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Presenting an empirical model for determining the sugar beet evapotranspiration by GDD parameter (Case study: Torbat-Jam, Iran)

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Abstract

So far, various methods have been presented for determining reference crop evapotranspiration in different parts of the world. The most popular and prestigious of them are probably the combined methods of Penman family, modified Blany-Criddle, Hargreaves - Samani and thornthwaite. Due to lack of lysimeter data in many parts of Iran, presenting an equation according to the regional condition with high precision is very paramount. The purpose of this paper is to present a method with higher precision for determining the evapotranspiration of sugar beet by using the meteorology and GDD (Growing Degree Day) parameters in Torbat_Jam, Iran. Determined methods were evaluated with FAO- Penman- Monteith method as a standard model**.** RMSE, R^2 and Nash-Sutcliffe, and NS indexes were used for comparing fitness indexes. Results showed that equation 4 is appropriate for calculating crop water requirements, also R^2, RMSE, and Nash-Sutcliffe coefficient were 0.683, 1.117 and 0.99, for equation 4, respectively.

Keywords: *Growing degree day, Lysimeter, Reference crop, Meteorology.*

1. Introduction

Evapotranspiration is one the most important parameters for determining crops water requirements and designing irrigation systems. Determining the accurate amount of water that is used for evapotranspiration is one of the most paramount elements for planning and achieving more yield, which due to water shortages for agriculture in Iran, accurate determination of crops water requirements is very useful for preserving water usage. The amount of evapotranspiration can be determined by multiplying the specific crop coefficient and potential evapotranspiration. Regarding water critics, which will become an important issue during the next decades, planning with higher precision for optimum usage of available water resources could be very significant, especially in the agriculture section, which is attributed with a great amount of water consumption. In order to achieve this aim, the first step is to determine the amount of water requirements of crops and garden plants (Mohseni et al., 2013). Sugar beet is one of the most important sources for producing sugar in the world (Rahimian et al., 2000). Thus, investigation and planning to increase the production of this product is very essential regarding self-sufficiency of the country and preventing the import of sugar from the country. Necessary studies must be made for determining crops water requirements. However, the main purpose of irrigation is supplying water requirements of the plant (evapotranspiration), whereas, little attention has been paid to determining the water requirements of crop in irrigation plans which has caused adverse proportion between cultivated land and water, in other words the project is designed at a higher or lower level than the adequate amount, which results in wasted investments. If a little amount of cost is allocated for determining plants water requirement before the implementation and during the designing step, the mentioned problems will not occur. Reasons for the existence of errors in determining plant water demands are lack of adequate knowledge of designers in agronomical problems and plant physiological properties in relation to water consumption and applying inappropriate methods for determining plants water requirements (Shahabi far et al., 2004). Sugar beet water requirement mainly depends on meteorological condition, irrigation management, and the length of growth period along with density and amount of consumed nitrogen (Koocheki et al., 1993). Due to the long growth period, sugar beet is counted amongst plants with high consumption such that the amount of its water requirement was measured to be 883 and 762.8 mm during the growth period in Karaj and Mashhad, respectively (Ghalebi, 2000, Rahimian et al., 2000).

Reference crop evapotranspiration is defined as the amount of evapotranspiration from the surface completely covered with grass, with 8 to 15 cm height, when there is no water crisis. Evapotranspiration is a zonal (not local) phenomenon and according to local changes of the effective factors in evaporation, such as evaporated surface and effective environmental factors in measuring the amount of the evaporation or evapotranspiration, distributional equation should be done (Allen et al., 2002). In order to calculate the amount of evapotranspiration of various plants such as maize and sugar beet, some models with meteorological-based parameters can be used (Jensen et al, 1990). These models measure the amount of evapotranspiration and if this amount is multiplied by the crop coefficient, the amount of the plants' evapotranspiration or ET_c can be calculated (write et al., 1982).

