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Evaluation of Methods for Estimation of Reference Evapotranspiration

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ABSTRACT

Reference evapotranspiration (ET_0) plays a key role in irrigation systems design and agricultural water management under both irrigated and rainfed situations. This study was carried out with the objective to compare the performance of Energy-Balance, Aerodynamic, Penman, Priestley-Taylor and Stephen-Stewart methods for the hilly and plain regions of north India for estimation of reference evapotranspiration with data intensive Modified Penman-Monteith (PENMON) method using the daily weather data acquired from automatic weather station during 2013-14 and 2014-15. The performance evaluation of selected methods was carried out using linear regression and simple statistical analysis. The Most suitable method was compared with the methods reported for the various hilly and plain regions of the north India to suggest a substitute of PENMON method for estimation of reference evapotranspiration using minimal climatic parameters which are easily available. It was observed that the Penman method performed the best for hilly as well as for the plain regions and was in line with estimated ET_0 by PENMON method with coefficient of determination (R^2) of 0.95 and 0.89 and root mean square error (RMSE) 0.60 mm day^{-1} and 0.58 mm day^{-1} during 2013-14 and 2014-15, respectively. However, as compared to plain regions the value of ET_0 estimated by Penman method was observed to be less for the hilly regions. Moreover, the Penman method requires only daily mean temperature, wind speed, air pressure, and solar radiation data.

1. Introduction

Evapotranspiration (ET) is considered to be the dominant component of the hydrologic cycle due to the fact that about 60% of annual precipitation falling over the land surface is returned to atmosphere as ET (FAO, 2003). Under the semi-arid or arid climatic conditions coupled with low and erratic rainfall, water is the most limiting factor for agricultural productivity and irrigation planning. Development of an efficient irrigation system is essential for the sustainable crop production and which ultimately govern by evaporative demand of atmosphere. Reference evapotranspiration (ET_0) is one of the most important parameter for climatological, hydrological and agricultural studies. FAO defined ET_0 as evapotranspiration from the reference crop such as *alfa-alfa* grass with an assumed height of 12 cm, with a surface resistance of 70 Sm^{-1} and an albedo of 0.23, actively growing in large area and without shortage of water during the entire growing period. Reference evapotranspiration (ET_0) is crucial for regional water balance studies, irrigation scheduling, agricultural and urban planning and agro climatological zoning investigations. Crop evapotranspiration is estimated by multiplying the reference evapotranspiration by crop-specific crop coefficient (K_c) values at different crop growth stages. Moreover, different reference evapotranspiration methods have been developed over the years range from direct measurement from a reference surface such as *alfa-alfa* grass (Doorenbos and Pruitt, 1977; Watson and Burnett, 1995) or can be computed from weather data based methods *i.e.* (a) temperature based (Thornthwaite, 1948; Doorenbos and Pruitt, 1977),(b) radiation based (Doorenbos and Pruitt, 1977;

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Hargreaves and Samani, 1985), and (c) combinations methids (FAQ-56 Penman-Monteith) (Allen *et al*., 1998. Numerous studios worldwide have shown that the FAQ-56 Penam-Monteith (PM) method is the most accurate method under various climatic conditions and declared as standard method for calculating reference evapotranspiration by FAO (Jensen *et al*., 1990; Allen *et al*., 1998; Irmak *et al*., 2003, 2008; Hargreaves and Allen, 2003; Tabari *et al*., 2011). However, the major drawback of FAO56 Penman-Monteith method is that it requires numerous weather data *viz.* maximum and minimum air temperature, maximum and minimum relative humidity, atmospheric pressure, wind speed, wet bulb and dry bulb temperature, dewpoint temperature, daily net radiation, daylight hours etc. which are not easily available in many meteorological stations especially in hilly regions of India. Therefore, application of alternative ET_0 equations that require a few meteorological parameters is necessary for locations where weather parameters required for PM method are not available. Keeping in view of the above, the present study was undertaken to compare different methods with standard FAO-56 Modified Penman-Monteith method (PENMON) for estimation of reference evapotranspiration (ET_0) and to recommend alternative methods for Plain and hilly region of North India. Therefore, in this study different empirical methods *viz.* Energy-balance method, Aerodynamic method, Penman method, Stephens-Stewart and Priestley- Taylor method have been analysed and compared with the PENMON method for estimation of ET_0.

