

# Quantification of Error in Estimation of Reference Crop Evapotranspiration by Class A Pan Evaporimeter and Its Correction

S. Praharaj, P. K. Mohanty and B. C. Sahoo

**Abstract** Today Penman–Monteith equation is assumed to be the most appropriate model for estimation of reference crop evapotranspiration ( $ET_0$ ) across the globe. However, as the model requires many weather parameters, so it has not been percolated down to the stakeholder's level. Instead pan evaporimeter is being widely used in many parts of the world for estimating approximate  $ET_0$  without considering the degree of error involved in this method. So an attempt has been made in the present study to quantify the percentage of error the stakeholders allowing in estimation of  $ET_0$  as well as crop water requirement. Weekly weather data were collected for 14 years from 2001 to 14 from the crop weather observatory of Orissa University of Agriculture and Technology and put into Penman–Monteith equation for estimation of actual  $ET_0$ . Further, the weekly  $ET_0$  values recorded at the observatory from the depletion of water level in Class A pan evaporimeter for the corresponding period were compared with the actual  $ET_0$ . It was found that the pan evaporimeter is underestimating the parameter to the tune of 50% of the actual  $ET_0$ . A regression analysis between pan  $ET_0$  and Penman–Monteith  $ET_0$  carried out for a period of 12 years from 2001 to 12 discloses linear relationship based on highest  $R^2$  value (0.81) among all the relation functions. Furthermore, the regression model was validated using pan  $ET_0$  data from the observatory for two years (2013–14) with the help of RMSE, percent deviation and Scatter plot. An average RMSE of 0.545 mm/week and percent deviation of  $-5.53$  and  $0.82\%$  in 2013 and 2014, respectively, along with the depiction of Scatter plots in both the years depict close agreement of the model prediction with the actual  $ET_0$  values. It is recommended to use the developed model for estimation of actual  $ET_0$  instead of error-infested pan  $ET_0$  for estimation of crop water requirement and scheduling irrigation in regions having similar agro-climatic conditions.

**Keywords** Reference crop evapotranspiration · Class A pan evaporimeter  
Penman–Monteith equation

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## Introduction

Agriculture accounts for more than 70% of global freshwater withdrawal (FAO 2011; Salazar et al. 2012), out of which 60% is wasted due to leaky irrigation systems and inappropriate application methods that leads to poor irrigation efficiency, decreased crop production and as a whole misuse of the scare resource. United Nations Department of Economic and Social Affairs (UNDESA) in its international decade for action 'Water for life' 2005–2015 reveals that around 700 million people in 43 countries across the globe suffer from water scarcity today.

In agriculture sector, scheduling of irrigation is considered to be the best management option for improving the present scenario of water use. Calculation of crop water requirement is not an easy task at farmer's level. As a result of an Expert Consultation held in May 1990, the FAO Penman–Monteith method is now recommended as the sole standard method for the definition and computation of the reference evapotranspiration ( $ET_0$ ). The FAO Penman–Monteith method requires large number of climatic variables for calculating  $ET_0$ . But, basically, pan evaporation is widely used in agricultural meteorology due to simplicity, low cost, ease of application for irrigation scheduling. However, the density of these stations is not adequate as per recommendation even in developed countries. Complex methods of determination of appropriate timing and depth of irrigation are beyond the capacity of the farmers. The simplest method widely used across the world for estimating reference crop evaporation is pan evaporation method. But the output of the method involves an error of 15% as a whole as compared to Penman–Monteith equation (FAO 24). It may lead to magnification of error while determining the crop evapotranspiration ( $ET_c$ ) of the crop.

Thus, there is a need to develop a user-friendly model for the farmers describing the relationship between the evaporation rate of the pan evaporimeter in the meteorology station and the complex Penman–Monteith as it closely approximates grass  $ET_0$  at the location evaluated, is physically based, and explicitly incorporates both physiological and aerodynamic parameters. This would help to simulate the evapotranspiration rate of the crops grown in his farm and use of the same to assess the soil moisture balance in the crop root zone on daily basis. Thus, the expected outcome would be derivation of a correct irrigation scheduling and calculation of appropriate depth of irrigation by the farmer prior to any irrigation event.

