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Comparison of Different Methods for Estimating Reference Evapotranspiration by Using Limited Meteorological Data

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Abstract Evapotranspiration (ET), one of the important components of the hydrological cycle, is called the sum of water losses given to the atmosphere through evaporation from the soil surface and perspiration from the plants. Accurate and reliable estimates of ET in irrigated agriculture are important for the planning and management of irrigation and water resources and for the effective use of water resources. For direct determination of ET, it is necessary to have special tools available and a sound measurement of various physical parameters or the soil-water balance in lysimeters. It is not easy to determine the ET directly because these methods are often expensive and require well trained research staff for measurement. Therefore, it is important to obtain ET by indirect methods. The most common method used in indirect estimation of ET is to correct the reference evapotranspiration (ETo) values with the plant coefficient (Kc). In this method, ETo is calculated for a standard surface using reference parameters and agro-meteorological data, and ET is then multiplied by the appropriate plant coefficient to yield ET. The FAO Penman-Monteith (FAO PM) equation has been proposed as the standard method for the calculation of ETO and requires solar radiation, temperature, humidity and wind speed data. All of these data may not be available in most places. However, in the absence of solar radiation, humidity and wind speed data, ETo can be calculated by different methods such as FAO PM equation from maximum and minimum temperature data. In this research, it was aimed to determine the method that best predicts the mean monthly ETO under the conditions of Erzurum Plain using the monthly mean maximum and minimum temperature data measured at the Erzurum Meteorological Station of Turkish State Meteorological Service for a 15 years period between 1996 and 2010. Calculation of evapotranspiration using maximum and minimum temperature values in FAO PM equation (FAO PM_{temp}), Hargreaves-Samani (HS) equation and two different models of Hargreaves-Samani equation calibrated locally with linear and non-linear methods ($HS_{lin\text{-}adj}$ and $HS_{nonlin\text{-}adj}$) were used as the methods. Based on FAO PM equation, the determination coefficient (R^2), root mean square error (RMSE), mean absolute error (MAE), standard error (SE) and relative error (RE) were used as criteria. The $HS_{nonlin\text{-}adj}$ model was the best performing method (R^2 = 0.992, RMSE = 0.185 mm day^{-1}, MAE = 0.147 mm day^{-1}, SE = 0.19 mm day^{-1} and RE = 0.07).

Keywords Irrigation scheduling, reference evapotranspiration, FAO Penman-Monteith equation, Hargreaves-Samani equation, Erzurum Plain

Introduction

Evapotranspiration (ET), one of the important components of the hydrological cycle, is called as the sum of water losses given to the atmosphere through evaporation from the soil surface and transpiration from the plants [1-2]. ET amount depends on atmospheric water demand and surface characteristics [3]. Accurate and reliable estimates of ET in irrigated agriculture are important for the planning and management of irrigation and water resources and for the effective use of water resources [4-5].

For direct determination of ET, it is necessary to have special tools available and a sound measurement of various physical parameters or the soil-water balance in lysimeters. It is not easy to determine the ET directly because these methods are often expensive and require well trained research staff for measurement. It is therefore important to obtain ET by indirect methods [2]. The most common method used in indirect estimation of ET is to correct the reference evapotranspiration (ETo) values with the plant coefficient (Kc) ($ET = ETo \cdot Kc$) [4-6].

Reference evapotranspiration (ETo), as characterized by Allen et al. [2] is defined as the amount of ET that is a hypothetical reference having a fixed height, surface resistance, and reflection coefficient [3]. ETo is a climate parameter and can be calculated from meteorological data, as the only factors affecting ETo are climate factors [2].

A great number of equations have been developed to determine the amount of ETo, since the introduction of the first ETo equation by Penman (1948) [4]. These equations are evaluated in three categories; heat-based, radiation-based, and combination-based (merging energy balance and mass transfer) equations [3].

The use of structurally different equations by researchers and practitioners has made it difficult to establish a cohesion basis for the interpretation and sharing of ET and Kc data between agri-water management communities. Therefore, the need to identify and define a benchmarking equation has emerged [4]. The American Society of Civil Engineers (ASCE) Irrigation Water Needs Committee has analyzed the properties of 20 different equations against lysimeter data carefully selected from 11 stations located in different climate zones worldwide. Penman-Monteith equation is listed as the best method for estimating daily and monthly ETo in all climates. The commission of experts and researchers organized by FAO in May 1990, together with the International Commission on Irrigation and Drainage (ICID) and the World Meteorological Organization (WMO), recommended that the Penman-Monteith combination equation be adopted as a standard new method for the calculation of reference evapotranspiration and also methods of calculating new parameters. This commission developed the FAO Penman-Monteith (FAO PM) equation by defining the reference plant as a hypothetical plant, with a height of 0.12 m, a surface resistance of 70 s m-1 and an albedo of 0.23 and hence represents the evaporation of a large grass surface that grows actively at uniform height and is adequately irrigated [1, 2, 4].

