ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 1, January 2014

A Statistical Comparison of Reference Evapotranspiration Methods: A Case Study from Jharkhand State of India

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ABSTRACT: Agricultural planning relying on evapotranspiration suffers due to inaccuracy in its estimation. The non-availability of meteorological parameters required for accurate estimation of reference evapotranspiration (ET_o) resulted in the development of different methods of ET_o estimation. The present study compares various universally accepted methods of ET_o estimation by considering the Penman Monteith as a standard method. Comparative analysis indicated the suitability of Hargreaves (1985) method followed by Christiansen (1968) method and Pan Evaporation method (1977). The improvement in ET_o estimation was carried out through transformation of standard equations using single or multi parametric approach after analyzing dependency and sensitivity of different meteorological parameters on ET_o. The developed transformed models indicated that during ET_o estimation morning time relative humidity (RH_1) can play the dominant role (99%). ET_o estimation by combination of bright sunshine hours and wind speed (WV) exhibit better role (98.8%) than the combination of minimum temperature (Tmin) and WV (98.6%).

Keywords: Evapotranspiration, statistics, transformed model, meteorological parameters

I. INTRODUCTION

Evapotranspiration constitutes the most significant component of the hydrologic budget apart from precipitation. It is simply the amount of water returned to the atmosphere through evaporation and transpiration. It is an important climatic factor, but its accurate estimation is very difficult. Evapotranspiration varies regionally and seasonally according to weather and wind conditions. Due to this variability, water managers who are responsible for planning the distribution of water resources need to have a thorough understanding of the evapotranspiration process and knowledge about the spatial and temporal rates of evapotranspiration. The evapotranspiration rate is a function of factors such as temperature, solar radiation, humidity, wind and characteristics of the specific vegetation that is transpiring, which may vary significantly between vegetation types [2]. Drastic changes in evapotranspiration rates occur during drought periods depending upon the availability of moisture at the onset of drought, its severity and duration. Weather conditions during drought commonly include below-normal cloud cover, humidity and above-normal wind speed. These factors increase the rate of evaporation from open bodies of water and from the soil surface. Reference evapotranspiration (ET_o) is defined as "the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 sec m^{-1} and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground" [16]. It is of great importance for the management of present and future water resources, and also for solving many theoretical problems in the field of hydrology and meteorology.

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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Reference evapotranspiration (ET_o) provides a standard crop (a short, clipped grass) with an unlimited water supply so that a user can calculate maximum evaporative demand from that surface for a given day. This value, adjusted for a particular crop, is the consumptive use (or demand), and deficit represents that component of the consumptive use that goes unfilled, either by precipitation or by soil-moisture use, during the given time period. This deficit value is the amount of water that must be supplied through irrigation to meet the water demand of the crop [2]. The field based direct measurement of ET_o by using Lysimetric method, though very much accurate, cannot be used everywhere because of high cost involved in installation and maintenance of lysimeter**.** Therefore computation of reference evapotranspiration with available meteorological data is one of the important tasks for irrigation planners, researchers to design storage reservoir, which can give the maximum benefit.

In search of the best ET_o model for wide application, many researchers ([14]; [11]; [3]; [20]; [18]; [4]; [16]; [15]) have compared different evapotranspiration models. Penman-Monteith equation gives the best estimate of ET_o where daily weather data are available [12]. This method is also reliable in a wide range of environments [1].

However, no single existing method using meteorological data is universally adaptable under all climatic regimes. Large number of data requirement also limits the application of many of these methods.

As per the estimates given by the United Nations and World Bank [5] about 70% of the world food demand towards 2025 will be provided through irrigated areas. Therefore for the efficient management of irrigation water, the proper computation of ET_o at micro level is highly essential.

The erratic rainfall and high evapotranspiration rate in some parts of the Jharkhand state render such areas highly vulnerable to drought during the southwest monsoon. Therefore it is essential to understand the spatial and temporal variability of the amount of rainfall received in relation to evapotranspiration rate in order to develop effective water management strategies to combat drought in these regions.