## Materials and Methods

The materials used and methods adopted during the investigation are presented in this section.

## Experimental Site

The experiment was conducted at the Central Research Station, Department of Agronomy, Orissa University of Agriculture and Technology, Bhubaneswar, Odisha, during the year 2013–14. The experimental site is located at 20° 15'N latitude and 82° 52'E longitude at an elevation of 25.9 m above mean sea level.

## Weather Condition

Odisha is characterised by warm and moist climate with hot and humid summer and mild winter. The mean annual rainfall is about 1451 mm out of which 80% downpours during four monsoon months (June–September). The mean maximum temperature during the hottest month of May and June varies from 38 to 40 °C, and the mean minimum temperature during the colder months of December and January varies from 11 to 14 °C. The atmosphere remains quite humid throughout the year with an average relative humidity of 84%. The average wind speed above 2 m from ground level is observed to be 6.5 m s<sup>-1</sup>. Occurrence of one or two cyclonic storms in each year during monsoon season is the natural climatic phenomenon, and it is mostly due to formation of low pressure at some point in the Bay of Bengal.

## Theoretical Consideration

FAO Penman–Monteith equation is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where  $ET_0$  = reference evapotranspiration [mm day<sup>-1</sup>],  $R_n$  = net radiation at the crop surface [MJ m<sup>-2</sup> day<sup>-1</sup>],  $G$  = soil heat flux density [MJ m<sup>-2</sup> day<sup>-1</sup>],  $T$  = mean daily air temperature at 2 m height [°C],  $u_2$  = wind speed at 2 m height [m s<sup>-1</sup>],  $e_s$  = saturation vapour pressure [kPa],  $e_a$  = actual vapour pressure [kPa],  $(e_s - e_a)$  = saturation vapour pressure deficit [kPa],  $\Delta$  = slope of vapour pressure curve [kPa °C<sup>-1</sup>],  $\gamma$  = psychrometric constant (kPa °C<sup>-1</sup>).

All these data were collected for a period of 15 years (2001–2014) from the meteorological observatory in the central station of OUAT, Bhubaneswar. Apart from these data, the net radiation at the crop surface, soil heat flux, saturation and actual vapour pressure, psychrometric constant etc., were estimated based on the geographical location of the experimental site and referring some standard table values.

$$R_n = R_{ns} - R_{nl} \quad (2)$$

$$R_{ns} = 0.77R_s = 0.77(0.25 - 0.5S)R_a \quad (3)$$

$$S = n/N$$

$$R_{nl} = \sigma \left[ \frac{T_{\max}K^4 + T_{\min}K^4}{2} \right] (0.34 - 0.14\sqrt{e_a}) \left( 1.35 \frac{R_s}{R_{so}} - 0.35 \right) \quad (4)$$

where  $R_{ns}$  = short-wave radiation [ $\text{MJ m}^{-2} \text{ day}^{-1}$ ],  $R_{nl}$  = net outgoing long-wave radiation [ $\text{MJ m}^{-2} \text{ day}^{-1}$ ],  $\sigma$  = Stefan–Boltzmann constant [ $4.903 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ day}^{-1}$ ],  $T_{\max}$   $K$  = maximum absolute temperature during the 24-h period [ $K = ^\circ\text{C} + 273.16$ ],  $T_{\min}$   $K$  = minimum absolute temperature during the 24-h period [ $K = ^\circ\text{C} + 273.16$ ],  $e_a$  actual vapour pressure [kPa],  $R_s/R_{so}$  relative short-wave radiation (limited to  $\leq 1.0$ ),  $R_s$  measured or calculated solar radiation [ $\text{MJ m}^{-2} \text{ day}^{-1}$ ],  $R_{so}$  calculated clear-sky radiation [ $\text{MJ m}^{-2} \text{ day}^{-1}$ ].

$$P = 101.3 \left( \frac{293 - 0.0065z}{293} \right)^{5.26} \quad (5)$$

where  $P$  = atmospheric pressure [kPa];  $z$  = elevation above sea level [m].