Approximating K_c is a complex process considering the actual evapotranspiration of the crops is done by management of aquatic communities (Air mark et al., 2013). Growth and development of the crops usually depends on operation time. Although this approach can be inadequate, considering that the temperature varies from one year to the other. Due to global changes in climate, usage of the Growing degree days (GDD) concept is extended to include the time and temperature information that the plant experiences during the growing period. The amount of water required for one product can be calculated by multiplying the reference evapotranspiration and the crop coefficient and this amount plays a paramount role in the hydrological rotation management of farming lands (Sou et al., 2013). Estimating the amount of transpiration is essential for water level, agricultural water, water resources, and flow forecasting studies and planning for groundwater sources, which plays an important role in agricultural and water resources management (Samaei et al., 2013). Achieving various equations for estimating evapotranspiration, requires abundant information and adequate experience regarding the correct usage of various equations, which makes it difficult to select the most appropriate method among the mentioned methods. Methods of evapotranspiration estimation have been studied by many researchers (Morton et al., 1994). Sentnelhas et al (2010) carried out a study in order to check the efficiency the evapotranspiration estimation using four methods: FAO- Penman Monteith, Priestley–Taylor, Hargreaves, and Thornthwaite. Results showed that if there are related data to the wind speed, net radiation and vapor pressure deficit, FAO- Penman Monteith has the best efficiency such that the amount of RMSE is 0.53 mm per day and if there are related data to the wind speed and vapor pressure deficit, or if there exist data related to temperature, Priestley–Taylor and modified Thornthwaite has the best efficiency with the RMSE amounts of 0.4 and 0.74 mm per day, respectively. One way to achieve a stable agriculture is evapotranspiration management and this management can be done on a zonal scale and under appropriate circumstances (Kaviani et al., 2013). Most studies suggested combinational methods especially Penman Monteith method in expanded climate domains (Gavilan et al., 2007). Considering different conducted studies and the issue of water crisis and the necessity of exact estimation of the ET0 amount, the aim of this study is to present a new equation for water requirements of sugar beet and a more precise estimation in Torbate-Jam zone (Iran). The GDD parameter was used in order to determine equations with more precision, as the daily amount of sugar beet evapotranspiration can be determined by equations that in which GDD parameter is used and results were compared with the evapotranspiration amount determined by FAO-Penman- Monteith and daily data were used for evapotranspiration.

2. Materials and Methods

This study was carried out in Torbate-Jam synoptic stations (35° 15’ N, 60° 35’ E) at a hight of 950.4 meters (Fig.1). Torbate-Jam has warm summer and cool winter and according to the Demarton climate graph view and Emberger climagram, has a dry and warm climate. The average amount of rainfall is 173 mm with a mean temperature of 16ºC. In this study, FAO- Penman- Monteith was used as a standard method due to the absence of lysimeter data and presence of complete meteorological data regarding synoptic station and considering FAO suggestion. The accuracy of all determined equation were compared with this equation. The duration of statistical period was 18 years (1993-2011) and all equations were defined by these data. Therefore in order to determine evapotranspiration, 21 effective climatic factors were used including minimum temperature, maximum temperature, average temperature, sunny hours, minimum humidity, maximum humidity, average humidity, wind speed, latent evaporation heat, slope of saturation vapor pressure temperature relationship, saturated vapor pressure, actual vapor pressure, vapor pressure deficit, Solar radiation angle, relative distance between sun and earth, hourly angle of sunset, extraterrestrial radiation, hours of day light, net radiation, and soil heat flux.

