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Abstract The Blaney-Criddle (BC) temperature-based equation is used in areas where the complete weather data to estimate reference evapotranspiration (ET₀) by the Penman-Monteith FAO-56 (PMF-56) standard model is complex. In this study, the BC equation was first tested and calibrated against the ET₀ values computed by the PMF-56 method using data from 17 weather stations in arid regions of Iran. Then, geographical information systems (GIS)-based spatially-distributed maps of ET₀ were prepared by means of geographic/topographic factors derived from a digital elevation model (DEM) for all months, separately. The results indicate that the original BC equation overestimated PMF-56 ET₀ by 4% at the study sites. The BC equation produced closer ET₀ estimates to the PMF-56 method after it was calibrated. The error rate of <3% for the spatial modelling approach suggests that the developed ET₀ maps are reliable.

Key words evapotranspiration; mapping; temperature-based model; calibration; GIS

INTRODUCTION

In arid and semi-arid regions where water resources are limited and crops are constantly under the influence of low rainfall and high temperature, reliable estimation of optimal water requirement for the main national agricultural products is very vital. Furthermore, having knowledge on the level of evapotranspiration (ET) in order to determine agricultural water use is as important as managing the water resources efficiently (Ahmadi and Fooladmand 2008). ET is one of the significant components for optimization of crop production, development of the best management practices to minimize groundwater and...
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The ET rate from an extensive surface of green cover, 0.08–0.15 m in height, actively growing, completely shading the ground and not short of water is called the reference evapotranspiration (ET0) (Temesgen et al. 2005). Reference evapotranspiration can be either estimated with lysimeter measurements or a water balance approach, or estimated from climatological data. As lysimeter field measurements are rarely available, ET0 is generally estimated from theoretical predictive equations requiring climatic data (Chauhan and Shrivastava 2009). Different methods, such as temperature-based (e.g. Thornthwaite 1948, Blaney and Criddle 1950, Hargreaves and Samani 1985), radiation-based (e.g. Turc 1961, Priestley and Taylor 1972), or combined methods (e.g. Penman 1948), were developed to indirectly estimate ET0 from various meteorological parameters measured at weather stations. However, this causes confusion as to which method to select for ET0 estimation. Therefore, the Food and Agriculture Organization of the United Nations proposed the Penman-Monteith model in its Irrigation and Drainage Paper No. 56 (referred to hereafter as PMF-56) as the standard method for determining ET0 from complete meteorological data (Chavez et al. 2008). The model has been accepted globally as a good ET0 estimator in various climates when compared with other methods (e.g. Allen 1996, Donatelli et al. 2006, Cai et al. 2007, Ali and Shui 2009, Xu et al. 2012). Nevertheless, the main shortcoming of the PMF-56 method is that it requires data for a large number of climatic parameters that are not always available for many locations in developing countries (Wang et al. 2007, Aytek 2009). Hence, ET0 is often estimated by means of simple empirical equations that require fewer climatic variables in these regions. Several authors showed that existing empirical methods require local calibration before they can be used for the estimation of ET0 because of their widely varying performances.

Xu and Singh (2002) evaluated the Hargreaves, Blaney-Criddle, Makkink, Priestley-Taylor and Rohwer equations based on the PMF-56 model using daily meteorological data from Changins station in Switzerland. They found that the original constant values involved in each empirical equation worked quite well for the study region, except for the constant value of the Priestley-Taylor equation. Tabari et al. (2011) tested 31 ET0 methods under humid conditions in Iran. 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 ET0. The Turc and Hargreaves models revealed better performances than the Makkink and Priestley-Taylor models in various climates of Iran (Tabari 2010). Tabari and Hosseinzadeh Talae (2011) calibrated the Hargreaves and Priestley-Taylor equations on the basis of the PMF-56 method in the arid and cold climates of Iran using data from 12 stations for the period 1994–2005. Razzaghi and Sepaskhah (2012) calibrated and validated four methods for estimation of daily to mean monthly ET0 by weighing lysimeter data for 2005/006 and 2004/05, in a semi-arid region.