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665 \times 10^{-3} P \quad (6)$$

where  $\gamma$  = psychrometric constant [ $\text{kPa } ^\circ\text{C}^{-1}$ ],  $P$  = atmospheric pressure [kPa],  $\lambda$  = latent heat of vaporisation,  $2.45 \text{ [MJ kg}^{-1}]$ ,  $C_p$  = specific heat at constant pressure,  $1.013 \times 10^{-3} \text{ [MJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}]$ ,  $\varepsilon$  = ratio molecular weight of water vapour/dry air = 0.622.

$$\text{RH} = 100 \frac{e_a}{e^o(T)} \quad (7)$$

The saturation vapour pressure is related to air temperature, and the following equation has been used to determine it.

$$e^o(T) = 0.6108 \exp \left[ \frac{17.27T}{T + 237.3} \right] \quad (8)$$

where  $e^o(T)$  = saturation vapour pressure at the air temperature  $T$  [kPa];  $T$  = air temperature [ $^\circ\text{C}$ ].

$$\Delta = \frac{4098 \left[ 0.6108 \exp \left( \frac{17.27T}{T + 237.3} \right) \right]}{(T + 237.3)^2} \quad (9)$$

where  $\Delta$  = slope of saturation vapour pressure curve at air temperature  $T$  [kPa °C<sup>-1</sup>];  $T$  = air temperature [°C]; exp[...] 2.7183 (base of natural logarithm) raised to the power [...].

$$e_a = \frac{e^\circ(T_{\min}) \frac{RH_{\max}}{100} e^\circ(T_{\max}) \frac{RH_{\min}}{100}}{2} \quad (10)$$

where  $e_a$  = actual vapour pressure [kPa];  $e^\circ(T_{\min})$  = saturation vapour pressure at daily minimum temperature [kPa];  $e^\circ(T_{\max})$  = saturation vapour pressure at daily maximum temperature [kPa];  $RH_{\max}$  = maximum relative humidity [%];  $RH_{\min}$  = minimum relative humidity [%].

$R_a$  and  $N$  are functions of latitude, date and time of day. Monthly values of  $R_a$  and  $N$  throughout the year for different latitudes are taken from the standard table (Kumar and Singh 2005).

$$\text{Equivalent evaporation [mm day}^{-1}] = 0.408 \times \text{Radiation [MJ m}^{-2} \text{ day}^{-1}] \quad (11)$$

$$G = c_s \frac{T_i - T_{i-1}}{\Delta t} \Delta z \quad (12)$$

where  $G$  = soil heat flux [MJ m<sup>-2</sup> day<sup>-1</sup>],  $c_s$  soil heat capacity [MJ m<sup>-3</sup> °C<sup>-1</sup>],  $T_i$  = air temperature at time  $i$  [°C],  $T_{i-1}$  = air temperature at time  $i - 1$  [°C],  $\Delta t$  = length of time interval [day],  $\Delta z$  = effective soil depth [m].

## Determination of ET<sub>0</sub> Using US Class A Pan Evaporimeter

Daily reference crop evapotranspiration was calculated from the US Class A pan evaporimeter installed in the crop weather observatory of the central farm.

The pan evaporation is expressed as:

$$ET_0 = K_p \times E_{\text{pan}} \quad (13)$$

where  $K_p$  = pan coefficient and its value is assumed to be 0.7;  $E_{\text{pan}}$  = pan evaporation rate, mm/day.

## Development of Model

Calculation of the ET<sub>0</sub> by both FAO Penman–Monteith equation and the US Class A pan evaporimeter was made on weekly basis for 12 years from 2001 to 2012. Using these two sets of data, the relationship between the ET<sub>0</sub> by Penman–Monteith

method and reference crop evapotranspiration estimated by pan evaporimeter was developed through putting the data to various relation functions such as linear, exponential, power, polynomial (2nd degree), and logarithmic inbuilt into the Microsoft Excel software. Thus, the  $ET_0$  models were developed.

