statistical indicators, FAO Penman Monteith, Blaney-Criddle, pan evaporation

Introduction

ET₀ is one of the key processes in the hydrological cycle and it is the loss of water to the atmosphere by the combined processes of evaporation from the soil and plant surfaces and transpiration from plants [1]. Evaporation from water bodies are about 112 % of precipitation. Information about ET₀, or consumptive water use, is significant for water resources planning and for irrigation scheduling in crops [2-5]. Estimation of ET₀ is one of the major hydrological components for determining the water budget and therefore reliable and consistent estimates of ET₀ are of great importance for the efficient management of water resources. Efficient water management requires an accurate ET₀ which can be derived from the meteorological variables. ET₀ is always the important research subjects on hydrology, soil, agriculture, meteorology; ET₀ also has important applications in water resources in arid areas, regional planning and management of agricultural production [6,7]. In the semi-arid and arid zones which cover most of the Iranian plateau, evaporation can be up to 96 % of annual precipitation. On average about 50 % of all precipitation is lost in evaporation in the catchments. Therefore, investigation on ET₀ processes could be very important in this country [8-10].

Empirical methods are used when all the data needed for Penman-type equations are not available. Direct measurement of ET₀ is usually not feasible in many field situations because it is expensive and time-consuming. The ET₀ computation methods can be classified into 3 types: temperature methods, radiation methods and combination methods. The Food and Agriculture Organization (FAO) recommends the use of the FAO-56 PM method for estimating ET₀ [1,11]. This method is the most widely used in the world and has been proven to accurately estimate ET₀ in different climates [1,12-16]. However, it
requires several measurements of climatic variables such as air temperature, relative humidity, solar radiation and wind speed. At the planning and design stages of irrigation and water conservation schemes, historical average daily values of \( E_T_0 \) for multi-day periods (e.g. weekly, ten-day and monthly) may be satisfactory for estimation of crop water use [17].

Qom province geographically is located in an arid and semi-arid region of Iran. The mountainous region is in the southern and western parts of Qom. The highest and lowest altitudes are 3209 and 792 m above sea level, respectively. This province has historically suffered from water scarcity problems. Qom province is one of the driest provinces in Iran and annual precipitation of Qom province is 135 mm. Water in this area is of great important and over 90% of water is used in agriculture and industry. \( E_T_0 \) measured using lysimeter data are scarce in central states of Iran and Qom station has complete data for use in the FAO-56 PM equation is available in this province. In this region there is no permanent river but there are some dry streams which lead to floods in the neighboring mountains to the salt lake [18]. An increase in water demand associated with rapid urban development and expansion of agricultural lands has led to overexploitation of water in this city. If water withdrawal continues, a water shortage crisis will happen in this area [19].

The objectives of this study were to (1) to evaluate, under arid conditions, the performance of empirical methods for estimating \( E_T_0 \) by comparing their values to those estimated using the FAO-56 PM equation using statistical parameters, (2) to develop a relationship between Class A pan evaporation and FAO-56 PM method with mean air temperature and (3) to determine the pan coefficient by regression analysis of Class A pan evaporation and FAO-56 PM method values, based on meteorological data of Qom synoptic in Qom province, in the north and center of Iran.

**Materials and method**

Qom Province is one of the 31 provinces in Iran with 11,243 km², covering 0.89% of the total area in Iran. It is located between 34° 15' and 35° 15' north latitude and 50° 30' and 51° 30' east longitude. Qom Province is bounded by Tehran Province in the north, Isfahan Province in the south, Semnan Province in the east, and Markazi Province in the west and its provincial capital is the city of Qom. In 2005, this province had a population of approximately 2,000,000. The province contains 4 synoptic stations. The location of the area of study and synoptic stations is shown in Figure 1 and the geographic characteristics, year of establishment, climate and annual average values of temperature, rainfall of each station are presented in Table 1.

![Figure 1](image_url)

**Figure 1** The area study on Iran map and the synoptic stations in the Qom province.
Table 1 Geographic Characteristics of synoptic stations of the Qom province.