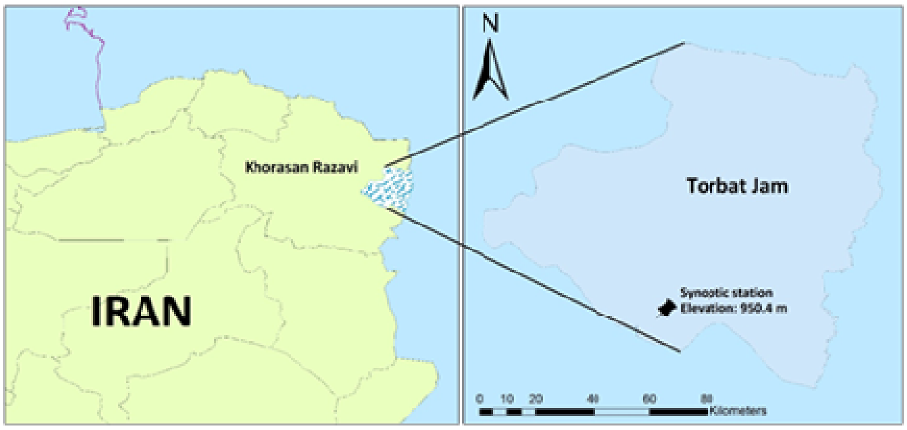


Fig.1. Geographical location of Study area

2.1 Determining the regional equations for calculating evapotranspiration

In this study, climate factors were collected from synoptic station of Torbat-Jam in an 18 year period (1993-2013). Then, FAO-Penman- Monteith was used as the most valid method for determining the reference evapotranspiration after crop coefficient was determined using cultivation method. Eventually if this amount is multiplied by the potential evapotranspiration determined from FAO-penman- Monteith method, the amount of sugar beet evapotranspiration will be determined. All of the calculations were performed according to the daily average of the climate factors. Equations were determined using nonlinear regression method along with SPSS software and in addition to Blaney-Criddle equation parameters, GDD was entered into these equations and at last, the amount of the RMSE, R^2 and NS were calculated with the amount of ET_c determined from FAO-penman-Monteith method. Also in a previous study, in order to define the amount of sugar beet evapotranspiration, Blaney-Criddle method had the highest precision among other equations such as Jensen-Heiz, Blaney-Criddle and tork, thus, the precision of the determined equations were compared using Blaney-Criddle. Finally, according to the results, the best equation for determining evapotranspiration was introduced for the whole region with minimum error, maximum R^2 and optimum NS coefficient. The determined equations are as follows:

$$ET_c = \frac{p}{n} + n + T + (-21.82) + \frac{n}{N} + GDD \quad \text{Eq (1)}$$

$$ET_c = \frac{p}{n} + n^{1.055} + T \times (-0.0004) + \frac{n}{N} \times (-11.661) + GDD \times 0.01032 \quad \text{Eq (2)}$$

$$ET_c = U + T + N \times (1.376) - (RH + (-66.84)) - GDD \times (-3.05) + n \quad \text{Eq (3)}$$

$$ET_c = GDD \times 0.175 + RH \times (-0.00609) + \frac{n}{N} \quad \text{Eq (4)}$$

$$ET_c = (\frac{p}{n}) \times 81.082 + n^{1.107} + T \times (-0.000283) + \frac{n}{N} \times (-14.3417) + GDD \times 0.0119 \quad \text{Eq (5)}$$

$$ET_c = (\frac{GDD}{N}) + P \times 26.502 + \frac{n}{N} \times (-7.832) \quad \text{Eq (6)}$$

$$ET_c = (\frac{n}{N}) + P \times (-10.1323) + T \times (-0.0982) + GDD + U \times (-1.0911) \quad \text{Eq (7)}$$

$$ET_c = (\frac{p}{n}) \times 80.47 + n^{1.0861} + T \times (-0.000206) + \frac{n}{N} \times (-13.4085) + GDD \times 0.023 + RH \times (-0.0377) \quad \text{Eq(8)}$$

$$ET_c = (\frac{p}{n}) + n \times 1.304 + T \times (-0.000289) + \frac{n}{N} \times (-12.091) + GDD \times 0.006105 \quad \text{Eq(9)}$$

where in all mentioned equations T is mean daily air temperature [°C], U is wind speed [m s^{-1}] , RH is relative humidity [%], P is the coefficient that is related to latitude, n is the actual amount of sunny hours and N is the maximum sunny, ET_c is the crop evapotranspiration[mmday^{-1}], and GDD is the Growth Degree Day index.