## Validation of Model

This model was used to predict  $ET_0$  using pan evaporimeter data for two years, namely 2013 and 2014. Based on a comparison study between these predicted values of  $ET_0$  and the actual  $ET_0$  values estimated by Penman–Monteith equation, the model validation process was carried out. Statistical methods such as root-mean-squared error (RMSE), percent deviation, Scatter plots and Nash–Sutcliffe model accuracy test were used to verify the prediction ability of the model developed.

## Root-Mean-Square Deviation or Error

$$RMSE = \sqrt{\frac{\sum_{t=1}^n (x_{1,t} - x_{2,t})^2}{n}}. \quad (14)$$

## Percent Deviation

$$\% \text{ deviation} = [(\text{Actual value} - \text{Expected value}) * 100] / \text{Expected value} \quad (15)$$

## Scatter Plot

A graph of plotted points shows the relationship between two sets of data. Scatter plots are important in statistics because they can show the extent of prediction efficiency of the model through eye observation only.

## Nash–Sutcliffe Model Accuracy Test

Nash–Sutcliffe model efficiency coefficient is used to assess the predictive power of hydrological models. It is defined as:

$$E = 1 - \left( \sum_{t=1}^T (Q_o^t - Q_m^t)^2 \div \sum_{t=1}^T (Q_o^t - Q_o^-)^2 \right) \quad (16)$$

where  $Q_o$  is the mean of observed discharges and  $Q_m$  is modelled discharge.  $Q_o^t$  is observed discharge at time  $t$ . Nash–Sutcliffe coefficient is an indicator of the model's ability to predict about the 1:1 line between observed and simulated data. With Nash–Sutcliffe measure, an r-square coefficient is calculated. Coefficient values equal to 1 indicate a perfect fit between observed and predicted data, and values less than or equal to 0 indicate that the model is predicting no better than using the average of the observed data.

## Results and Discussion

### *Comparison of $ET_0$ Values Estimated by Penman–Monteith and Pan Evaporimeter*

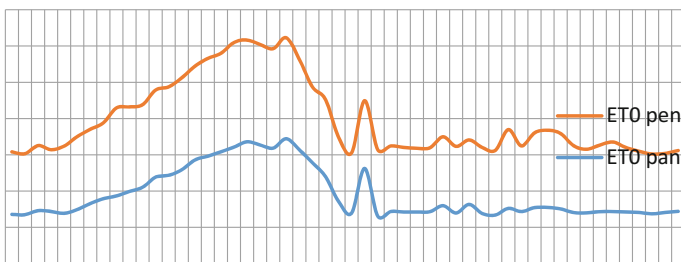
Weekly  $ET_0$  values are estimated by FAO Penman–Monteith equation and pan evaporimeter for 14 years from 2001 to 2014. The average  $ET_0$  values for each week are presented in Table 1. It is observed that in almost all the weeks, the actual  $ET_0$  value estimated by FAO Penman–Monteith equation remains higher than the corresponding  $ET_0$  values measured by pan evaporimeter. The fact has been illustrated through Fig. 1. It may be seen that the  $ET_0$  values in both the methods are remaining highest during 17th week to 24th week of the year and this period coincides with the peak summer in the region. Similarly, the  $ET_0$  values estimated by both the methods are found lying low during initial and end weeks of the year and this period coincides with peak winter in the region.

The point of concern is that the  $ET_0$  values obtained from the pan evaporimeter throughout the year are lying considerably low as compared to the actual  $ET_0$  estimated by FAO Penman–Monteith equation. The difference is observed to vary from 3 to 6.2 cm per week. The percent of error in estimation of  $ET_0$  by pan evaporimeter is sometimes more than 50% in the study region. Thus, keeping the high level of error involved in estimation of  $ET_0$  by pan evaporimeter, it is not at all recommended to use pan evaporation data as such for deciding the irrigation scheduling as well as computing the crop water requirement.