<table>
<thead>
<tr>
<th>Synoptic stations</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Altitude (m)</th>
<th>Ave. temp (°C)</th>
<th>Ave. rain (mm)</th>
<th>Year of Establishment</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kahak</td>
<td>34°-24'</td>
<td>50°-52'</td>
<td>1403.20</td>
<td>16.30</td>
<td>173.60</td>
<td>2004</td>
<td>Arid</td>
</tr>
<tr>
<td>Koshk Nosrat</td>
<td>35°-05'</td>
<td>50°-54'</td>
<td>948.00</td>
<td>19.80</td>
<td>116.60</td>
<td>2006</td>
<td>Arid</td>
</tr>
<tr>
<td>Qom</td>
<td>34°-42'</td>
<td>50°-51'</td>
<td>877.40</td>
<td>18.00</td>
<td>151.10</td>
<td>1952</td>
<td>Arid</td>
</tr>
<tr>
<td>Salafchegan</td>
<td>34°-29'</td>
<td>50°-28'</td>
<td>1380.50</td>
<td>16.80</td>
<td>187.40</td>
<td>2003</td>
<td>Arid</td>
</tr>
</tbody>
</table>

The climate of Qom province varies between a desert and semi-desert climate, and comprises mountainous areas, foothills and plains. Due to being located near an arid region and far inland, it experiences a dry climate, with low humidity and limited rainfall. Qom station (international code: 40770) is located in the center of the province and selected for the study of the province [9]. The meteorological data of 21 years at the Qom station covering the period from January 1987 to December 2007 were analyzed for the purpose of calculating ET₀ by different methods. Figure 2 shows the monthly precipitation, temperature, wind speed, relative humidity, dew point, sunshine hours, solar radiation and net radiation data used for ET₀ estimations.
Figure 2 Monthly variations of input parameters used in the calculation of ET₀ by different methods at Qom synoptic (1987 - 2007) (a) average temperature (°C); (b) precipitation (mm); (c) wind speed (m.s⁻¹); (d) relative humidity (%); (e) net radiation (MJ m⁻² d⁻¹); (f) solar radiation (MJ m⁻² d⁻¹); (g) sunshine hours (hr) and, (h) dew point (°C), respectively.

Monthly ET₀ was estimated using methods developed by Blaney-Criddle [20], Hargreaves-Samani [21], Jensen-Haise [22], Linacre [23,24], Rn-based method [25], Thorthwaite [26] and Turc [27], respectively (Table 2).
Table 2 Methods for calculation of evapotranspiration (ET0), in mm.d⁻¹.

<table>
<thead>
<tr>
<th>Method</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaney-Criddle (1988)</td>
<td>( ET_0 = a + b \times \left[ P(0.46T_{\text{mean}} + 8.13) \right] )</td>
</tr>
<tr>
<td>Hargreaves-Samani (1985)</td>
<td>( ET_0 = 0.0023 \times R_d (T_{\text{mean}} + 17.80) \times \sqrt{(T_{\max} - T_{\min})} )</td>
</tr>
<tr>
<td>Jensen-Haise (1963)</td>
<td>( PET = \frac{1}{38 - \left[ 2 \times \frac{\text{Elevat}}{305} \right] + 7.6 \times 50} \times \frac{\left[ T_{\text{mean}} - \left( -2.5 - 0.14 \left( \frac{e_{S(\text{max})} - e_{S(\text{max})}}{550} \right) \right) - \frac{\text{Elevat}}{550} \right]}{R_n} )</td>
</tr>
<tr>
<td>Linacre (1983)</td>
<td>( ET = \frac{700 \times (T_{\text{mean}} + 0.006 \times Z)}{100 - L} + 15 \times (T_{\text{mean}} - T_d) )</td>
</tr>
<tr>
<td>Rn-based radiation (Irmak 2003)</td>
<td>( ET_0 = 0.489 + 0.289 \times R_n + 0.023T_{\text{mean}} )</td>
</tr>
<tr>
<td>Thornthwaite (1948)</td>
<td>( PET = 16 \times \left( \frac{10T_{\text{mean}}}{I} \right)^a )</td>
</tr>
<tr>
<td>Turc (1961)</td>
<td>( PET = 0.013 \left( \frac{T_{\text{mean}}}{15 + T_{\text{mean}}} \right) (R_d + 50) \quad \text{RH} &gt; 50 % )</td>
</tr>
<tr>
<td></td>
<td>( PET = 0.013 \left( \frac{T_{\text{mean}}}{15 + T_{\text{mean}}} \right) (R_d + 50) \left( 1 + \frac{50 - \text{RH}}{70} \right) \quad \text{RH} &lt; 50 % )</td>
</tr>
</tbody>
</table>