The Blaney-Criddle (BC) temperature-based equation is one of the earliest methods for estimating ET0. The BC equation is still used for ET0 estimation in many areas in developing countries, because of the advantage of its simplicity in requiring only air temperature data. The BC equation has the added benefit that air temperatures can usually be interpolated reasonably accurately using lapse rate adjustments to areas where measurements are not available. Interpolating air temperature data results in spatially-distributed values of BC ET0 that can be used to produce ET0 maps (Temesgen et al. 2005).

Many hydrological, agricultural and environmental models require a spatially-distributed measure of ET0 (McVicar et al. 2007). In addition, the spatial distribution of ET0 provides valuable information and data for regional hydrological studies and water resources planning and management (Xu et al. 2006). However, climatic variables are usually characterized by strong spatial variability, which is caused by a complicated interaction between topographical features and the nature of the climate variable itself. Consequently, for accurate estimation of the spatial distribution of ET0, a very dense network of weather stations which would record the full weather data, should be established. However, the existing weather station network is very sparse, especially in developing countries, due to installation and operational costs. In addition, vandalism or failure of the observer to make the necessary visit to the weather station may result in an even lower sampling density. Thus, the development of sound techniques that could generate reliable spatial distribution of ET0 at unrecorded locations from point data from records at surrounding sites should be addressed (Mardikis et al. 2005).

To solve this problem, various statistical methods have been developed to predict the spatial distribution of climatic variables in areas without weather stations.
The geographical information system (GIS) has provided an interesting solution for this problem since it allows one to combine a digital elevation model (DEM), numerical modelling and cartographic tools in the same environment (Pons and Ninyerola 2008). In spite of the numerous studies carried out to model climatic variables such as precipitation, temperature and solar radiation, few studies have addressed the task of ET₀ modelling using GIS. Chuanyan et al. (2004) evaluated the performances of the Behnk-Maxey, Priestley-Taylor and Hargreaves methods for estimation of potential evapotranspiration (PET) in the Zuli River basin, China. They found that the Hargreaves model was the best way to estimate PET in the study area. Then, they spatially estimated PET with the Hargreaves model using the spatially-distributed physical parameters within the GIS platform. Chuanyan et al. (2005) examined seven models commonly used to estimate ET₀ to choose the appropriate model for estimating the areal distribution of ET₀ through GIS in the middle Heihe River basin of the arid northwestern part of China. The results indicated that the FAO-Penman equation was the best model to estimate ET₀, and the spatially-modelled ET₀ values (R² = 0.88) were in agreement with the corresponding in situ data. Vicente-Serrano et al. (2007) compared different procedures for mapping the Hargreaves model ET₀ by means of regression-based techniques and GIS in the northernmost semi-arid region of Europe, the Ebro Valley. They calculated the extra-terrestrial radiation (Rₙ) parameter using two approaches: (a) determination of Rₙ as a function of latitude; and (b) estimation of the parameter using a digital terrain model (DTM) and GIS modelling. The results demonstrated that calculation of Rₙ from a DTM and GIS modelling provided a more realistic spatial distribution of ET₀ than that derived by only considering latitude. Sabziparvar and Tabari (2010) tested the Makkink, Priestley-Taylor and Hargreaves models in estimating ET₀ versus the PMF-56 method in the northeast of Iran, and selected the Hargreaves model as the best one. Afterwards, they estimated the regional distribution of monthly ET₀ by applying the spatially-modelled climatic variables as the inputs of the Hargreaves model.

The main purposes of the present study were: (a) to evaluate the BC equation against the PMF-56 model at 17 weather stations in the arid regions of Iran, (b) to calibrate the BC equation based on the PMF-56 model as the reference standard for every month at each station, and (c) to estimate the spatial distribution of the ET₀ computed by the calibrated BC equation using GIS.