As the  $ET_0$  values are under-predicted in all the weeks by pan evaporimeter method, so the crop water requirement estimated would be very low in comparison with the actual. The irrigation amount applied based on this value would again be inadequate as compared to the actual water requirement of the crop. Thus, the yield of crop is bound to remain below the normal yield of the crop. On the other hand, the irrigation frequency will be quicker leading to application of more water to the crop. Thus, a relationship needs to be developed between the  $ET_0$  values observed

**Table 3.1** Average weekly ET<sub>0</sub> values estimated by FAO Penman–Monteith and pan evaporimeter

Week no.	ET <sub>0</sub> pan	ET <sub>0</sub> P–M	Week no.	ET <sub>0</sub> pan	ET <sub>0</sub> P–M
1	2.71	3.45	27	2.79	3.32
2	2.70	3.36	28	5.25	3.74
3	2.92	3.59	29	2.62	3.66
4	2.87	3.40	30	2.87	3.62
5	2.77	3.71	31	2.85	3.56
6	2.98	4.03	32	2.85	3.51
7	3.31	4.09	33	2.86	3.53
8	3.58	4.19	34	3.19	3.80
9	3.73	4.86	35	2.79	3.67
10	3.98	4.66	36	3.27	3.55
11	4.20	4.56	37	2.76	3.64
12	4.76	4.80	38	2.68	3.57
13	4.86	4.88	39	3.05	4.34
14	5.17	5.07	40	2.87	3.62
15	5.71	5.17	41	3.08	4.12
16	5.93	5.39	42	3.10	4.26
17	6.17	5.43	43	3.02	4.16
18	6.43	5.77	44	2.81	3.69
19	6.72	5.61	45	2.80	3.51
20	6.54	5.54	46	2.87	3.67
21	6.37	5.49	47	2.87	3.84
22	6.89	5.57	48	2.85	3.55
23	6.28	4.99	49	2.82	3.37
24	5.57	4.18	50	2.75	3.29
25	4.80	4.25	51	2.82	3.26
26	3.43	3.55	52	2.88	3.36



**Fig. 3.1** Comparison between ET<sub>0</sub> measured by pan evaporimeter and estimated by FAO Penman–Monteith method



by pan evaporimeter and those of the FAO Penman–Monteith which would enable the stakeholders to compute the crop water requirement accurately and develop a correct approach for deciding irrigation scheduling for the crops grown in the zone.

### Relationship Between $ET_0$ Calculated by Pan Evaporimeter and Penman–Monteith Methods

Average values of  $ET_0$  estimated on weekly basis by FAO Penman–Monteith and pan evaporimeter methods were put into regression analysis, and the relationship between them is shown through Fig. 2a–e. Relationship between  $ET_0$  measured