In this study, the amount of reference evapotranspiration was calculated, using the FAO-56 PM method, in 15 selected synoptics. The FAO-56 PM ET0 equation is given by Allen et al. [1] for predicting ET0 where applied on 24 h calculation time steps and has the form;

\[
ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \left[ \frac{900}{(T_d + 273)} \right] U_2 (e_s - e_d)}{\Delta + \gamma(1.0 + 0.34 U_2)}
\]  

(1)

where FAO-56 PM ET0 = the grass reference evapotranspiration (mm/day); \( R_n \) = the net radiation at the crop surface (MJ/m².day); \( G \) = the soil heat flux density (MJ/m².day); \( T \) = the mean daily air temperature at 2 m height (°C); \( U_2 \) = the wind speed at 2 m height (m/sec); \( e_s \) = the saturation vapor pressure (kPa); \( e_a \) = the actual vapor pressure (kPa); \( e_s - e_a \) = the saturation vapor pressure deficit (kPa); \( \Delta \) = the slope vapor pressure curve (kPa/°C); and \( \gamma \) = the psychometric constant (kPa/°C).

ET0 was estimated using various empirical equations and compared with the FAO-56 PM equation. The models were compared using standard statistics and linear regression analysis [28]. Pearson’s correlation (R²), root mean squared error (RMSE), mean absolute error (MAE), maximum absolute error

Walailak J Sci & Tech 2015; 12(1) 99
(MAXE), volume error (VE), CORR, efficiency (EF) and agreement index (D) were computed using the equations described below;

$$R^2 = \left[ \frac{\sum_{i=1}^{N} (ET_{EQ} - \bar{ET}_{EQ})(ET_{FAO} - \bar{ET}_{FAO})}{\left( \sum_{i=1}^{N} (ET_{EQ} - \bar{ET}_{EQ})^2 \sum_{i=1}^{N} (ET_{FAO} - \bar{ET}_{FAO})^2 \right)^{\frac{1}{2}}} \right]^2$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (ET_{EQ} - ET_{FAO})^2}{N}}$$

$$\text{MAE} = \frac{1}{N} \sum_{i=1}^{N} |ET_{EQ} - ET_{FAO}|$$

$$\text{MAXE} = \text{MAX}(|ET_{EQ} - ET_{FAO}|)_{i=1}^n$$

$$\text{VE(\%)} = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{ET_{EQ} - ET_{FAO}}{ET_{EQ}} \right|$$

$$\text{CORR(\%)} = \frac{\text{COV}(ET_{EQ}, ET_{FAO})}{\sigma_{ET_{EQ}} \times \sigma_{ET_{FAO}}}$$

$$\text{EF} = \frac{\sum_{i=1}^{n} (ET_{EQ} - \bar{ET}_{EQ})^2 - \sum_{i=1}^{n} (ET_{EQ} - ET_{FAO})^2}{\sum_{i=1}^{n} (ET_{EQ} - \bar{ET}_{EQ})^2}$$

$$D = 1 - \frac{\sum_{i=1}^{n} (ET_{FAO} - ET_{EQ})^2}{\sum_{i=1}^{n} (ET_{FAO} - ET_{EQ} + |ET_{EQ} - ET_{EQ}|)^2}$$

In order to have a quantitative evaluation, the calibration parameters were defined using the following equation [29];

$$ET_{EQ} = A + B \cdot ET_{FAO}$$
where \( ET_{EQ} \) represents the ET\(_0\) values estimated using empirical methods. The calibration parameters A and B are determined by regression analysis using \( ET_{FAO} \) with the FAO-56 PM method as the reference. The best prediction model is the one with the smallest RMSE, MAE and VE, the highest coefficient of determination (\( R^2 \)), B value closest to zero, and A value closest to unity.