The FA0 PM equation requires a large amount of data, including maximum and minimum air temperature, maximum and minimum relative humidity (or actual vapor pressure), wind speed at 2 m height and solar radiation (or sunlight hours). Since the data required by the FA0 PM equation cannot be obtained at most weather stations, the use of this equation is prohibited [1, 2, 3]. Allen et al. [2] have suggested methods for eliminating the deficiency of climate parameters such as net radiation, vapor pressure and wind speed, and have stated that ETo can be calculated by FAO PM equation, by using the climate parameters obtained by these methods. In addition, Allen et al. [2] also suggest that reference evapotranspiration, as an alternative when no solar radiation, relative humidity and wind speed data are available, can be estimated with the Hargreaves-Samani (HS) equation. However, they have indicated that the ETo values obtained by HS equation for any region should be verified against the ETo values obtained by FAO PM equation, and if necessary HS equation may be calibrated by FAO PM equation on a monthly or yearly basis using simple regression analysis.

The above-mentioned methods have been tested by some researchers (Stöckle et al., 2004; Popova et al., 2006 and Jabloun and Sahli, 2008) to test their applicabilityin different countries and climates [5]. Similarly, this study has been conducted to evaluate the performance of FAO PM equation and alternative methods in estimating reference evapotranspiration with limited meteorological data in Erzurum Plain conditions.

Material and Methods

Material

Erzurum province is selected as a research area and it is located in the Upper Euphrates Basin in the Eastern Anatolia Region, Turkey, and it is located between 39 ° 10′and 40 ° 57′ northern latitudes and between 40°15′and 42° 35′ east longitudes.

In the area of research, the dominant climate is terrestrial climate, where winters are long, cold and generally snowy and summers are short, hot and arid. Annual average rainfall is 437.3 mm, annual average temperature is 5.7 ° C, annual average relative humidity is 64.2%, annual average wind speed is 2.6 m / s and annual average sunshine duration is 6.9 h / day [7,8].

The bases in Erzurum Plain have an alluvial structure composed of silty and sandy sediments and the slopes have a colloidal structure composed of rough material [9, 10]. Soils of research area are usually medium and heavy structure. A small part of the soil is lightweight [9].

In this study, the meteorological data observed by Erzurum Meteorological Station of Turkish State Meteorological Service have been used. Erzurum Meteorological Station is located in Erzurum Plain at 39º 04'northern latitude and 41º 25' east longitude and its height from the sea level is 1758 m.

Daily maximum temperature, minimum temperature, relative humidity, wind speed at 2 m height, sunshine hours observed during the 15 years period between 1996 and 2010 in Erzurum Meteorological Station have been used. Monthly mean values of daily meteorological data have been obtained for each year to get the average monthly values. The 15-year averages of the monthly meteorological data observed in Erzurum Meteorological Station are given in Table 1.

Methods

FAO Penman-Monteith Equation

The FAO PM equation used to estimate ETo with limited data and to compare it to other methods that estimate ETo with limited data is given below [2].

$$ETo = \frac{0.408 \cdot \Delta \cdot (Rn - G) + \gamma \cdot \left(\frac{900}{T+273}\right) \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \quad (1)$$

Where; ETo is reference crop evapotranspiration (mm day^{-1}), T is mean daily air temperature at 2 m height (ºC), Rn is net radiation at the crop surface (MJ $m^{-2}day^{-1}$), G is soil heat flux density (MJ $m^{-2}day^{-1}$), U_2 is wind speed at 2 m height (m s^{-1}), es is saturation vapour pressure (kPa), ea is actual vapour pressure (kPa), Δ is slope vapour pressure curve (kPa $°C^{-1}$),and γ is psychrometric constant (kPa $°C^{-1}$).

Using FAO Penman-Monteith Equation with Limited Data

As mentioned above, temperature, radiation (or sunshine time), vapor pressure and wind speed data are required to calculate ETo with the FAO PM equation. Most meteorological stations do not measure all of these meteorological data needed. Therefore, if one or more of these data required calculating ETo with FAO PM equation is not available, the method to calculate it is given below.