In the present study, the authors attempted computation of ET_o for a dry semi humid region of Jharkhand, on similar lines as proposed by [16] for semi arid region in Gujarat state of India. Additionally model comparison and validation was done based on error estimation by computing root mean square error (RMSE), percentage error (PE), coefficient of variation (CV), coefficient of determination (R^2) and F test. Considering the Penman-Monteith method as a standard method, the regression equations were developed using various meteorological parameters. The resultant regression equations, which have lower values of R^2 were transformed to develop improved regression models. The results of the present work demonstrated the validity of different models along with the importance of meteorological parameters both individually and collectively in deducing ET_o.

II. MATERIAL AND METHODS

CLIMATIC DATA AND STUDY AREA

The daily records of meteorological parameters i.e. maximum temperature (Tmax), minimum temperature (Tmin), relative humidity morning, afternoon (RH_1, RH_2), wind speed (WV), bright sunshine hours (BSS) and Pan evaporation (EP) recorded for the period of 35 years (1970 to 2005) were acquired from Birsa Agricultural University, Ranchi. The daily data was further converted into the monthly data. Nine standard methods as mentioned below were used to estimate $ET_{o.}$

Topographically Ranchi (23°23'N, 85°23'E) is a plateau region with an elevation of 610m asl. The region is characterized by dry semi humid climate [10] with an average annual rainfall of about 1370 mm received mainly during southwest monsoon (June to September). The peak monsoon months are July and August and monsoon normally withdraws from the region in the first week of October. Due to good amount of rainfall in the rainy season, mean relative humidity ranges from 65 to 82% in comparison to rest of the months. The area is characterized by mainly mono cropping agriculture system with paddy (rice) as main crop during the Kharif season (June-October). Over the past few years a rise in the drought events in the region is noticed. The period from 2000-2005 witnessed continuous droughts in many parts of the state owing to erratic rainfall during southwest monsoon season.

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SELECTION OF METHODS FOR ET_O ESTIMATION

The primary choice for selection of a particular method for estimation of ET_o depends primarily on the degree of accuracy needed and the availability of meteorological parameters. The various methods used by earlier workers for estimation of ET_o include Pan Evaporation method (EP), Thornthwaite method (TW), Hargreaves method (HM), Turc method (TC), Christiansen method (CM), Modified Penman method (MP), Makkink Radiation method (MR), FAO Blaney Criddle method (FBC) and Penman Monteith method (PM). The formulation of these methods are given as under

Pan evaporation method (Doorenboss and Pruitt 1977)

$ET_o = E_{pan} K_p$ where, E_{pan} = pan evaporation in mmday^{-1} K_p = pan coefficient

For the Class A evaporation pan, the K_p varies between 0.35 and 0.85. Average K_{pan} = 0.70

Thornthwaite method (1948)

$ET_0 = 1.6L(10T/I)^a$ where, L is the day length factor and is calculated by possible hours of sunshine. I is the annual heat index and is determined as I = Σi, monthly heat index values, i, obtained from $i = (T_a/5)^{1.514}$; a is exponential constant

Hargreave method (Hargreave and Somani 1985)

$ET_o = 0.0023\, R_a (TC + 17.8) TR^{0.5}$ where, R_a = extra terrestrial radiation (Lyday^{-1}); $TR = T_{max} - T_{min}$. (°C); TC = mean temperature (°C)

Turc method (1968)

$$ETp = \left[((0.0239001 \times Rs) + 50) \times \left(\frac{Ta}{(Ta + 15.0)} \right) \times \frac{0.4}{30.0} \right]$$

where, ET_p = mean daily potential evapotranspiration (mm/day); R_s = daily global solar radiation (kJ/m^2/day); T_a = mean daily air temperature (°C).

Christiansen method using pan evaporation (1968, 69)

$ET = 0.755\, E_{pan}\, C_T C_W C_H C_S$ where, E_{pan} is measured pan evaporation, and the C terms are dimensionless coefficients for temperature (T), mean wind speed (W), mean relative humidity (H) and percent of bright shunshine hours (S).

Modified Penman method (Doorenboss and Pruitt 1977)

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

where: ET_o reference evapotranspiration [mm day^{-1}], R_n net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], T mean daily air temperature at 2 m height [°C], u_2 wind speed at 2 m height [m s^{-1}], 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^{-1}], γ psychrometric constant [kPa °C^{-1}].