2.2 FAO-Penman- Monteith equation:

FAO-penman-Monteith equation is defined as a theoretical equation presented on the basis of energy balance on a wet surface covered with plant. This method is the most valid for a more real determination of plants water requirements and was revised by FAO organization experts and assumes a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, and leaf area index 4 times more than its height. Nowadays, FAO-Penman- Monteith equation is the basis of water requirement calculations. Due to the absence of lysimeter data in long term and according to the FAO paper No. 56 recommendations, this method is used as the standard method for evaluating other methods.

FAO-Penman-Monteith equation is as follows (Allen, et al., 1998):

$$\frac{0.408\Delta(R_n - G) + \gamma\left[890/(T+273)\right]U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34 \times U_2)} \quad \text{Eq (10)}$$

where ET_0 is reference evapotranspiration (mmday^{-1}), Rn is net radiation at the crop surface [MJ m^{-2} day^{-1}], G is soil heat flux density [MJ m^{-2} day^{-1}], T is mean daily air temperature at 2 m height [°C], U_2 is wind speed at 2 m height [m s^{-1}], e_s is saturation vapor pressure [kPa], ea is actual vapor pressure [kPa], e_s-e_a is saturation vapor pressure deficit [kPa], Δ is slope vapor pressure curve [kPa °C^{-1}], γ is psychometric constant [kPa °C^{-1}].

Blaney-Criddle equation:

One of the oldest methods for determining potential evapotranspiration is Blaney-Criddle equation. This equation has been formulated by Pruitt, a professor at California University. This equation is presented as follows for determining grass evapotranspiration (Allen et al., 1986):

$$ET_o = a + b[p(0.46T + 8.13)] \quad \text{Eq (11)}$$

Where ET_0 is the potential evapotranspiration [mmday^{-1}], P is the coefficient that is related to latitude, a and b are empirical parameters and T is the mean daily air temperature [°C]. Amounts of “a” and “b” can be calculated as follows:

$$a = 0.0043(RH_{\min}) - (\frac{n}{N}) - 1.41 \quad \text{Eq (12)}$$

$$b = 0.82 - 0.0041(RH_{\min}) + 1.07 \times (\frac{n}{N}) + 0.066U - 0.006(RH_{\min}) \times (\frac{n}{N}) - 0.0006(RH_{\min}) + U \quad \text{Eq (13)}$$

where RH_{min} is the minimum relative humidity, n is the actual amount of sunny hours and N is maximum sunny hours, and U is wind speed [m s^{-1}].

In former investigations carried out in order to determine daily potential evapotranspiration, after different methods were compared with FAO-Penman- Monteith equation, Blaney-Criddle method had higher precision compared to other methods, thus, this equations' parameters were used for composing the new equations of the presented paper. In this method, the amount of sugar beet evapotranspiration was determined by multiplying sugar beet crop coefficient with potential evapotranspiration. The result was compared with the determined equations. The following parameters were used for all the determined equations:

where, ET_c is the evapotranspiration of plant, n is the number of sunny hours (hr), P is daily average of light hours in proportion to the total hours of lights in different months of a year, T is average of daily temperature(°C), GDD is growing degree day parameter, U is the average of wind speed at 2 meter height of the surface, N is the number of the light hours in a day, RH is the amount of relative humidity during the day and "a" and "b" are climatic coefficients.