MATERIALS AND METHODS

Study area and data

The study was carried out in the southeast of Iran, which is the most arid part of the country with a mean annual precipitation of less than 120 mm, and an obvious rise in humidity towards the coastal regions. Mean air temperature is 20°C and may increase above 40°C on the warmest days. To estimate ET₀, climatic data recorded at 17 synoptic stations managed by the Islamic Republic of Iran Meteorological Office were used (Fig. 1 and Table 1). The stations were equipped with mercury and alcohol thermometers, a cup anemometer, a Campbell sunshine recorder, a wet-bulb thermometer and some other meteorological instruments. All selected stations had good quality data records from 1994 to 2005 for estimating ET₀, including maximum, minimum and mean air temperatures, actual vapour pressure, sunshine duration, relative humidity and wind speed. Since all of the selected stations are located in non-reference weather sites, the temperature data were corrected with the procedure proposed by Allen et al. (1998).

The Penman-Monteith FAO-56 model

The PMF-56 method is considered as a standard and the most precise method to estimate ET₀. It is expressed as (Allen et al. 1998):

\[
ET_{0PMF-56} = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)}
\]

(1)

where \(ET_{0PMF-56}\) is the reference evapotranspiration (mm d⁻¹) calculated by the PMF-56 model; \(R_n\) is the net radiation (MJ m⁻² d⁻¹); \(G\) is the soil heat flux (MJ m⁻² d⁻¹); \(\gamma\) is the psychrometric constant (kPa °C⁻¹); \(e_s\) is the saturation vapour pressure (kPa); \(e_a\) is the actual vapour pressure (kPa); \(\Delta\) is the slope of the saturation vapour pressure–temperature curve (kPa °C⁻¹); \(T_a\) is the average air temperature (°C); and \(U_2\) is the mean wind speed at 2 m (m s⁻¹) (Allen et al. 1998). In the absence of actual \(R_n\) data, \(R_n\) is often estimated from sunshine data using the Angstrom equation:

\[
R_s = \left( a_s + b_s \frac{n}{N} \right) R_a
\]

(2)
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Fig. 1 Location and topography of the study area.
The Blaney-Criddle model

The usual form of the BC equation converted to metric units is written as:

\[
ET_{0BC} = kp \left(0.46 T_a + 8.13\right)
\]  

where \(ET_{0BC}\) is the reference evapotranspiration (mm) computed by the BC equation, for the period in which \(p\) is expressed; \(T_a\) is the mean air temperature (°C); \(p\) is the percentage of total daytime hours for the period (daily or monthly) out of total daytime hours of the year (365 × 12); and \(k\) is the monthly consumptive use coefficient, depending on vegetation type, location and season and for the growing season (May–October) (Xu and Singh 2002).

The adjusted coefficient of the BC equation \(k_{\text{adj}}\) was calculated for each month at all the stations using the following formula:

\[
k_{\text{adj}} = \frac{k}{ET_{0BC}/ET_{0PMF-56}}
\]

where \(k\) is the original coefficient of the BC equation. According to the recommendation of Blaney and Criddle (1950), values of \(k = 0.85\) and \(k = 0.45\) were used for the growing season (April–September) and the non-growing season (October–March), respectively.

### Assessment of model performance

Several statistical measures could be used for comparison between the \(ET_0\) values calculated by the BC equation and those obtained by the PMF-56 method. For each location, the following parameters were calculated: root mean square error (RMSE), percentage error of estimate (PE), mean bias error (MBE) and coefficient of determination \(R^2\). The RMSE, MBE
and PE parameters provide information on the performance of an equation and their low values are desired. Ideally a zero value should be obtained. In addition, a positive MBE value gives the average amount of overestimation in the estimated values and vice versa. The R² was also used to test the “goodness of fit” between the ET₀ values calculated by the BC and PMF-56 equations. The RMSE, PE, MBE and R² are defined as:

