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Assessment of Reference Evapotranspiration by the Hargreaves Method in Southern Punjab Pakistan

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ABSTRACT

Several methods are available for estimating reference evapotranspiration (ET_o) which require many weather variables that are not always available at all weather stations specially in developing countries. The Hargreaves equation (HG) requires only daily air temperature data and extraterrestrial radiation for ET_o estimates. The HG method often tends to overestimate or underestimate ET_o, so it become necessary before using HG method it must be calibrated according to local conditions. The HG equation was evaluated under semiarid conditions by using 15, 10 and 9-years of complete daily climatic data from the Bahawalpur, Bahawalnagar and Khanpur weather stations of Southern Punjab, Pakistan, respectively. The HG method was compared to FAO56 Penman Monteith equation (PM). The original HG equation overestimated for all time steps of three weather stations. The original HG equation overestimated ET_o by 14, 12, and 8 % for daily, 10-daily (decade), and monthly ET_o for Bahawalpur and by 8, 6 and 5 % of Bahawalnagar and by 25, 10 and 8% of Khanpur stations, respectively, as compared to PM equation. A simple mathematical logic applied to obtain the modified HG coefficients for all time steps showed that the modified HG equation improved the results of ET_o estimation to 4, 3, and 2% for daily, 10-daily and monthly time steps of Bahawalpur station 4, 2.5 and 2% of Bahawalnagar station and 6, 3.5 and 3% of Khanpur station, difference from ET_o computed by the PM method, with root mean square error (RMSE) of 1.411, 1.105 and 0.950 mm d^{-1} for daily, 10-daily, and monthly ET of Bahawalpur and 1.800, 1.121 and 0.865 mm d^{-1} of Bahawalnagar and 1.13, 0.971 and 0.595 mm d^{-1} of Khanpur stations, respectively. For more accuracy, further improvement in modified HG method achieved by adding the wind speed, reaching an average difference of 1% for all timescales. The original HG equation overestimated for all time steps before modification.

Key words: Reference Evapotranspiration, Modification, Hargreaves Equation, Southern Punjab

INTRODUCTION

Evapotranspiration (ET) is an important element of water-cycle of agricultural systems. Types of crop and land use affect the evapotranspiration process. Evapotranspiration information is needed in determining the volume of water required to overcome short term and seasonal water requirement for fields, farms and irrigation projects. The incorrect estimation of the irrigation water requirement may lead to serious failures in the system performance and wastage of valuable water resources. The FAO Penman-Monteith (PM) method now a day accepted as a standard method for the calculation of ET_o [1]. The PM equation requires huge input data that is air temperature, humidity, sunshine hours and wind speed, which is not available for all weather stations. When input data for PM equation is insufficient especially in developing countries like Pakistan, then equation developed by Hargreaves and Samani can be used with confidence after local adjustment in parameters. The Hargreaves equation requires very short climatic data i-e only air temperature data.

Different researchers tried to assess the performance of Hargreaves (HG) equation by calibrating it according to local conditions [2-3]. Hargreaves and Allen [6] suggested that Hargreaves equation can be used with confidence after modification according to local conditions and gives best result for longer time step because at daily time step there are more fluctuation in temperature, wind speed etc. The HG equation is used after local calibration when complete required data for PM equation is not available [5].

MATERIALS AND METHODS

Study Area

Southern Punjab is geographically situated approximately between 27-31 °N latitudes and 70-73 °E longitudes. The main cities in the region are Multan, D.G. Khan, Muzaffargarh, Bahawalpur, Bahawalnagar, Khanpur and Rahim Yar Khan. In this research data of three stations was used i.e. Bahawalnagar, Bahawalpur and Khanpur. The region is amongst warmest areas of Pakistan where summer temperature goes above 40°C very frequently. Due to high temperature in summer, evapotranspiration rate rises to 8-10 mm/day resulting in higher crop water demand. Major portion of culturable area of Pakistan lies in this region, due to high temperature and evapotranspiration rate, there need to be proper irrigation scheduling and irrigation design.