2. Materials and Methods

The daily weather data were acquired for the reported period of two years from automatic weather station (AWS) located between 28° 37’ 22” to 28° 39’ 00” N latitude and 77^0 8' 45" to 77^0 10' 24" E longitudes with an average elevation of 230 m above mean sea level in the ICAR-IARI campus, New Delhi. The study area falls under the agro-climate region (ACR) –VI of Trans Gangetic plains. The hilly region oh Himalaya starts from the distance of 300 km and extends up to the borders of China, Bhutan, and Nepal. The maximum temperature varies from 41°C to 46 °C (May-June) while minimum temperature ranges from 4 °C to 7 °C (during January), The mean open pan evaporation reaches as high as 12.88 mm per day during the month of June, however it is as low as 0.6 mm per day during January. Average annual rainfall of Delhi is about 611 mm, 74% of which is received during active south-west monsoon month’s *viz.* July, August and September. The mean wind velocity varies from a minimum of 3.5 km hr^{-1} during October to 6.4 km hr^{-1} during April. Storms with high wind speed are generally associated with winter showers.

Input parameters used in the calculation of ET_0 by different ET_0 estimation methods are presented in Figs. 1 & 2, respectively Methods and equations for estimation of Reference evapotranspiration (ET_0): The selection of the 5 reference evapotranspiration equations was based on their simplicity in terms of number of climate parameters available at any region to obtain the ET_0.

Modified Penman-Monteith method: Modified Penman-Monteith method by FAO is the well-known standard method for the estimation of reference evapotranspiration. Allen *et al.,* (1998) presented the following form of the Penman-Monteith model for estimation of ET_0 in mm/day:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U_2(e_a - e_d)}{\Delta + \gamma(1 + 0.34\, U_2)}$$

Where: ET_0 is reference evapotranspiration (mm day^{-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_a is saturation vapor pressure (kPa); e_d is actual vapor pressure (kPa);(e_a - e_d) is saturation vapor pressure deficit (kPa); Δ is slope vapor pressure curve (kPa $^oC^{-1}$) and γ is psychometric constant (kPa $^oC^{-1}$).

Energy Balance method: Evaporation in mm, E_r by energy balance method can be calculated using following equation:

$$E_r = \frac{1}{\rho_w l_v}(R_n - H_s - G)$$

Where: E_r is evaporation (mm) by energy balance method; l_v is latent heat of vaporization (kJ/kg); ρ_w is water density (kg/m^3); R_n is net radiation flux (W/m^2); H_s is sensible heat flux (W/m^2) and G is ground heat flux (W/m^2).

Aerodynamic method: Aerodynamic evaporation, Ea (mm) was calculated using the following equation:

$$E_a = B\,(e_w - e_a)$$

Where: B is vapour transfer coefficient; e_a is actual vapour pressure (kPa) at air temperature and e_s is saturated vapour pressure (kPa).

Penman method: The equation was developed by Penman (1948) to compute evaporation from open water surface using weather data. Penman equation is based on physical principles of energy budget and mass transfer. This combination type of equation is given as:

$$E_{Penman} = \frac{\Delta}{\Delta + \gamma} E_r + \frac{\gamma}{\Delta + \gamma}\, E_a$$