Makkink Radiation (1957)

$ET = 0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\frac{R_s}{58.5} - 0.12$ where, R_s is in equivalent energy units, ly day^{-1}, and ET is in mm/day.

In a new calibration, Doorenbos and Pruitt (1977) shows an adaptation of the Makkink method as: $ET_{rg} = 0.61\left(\frac{\Delta}{\Delta+\gamma}\right)\frac{R_s}{58.5} - 0.12$, where, a and b are empirical factors which account for relative humidity and daytime wind movement. ET and R_s/λ are in mm/day.

FAO-24 Blaney-Criddle method (Doorenbos and Pruitt, 1977)

$$ET_{rg} = a + bf$$
$$f = p(0.46T + 8.13)$$
$$a = 0.0043RH_{\min} - n/N - 1.41$$
$$b = a_0 + a_1 RH_{\min} + a_2\, n/N + a_3 U_d + a_4\, RH_{\min}\, n/N + a_5 RH_{\min} U_d$$

where, ET_{rg} is reference crop ET in mm/day, p is the percent of daytime hours for a single day compared to the day length of an entire year, T is the average temperature in degree Celsius, n/N is measured sunshine divided by possible sunshine, $RH_{\min}$ is minimum relative humidity in percent, U_d is daytime wind speed in m/s.

Penman-Monteith method (1965)

$$\lambda ET = \frac{\Delta.H + \rho C_p Q}{\Delta + \gamma^{\bullet}} \qquad Q = [e^0{}_{T_z} - e_z]/r_a\,, \quad H = R_n + G\,, \quad \gamma^* = \gamma\left[1 + \frac{r_c}{r_a}\right]$$

where, Δ is the slope of the saturation vapour pressure- temperature curve (kPaK^{-1}), γ is the psychrometer coefficient kPaK^{-1}, C_p is the coefficient of specific heat for moist ambient air at constant pressure in kJkg^{-1}K^{-1}, r_a is known as aerodynamic resistance in sec/m to the diffusion of water vapor from the evaporating surface, z is measurement elevation in m, and r_c is canopy resistance in sec/m.

$h = 1/r_a$ where, h is known as the convective heat transport coefficient (Wm^{-2} K^{-1}).

FAO Bulletin No. 24 has recommended Blaney–Criddle, Makkink Radiation, Modified Penman and Pan Evaporation methods for estimation of $ET_{o.}$ Later on FAO Bulletin No. 56 recommended Penman-Monteith method over others. Christiansen method is used by Indian Meterological Department (IMD) for estimation of ET_o in many stations of India. Thronthwaite and Turc methods are relatively simple and requires very few parameters. In the present study considering the

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 1, January 2014

more acceptability of Penman-Monteith method over others, we considered it as a standard method for comparison and validation.

After giving due consideration to the merits and applicability of different methods, ET_o were obtained for the study area along with various measures of error estimation viz, CV, PE and RMSE.

The selected method of ET_o were then fitted to regression equations with Tmax, Tmin, Tmean, RH_1, RH_2, RH, WV, BSS, to examine which parameter plays important role in the estimation of ET_o. Further the regression equations that were showing lower values of R^2 were transformed into the new regression models.

III. RESULTS AND DISCUSSIONS

COMPUTATION OF DAILY ETO

ET_o observed by Penman Monteith method was (3.9 mmday^{-1}). The values obtained by Thornthwaite (3.6 mmday^{-1}) and Hargreaves (4.4 mmday^{-1}) methods exhibit proximity to ET_o values obtained from Penman Monteith method. However the ET_o computed by Makkink Radiation (2.6 mmday^{-1}) produced underestimated ET_o values whereas Modified Penman (4.9 mmday^{-1}), Christiansen (5.4 mmday^{-1}), FAO Blaney Criddle (6.8 mmday^{-1}) and Pan Evaporation (7.4 mmday^{-1}) methods overestimates ET_o values. Turc method (13.5 mmday^{-1}) produced highly overestimated values of $ET_{o.}$ Higher ET_o estimates by about 6% using Hargreaves method in comparison to FAO56PM method were reported by [13].