**Results and discussion**

The 21 year-monthly weather data were used to validate the performances of the commonly used ET\(_0\) estimation methods. Comparison of monthly ET\(_0\) values specifically for the FAO-56 PM, Blaney-Criddle, Hargreaves-samani, Jensen-Haise, Linacre, Rn-based radiation, Thornthwaite and Turc equations are presented in Figure 3.
Figure 3 Estimated ET₀ derived from different methods at Qom synoptic (1987 - 2007), in mm.d⁻¹ (a) FAO-56 PM; (b) Blaney-Criddle; (c) Hargreaves-Samani; (d) Jensen-Haise; (e) Linacre; (f) Rn-based radiation; (g) Thornthwaite; (h) Turc and, (i) Class A Pan measurements for years of 1993 - 2007, respectively.

It can be seen that Blaney-Criddle followed the same trend as that of the FAO-56 PM method. Seasonal variations in the ET₀ estimation reflect the differences in the variables applied in each method. Figure 4 shows a comparison of the annual ET₀ estimations.
Figure 4 Total annual ET₀ estimates given by the different methods at Qom synoptic (1987 - 2007), in mm.year⁻¹.

The annual sum of ET₀ estimations by Blaney-Criddle from 1840 mm yr⁻¹ in 1987 to 1980 mm yr⁻¹ in 2007, while 1670 mm yr⁻¹ in 1996 to 1894 mm yr⁻¹ in 2007 for the FAO-56 PM method, respectively. The Rn and Linacre methods have the lowest and highest values, respectively. The maximum annual sum of ET₀ estimations by Blaney-Criddle method and FAO-56 PM method is in 2005. The details of statistical comparison are shown in Table 3. Table 3 shows the performance of the models by comparison between the models’ predicted ET₀ and the FAO-56 PM model. According to all the statistics, the best results are obtained by Blaney-Criddle and Turc, while weakest statistics are obtained by the Linacre and Jensen-Haise methods.
Table 3 Statistical values of the comparison between $ET_0$ calculated by different empirical methods with the FAO-56 PM method.

<table>
<thead>
<tr>
<th>Method</th>
<th>$R^2$</th>
<th>RMSE mm.d$^{-1}$</th>
<th>MAE mm.d$^{-1}$</th>
<th>MAXE mm.d$^{-1}$</th>
<th>VE %</th>
<th>CORR %</th>
<th>EF</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blaney-Criddle</td>
<td>0.974</td>
<td>0.690</td>
<td>0.545</td>
<td>2.303</td>
<td>14.20</td>
<td>98.31</td>
<td>0.948</td>
<td>0.988</td>
</tr>
<tr>
<td>Hargreaves Samani</td>
<td>0.967</td>
<td>0.865</td>
<td>0.621</td>
<td>2.989</td>
<td>14.24</td>
<td>97.93</td>
<td>0.919</td>
<td>0.976</td>
</tr>
<tr>
<td>Jensen-Haise</td>
<td>0.965</td>
<td>3.575</td>
<td>2.647</td>
<td>8.750</td>
<td>47.57</td>
<td>97.84</td>
<td>-0.389</td>
<td>0.842</td>
</tr>
<tr>
<td>Linacre</td>
<td>0.926</td>
<td>4.317</td>
<td>3.894</td>
<td>8.243</td>
<td>102.70</td>
<td>95.85</td>
<td>-1.030</td>
<td>0.749</td>
</tr>
<tr>
<td>Rn-based radiation</td>
<td>0.971</td>
<td>1.798</td>
<td>1.347</td>
<td>4.852</td>
<td>26.36</td>
<td>98.12</td>
<td>0.649</td>
<td>0.865</td>
</tr>
<tr>
<td>Thorthwaite</td>
<td>0.933</td>
<td>2.235</td>
<td>1.836</td>
<td>6.832</td>
<td>49.10</td>
<td>95.12</td>
<td>0.457</td>
<td>0.919</td>
</tr>
<tr>
<td>Turc</td>
<td>0.965</td>
<td>0.721</td>
<td>0.564</td>
<td>2.403</td>
<td>14.20</td>
<td>97.83</td>
<td>0.944</td>
<td>0.985</td>
</tr>
</tbody>
</table>

The resulting regression equations together with the cross-correlation ($R^2$) are presented in Figure 5. It displays the scatter plot between $ET_0$ estimates of the methods with FAO-56 PM at the Qom station.
This figure reveals a very good agreement (slope = 1.08 and $R^2 = 0.974$) between the Blaney-Criddle and FAO-56 PM. The high correlation of $ET_0$ between the Blaney-Criddle with FAO56-PM methods clearly reflects the importance of the temperature and solar radiation.