The required 15-year data of Bahawalpur Station (2000-2014), 9-year data of Khanpur Station (2006-2014) and 10-year data of Bahawalnagar Station (2005-2014) were used for the calibration/modification of Hargreaves equation.

Description of FAO56 Penman-Monteith (PM) Equation

For the calculation of Penman-Monteith ET_o computer model CROPWAT 8.0 was used which was recommended by FAO (Food and Agriculture organization). The input data required was minimum and maximum air temperature data, humidity, wind speed and sunshine hours. At different time steps (daily,10-daily, and monthly) ET_o was calculated by using computer model, [4] 'CROPWAT 8.0' the following PM equation used as suggested [1]:

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

Where, ET_o = reference evapotranspiration [mm day^{-1}]; R_n = net radiation at the crop surface [MJm^{-2} /day]; G = soil heat flux density [MJ m^2/day]; T = mean daily air temperature at 2 m height [°C]; U_2 = wind speed at 2 m height [m/s]; e_s =saturation vapour pressure [kPa]; e_a = actual vapour pressure [kPa]; e_s-e_a = saturation vapour pressure deficit [kPa]; Δ = slope vapour pressure curve [kPa/ °C]; γ= psychrometric constant [kPa /°C]. The computation of all data is done as given in [1].

Hargreaves Method

The ET_o estimated by using Hargreaves Method [7]:

$$ET_{o\,HG} = 0.0023\, R_a\, (T + 17.8)\, (T_{max} - T_{min})^{0.5} \quad (2)$$

Where, ET_{oHG}= reference evapotranspiration (mm/day); T, T_{max} and T_{min}= mean, maximum and minimum temperature (^{o}C) respectively.

Modification of Hargreaves Equation

To improve the ET_o estimated by Hargreaves equation (HG), the parameter of the original HG equation can be fit according to local conditions. The HG equation was modified by finding new value of constant by using simple mathematical logic.

In the above equation, ET_{oHG} was set equal to ET_{oPM} and the constant '0.0023' was set as '*B*' to be determined. Hence, the modified equation was written as

$$ET_{o\,HG} = ET_{o\,PM} = B\, Ra\, (T_{max} - T_{min})^2 [\, T + 17.8]$$

The modified HG equation is in the form

$$Y=BX$$

Where, Y= $ET_{o\ PM}$; X=Ra $(T_{max} - T_{min})^2[T + 17.8]$. By the known set of values of Y and X, the constant B was determined. the Hargreaves equation achieved by using above logic i-e by changing the value of constant, has been written as HG_{mod1} equation. The value of Ra (extraterrestrial radiation) used in Hargreaves equation was found in literature given by Samani and Hargreaves.

The significance of weather parameter was also tested to determine if the modified HG equation need to be further improvement. This was done using a variable selection method by using the computer model i-e Statistical Package for the Social Sciences (SPSS) in which all the weather parameters are included in the model as variables. These variables are used as potential predictors, and then the least significant variable with the highest P-value is dropped. This step is repeated successively until all the remaining variables are statistically significant level at the α = 0.05. The wind speed is added in adjusted form of HG equation, which is most significant than other climatic variables and Hargreaves equation in this form (adding wind speed) has been written as HG_{mod2} equation.

Performance Evaluation

All comparisons between the different forms of the equations performed by simple linear regression

$$y = b_o + b_1 x$$

where, 'y' is the dependent variable, ET_o_PM; 'x' is the independent variable (ET_o by the different HG forms); 'b_o' is the intercept; and 'b_1' is the slope. The coefficient of determination, R^2, and the RMSE were used for evaluating the different forms of equations. These are based on two sums of squares: Sum of Squares Total (SST) and Sum of

Squares Error (SSE). SST measures how far the data are from the mean and SSE measures how far the data are from the model's predicted values. Different combinations of these two values provide different information about how the regression model compares to the mean model.