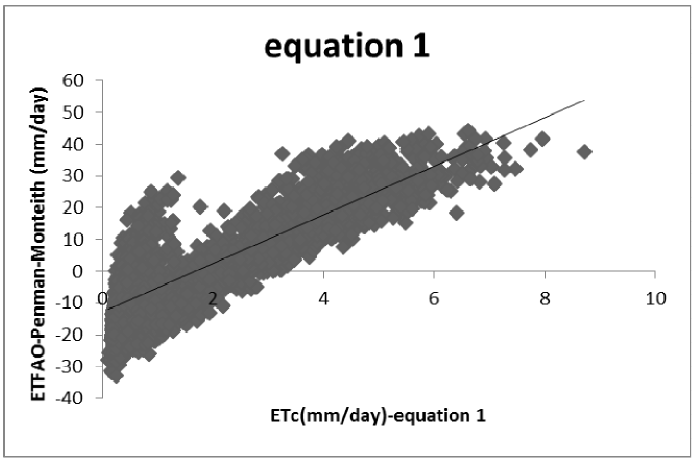
2.3 Fitness Indexes

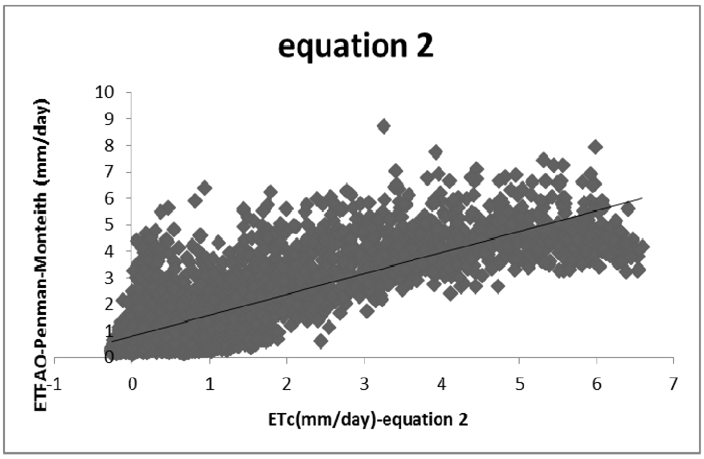
The amounts of NS, RMSE and R^2 were defined to compare results.

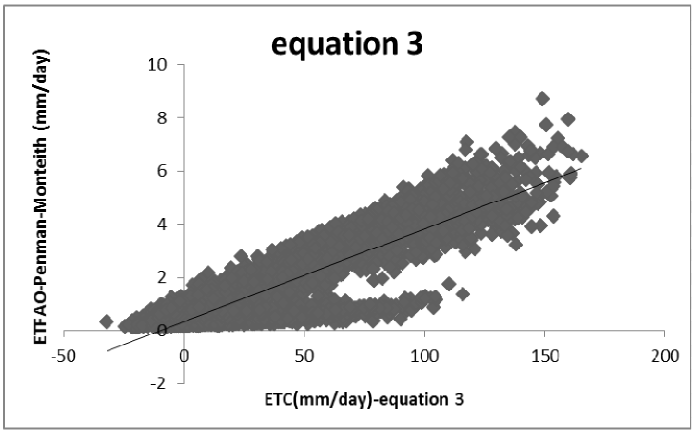
2.4 Growing degree day parameter (GDD):

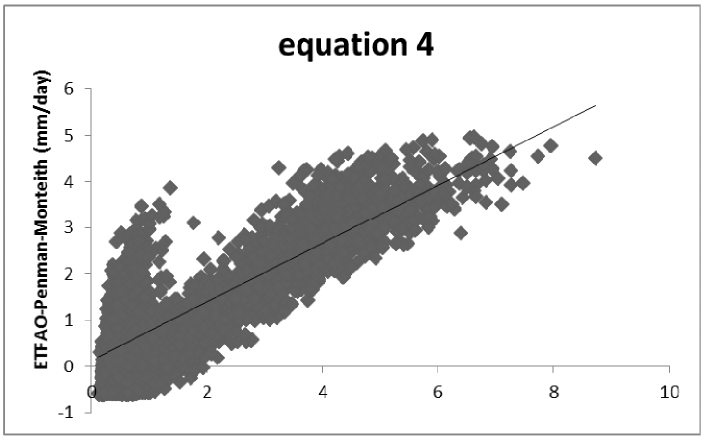
Plant growth and crop production is mainly effected by temperature, sun radiation, evaporation availability, and temperature domain changes. Every plant needs specific amounts of temperature unite or degree days (GDD) to complete its growth period and produce product. Any plant grows well in a finite domain of temperature changes defined as cardinal temperature. The amount of cardinal temperatures for sugar beet are 5°C and 30 °C, respectively. The amount of GDD is defined as daily average temperature minus minimum cardinal temperature. GDD cannot be smaller than zero or more than cardinal temperature differences.