Figure 1. Weekly meteorological data during November-March 2013-14

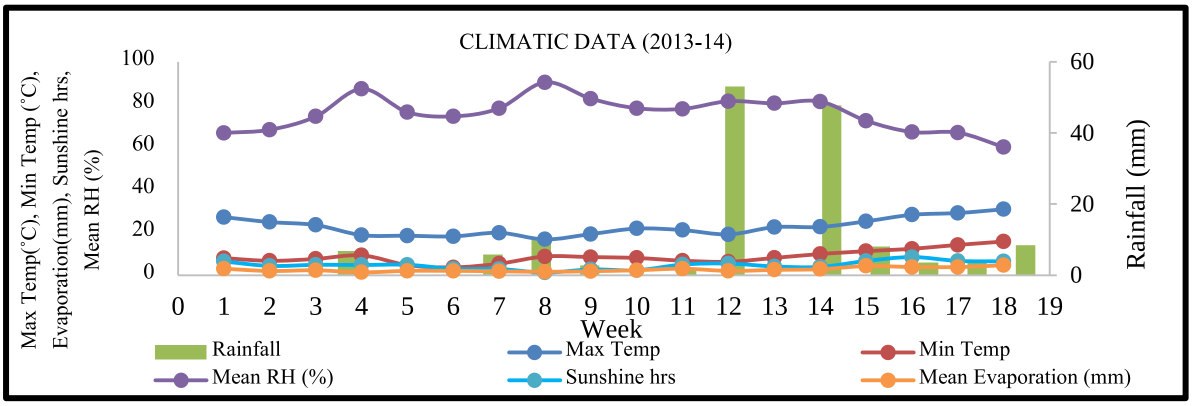
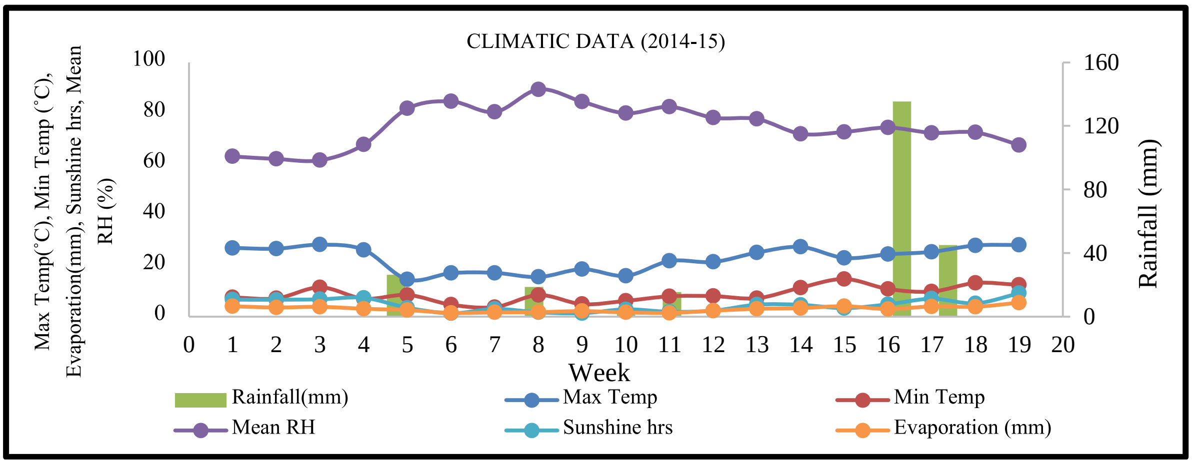


Figure 2. Weekly meteorological data during November-March 2014-15



Where: E_{Penman} is evaporation (mm) calculated by Penman model; Er is the net radiation expressed in terms of equivalent evaporation (mm/day); Ea is evaporation by aerodynamic method (mm/day); Δ is the slope of the saturation vapour pressure curve at given air temperature (kPa $^{o}C^{-1}$) and γ is the psychrometric constant (kPa $^{o}C^{-1}$).

Priestley-Taylor method: Priestley and Taylor (1972) proposed an equation to calculate potential evaporation. The aerodynamic component was deleted and the energy component was multiplied by a short wave reflectance coefficient (albedo), α = 1.26. The Priestley–Taylor approach for estimating evaporation under conditions of minimum advection and neglecting heat flux into ground for daily interval is described as: $E_{PT} = \alpha \frac{\Delta}{\Delta+\gamma} E_r$

Where: E_{PT} is evaporation (mm) by Priestley-Taylor model; α is a constant and E_r is the net radiation expressed in terms of equivalent evaporation (mm/day); Δ is the slope of the saturation vapor pressure curve at given air temperature (kPa $^{o}C^{-1}$) and γ is the psychrometric constant (kPa $^{o}C^{-1}$).