Hargreaves and Samani [11] stated that when solar radiation and sunshine data are not available, solar radiation can be calculated by the following equation, using the difference between the maximum and minimum temperatures [2, 3].

$$R_s = K \cdot (T_{max} - T_{min})^{0.5} \cdot R_a \quad (2)$$

Where; Rs is solar radiation calculated from air temperature differences (MJ $m^{-2}day^{-1}$); Ra is extraterrestrial radiation (MJ $m^{-2}day^{-1}$); Tmax and Tmin are maximum and minimum air temperature (°C), and K is adjustment coefficient. Allen et al. [2] suggested using values of K = 0.16 and K = 0.19 for internal and coastal locations, respectively.

When there is no available relative humidity data, required to calculate the actual vapor pressure, the actual vapor pressure is calculated using the following equation, by assuming that the minimum temperature (Tmin) is close to the dew temperature (Tdew) [2, 5, 12].

$$e_a = e^o{}_{(Tmin)} = 0.611 exp\left[\frac{17.27Tmin}{Tmin + 237.3}\right] \quad (3)$$

Where; ea is actual vapour pressure (kPa), e° (Tmin) is actual vapour pressure at the dew point temperature (kPa), and Tmin is minimum air temperature (°C).

Wind speed data is a climate parameter that is difficult to estimate and obtain, and if it is not available, two different approaches are applied. In the first approach, the local wind speed average of the past years is used, and in the second, the global average wind speed values of 2 m s^{-1} are used [2, 5, 12].

Hargreaves-Samani Equation

In case the climate parameters required for FAO PM equation are not available, Allen et al. [2] suggest that the ETo can be predicted by Hargreaves-Samani equation. The Hargreaves-Samani equation used for calculating the ETo using maximum and minimum temperatures and extraterrestrial radiation is given below [11].

$$ET_o = 0.0023 \cdot (T_{ort} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot R_a \quad (4)$$

Where; ETo is reference evapotranspiration (mm day^{-1}), Ra is extraterrestrial radiation (mm day^{-1}); Tort, Tmax and Tmin are mean, maximum and minimum air temperature, respectively (°C).

Table 1: Monthly average values of some meteorological data observed in Erzurum Meteorological Station during the 15- years period between 1996 and 2010

Months	Min. Temp. (°C)	Max. Temp. (°C)	Mean Relative Humid. (%)	Wind Speed (m s^{-1})	Sunshine Time (h day^{-1})	Ekstraterr. Radiation (MJ m^{-2} day^{-1})*
January	-16.34	-4.24	77.26	1.46	3.17	15.66
February	-14.50	-1.99	76.34	1.59	4.08	20.81
March	-7.48	3.87	73.75	2.00	4.59	27.88
April	-0.90	11.53	67.61	2.24	5.65	35.00
May	2.89	17.73	62.76	2.13	7.79	39.73
June	5.79	22.86	57.86	2.05	9.95	41.73
July	9.76	27.57	52.54	2.28	10.47	40.87
August	9.80	28.48	48.63	2.15	10.09	37.21
September	4.18	23.38	52.70	1.79	8.06	31.00
October	0.46	16.16	65.90	1.70	6.04	23.76
November	-5.95	8.08	71.17	1.56	4.77	17.34
December	-11.97	-0.18	77.68	1.40	2.77	14.37

*Extraterrestrial radiation values were taken from the related literature.

Adjusted Hargreaves-Samani Equations

As mentioned above, it has been proposed by Allen et al. [2] that ETo can be estimated by Hargreaves-Samani (HS) equation as an alternative, if solar radiation, relative humidity and wind speed data are not available. However, Allen et al. [2] reported that HS equation predicts a lower ETo when the wind speed is greater than 3 m s^{-1} and predicts a higher ETo under high humidity conditions, and that the ETo values obtained with HS equation for any region should be verified by comparing the ETo values obtained through FAO PM equation.