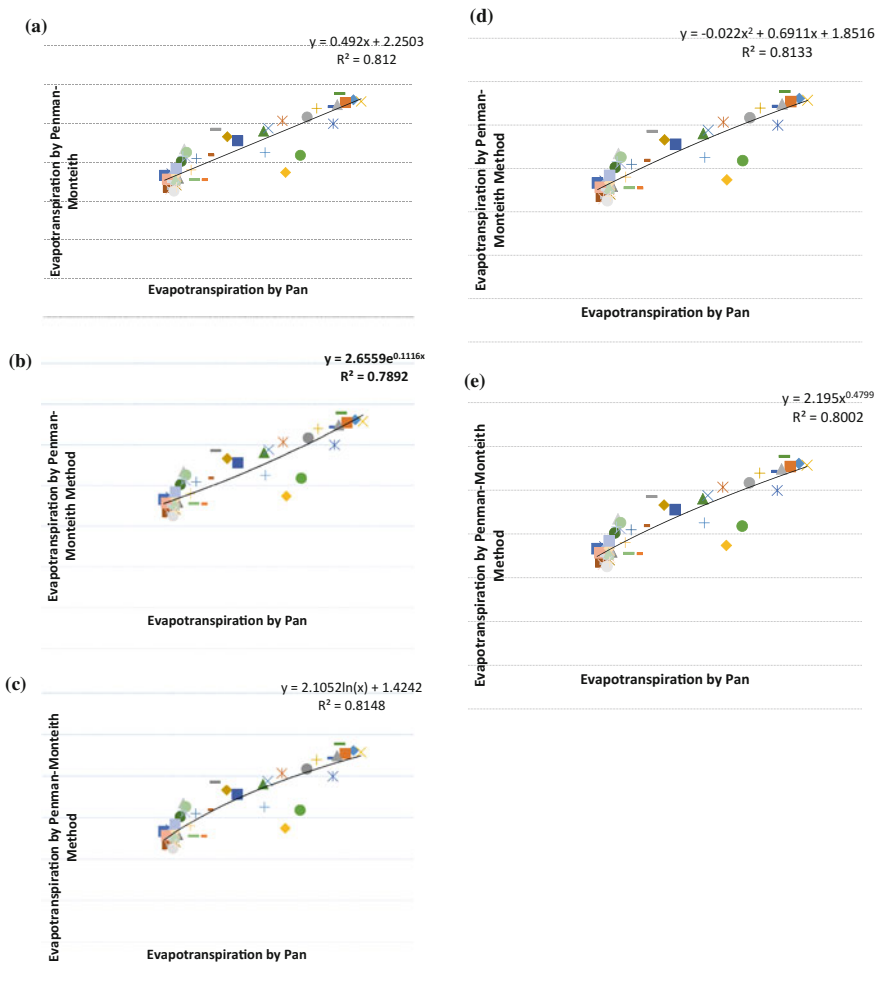


Fig. 3.2 Relationship between  $ET_0$  estimated by FAO P–M method and pan evaporation method

by pan evaporimeter and that estimated by Penman–Monteith method had been described through various relation functions such as linear, exponential, power, polynomial (2nd degree), and logarithmic. Among the relation functions, the data set are showing a perfect matching trend under linear function based on highest value of coefficient of determination ( $R^2$ ) i.e. 0.8148. In rest of the functions, though the data sets are matching, the  $R^2$  values are found to be smaller than the former. Hence, the relation function between  $ET_0$  estimated by FAO Penman–Monteith and pan evaporimeter is found to be linear as shown in Fig. 2a. The corresponding equation that describes the relation between the Penman–Monteith and pan evaporimeter is expressed as:

$$Y = 0.492(X) + 2.2503 \quad (17)$$

where  $Y$  = predicted  $ET_0$  and  $X$  =  $ET_0$  measured by pan evaporimeter.

The model developed for converting pan  $ET_0$  to the actual  $ET_0$  (FAO Penman–Monteith  $ET_0$ ) has been validated using the pan evaporation data for two years, namely 2013 and 2014.

## Validation of the Model

The developed  $ET_0$  model was used to convert the  $ET_0$  values obtained from the pan evaporimeter during the year 2013–2014. The predicted values thus obtained were compared with the  $ET_0$  values estimated by FAO Penman–Monteith equation in the respective years. The estimated and predicted  $ET_0$  values for both the years are presented in Appendix A. Statistical tools like RMSE, percent deviation, Scatter plots and Nash–Sutcliffe model accuracy test have been used in the process of validation of the model.

The values of RMSE between the predicted and actual  $ET_0$  were found to be very less in both the years. While in case of the year 2013, the error came around 0.622 mm/week and it was 0.468 mm/week in the year 2014. It indicates that there is marginal error in using the model for prediction of the  $ET_0$  values. In addition to it, the prediction efficiency of the model was again established by the minimal percent deviation of  $-5.53\%$  in 2013 and  $0.82\%$  in the year 2014. In the first year of simulation, the model is observed to under-predict the  $ET_0$  values by  $5.53\%$  only, and in the year 2014, the same has been over-predicted by an amount of only  $0.82\%$ . In both the years, the deviation of the predicted  $ET_0$  values is very less and so, it may be taken for granted that the developed model is capable of converting the pan evaporimeter  $ET_0$  values to the actual  $ET_0$  values as estimated by FAO Penman–Monteith equation.