Stephens and Stewart Method: Stephens and Stewart model (Stephens and Stewart, 1963) is an empirical linear equation and require only radiation and temperature data.

$$E_{SS} = SR(a + bT_{mean})$$

Where: Ess is evaporation in mm by Stephens and Stewart model; SR is solar radiation expressed as equivalent water evaporation (mm/day); T_{mean} is mean air temperature (^{o}C), a and b are fitting constants. The value of a and b was used 0.10 and 0.027, respectively. Solar radiation was calculated with the Angstrom formula, which relates solar radiation to extra-terrestrial radiation and relative sunshine duration (Allen *et al.,* 1998).

Estimation of ET0 by different methods: Reference Evapotranspiration using the weather data for the reported period of 2013-14 and 2014-15 was estimated using an interface in MATLAB software named as EEIS ver 1.0. The captured screen of the EEIS 1.0 interface in MATLAB is presented in Fig. 1. The interface provide the option to identify available weather parameter and then suggests different ET_0 estimation methods based on the available data. Besides this, the software calculates ET_0 for six different methods both in graphical plot and data output in excel format for further analysis.

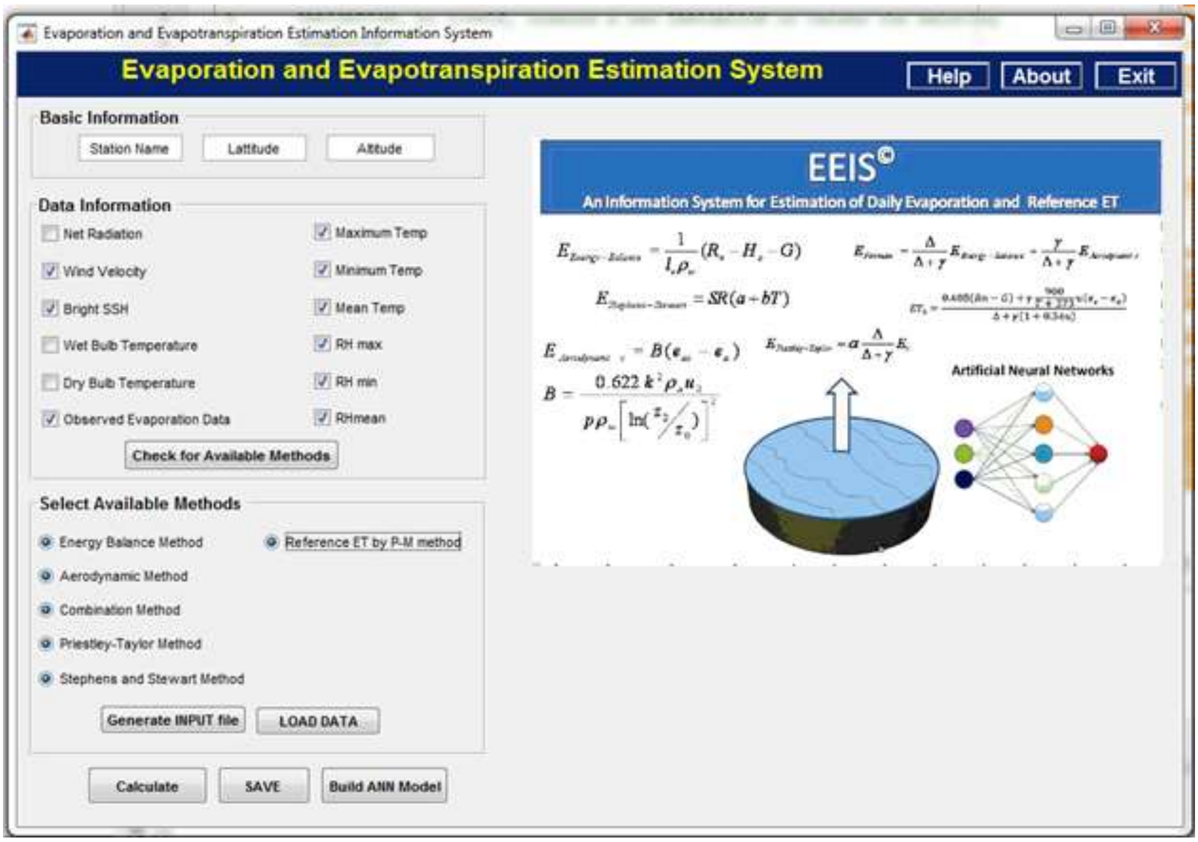


Figure 1. Captured windows of EEIS ver 1.0 interface in MATLAB for estimation of ET0 using different methods