It was observed that the ET_o decreases during the months of July, August and September, which comprised the peak monsoon season with high relative humidity, low wind speed and lower temperature [16]. Similar ET_o values were observed in the month of November, December and January that comprises the winter season with low temperature causing low evaporation rates as shown in figure 1. In fig 1 it was observed that the values obtained by the turc method were overestimated, however Hargreaves method shows values close to Penman Monteith method. Makkink Radiation produced underestimated ET_o values as compared to the Penman Monteith method.

Lower values of coefficient of variation (CV) were obtained during ET_o computation by Turc (17.2%) and Modified Penman (19.9%) methods followed by FAO Blaney Criddle (23.5%) and Hargreaves (27.4%) methods. Penman Monteith (30.1%) and Christiansen (37%) methods yielded relatively higher CV values whereas Pan Evaporation (42.6%), Makkink Radiation (43.6%) and Thornthwaite (55.9%) methods produced significantly higher CV values. The high CV values in these methods are due to the significant influence of total sunshine hours, wind speed and humidity. The RMS error was lowest in Christiansen (2.3 mmday^{-1}) and FAO Blaney Criddle (2.7 mmday^{-1}) methods whereas its highest values were obtained while using Makkink Radiation and Turc method (5.2 and 6.4 mmday^{-1} respectively). The Percentage Error (PE) was lowest in Christiansen (25.4%) and Modified Penman (27%) methods. In remaining methods PE values were quite high (37.5% to 64.6%). However in FAO Blaney Criddle and Turc method the PE values were negative i.e –2.5% and –99.4% respectively. Very high PE in some of the methods could be due to wide variation of input meteorological parameters, which are significantly related to the ET_o estimates. The values of CV, PE, RMSE calculated for various methods are given in table 1.

SENSITIVITY OF DIFFERENT METHODS OF ETO

The linear regression equation between ET_o derived through Penman Monteith method and rest of the methods used in the present study are presented in table 2. It revealed that the most acceptable method of computing ET_o is Hargreaves method (R^2 = 97.2%) which requires only extra-terrestrial radiation and air temperature data. Christiansen method (R^2 = 95.3%), which requires many parameters viz. daily/weekly/monthly radiation, mean temperature, mean wind speed and mean RH data is apparently the second best method to obtain reliable ET_o value followed by Pan Evaporation method (R^2 = 94.6%), which requires only pan evaporation rate and pan coefficient. Makkink Radiation methods although requires data on radiation, temperature and wind speed still ET_o estimates had lower value of R^2 (85.4%). Thornthwaite, Turc and Modified Penman methods produced further lower R^2 values of 76.5%, 73.6% and 67.2% respectively. FAO Blaney Criddle

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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(R^2=28.1%) method produced substantially lower R^2 values. The value of F test revealed that in all the select methods the values were significant, except in the case of FAO Blaney Criddle method with F value of 3.91 as compared to its table value of 4.84 at 5% level of significance.

SENSITIVITY OF METEOROLOGICAL PARAMETERS FOR DEVELOPED MODELS

Individual meteorological parameter has its own contribution towards ET_o. These parameters in isolation and in combination cause different magnitude of evapotranspiration [10]. [21] determined the ET_o as a function of temperature f(T), temperature and relative humidity f(T,RH), temperature, relative humidity and wind speed f(T,RH,WV), temperature, relative humidity, wind speed and sunshine hours f(T,RH,WV,BSS) using the Penman-Monteith method and found that in most of the cases the combination of T,RH,WV,BSS shows significant results. Therefore in the present study the effect of individual meteorological parameter was also studied in isolation and in combination to deduce different sets of equations for estimation of ET_o. We selected Penman Monteith method to derive the regression equations with Tmax, Tmin, Tmean, RH_1, RH_2, RH, WV, BSS. Therefore ET_o was estimated by selecting one, two, three and four parameters as given in the equation below.