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - P_i)^2}
\]

\[
\text{PE} = \frac{\bar{O} - \bar{P}}{\bar{O}} \times 100\% \quad (7)
\]

\[
\text{MBE} = \frac{1}{n} \sum_{i=1}^{n} (O_i - P_i) \quad (8)
\]

\[
\text{R}^2 = \frac{\left[\frac{1}{n} \sum_{i=1}^{n} (P_i - \bar{P})(O_i - \bar{O})\right]^2}{\frac{1}{n} \sum_{i=1}^{n} (P_i - \bar{P})^2 \frac{1}{n} \sum_{i=1}^{n} (O_i - \bar{O})^2} \quad (9)
\]

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

### RESULTS AND DISCUSSION

**Evaluation of the BC equation**

The statistical analyses for each station between the estimated ET₀ by the PMF-56 and BC equations are presented in Table 2. As shown, the BC equation significantly overestimated ET₀ with respect to PMF-56 ET₀ at 14 stations, and at three stations it underestimated ET₀. The underestimations of the BC equation were observed at Zabol, Rafsanjan and Zahak stations where the wind speed is above 4 m s⁻¹. Wang et al. (2007) reported that ET₀ is sensitive to wind and the performance of the estimation method may also be influenced. In general, the highest overestimations of the BC equation were found at Miandeh Jiroft and Bam stations; the lowest overestimations were obtained at Baft and Kerman stations. Overestimations of the BC equation with respect to the PMF-56 method were also reported in the arid climate of California, USA (George et al. 2002), in semi-arid climates of Spain (Gavilan 2002, López-Urrea et al. 2006) and in the dry tropical climate of Burkina Faso (Wang et al. 2007).

Furthermore, comparison between the ET₀ values estimated using the BC and PMF-56 models indicates that the R² values ranged from 0.869 to 0.982 with a mean of 0.955; however, all coefficients of determination were high. Considering all stations, the PE values ranged from 0.234 to 18.995%, with a mean of 8.13% (Table 2). The RMSE values ranged from 0.331 to 2.684 mm d⁻¹, with an average value of 0.983 mm d⁻¹. The BC model had a RMSE of less than 1.0 mm d⁻¹ at the majority of the stations (12 out of 17 stations), suggesting that the model provides fairly good approximations of the PMF-56 method. However, even an error of only 1.0 mm d⁻¹ of evapotranspiration on a 1 ha field amounts to approximately 10 000 L of water per day, or over 3.65 × 10⁶ L per year. Hence, local correction would be required for the BC equation, especially at windy locations in the arid region.

### Calibration of the BC equation

In order to improve the accuracy of the BC equation, it was calibrated against the PMF-56 model for each month. The adjusted coefficients of the BC equation for every month at each station are presented in Table 3. When two periods were considered, i.e. a growing season from April to September and a non-growing season from October to March, no further improvement could be obtained by calibration data.
Table 3 Adjusted coefficients of the BC equation for each month at the stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<td>0.51</td>
<td>0.72</td>
<td>0.70</td>
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<td>1.18</td>
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<td>0.75</td>
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<td>0.54</td>
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<td>0.72</td>
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<td>0.44</td>
<td>0.51</td>
<td>0.62</td>
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<td>0.78</td>
<td>0.71</td>
<td>0.86</td>
<td>0.80</td>
<td>0.81</td>
<td>0.84</td>
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<td>0.68</td>
<td>0.52</td>
<td>0.58</td>
<td>0.70</td>
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for the BC equation, and the values of $k = 0.85$ and $k = 0.45$ for the two respective seasons could be used for the region. However, it is necessary to define October, March, April and September as transition periods. Similar to Xu and Singh (2002), a value of $k = (0.85 + 0.45)/2 = 0.65$ was used for the transition periods. Based on the results presented in Table 3, the highest $k_{adj}$ values averaged over all the stations were observed in August (0.83) and July (0.82). In contrast, the lowest $k_{adj}$ values were found in November (0.43) and December (0.47). The $k_{adj}$ values in the growing season (May, June, July and August) were entirely lower than the original coefficient (0.85). The average $k_{adj}$ value of 0.81 was obtained for the growing season, which is about 4.7% lower than the original value. In addition, the $k_{adj}$ values for the non-growing season months of December, January and February were higher than the original coefficient of 0.45. On average, the $k_{adj}$ value of 0.49 was obtained in the non-growing season, which is about 9% higher than the original value. The $k_{adj}$ values in the transition months were lower than the used coefficient (0.65), except for March. The adjustment of the BC equation led to the decrease of the used coefficient (0.65) for the transition period at the rate of 1.92%. Overall, the largest and smallest differences between the original coefficient and $k_{adj}$ were observed in January and April at the rates of +15.5% and −1.5%, respectively.