Prediction error statistics: The performance evaluation of the different methods was undertaken by comparing the values obtained by the FAO-Penman Montieth equation by following statistical methods to obtain the prediction error:

The average bias (AB) of the evaluated methods was calculated using the equation

$$AB = N^{-1}\sum_{i=1}^{N}(P_i - O_i)$$

In which: O_i is the ET_0 estimated by the standard method (mm day^{-1}); P_i is the ET_0 estimated by the considered method (mm day^{-1}), and N is the total number of observations. The errors of the evaluated methods were calculated by root mean square error (RMSE) and by mean absolute error (MAE), as equations:

$$RMSE = \sqrt{N^{-1}\sum_{i=1}^{N}(P_i - O_i)^2}$$

$$MAE = N^{-1}\sum_{i=1}^{N}|P_i - O_i|$$

The estimated standard error (ESE) was calculated using the equation: $ESE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N-1}}$

3. Results and Discussions

Estimated values of ET_0: The vales of ET_0 estimated by all selected methods is given in Table 1. Figures 3 and 4 shows the variation of ET_0 calculated by different methods.Total reference evapotranspiration (ET_0) calculated by standard FAO Penman-Montieth method was obtained to be 405.99 mm and 387.46 mm during 2013-14 and 2014-15, respectively. There was considerable differences in the values obtained by Aerodynamic method and Stephens-Stewart method during 2013-14, whereas during 2014-15 the difference was for Stephens-Stewart method. The average daily ET_0 observed by Penman Monteith method was 3.15 mm day^{-1} and 3.01 mm day^{-1} during 2013-14 and 2014-15, respectively. The values obtained by Penman method (3.18 mmday^{-1}) and Energy balance method (3.03 mmday^{-1}) were close to the ET_0 values obtained using FAO Modified Penman Monteith method. However, during both the years, ET_0 computed by Stephen-Stewart method (2.71 mm day^{-1} and 2.52 mmday^{-1}) was least whereas Aerodynamic method (3.74 mm day^{-1} and 3.24 mm day^{-1}) produced highest average daily ET_0 value. Baink *et al., (*2014) reported the value of average daily ET_0 3.15 mm/day for Dehradun, Uttarakhand which is closely related to the values obtained by Penman method.

Table 1. Total and daily average value of reference evapotranspiration calculated by selected methods

Reference ET0 (mm)	Energy Balance	Aerodynamic	Penman	Priestley-Taylor	Stephens-Stewarts	FAO Penman-Montieth
2013-14						
Total	440.50	482.82	410.22	371.47	349.56	405.99
Daily average	3.41	3.74	3.18	2.88	2.71	3.15
2014-15						
Total	390.99	418.29	420.27	358.27	325.22	387.46
Daily average	3.03	3.24	3.25	2.77	2.52	3.01

Figure 3. Variation of daily reference evapotranspiration (ET_0) calculated by selected methods during 2013-14.