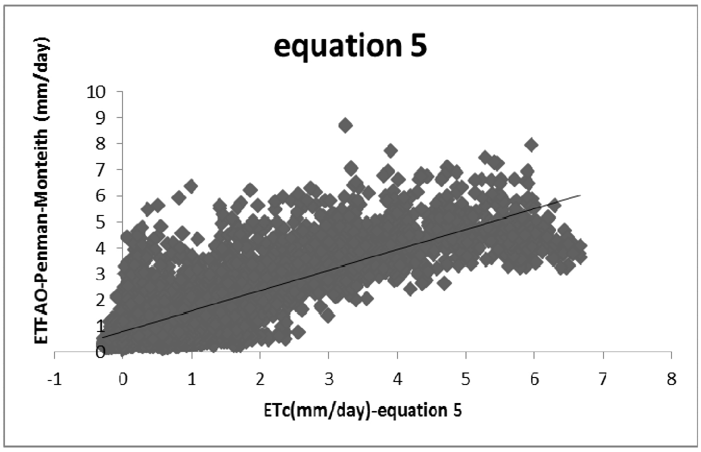
$$GDD = 0.5(T_{\min} + T_{\max}) - \min cardinal \quad \text{Eq (14)}$$






equation 3
ETFAO-Penman-Monteith (mm/day)
ETC(mm/day)-equation 3
10
8
6
4
2
0
-2
-50
0
50
100
150
200


equation 4
ETFAO-Penman-Monteith (mm/day)
6
5
4
3
2
1
0
-1
0
2
4
6
8
10


equation 5
ETFAO-Penman-Monteith (mm/day)
ETc(mm/day)-equation 5
10
9
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7
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5
4
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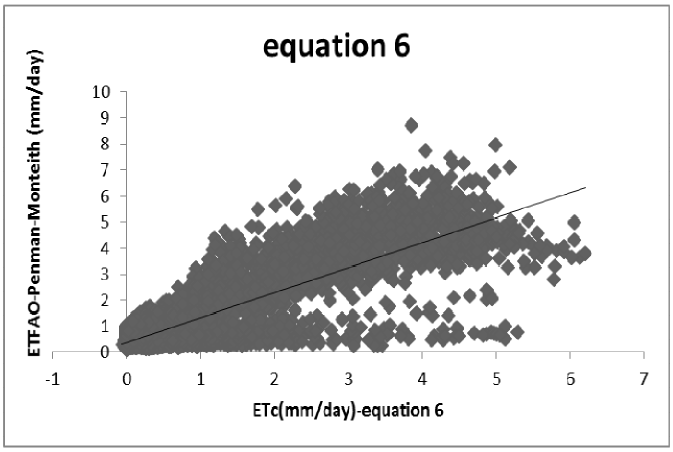
2
1
0
-1
0
1
2
3
4
5
6
7
8