Thus, two different models of HS equation ($HS_{lin-adj}$ and $HS_{nonlin-adj}$) have been obtained by linear and nonlinear regression methods based on FAO PM equation. The HS equation amended by the linear regression method is given below.

$$ET_{O(HS-lin-adj)} = a + b \cdot ET_{O(HS)} \quad (5)$$

Where; $ETo_{(HS-lin-adj)}$ is the value of ETo obtained from HS equation corrected by linear regression against FAO PM equation (mm day^{-1}), a is the intercept value, b is the regression coefficient, and $ET_{O(HS)}$ is the ETo value obtained from the original HS equation (mm day^{-1})

The HS equation amended by the nonlinear regression method is given below.

$$ET_{(HS-nonlin-adj)} = c \cdot (T_{ort} + 17.8) \cdot (T_{max} - T_{min})^{d} \cdot R_a \quad (6)$$

Where; $ETo_{(HS-nonlin-adj)}$ is the ETo value obtained by HS equation corrected by nonlinear regression method against FAO PM equation (mm day^{-1}), Ra is the extraterrestrial radiation (mm day^{-1}), Tort, Tmax and Tmin are the mean, maximum and minimum air temperatures, respectively (°C), c is the numericvalue corresponding to the coefficient 0.0023 in the original HS equation, and d is the numeric value corresponding to the exponent value of 0.5 in the original HS equation

Application of Methods

The monthly mean values of daily maximum temperature, minimum temperature, mean relative humidity, wind speed and sunshine values observed for the 15 years period between 1996 and 2010 in Erzurum Meteorological Station, which are required for the above mentioned ETo calculation methods, have been obtained. The monthly values of extraterrestrial radiation have been obtained from related literature [13, 14]. By using the mean monthly values of climate parameters required for FAO PM and HS equations, the mean monthly $ETo_{(FAO\ PM)}$ and $ETo_{(HS)}$ values have been calculated per year for the equations in question. These values, 12 data for each year, consist of a total of 180 pieces of data for the 15 year period. Cropwat 8.0 irrigation scheduling program was used to calculate the $ETo_{(FAO\ PM)}$ by means of FAO PM equation [15]. MS Excel software was used to calculate ETo (HS) values.

Then, only the monthly mean maximum and minimum temperature values were used in the Cropwat 8.0 irrigation scheduling program to calculate the monthly mean $ETO_{(FAO\ PM,\ temp)}$ value consisting of 180 pieces of for the 15 year period. The Cropwat 8.0 irrigation scheduling program determines the missing solar radiation, actual vapor pressure and wind speed data according to the methods mentioned above, and then calculates ETo using the FAO PM equation. The Cropwat 8.0 program considered the missing wind speed to be the local value of 2 m s^{-1} [15].

Monthly mean $ETo_{(FAO\ PM)}$ and $ETo_{(HS)}$ values (each consisting of 120 pieces of data) for the 10 years randomly selected from the 15 year period of 1996-2010 have been used as training (calibration) data. The values of (a) and (b) in equation (5) were obtained by correlating (by graphing) $ETo_{(FAO\ PM)}$ and $ETo_{(HS)}$ training data with linear regression method. Similarly, based on $ETo_{(FAO\ PM)}$ training data and byusing equation (6), the values of (c) and (d),which allow the most suitable curve (the most suitable nonlinear regression) to be obtained, have been obtained by using the least squares method. JMP 13.1 software [16]was used to obtain the most suitable curve with least squares method.

(a) and (b) values obtained through training data, and the monthly mean ETo(HS) values for the remaining 5 years (1996, 2000, 2004, 2005 and 2007) have been used in equation (5) to obtain the 60 units of monthly $ETo_{(HS\text{-}lin\text{-}adj)}$ values. Similarly, the (c) and (d) values and the monthly mean Tort, Tmax, Tmin and Ra values for the five years in question have been used in equation (6) to obtain the monthly $ETo_{(HS\text{-}nonlin\text{-}adj)}$ values, which each consist of 60 pieces. The $ETo_{(HS\text{-}lin\text{-}adj)}$ and $ETo_{(HS\text{-}nonlin\text{-}adj)}$ values obtained through equations (5) and (6), and the monthly $ETO_{(FAO\ PM)}$, $ETO_{(HS)}$ and $ETo_{(FAO\ PMtemp)}$ values consisting of 60 pieces each for the 5 years, have been used as test data. $ETo_{(HS\text{-}nlin\text{-}adj)}$, $ETo_{(HS\text{-}nonlin\text{-}adj)}$, $ETo_{(HS)}$ and $ETo_{(FAO\ PM,\ temp)}$ test data have been evaluated in accordance with the following criteria, by making based on $ETo_{(FAO\ PM)}$ test data the starting point.