One parameter

(1) ET_o= 0.266 Tmax -3.84 R^2 = 94.0%
(2) ET_o= 0.132 Tmin+ 1.62 R^2 = 43.1%
(3) ET_o= 0.206 Tmean-1.04 R^2 = 69.2%
(4) ET_o= -0.102 RH_1+12.1 R^2 = 54.9%
(5) ET_o= -0.0206 RH_2+ 4.91 R^2 = 8.9%
(6) ET_o= -0.0438 RH + 6.71 R^2 = 20.4%
(7) ET_o= 0.655 WV+ 0.853 R^2 = 52.7%
(8) ET_o= - 0.010 BSS+ 3.96 R^2 = 0.0%

Two parameters

(9) ET_o= 0.282 Tmax - 0.069 WV- 4.00 R^2 = 94.3%
(10) ET_o= 0.0150 Tmin + 0.596 WV+ 0.87 R^2 = 52.9%
(11) ET_o= 1.08 WV + 0.451 BSS - 4.36 R^2 = 86.0
(12) ET_o = 0.220 Tmean - 0.0524 RH +2.01 R^2 = 98.1%

Three parameters

(13) ET_o= 0.206 Tmax + 0.319 WV + 0.201 BSS - 4.99 R^2 = 97.8%
(14) ET_o= 0.217 Tmax + 0.171 WV - 0.0175 RH_2- 2.33 R^2 = 97.8%
(15) ET_o= 0.153 Tmin + 0.595 WV + 0.577 BSS-5.63 R^2 = 96.6%
(16) ET_o =0.200 Tmean - 0.0528 RH + 0.0842 WV+2.13 R^2 = 98.3%

Four parameters

(17) ET_o= 0.209 Tmax + 0.250 WV - 0.0096 RH_2 + 0.097 BSS- 3.56 R^2 = 97.9%
(18) ET_o= 0.191 Tmean - 0.0349 RH + 0.232 WV + 0.151 BSS- 0.58 R^2 = 98.7%

The developed equations indicated that in case of one parameter, maximum temperature plays major role whereas mean temperature, relative humidity (morning) and wind velocity has minor role in the estimation of ET_o. However RH (mean), RH_2 (afternoon) and BSS individually are not affecting evapotranspiration directly (R^2 values are 20.4%, 8.9% and 0% respectively). This shows that individual parameter does not play an important role in ET_o estimation. In case of two parameters Tmean with RH, Tmax with WV play significant role, whereas estimation using three parameters like Tmean, RH, WV provide more accurate values of ET_o. Combination of Tmean, WV, RH and BSS are the good governing factors for determining the ET_o.

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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RESIDUAL ANALYSIS

The residual of regression model could be examined to see if they provide any indication that the model is adequate or not [9]. The residuals are the differences between what is actually observed, and what is predicted by the regression equation.

The residuals are defined as $e_i = Y_i - \hat{Y}_i$, i = 1,2,3…n where Y_i is an observed value and $\hat{Y}_i$ is the corresponding fitted / predicted value obtained by use of the regression model. The residuals of different regression equations were plotted in the time order sequence plot (figure 2).

The i-th standardized residual e_{is} is defined as $e_{is} = e_i /s$, where s is the standard deviation of residuals. The standardized residuals e_{is} have zero mean and unit standard deviation. The residuals should be distributed approximately as independent, normal deviates for a large sample [6].

The developed regression equations (1 to 18) were checked for the residual plots and it was observed that some of the equations were showing good scatter plots in the time order sequence (figure 2). Therefore from the entire set of derived equations only some of the equations as 9, 12, 13, 14, 15, 16, 17 and 18 can be selected for accurate estimation of ET_o based on their best-fit method.

TRANSFORMATION OF THE VARIABLES

In regression analysis, a convenient starting point is that the model describing the data is linear in the parameters. The necessity for transforming the data arises because the original variables, or the model in terms of the original variables, violate one or more of the standard assumptions. The most commonly violated assumptions are those concerning the linearity of the model and the constancy of the error variance. When the error variance is not constant over all the observations, the error is said to be heteroscedastic, which can be removed by means of a suitable transformation. The transformation is not only to stabilize the variance, but also have the effect of making the distribution of the transformed variable closer to the normal distribution [6].