equation 6
ETFAO-Penman-Monteith (mm/day)
ETc(mm/day)-equation 6
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1
0
-1
0
1
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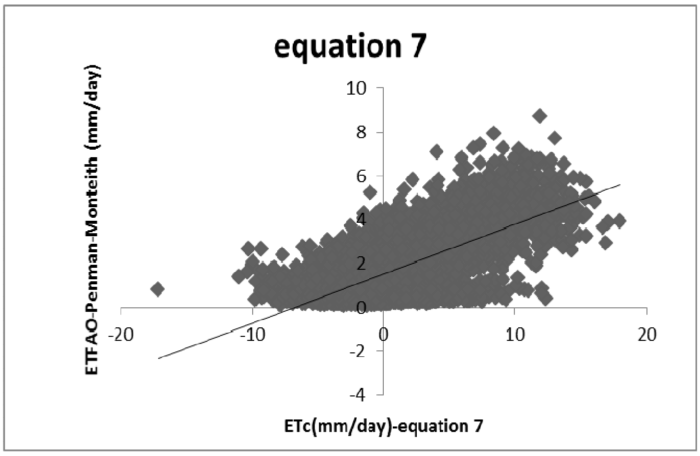
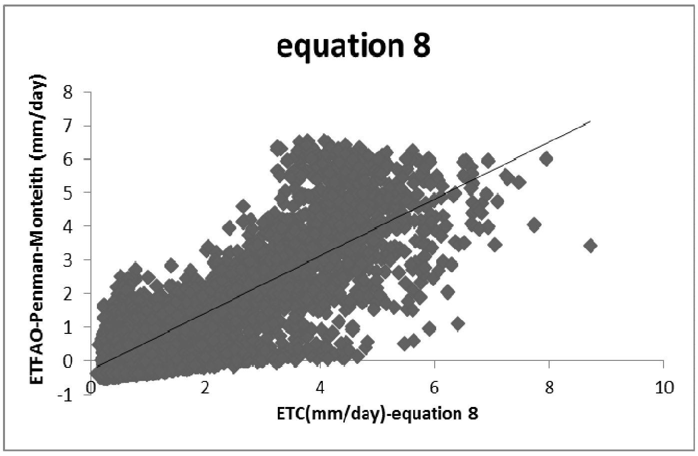
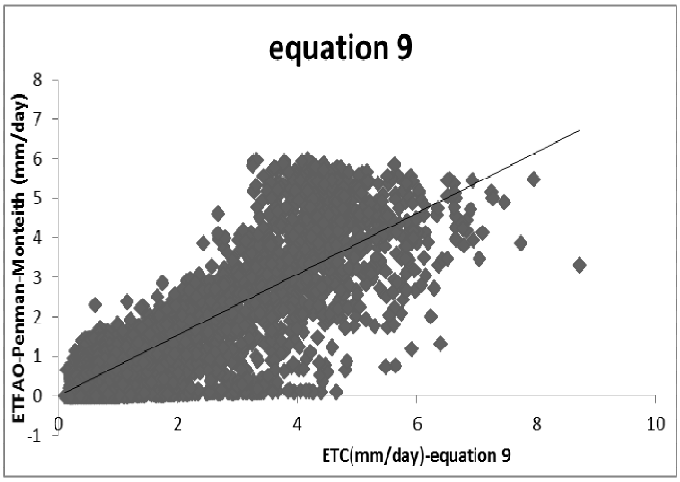
6
7


equation 7
ETFAO-Penman-Monteith (mm/day)
ETc(mm/day)-equation 7
10
8
6
4
2
0
-2
-4
-20
-10
0
10
20


equation 8
ETFAO-Penman-Monteith (mm/day)
ETC(mm/day)-equation 8
8
7
6
5
4
3
2
1
0
-1
0
2
4
6
8
10



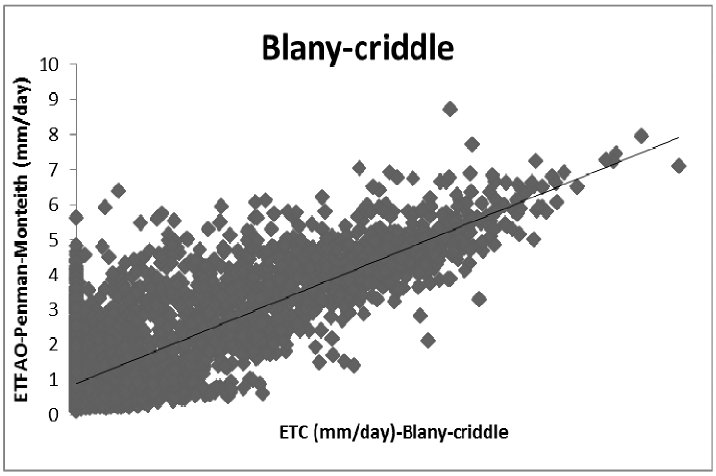


Fig.2. The correlation lines between every equation and FAO- Penman- Monteith equation.