On average, Zabol, Zahak and Rafsanjan stations, with the highest wind speeds, showed the greatest $k_{adj}$ values, whereas the lowest $k_{adj}$ values were obtained at Miandeh Jiroft, Bam and Kahnouj stations.

Figure 2 shows the comparisons between the ET$_0$ values calculated by the PMF-56 method against the values computed by the BC and adjusted BC models at Bam and Saravan stations. As shown, a great improvement was achieved using the adjusted BC equation. The statistical analysis of the ET$_0$ estimates using the BC and adjusted BC equations against the calculated ones by the PMF-56 model in the study region is given in Table 4. As expected, the
calibration resulted in decreasing the RMSE values from 0.983 to 0.092 mm d\(^{-1}\), the MBE values from –0.150 to –0.060 mm d\(^{-1}\) and the PE values from 8.126% to 0.951%, indicating that the BC equation produced \(\text{ET}_0\) estimates closer to the PMF-56 model after it was calibrated at the study stations. The monthly PE values obtained by the BC and adjusted BC equations averaged over all the stations are presented in Fig. 3.

The biggest decreases in the PE values were found in November. In general, the biggest decreases in the PE values were observed in the transition period (i.e. March, April, September and November). This shows that the accuracy of the BC equation can be significantly improved by defining March, April, September and November as transition period (i.e. March, April, September and November). As shown in Table 5, the coefficients of determination \(R^2\) values in the non-growing period (October–March) were better than those in the growing period (April–September). In fact, the average \(R^2\) values in the non-growing period (0.85) was 28% higher than that in the growing period (0.66).

### Spatial distribution of \(\text{ET}_0\)

#### Spatial modelling of air temperature

For calculation of \(\text{ET}_0\), the BC model requires only mean air temperature \((T_{\text{mean}})\). For modelling \(T_{\text{mean}}\), multivariate linear regression (MLR) relationships were initially established between the observed \(T_{\text{mean}}\) at the 17 stations in the study area and the associated geographical/topographic factors (i.e. altitude and latitude) that were obtained by GIS-processing from DEM data. In MLR, geographical/topographic factors that control the spatial distribution of climate were used as independent variables and \(T_{\text{mean}}\) as the dependent one. Then, \(T_{\text{mean}}\) was spatially modelled based on MLR relationships for each month. The main advantage of this technique is that maps are compiled not only from information from various weather stations, but also from auxiliary information that describes geographic and topographic variables; this improves the accuracy and spatial detail of the resulting maps (Vicente-Serrano et al. 2007).