R-squared has its ranges from zero to one, zero indicating that the proposed model does not fit to predicted value and one indicating perfect prediction. R^2 is the fraction of the total sum of squares. It was computed as:

$$R^2 = \frac{\left[\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})\right]^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2} \quad (3)$$

Where, y_i = estimated ET_o by the PM method for day i (mm/day); x_i = estimated ET_o by the different types of the HG equation for day i (mm/day) $\bar{x}$ and $\bar{y}$ = average of x_i and y_i; n = total number of observations. The RMSE is the square root of the variance of the residuals. Residuals are the difference between the actual values and the predicted values. It indicates the absolute fit of the model to the data how close the observed data points are to the model's predicted values. Whereas R-squared is a relative measure of fit, RMSE is an absolute measure of fit. Lower values of RMSE indicate better fit.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - x_i)^2}{n}} \quad (4)$$

Where, y_i = estimated ET_o by the PM method for day i (mm/day); x_i = estimated ET_o by the different types of the HG equation for day i (mm/day); n= total no of observations.

RESULTS AND DISCUSSION

The original HG method compared with PM equation for daily, 10-daily, and monthly ET_o estimates. The HG method showed an overestimation of ET_o for all time steps, as shown in Fig. 1 to Fig 2. For daily ET_o, the overestimation is approximately 14% for Bahawalpur, 8% for Bahawalnagar and 25% for Khanpur station. Therefore, the HG method is not recommended for use in the semiarid conditions of the Southern Punjab without being modified according to local conditions. The deviation of results from PM equation is minimized with longer time steps. The results difference between the PM and HG equation were 12% for 10-daily (decade) and 8% for monthly ET estimates for Bahawalpur [Fig.1 (b), (c)], 6% for 10-daily and 5% for monthly ET_o estimates for Bahawalnagar [Fig.2 (b), (c)] and 10% for 10-daily and 8% for monthly estimates for Khanpur stations [Fig.3 (b), (c)], respectively.

Modification of Hargreaves Equation

The modification to the Hargreaves equation is by finding value of constant parameter that minimize the RMSE between ET_o value computed by PM method. The resulting modified HG (HG_{mod1}) equation forms are as follows (eq.5 to eq. 13):

***For Bahawalpur station*;**

For daily ET_o estimation:

$$HG_{mod1} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (5)$$

For 10-daily ET_o estimation;

$$HG_{mod1} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (6)$$

For monthly ET_o estimation:

$$HG_{mod1} = 0.0018Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (7)$$

***For Bahawalnagar station*;**

For daily ET_o estimation:

$$HG_{mod1} = 0.0020Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (8)$$

For 10-daily ET_o estimation:

$$HG_{mod1} = 0.0021Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (9)$$

For monthly ET_o estimation:

$$HG_{mod1} = 0.0020Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (10)$$

***For Khanpur station*;**

For daily ET_o estimation:

$$HG_{mod1} = 0.0017Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (11)$$

For 10-daily ET_o estimation:

$$HG_{mod1} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (12)$$

For monthly ET_o estimation:

$$HG_{mod1} = 0.0017Ra(T + 17.8)\sqrt{(Tmax - Tmin)} \quad (13)$$

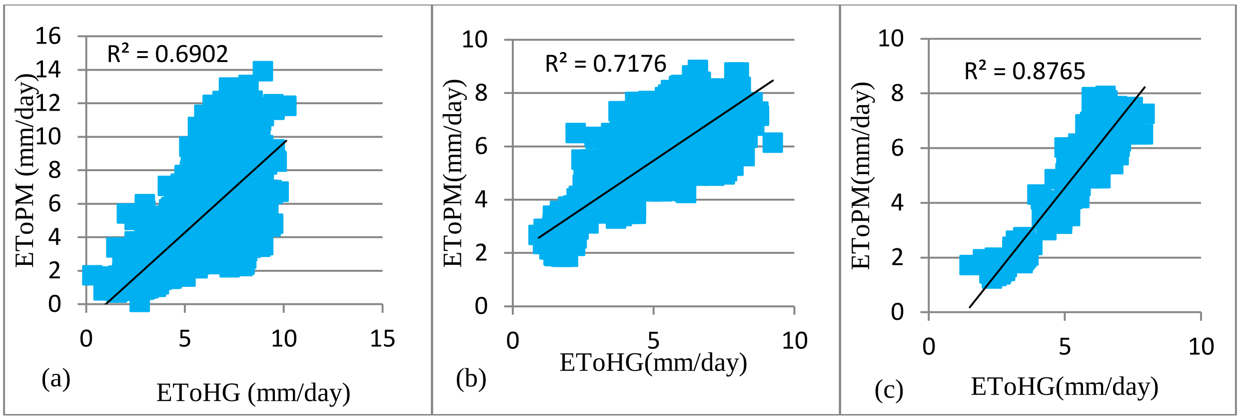

Fig.1Comparison of ET_o_PM with original HG eq. for (a) daily, (b) 10-daily and (c) monthly of Bahawalpur station

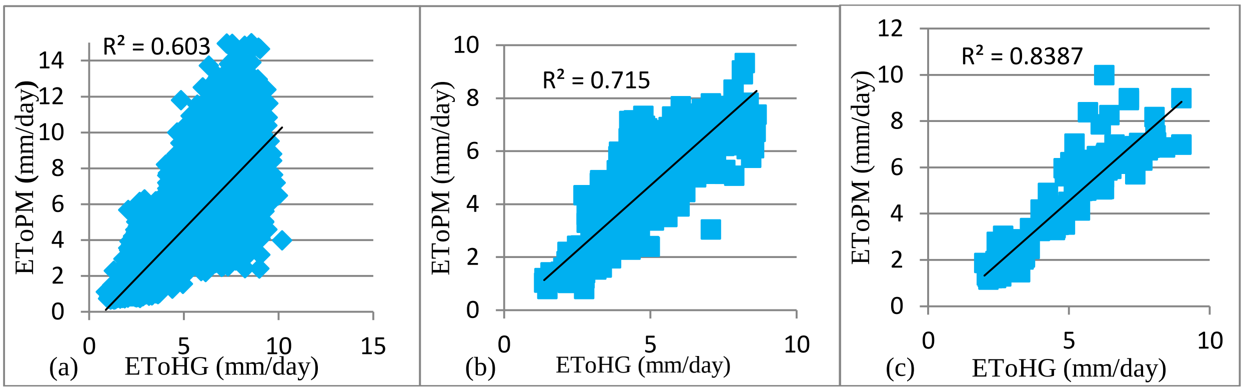

Fig. 2 Comparison of ET_o_PM with original HG for (a) daily, (b) 10-daily and (c) monthly of Bahawalnagar station

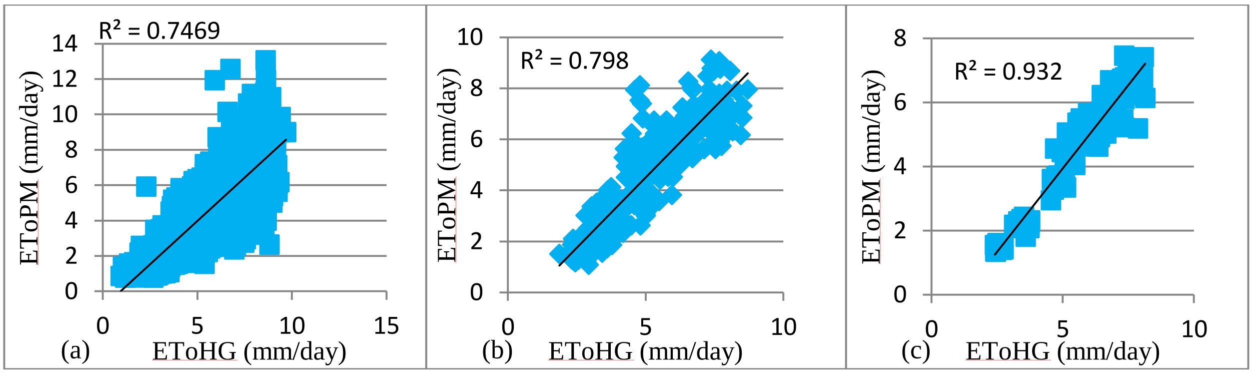

Fig. 3 Comparison of ETo_PM with original HG for (a) daily, (b) 10-daily, (c) monthly of Khanpur station