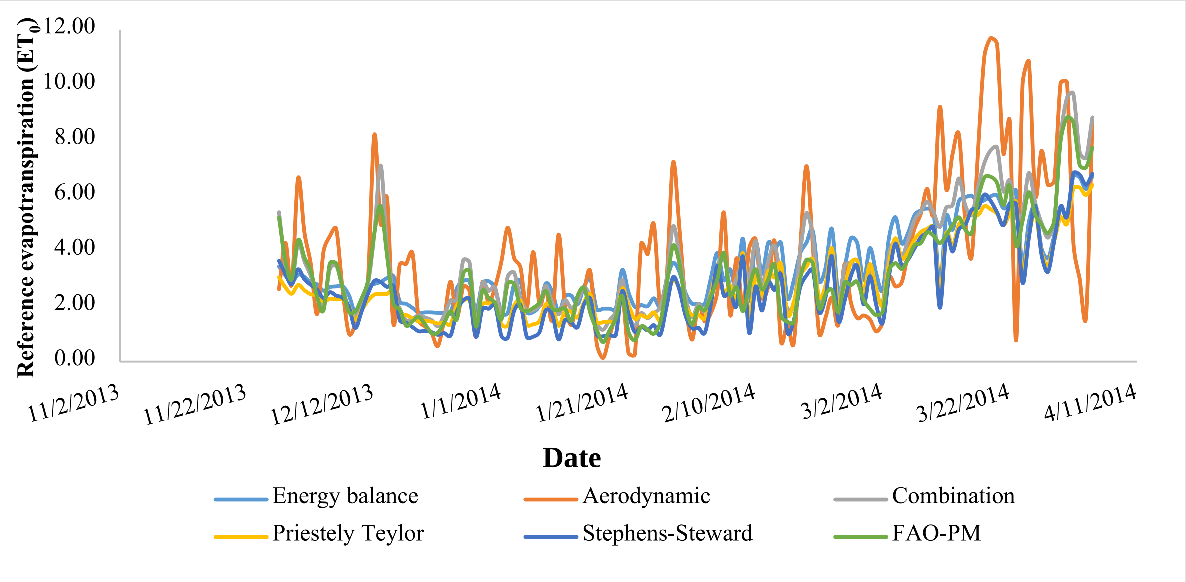
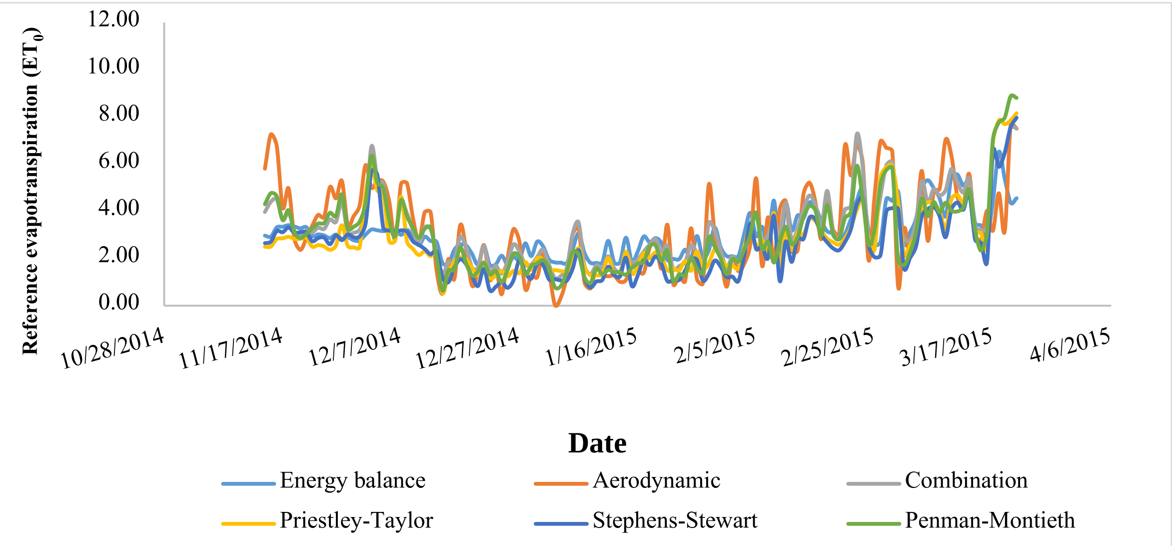


Figure 4. Variation of daily reference evapotranspiration (ET_0) calculated by selected methods during 2014-15.



***Performance evaluation of different**: ET_0 estimation methods:* Relationship between the daily reference evapotranspiration (ET_0) estimated by selected methods and the FAO-Penman–Monteith method are shown in figure 5. Different prediction error statistical parameters between ET_0 calculated through selected methods and FAO Modified Penman Monteith method is presented in Table 2. It was observed from Table.2 that during both years, the most acceptable method of computing ET_0 was the Penman method with coefficient of determination (R^2) 0.95 and 0.89 which requires weather parameters pertaining to radiation, air temperature, relative humidity and wind velocity. Nearly similar correlation between the FAO Modified Penman Monteith and Penman method was observed by Tomar *et al*., 2015 for the Tarai region of Uttarakhand. Singh *et al.,* 2006 also observed the good correlation (R^2=0.98) between Modified Penman Monteith and temperature based methods for the Kashmir valley. However Energy Balance method with (R^2) values 0.67 and 0.52 during 2013-14 and 2014-15, respectively and Aerodynamic method with (R^2) values 0.67 and 0.52 during 2013-14 and 2014-15, respectively indicated poor correlation with FAO Modified Penman-Monteith method. It was observed that the average bias (AB) using values of Priestley Taylor method and Stephens-Stewart method tends to underestimate ET_0whereas Aerodynamic method tends to overestimate $ET_{0.}$ The penman, Energy Balance methods were predicted proximity value to FAO Penman-Montieth method. Root mean square error (RMSE) and estimated standard error (ESE) was lowest for Penman method. However mean absolute error (MAE) was observed to be the lowest for Energy Balance method during both the year.