The multivariate linear regression relationship between \(T_{\text{mean}}\) and the geographical/topographic factors is given as:

\[
T_{\text{mean}} = aH + bY + c
\]

where \(H\) is the altitude (m); \(Y\) is the latitude (UTM); and \(a\), \(b\) and \(c\) are regression coefficients. The regression coefficients were obtained based on the data from 17 weather stations (Table 5) and the spatial distribution of the \(T_{\text{mean}}\) was generated for each month. As shown in Table 5, the coefficients of determination are greater than 0.60 for all months, and were statistically significant at the 1% confidence level, indicating that the spatial change of \(T_{\text{mean}}\) is influenced mainly by the geographical/topographic factors. The \(R^2\) values in the non-growing period (October–March) were better than those in the growing period (April–September). In fact, the average \(R^2\) values obtained between the geographical/topographic factors and \(T_{\text{mean}}\) in the non-growing period (0.85) was 28% higher than that in the growing period (0.66).

#### Statistical analysis for comparison between the \(\text{ET}_0\) values estimated using the PMF-56, BC and adjusted BC equations.

<table>
<thead>
<tr>
<th>Equation</th>
<th>RMSE (mm d(^{-1}))</th>
<th>MBE (mm d(^{-1}))</th>
<th>PE (%)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>0.983</td>
<td>−0.150</td>
<td>8.126</td>
<td>0.955</td>
</tr>
<tr>
<td>Adjusted BC</td>
<td>0.092</td>
<td>−0.060</td>
<td>0.951</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Table 4

![Fig. 3](image-url) The PE values obtained by the BC and adjusted BC equations in the study area.

### Table 5

<table>
<thead>
<tr>
<th>Month</th>
<th>(a)</th>
<th>(b)</th>
<th>(c)</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>−0.00449</td>
<td>−0.000012</td>
<td>52.0</td>
<td>0.749</td>
</tr>
<tr>
<td>Feb</td>
<td>−0.00487</td>
<td>−0.000013</td>
<td>58.9</td>
<td>0.860</td>
</tr>
<tr>
<td>Mar</td>
<td>−0.00533</td>
<td>−0.000010</td>
<td>54.6</td>
<td>0.836</td>
</tr>
<tr>
<td>Apr</td>
<td>−0.00570</td>
<td>−0.000007</td>
<td>48.8</td>
<td>0.788</td>
</tr>
<tr>
<td>May</td>
<td>−0.00549</td>
<td>−0.000006</td>
<td>49.8</td>
<td>0.688</td>
</tr>
<tr>
<td>Jun</td>
<td>−0.00502</td>
<td>−0.000002</td>
<td>43.1</td>
<td>0.624</td>
</tr>
<tr>
<td>Jul</td>
<td>−0.00467</td>
<td>0.000002</td>
<td>30.4</td>
<td>0.611</td>
</tr>
<tr>
<td>Aug</td>
<td>−0.00471</td>
<td>0.000002</td>
<td>29.6</td>
<td>0.607</td>
</tr>
<tr>
<td>Sep</td>
<td>−0.00474</td>
<td>−0.000003</td>
<td>41.0</td>
<td>0.652</td>
</tr>
<tr>
<td>Oct</td>
<td>−0.00505</td>
<td>−0.000008</td>
<td>53.4</td>
<td>0.830</td>
</tr>
<tr>
<td>Nov</td>
<td>−0.00500</td>
<td>−0.000012</td>
<td>59.3</td>
<td>0.903</td>
</tr>
<tr>
<td>Dec</td>
<td>−0.00433</td>
<td>−0.000015</td>
<td>64.3</td>
<td>0.923</td>
</tr>
</tbody>
</table>

Table 5

Spatial modelling of reference evapotranspiration using adjusted Blaney-Criddle equation in an arid environment
relationship between the geographical/topographic parameters and $T_{\text{mean}}$ in the non-growing period is stronger than that in the growing period. Vicente-Serrano et al. (2007) reported slightly higher $R^2$ values for maximum and minimum air temperatures in summer than winter. Figure 4 illustrates air temperature maps for July and December, representative of the growing and non-growing periods, respectively. Both maps in the figure show strong gradients, with coldest temperatures corresponding to the south of the study region and lower values obtained towards the northwest of the region, coinciding with the highest elevation areas.