While fitting equations to data, [7] was consulted. Regression equations 3, 4, 7, 10 and 11 which produced lower values of R^2 were modified by applying suitable transformation. While applying transformation, emphasis was given to improve R^2 value which indicates better estimation of ET_o.

The new transformed models for the select equations are given below:

(1) Equation (3) ETo= 0.206*Tmean-1.04 (R^2 = 69.2%) is transformed to

- 3(a) $1/ ET_o = 0.931*1/T + 0.211$ — $R^2 = 97.4\%$
- 3(b) $\log ET_o = 0.864*1/T + 0.501$ — $R^2 = 96.1\%$

(2) Equation (4) ET_o = -0.102*RH1+12.1 (R^2 = 54.9%)

- 4(a) $1/ ET_o = 1.63*\log RH1 – 2.81$ — $R^2 = 99.6\%$
- 4(b) $1/ ET_o = 0.924*1/RH1+ 0.240$ — $R^2 = 97.3\%$

(3) Equation (7) ET_o= 0.655WV+ 0.853 (R^2 = 52.7%)

- 7(a) $1/ ET_o = 1.05*\log WV – 0.341$ — $R^2 = 97.0\%$
- 7(b) $1/ ET_o = 0.975*1/WV + 0.0238$ — $R^2 = 97.7\%$

(4) Equation (10) ET_o= 0.0150 Tmin + 0.596 WV+ 0.87 (R^2 = 52.9%)

- 10(a) $1/ ET_o = 1.47* 1/Tmin - 0.0313* 1/WV+ 0.176$ — $R^2 = 98.6\%$
- 10(b) $\log ET_o = 1.43*1/Tmin - 0.0330*1/WV + 0.468$ — $R^2 = 97.5\%$

(5) Equation (11) ET_o= 1.08 WV + 0.451 BSS - 4.36 (R^2 = 86.0)

- 11(a) $1/ ET_o =1.48*1/WV - 0.0283*1/BSS – 0.0725$ — $R^2 = 98.8\%$
- 11(b) $1/ ET_o = 0.916 *sqrtWV + 0.0254*1/BSS –1.68$ — $R^2 = 94.9\%$

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 3, Issue 1, January 2014

The transformed models indicated that while estimating evapotranspiration in terms of individual parameter, relative humidity (RH_1) play the highest role (99.6%) followed by wind speed (WV, 97.7%) and mean temperature (Tmean, 97.4%) whereas among the combined parameters combination of Tmin and WV (98.6%) and combination of BSS and WV (98.8%) have similar impact on ET_o estimation.

Among the new transformed models shown above, equation 4a shows more positive and few negative points in the plot in comparison to 7b with entire negative points. Equation 7a and 11b shows the entire positive and one negative point. These equations which violate randomness therefore can be rejected as accurate models. The equations 3a, 3b, 4b, 10a, 10b and 11a were showing random plots and therefore can be accepted as models although some pattern points to the requirement of some more parameters in the required model (figure 3). The examination of pattern of scatter plot of new transformed models also suggests that as compared to a single parameter multi-parameters estimation produces better results. It can be remarked that for the estimation of ET_o more than two parameters are important, especially Tmean, RH, WV and BSS.

IV. CONCLUSIONS

Regression equations between ET_o estimated through Penman Monteith method and other methods indicated that the most significant method of computing ET_o is Hargreaves (1985) method (R^2=97.2%). This method requires only extra-terrestrial radiation and air temperature data to obtain reliable ET_o value and therefore can be applied to regions where data pertaining to other meteorological parameters are not available.

In ET_o estimation, Tmax as a single parameter plays prime role, whereas combination of Tmean with RH and Tmax with WV also play significant role. High accuracy in ET_o estimation can be achieved by employing three parameters (Tmean, RH, WV) or four parameters (Tmean, WV, RH and BSS)

The developed transformed models indicated that while estimation of ET_o, RH_1 can play the dominant role (99.6%) followed by WV (97.7%) and mean temperature (97.4%). Combination of BSS and WV (98.8%) exhibit better role than Tmin and WV (98.6%).