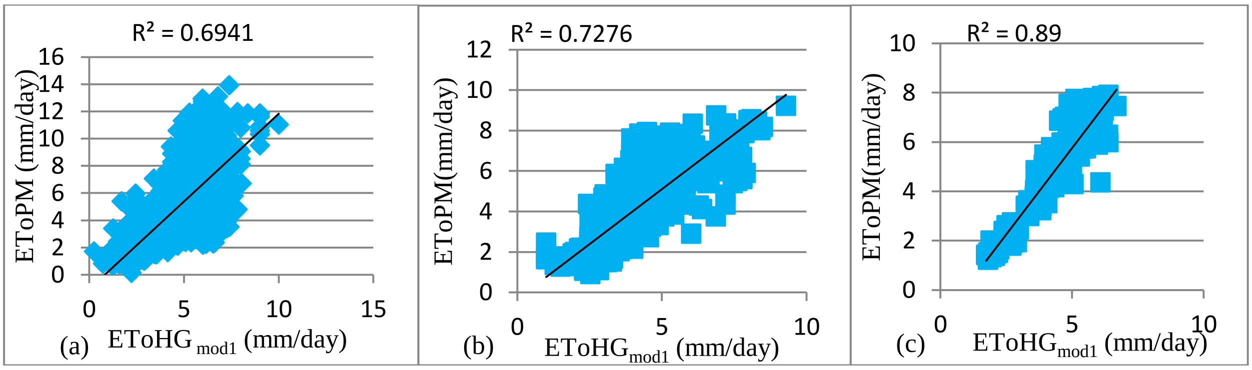

Fig.4 Comparison of ET_o_PM with modified HG (HG_{mod1}) for (a) daily, (b) 10-daily and (c) monthly of Bahawalpur station

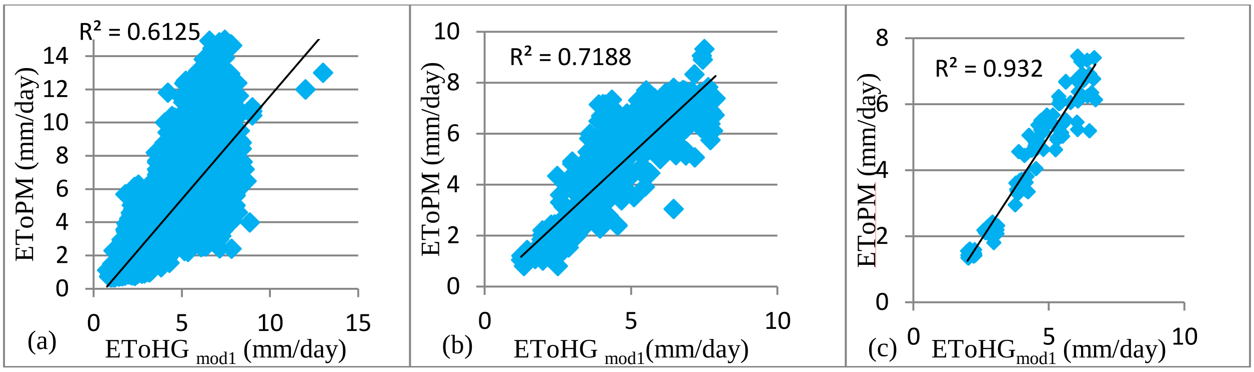

Fig. 5 Comparison of ET_o_PM with modified HG (HG_{mod1}) for (a) daily, (b) 10-daily and (c) monthly of Bahawalnagar station