Blaney-Criddle is considered a temperature method and using few weather inputs is suitable to study areas where the complete data required for $ET_0$ estimation is complex [30,31] and in different locations of the world with different climates [32-39]. This fact is also supported by many studies which reveal that the Blaney-Criddle method is nearly as accurate as the FAO56-PM method in estimating $ET_0$. For arid conditions of Iran, Mostafazadeh-Fard et al. [40] compared 9 different methodologies with lysimeter data and observed that the Blaney-Criddle and Turc methods showed very close agreement with the lysimeter data. Also, Blaney-Criddle is best method in Isfahan province [41], Mazandaran province [42], South Balochestan province [43] and in the center of Iran-Ardestan city.

The importance of temperature and its effect on evaporation in this region and the process parameters temperature and evaporation, which together have a lot of similarity with respect to time, a strong relationship between these 2 parameters is determined. The linear regression relationship was produced between Class A pan evaporation (1993 - 2007) and the FAO-56 PM method (1987 - 2007) with mean air temperature data (Figure 6).
The advantage of this method is that only climatic parameters used is temperature and in all weather stations is available. Often, the meteorological data are missing or incomplete due to instrument failure, contamination by measurement errors. For this reason, the pan Evaporation (Ep) has become a widespread method due to its simplicity, low cost, ease of data interpretation and application and suitability for locations with limited availability of meteorological data [44-46]. Commonly, $ET_0$ is estimated as the product of the Ep data and a pan coefficient ($K_p$).

$$ET_{PM} = K_p \times Ep$$  \hspace{1cm} (11)

Based on a literature review, the values of $K_p$ cover a range between 0.3 and 1.1, and are proportional to relative humidity and inverse proportional to wind speed [47,48]. Linear regression analysis was performed to examine the relationship between the mean monthly values using the FAO-56 PM method and mean monthly values of Ep in Qom synoptic (1993 - 2007). Figure 7 shows a plot of $ET_0$ versus Ep for this station. The value of $K_p$ derived for the total period, was 0.583 ($R^2 = 0.85$).
Conclusions

In the presented research, 21 years of meteorological data derived from the Qom station located in Qom province, in the north and center of Iran was applied as input parameters for comparing different methods to estimate ET₀ under the existing arid and warm climatic conditions in Qom. The FAO-56 PM method as recommended by FAO was taken as a standard in evaluating the different methods. By using statistical indicators, the best method to estimate ET₀ in Qom province is Blaney-Criddle. The Blaney-Criddle method underestimates FAO-56 PM in all months. Because the maximum and minimum temperature difference is very high in this station, these deviations are expected. It could be recommended to use the Blaney-Criddle method in arid and semi-arid climates. Due to the similarity of many other cities to Qom city, this study may serve as a good pattern for resolution of ET₀. The linear regression between the FAO-56 PM method and Class A Pan evaporation with mean air temperature are ET₀ = 0.275×T (R² = 0.90) and ET₀ = 0.471×T (R² = 0.89), respectively. Additionally, this study showed that, when measurements of meteorological parameters needed for estimating ET₀ (which are not always available especially in developing countries) are lacking, the mean air temperature provides an alternative and effective solution to estimate ET₀. In this area, as the evaporative demand increases (i.e., with lower humidity and lower wind speed), the difference between Ep and ET₀ increases and the Kp value decreases to nearly 0.58. However, it should be noted that this study was based on the analysis of a limited data set.

References


Performance of Some Evapotranspiration Equations at Arid Region

Mohammad Mehdi HEYDARI et al.

http://wjst.wu.ac.th