Evaluation Criteria

The root mean square error (RMSE), the mean absolute error (MAE), the standard error (SE), and the relative error (RE) have been used as the criterion for the comparison and performance evaluation of the ETo estimation methods. The equations used for the calculation of R^2, RMSE, MAE, SE and RE are given below [3, 11, 17].

$$R^2 = \frac{\left[\sum_{i=1}^{N}(P_i-\bar{P})\cdot(O_i-\bar{O})\right]^2}{\sum_{i=1}^{N}(P_i-\bar{P})^2\cdot\sum_{i=1}^{N}(O_i-\bar{O})^2} \quad (7)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(P_i-O_i)^2\right]^{0.5} \quad (8)$$

$$MAE = \sum_{i=1}^{N}\frac{|Pi-Oi|}{N} \quad (9)$$

$$SE = \left[\frac{\sum_{i=1}^{N}(Pi-Oi)^2}{N-1}\right]^{0.5} \quad (10)$$

$$RE = \frac{RMSE}{\bar{O}} \quad (11)$$

Where; Pi is the ETo value estimated by four different methods, Oi is the value of $ETo_{(FAO\ PM)}$, $\bar{P}$ and $\bar{O}$ are the mean values of Pi and Oi respectively, and N is number of data. In order for an equation to perform perfectly, it's RMSE and MAE values must be zero (0), R^2 must be one (1), and SE and RE values must be close to zero (0) [18]. Therefore, the model with the lowest RMSE, MAE, SE and RE values, and the highest R^2 values was selected as the best fitting model.

Results and Discussion

By using the training data, (a), (b), (c) and (d) values in equation (5) and equation (6) have been found to be 0.097, 0.8938, 0.00155 and 0.611 respectively. (c) and (d) values were found to be 0.0020 and 0.46 respectively by Zhang et al [19].The monthly mean $ETo_{(HS\text{-}lin\text{-}adj)}$ and ETo $_{(HS\text{-}nonlin\text{-}adj)}$ values obtained by placing these (a), (b), (c) and (d) values into equations (5) and (6) (in $HS_{lin\text{-}adj}$ and $HS_{nonlin\text{-}adj}$ models) (as test data for 5 different years), and the monthly $ETO_{(HS)}$, $ETO_{(FAO\ PMtemp)}$ and $ETO_{(FAO\ PM)}$ values obtained by HS equation, FAO PM_{temp} method and FAO PM equation for the same years are given in Figure 1. The performances displayed by HS equation, HSlin-adj and HSnonlin-adj models and FAO PM_{temp} method against FAO PM equation are given in Table 2. Table 2 shows that the annual mean ETo values obtained by the FAO PM_{temp} method and the HS equation (2.80 and 2.77 mm day^{-1}, respectively) are higher than the ETo value obtained by the FAO PM equation taken as a basis (2.63 mm day^{-1}), while the ETo values obtained with the $HS_{lin\text{-}adj}$ and $HS_{nonlin\text{-}adj}$ models (2.57 and 2.55 mm day^{-1}, respectively) are lower than the ETo value obtained with the FAO PM equation.

Figure 1 indicates that this is due to the fact that generally in all months, and particularly during the months where humidity is low and temperature is high, HS and FAO PM_{temp} methods yield higher ETo values compared to FAO PM equation and other methods, while $HS_{(lin\text{-}adj)}$ ve $HS_{(nonlin\text{-}adj)}$ models yielded lower ETo values in all months. Similar to this result, Trajkovic [17] stated that under the temperate Southeast European conditions the HS equation predicts the ETo value 22% higher than the FAO PM equation, and that the adjusted HS equation, where 0.424 is used instead of the 0.5 value, predicts ETo value 1% higher than the FAO PM equation. In addition, Sentelhas et al. [5] stated that HS equation yields higher values than FAO PM equation in Southern Ontario (Canada).