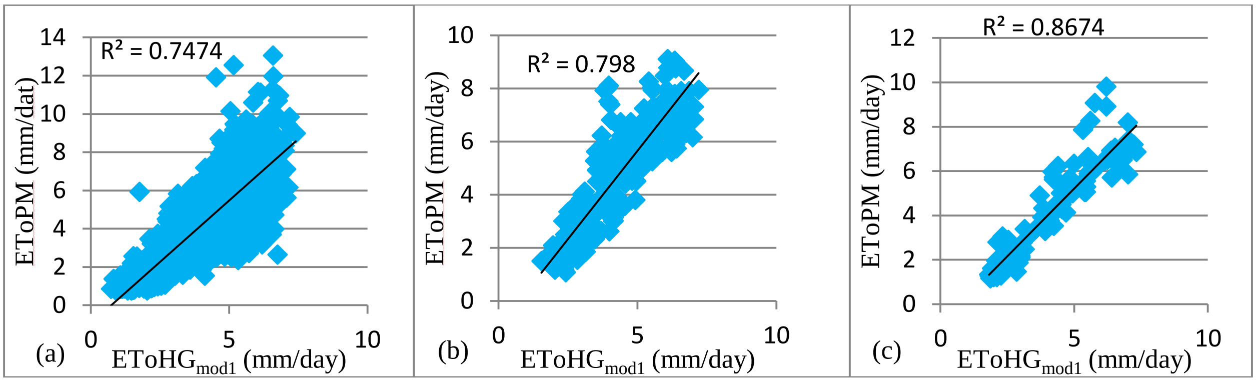

Fig. 6 Comparison of ET_o_PM with modified HG eq (HG_{mod1}) for (a) daily, (b) 10-daily and (c) monthly of Khanpur station

Table -1 Summary results of different forms of HG eq. compared with PM eq. at Bahawalpur station

Summary results of estimated ET_o by HG and PM equations at Bahawalpur Station									
Time Scale	Daily			10-daily			Monthly		
Equation Form	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2
HG	14	1.513	0.690	12	1.297	0.717	8	0.953	0.876
HG_{mod1}	4	1.411	0.694	3	1.105	0.727	2.5	0.950	0.890
HG_{mod2}	0.97	1.327	0.698	0.98	1.070	0.765	0.99	0.805	0.916

Table -2 Summary results of different forms of HG eq. compared with PM eq. at Bahawalnagar station

Summary results of ET_o estimated by HG and PM equations at Bahawalnagar Station									
Time Scale	Daily			10-daily			Monthly		
Equation Form	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2
HG	8	1.821	0.603	6	1.153	0.715	5	1.020	0.838
HG_{mod1}	4	1.800	0.612	2.5	1.121	0.719	2	0.865	0.867
HG_{mod2}	0.97	1.327	0.698	0.98	1.070	0.766	0.98	0.817	0.881

Table -3 Summary results of different forms of HG eq. compared with PM eq. at Khanpur station

Summary results of ET_o estimated by HG and PM equations at Khanpur Station									
Time Scale	Daily			10-daily			Monthly		
Equation Form	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2	Percentage Error	RMSE	R^2
HG	25	1.47	0.746	10	1.078	0.798	8	0.991	0.932
HG_{mod1}	6	1.13	0.747	3.5	0.971	0.801	3	0.595	0.932
HG_{mod2}	1	1.07	0.758	0.98	0.924	0.834	0.98	0.265	0.963