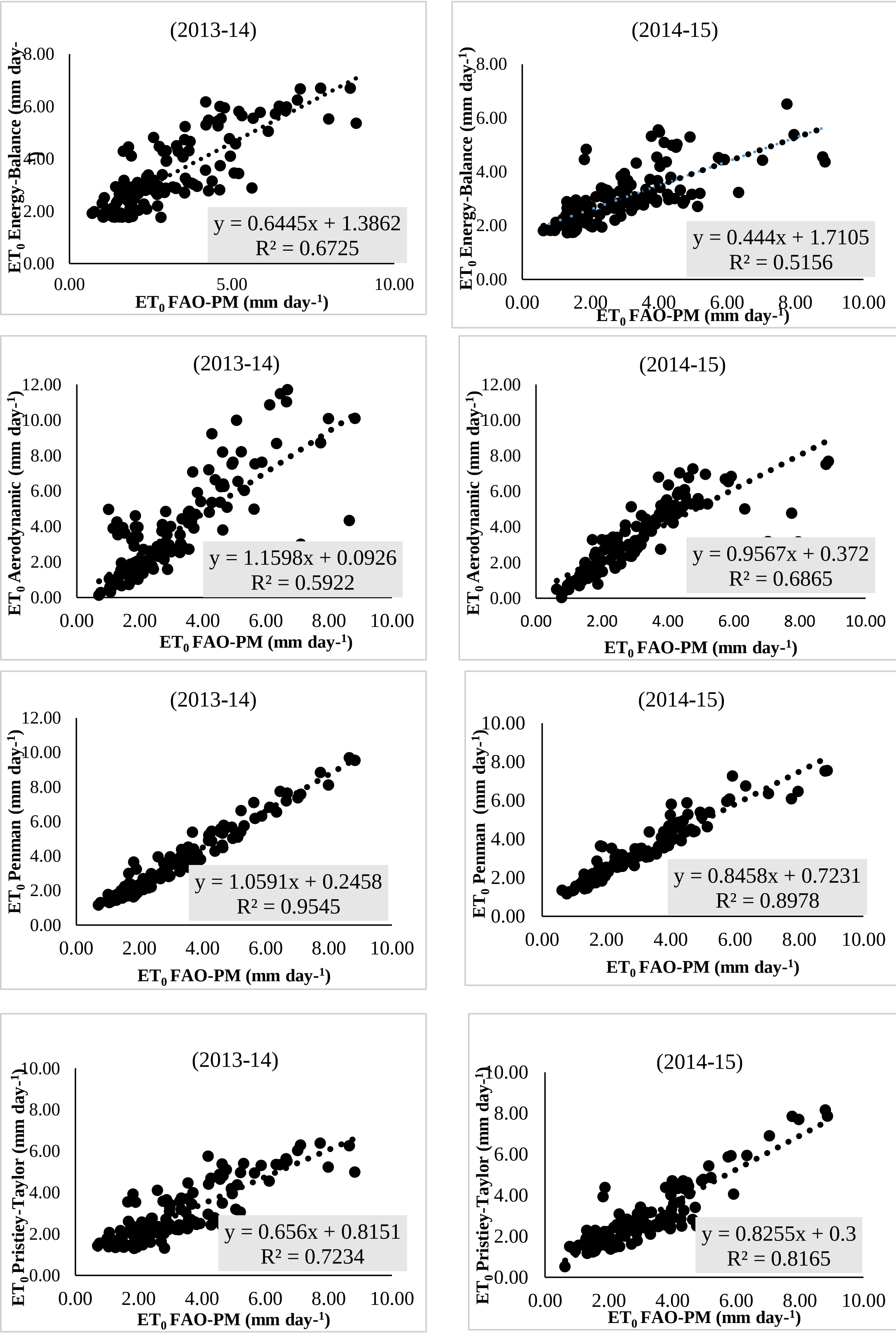
Conclusion

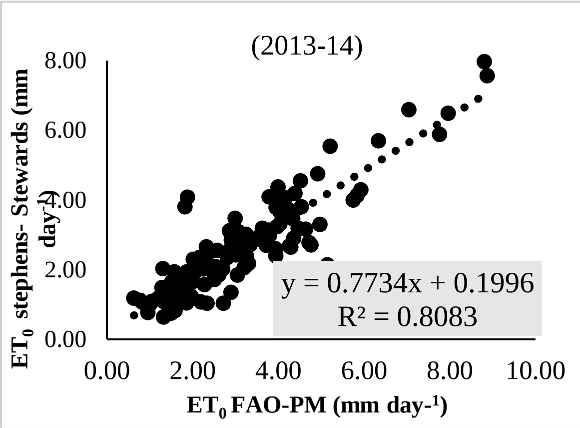
Five empirical methods for calculating ET_0 *viz.* Energy-Balance, Aerodynamic method, Penman method, Priestley-Taylor and Stephen-Stewart methods were compared with the standard method of reference evapotranspiration *i.e.* the FAO Penman-Monteith method to compare their performance for hilly regions as well as plain regions of north India using meteorological data obtained from the automatic weather station during 2013-14 and 2014-15. It is revealed that the Penman method resulted in estimation of ET_0 values which was in close agreement with the FAO Penman-Monteith method for the both regions. Hence Penman method can be recommended for use as alternative methods to calculate reference evapotranspiration in hilly and plain regions of north India. Besides this, the weather parameters required for use in these two methods are comparatively less than the PENMON method. Nonetheless, the findings of this study would assist stakeholders in selection of an alternative method in climatic data scarce regions for estimation of ET_0 for judicious irrigation scheduling and enhancing water productivity of the both region.