Table 2 shows that $HS_{(lin\text{-}adj)}$ and $HS_{(nonlin\text{-}adj)}$ models have a closer alignment with FAO PM equation than HS equation and FAO PM_{temp} method. The $HS_{(nonlin\text{-}adj)}$ model was the best performing method with the lowest RMSE, SE and RE values (0.185 mm day^{-1}, 0.19 mm day^{-1} and 0.07, respectively). $HS_{(lin\text{-}adj)}$ model, which has the lowest MAE (0.145 mm day^{-1}) and second lowest RMSE, SE and RE values (0.204 mm day^{-1}, 0.21 mm day^{-1} and 0.08, respectively), ranks second. Similar to these results, Trajkovic [17] reported that the corrected HS equation is in good agreement with the FAO PM equation in humid locations in the Western Balkans and is proposed for the calculation of reference evapotranspiration. In addition, Sentelhas et al. [5] reported that the best method for estimating evapotranspiration is the corrected Hargreaves method when only temperature data are available in Southern Ontario (Canada) conditions. Despite having the highest R^2 value (0.994), the FAO PM_{temp} method ranked third in terms of compliance with FAO PM equation when other criteria were taken into consideration. Despite the fact that the annual mean ETo value (2.77 mm day^{-1}) obtained with HS equation is closer to the FAO PM ETo value (2.63 mm day^{-1}) than the value obtained from the FAO PM_{temp} method (2.80 mm day^{-1}), the HS equation was the lowest performing method in terms of all the other criteria.

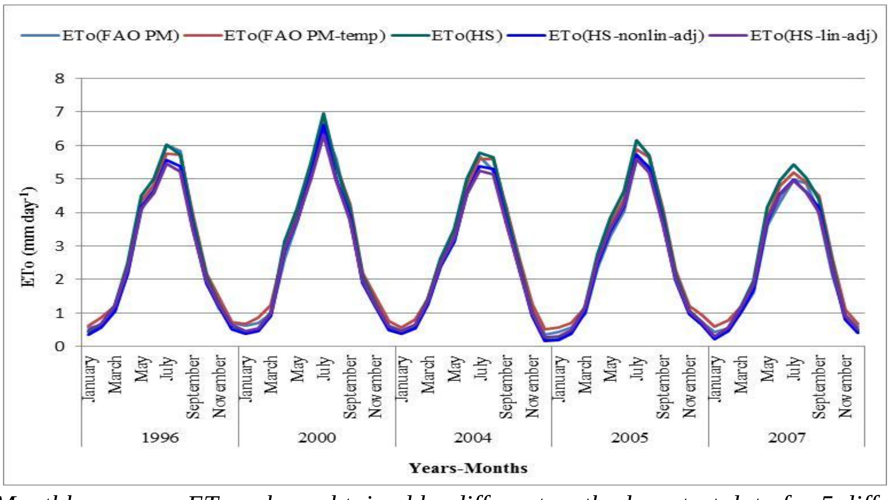

Figure 1: Monthly average ETo values obtained by different methods as test data for 5 different years

The higher performance by the $HS_{(lin\text{-}adj)}$ and $HS_{(nonlin\text{-}adj)}$ models was due to the fact that these equations have been developed by taking the comparison-oriented FAO PM equation as the basis. HS equation has been the worst performing equation because it is used only with maximum and minimum temperature values and is not associated with FAO PM equation at all. The poor performance of the FAO PM_{temp} method is due to the use of regional wind speed (2 m s^{-1}) in FAO PM equation, while local wind speed values are used in this method. Because, Trajkovic and Kolakovic [12] and Rojas and Sheffield [3] have reported that when wind speed data are not available, lower RMSE and MAE values are obtained if local data or near-station data are used instead of global wind speed data.In addition, Irmak et al. [4] reported that after VPD, ETo was most sensitive to wind speed in semiarid regions during the summer months.

Table 2: Performance values of the methods against FAO PM equation

Methods	R^2	**RMSE** (mm day^{-1})	**MAE** (mm day^{-1})	**SE** (mm day^{-1})	**RE**	**Annual Mean ETo** (mm day^{-1})
FAO PM	-	-	-	-	-	2.63
FAO PM_{temp}	0.994	0.229	0.197	0.23	0.09	2.80
HS	0.990	0.278	0.220	0.28	0.11	2.77
$HS_{(lin\text{-}adj)}$	0.990	0.204	0.145	0.21	0.08	2.57
$HS_{(nonlin\text{-}adj)}$	0.992	0.185	0.147	0.19	0.07	2.55

Conclusion

The FAO PM equation is proposed as the standard method for calculating the reference evapotranspiration. The use of this method is limited because the required meteorological data cannot be obtained in most places. Therefore, it is important to calculate the reference evapotranspiration by using limited meteorological data. This study has been conducted to compare the reference evapotranspiration values obtained by using 15-year limited meteorological data observed in Erzurum Meteorological Station in FAO Penman-Monteith equation, Hargreaves-Samani equation, and Hargreaves-Samani models adjusted by linear and nonlinear regression methods. Hargreaves-Samani model adjusted by nonlinear regression method has been identified as the method with the best performance.

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