Spatial modelling of ET$_0$ Mapping to obtain a continuous surface is very interesting for integrating and analysing spatial information coming from irregularly distributed point data (weather stations). The ET$_0$ maps were generated using $T_{\text{mean}}$ as input of the calibrated BC equations for each month of the growing and non-growing periods. Figures 5 and 6 illustrate ET$_0$ maps for the growing and non-growing periods, respectively. A strong gradient exists in all the maps, with higher ET$_0$ values corresponding to the south of the study area due to the higher air temperature and lower ET$_0$ values found in the northwest.

The maps provide significant detail of local differences between valleys and mountains. The ET$_0$ maps also show that the ET$_0$ values have temporal variations throughout the year. As shown, the maximum and minimum ET$_0$ were encountered in July and January, respectively.

The ET$_0$ maps must be assessed by statistics that indicate the degree of concordance between the modelled and observed ET$_0$. To evaluate the model results (Figs 6 and 7), the spatially-modelled ET$_0$ values were compared with those estimated by the calibrated BC equation during the growing period at the 17 weather stations (Fig. 7). The coefficient of determination ($R^2 = 0.97$) suggests that the ET$_0$ maps (Figs 5 and 6) are reliable. Furthermore, the PE values obtained by the modelling approach for each month are shown in Fig. 8. As shown, the highest PE values of 8.75% and 6.01% were found in March and February, respectively, while June gave a PE value of <1%. The average PE value obtained in the non-growing season (2.11%) was about 44% higher than that (3.75%) in the growing season. The high coefficient of determination and low errors indicate that the developed ET$_0$ maps (Figs 5 and 6) have a desirable level of accuracy and can be applied for hydrological and agricultural management practices in the region.

CONCLUSIONS

The Blaney-Criddle equation was evaluated and calibrated to estimate reference evapotranspiration using weather data from 17 arid stations in the southeast of Iran. The Penman-Monteith FAO 56 method was assumed as the standard for comparing ET$_0$ estimates by the BC equation for all locations. Afterwards, GIS-based spatially distributed maps of ET$_0$ were generated using geographic/topographic factors derived from a DEM for all months, separately. The results showed that the BC equation had a tendency to over-predict PMF-56 ET$_0$ at the majority of the stations in the arid environment. The calibration of the BC equation resulted in decreasing the RMSE values from 0.983 to 0.092 mm/d, the MBE values from
Spatial modelling of reference evapotranspiration using adjusted Blaney-Criddle equation in an arid environment

Fig. 5 Reference evapotranspiration maps of the growing months (April–September) obtained from MLR models via algebraic calculations in GIS using air temperature maps.

−0.150 to −0.060 mm/d and the PE values from 8.126 to 0.951%, indicating that the performance of the BC equation significantly improved after it was calibrated at the study stations.

Considering the limitations associated with the availability and reliability of the climatic data, the BC equation calibrated in this study is suggested as a practical method for estimating ET₀ in arid regions where the data input for applying the PMF-56 method are not available. Furthermore, the spatial modelling approach used in this study provides a huge opportunity for solving the problem of spatial data gaps for mapping ET₀ in hydrological and agricultural management practices. It will also increase the accuracy of ET₀ values calculated at unrecorded locations, since air temperature can be spatially modelled more accurately than any other climatic variable. Further research is recommended for mapping ET₀ by the modelling approach in other climates and locations.
Fig. 6 Reference evapotranspiration maps of the non-growing months (October–March) obtained from MLR models via algebraic calculations in GIS using air temperature maps.

Fig. 7 Linear regression between the areal mean monthly ET0 values calculated by the calibrated BC equation and those from the resultant GIS maps.
Acknowledgements  The writers acknowledge the Islamic Republic of Iran Meteorological Office (IRIMO) for providing the climatic data.

REFERENCES


Fig. 8 The PE values obtained by the modelling approach for each month.