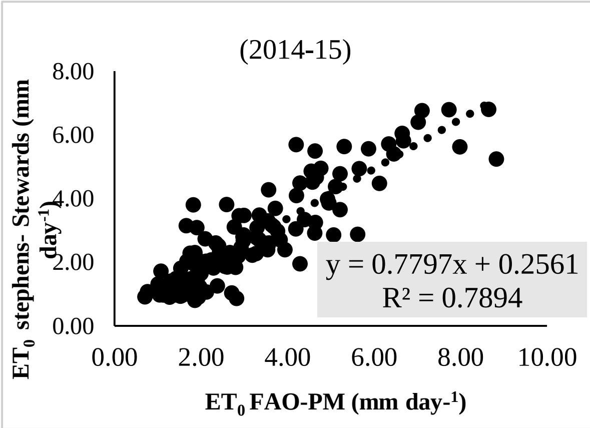
Table 2. Prediction error statistics of different estimation methods of ET_0 for 2013-14 and 2014-15.

Methods	**AB (mm day^{-1})**	**RMSE (mm day^{-1})**	**MAE (mm day^{-1})**	**ESE (mm day^{-1})**	**R^2**
2013-14					
Energy -Balance	0.27	1.05	0.26	1.04	0.67
Aerodynamic	0.60	1.82	0.59	1.83	0.59
Penman	0.43	0.60	0.43	0.65	0.95
Priestley- Taylor	-0.27	0.97	0.27	0.97	0.72
Stephens- Stewart	-0.48	0.92	0.48	0.92	0.81
2014-15					
Energy Balance	0.03	1.14	0.03	1.14	0.52
Aerodynamic	0.24	1.07	0.24	1.07	0.68
Penman	0.25	0.58	0.25	0.58	0.89
Priestley- Taylor	-0.23	0.73	0.22	0.73	0.82
Stephens- Stewart	-0.48	0.86	0.48	0.86	0.79

Figure 5. Relationship between the daily reference evapotranspiration (ET_0) estimated by selected methods versus the FAO-Penman–Monteith method during 2013-14 and 2014-15, respectively







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