Different studies have done to modified the HG equation by changing the constant value [2-3]. The ETo results calculated by the modified HG equations were again compared to estimated ETo by the PM method. There was an improvement in ET_o estimated by HG equation There was also improvement in R^2 and RMSE, statistical results are shown here in table 1 to table 3 for all time steps. After modifying the HG equation coefficient, and to determine whether an improve estimation of daily, 10-daily and monthly ETo could be achieved by using adjusted HG method, a variable selection method was applied by using Statistical Package for the Social Sciences (SPSS) computer model that suggested the important weather variable to be added to the modified equations for a more accurate ET_o estimate. The wind speed selected by the model as the significant variable for all time steps and added to the modified HG equation. The results of HG equation were improved after adding wind speed, which gives HG_{mod2} equation. The estimation of ET_o from that equation left the percentage error up to 1%. The percentage difference 0.97%, 0.98% and 0.99% with RMSE of 1.327, 1,070 and 0.805 mmd^{-1} were noted at daily, 10-daily and at monthly time steps for Bahawalpur [Fig.4 (a), (b) and (c)], percentage difference 0.97%, 0.98% and 0.98% with RMSE of 1.327, 1.070 and 0.817 mmd-1 were noted at daily, 10-daily and at monthly time step for Bahawalnagar station [Fig.5 (a), (b) and (c)]and %age difference 1%, 0.98% and 0.98% with RMSE of 1.07, 0.924 and 0.265 mmd-1 were noted at daily, 10-daily and at monthly time step for Khanpur station [Fig.6 (a), (b) and (c)], respectively. There was also improvement in coefficient of correlation for all time steps.

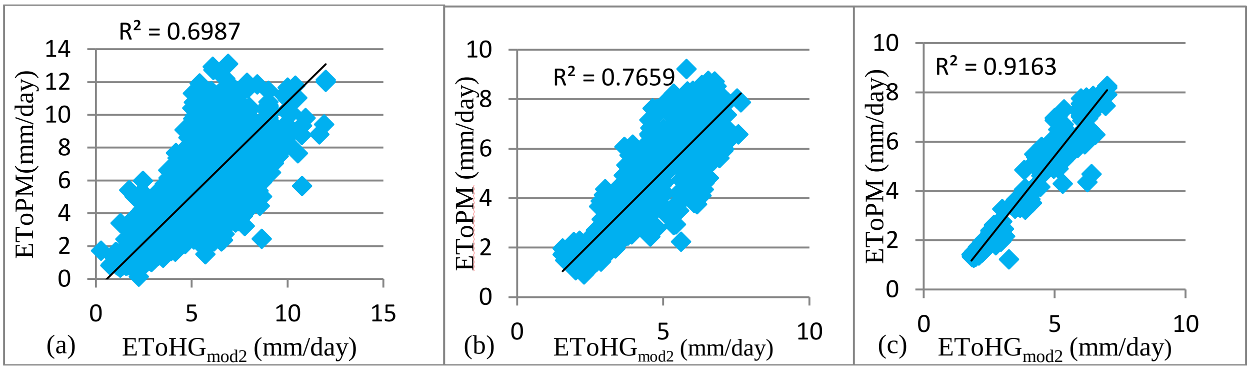

Fig.7 Comparison of ET_PM with modified HG eq. (HG_{mod2}) for (a) daily, (b) 10-daily and (c) monthly of Bahawalpur station