Also, the strong prediction efficiency of the developed model in converting pan  $ET_0$  to Penman–Monteith  $ET_0$  has been established through the use of Scatter plots as shown in Figs. 3 and 4 for the year 2013 and 2014, respectively. It is depicted from Fig. 3 that the predicted values of  $ET_0$  are both over-and

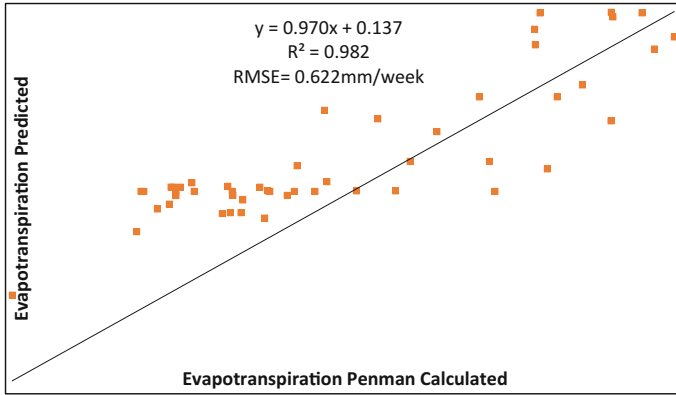


Fig. 3.3 Scatter plot of P–M  $ET_0$  versus pan  $ET_0$  during 2013

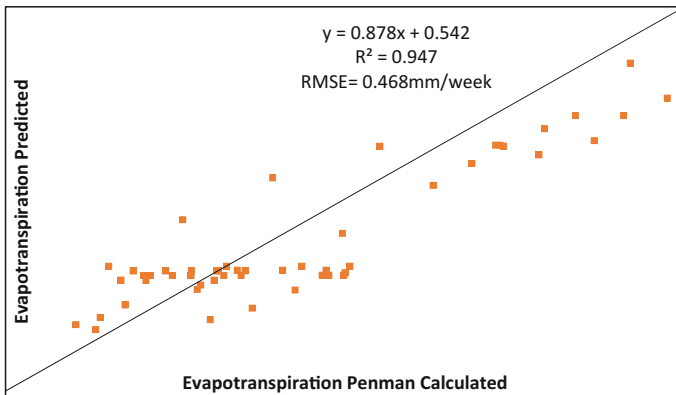


Fig. 3.4 Scatter plot of P–M  $ET_0$  versus pan  $ET_0$  during 2014

under-predicted but the predicted values lie close to the 1:1 line. The percent deviation is within 10%, and thus it establishes the fact that the prediction efficiency of the model is very high. Similarly, in the year 2014, the Scatter plot of  $ET_0$  by pan evaporimeter and Penman–Monteith as illustrated in Fig. 4 indicates the minimal gap between the predicted and the actual values of  $ET_0$ . The percent deviation of only 0.82% emphatically pronounces the high-degree predictability of the model. In this case, the RMSE is still lower than the previous year. The distribution of predicted points very close to and at both sides of 1:1 line implies a high degree of prediction efficiency of the model.

Finally, the Nash–Sutcliffe model accuracy tests give  $r^2$  value of 0.94 in the model validation process. This value is very close to unity which clearly shows accuracy of the model. From the discussion made above, it may be concluded at this point that using pan evaporimeter data for estimation of crop water requirement as

well as taking decision on irrigation scheduling should not be recommended for the study area. Whenever there is no access to Penman–Monteith  $ET_0$  values, the developed model should be used to convert the pan  $ET_0$  values to the actual  $ET_0$  values correctly.

## Conclusions

The following conclusions may be drawn at the end of the present study. These are:

- Measurement of  $ET_0$  by pan evaporimeter is an erroneous approach as a high degree of difference is observed between the pan  $ET_0$  and FAO Penman–Monteith  $ET_0$  values throughout the year. The difference is observed to be more than 50% in almost all the weeks of the year. Hence, use of pan data for computation of crop water requirement and taking decision on irrigation scheduling involves considerable error.
- Pan  $ET_0$  values should be put to the model developed in the present study to convert the erroneous pan  $ET_0$  values to actual FAO Penman–Monteith  $ET_0$  values. It is so because the model predicts the  $ET_0$  values accurately close to the actual with minimal percent deviation (<10%) and less RMSE (<0.65 mm/week).
- The model developed in the present study may be reliably used for converting the pan  $ET_0$  values to the actual FAO Penman–Monteith  $ET_0$  values in the regions having similar agro-climatic conditions.

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