3. Results

Determining the actual amount of evapotranspiration or plant water demand is an important aspect in water resource management in arid and semiarid areas. There are not adequate lysimeter data and this method is so expensive and time-consuming in defining the amount of evapotranspiration, so that empirical methods have more importance. Specifying the amount of evapotranspiration of reference crop with minimum climatic data and high precision and using the crop coefficient in order to achieve the amount of evapotranspiration in standard and nonstandard condition (potential and actual amount of the evapotranspiration) is one the most important issues that the researchers and experts of water pay specific attention to. This problem highlighted in arid and semiarid areas and also in regions that there do not have adequate climatic data. Several methods have been suggested around the world for determining amount of evapotranspiration, however, most of them need to be calibrated or are not usable due to the lack of climatic data or requiring many input data. Defining the exact amount of evapotranspiration has great importance regarding water thrift. The aim of this study was to define a zonal equation with minimum climatic recorded data that can be used to estimate the amount of sugar beet evapotranspiration with high precision.

In this study, efforts were made to present a more precise equation in order to define the amount of sugar beet water demand in TorbateJam with the use of FAO-Penman-Monteith method for comparing the amount of defined equations precision, as a standard method in determining the amount of evapotranspiration.

The amount of RMSE, R^2, and NS were calculated for every one of the defined equations. Each of these indexes has a domain of precision, for example, RMSE can vary between zero to extreme. This index represents the amount of error, so if the amount near zero, then the error rate is lower. Domain changes of R2 vary between zero and one. This index demonstrates the numeric correlation, so if the amount of the correlation coefficient is higher, that equation is closer to FAO- Penman-Monteith equation. NS index was used for more precision. The Range of this index changes between one and minus extreme, so if this index is nearer to one the mentioned equations are more similar to FAO- Pen-man- Monteith equation.

The amount of the correlation between the amounts of the calculated evapotranspiration with FAO- Penman- Monteith and every one of defined equations were demonstrated in fig.2. The average error between the 9 presented equations was 9.33 and the amount of the correlation coefficient average was 0.646. As it can be seen from fig. 2, the maximum and minimum amount of respective correlation belongs to the third and seventh equations with a maximum of 0.719 and a minimum of 0.47, respectively, however, the amount of error is also important in determining the best equation. The third and sixth equation have the maximum and minimum amount of error with the amounts of 58.97 and 1.048, respectively.

The maximum amount of NS coefficient belongs to the first and eighth equation and Blaney-Criddle equation and the minimum amount of it belongs to the third equation. As it was indicated before, the third equation had the most amount of correlation coefficient but its error rate was high (59.67) and the amount of NS coefficient was not appropriate (1229), therefore, although this equation has more correlation compared to other equations, it has less precision. Using the presented equation resulted in higher precision and less time. The innovations in presenting this equation were using GDD parameter for calculating daily evapotranspiration of sugar beet with no need to calculate the crop coefficient in cultivation duration.

Table 1. Amounts of correlation coefficient, error, and NS for each method.

Equation	R^2	RMSE	NS
1	0.693	14.082	0.99
2	0.651	1.169	0.515
3	0.719	58.97	-1229
4	0.678	1.117	0.558
5	0.64	1.183	0.503
6	0.64	1.048	0.611
7	0.47	4.147	-5.08
8	0.64	1.21	0.99
9	0.683	1.05	0.99
(10) Blany-Criddle	0.657	1.22	0.99

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