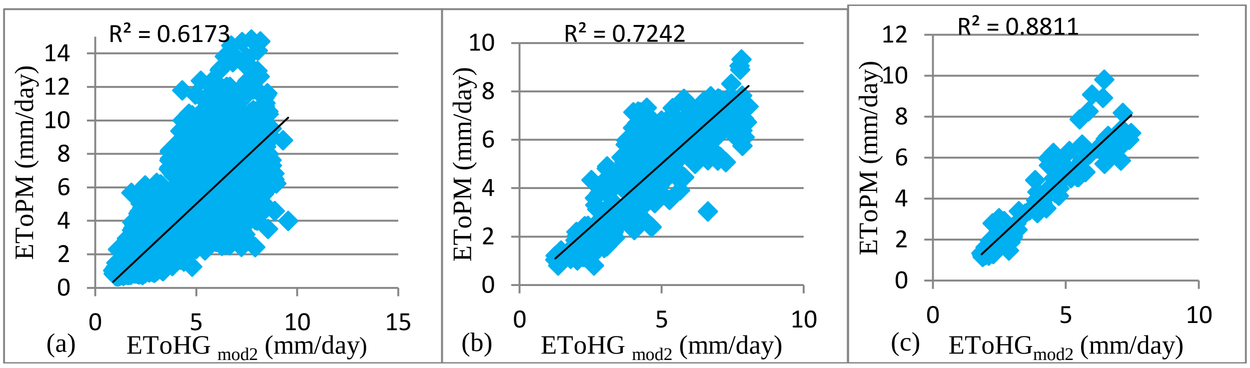

Fig.8 Comparison of ET_PM with modified HG eq. (HG_{mod2}) for (a) daily, (b) 10-daily and (c) monthly of Bahawalnagar station

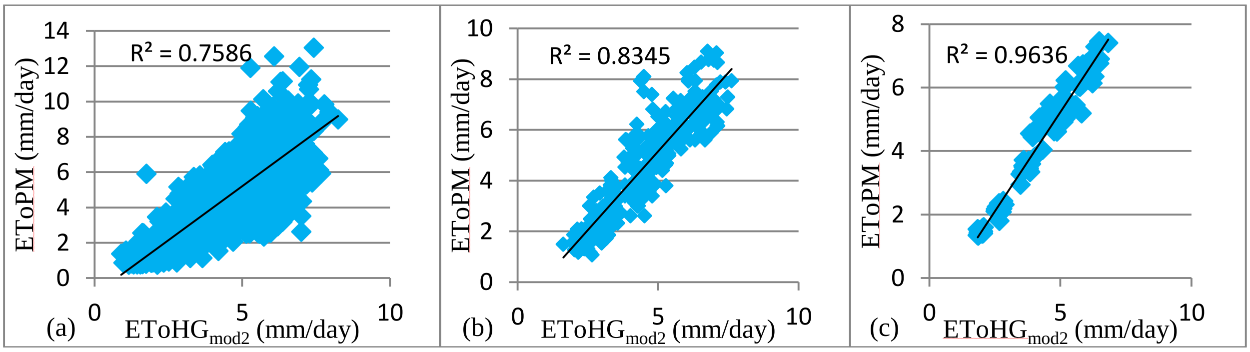

Fig.9 Comparison of ET_PM with modified HG eq. (HG_{mod2}) for (a) daily, (b) 10-daily and (c) monthly of Khanpur station

By adding wind speed in modified HG equation (HG_{mod1}) the following HG equation were developed (eq. 14 to eq. 22), written as HG_{mod2}.

***For Bahawalpur station*;**

For daily ET_o estimation:

$$HG_{mod2} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.0148U \quad (14)$$

For 10-daily ET_o estimation:

$$HG_{mod2} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.2206 \quad (15)$$

For monthly ET_o estimation:

$$HG_{mod2} = 0.0018Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.143U \quad (16)$$

***For Bahawalnagar station*;**

For daily ET_o estimation:

$$HG_{mod2} = 0.0020Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.194U \quad (17)$$

For 10-daily ET_o estimation:

$$HG_{mod2} = 0.0021Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0113U \quad (18)$$

For monthly ET_o estimation:

$$HG_{mod2} = 0.0020Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.060 \quad (19)$$

***For Khanpur station*;**

For daily ET_o estimation:

$$HG_{mod2} = 0.0017Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.1622 \quad (20)$$

For 10-daily ET_o estimation:

$$HG_{mod2} = 0.0019Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.2856U \quad (21)$$

For monthly ET_o estimation:

$$HG_{mod2} = 0.0017Ra(T + 17.8)\sqrt{(Tmax - Tmin)} + 0.314U \quad (22)$$

CONCLUSION

The comparison of daily, 10-daily, and monthly estimates of ET_o showed that the original Hargreaves (HG) equation overestimated ET_o compared to the PM method in Southern Punjab of Pakistan. The HG equation gave better estimates of ET_o when the coefficient was modified and wind speed was added in original Hargreaves equation for Southern Punjab, Pakistan. So, it is suggested that before using HG equation it must be calibrated according to local conditions.

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