Proposed regression equations developed for accurate estimation of ET_o:

ET_o= 0.282 Tmax - 0.069WV- 4.00 R^2 = 94.3%

ET_o = 0.220 Tmean - 0.0524 RH +2.01 R^2 = 98.1%

ET_o= 0.206 Tmax + 0.319 WV + 0.201BSS - 4.99 R^2 = 97.8%

ET_o= 0.217 Tmax + 0.171WV - 0.0175RH_2- 2.33 R^2 = 97.8%

ET_o= 0.153 Tmin + 0.595 WV + 0.577 BSS-5.63 R^2 = 96.6%

ET_o =0.200 Tmean - 0.0528 RH + 0.0842 WV+2.13 R^2 = 98.3%

ET_o= 0.209 Tmax + 0.250WV - 0.0096RH2 + 0.097BSS - 3.56 R^2 = 97.9%

ET_o= 0.191 Tmean - 0.0349RH + 0.232WV + 0.151BSS- 0.58 R^2 = 98.7%

The proposed transformed models for estimation of ET_o:

1/ ET_o = 0.931*1/T + 0.211 R^2 = 97.4%

log ET_o = 0.864*1/T + 0.501 R^2 = 96.1%

1/ ET_o = 0.924*1/RH1+ 0.240 R^2 = 97.3%

1/ ET_o = 1.47* 1/Tmin - 0.0313* 1/WV+ 0.176 R^2 = 98.6%

log ET_o = 1.43*1/Tmin - 0.0330*1/WV + 0.468 R^2 = 97.5%

1/ ET_o =1.48*1/WV - 0.028*1/BSS – 0.0725 R^2 = 98.8%

Regarding those residual plots in which patterns has been observed, our investigations are ongoing to explore the possibilities of other assignable factors influencing the response (other meteorological parameters) to be included in the model, so that the final residual plot become random.

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 3, Issue 1, January 2014

The study demonstrated the usefulness of statistical techniques for validating the reference evapotranspiration values obtained by using different ET_o estimation methods. The inaccuracies in ET_o estimations are a major hindrance in developing effective water management strategies for maintaining crop water requirement during drought periods. Therefore application of developed models of evapotranspiration estimation proposed in the study can also benefit toward drought mitigation based on reliable ET_o estimates in data scarce region of Jharkhand state.

ACKNOWLEDGEMENTS

Authors are thankful to Prof. A Wadood, Birsa Agricultural University (BAU), Ranchi for providing meteorological data. Authors are also thankful to Dr. M.K. Khandelwal, Principal Scientist, Central Soil Salinity Research Institute, Bharuch (ICAR) for his valuable inputs during the manuscript preparation.

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ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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MON	EP	TW	HM	TC	CM	MP	MR	FBC	PM
JAN	4.1	0.9	3	9.8	3	4.8	1.2	7.3	2.5
FEB	5.8	1.6	3.9	11.8	4.1	5.5	1.7	8.3	3.4
MAR	8.6	3	5.3	13.7	6	6.1	2.7	8.6	4.5
APR	12.2	5.4	6.3	15.5	8.1	6.2	4.1	9	5.7
MAY	14.4	7.1	6.7	16.6	9.9	6.4	4.5	9.2	6.1
JUN	10.1	6.2	5.6	16.6	7.4	5.7	4.1	6	4.8
JUL	6.5	4.6	4.1	15.2	5.2	3.8	3.4	4.2	3.6
AUG	6.3	4.5	3.9	14.8	5.1	4	2.8	4.7	3.6
SEP	6	4.1	3.8	14.2	4.9	4.5	2.5	5.7	3.7
OCT	5.3	2.9	3.9	12.9	4.3	4.4	2	6.3	3.4
NOV	4.9	1.6	3.3	11.1	3.7	3.8	1.5	6.5	2.7
DEC	4.4	0.9	3	9.9	3.3	3.7	1	6	2.2
Aver	7.4	3.6	4.4	13.5	5.4	4.9	2.6	6.8	3.9
CV	42.6	55.9	27.4	17.2	37.0	19.9	43.6	23.5	30.1
RMSE		4.2	3.6	6.4	2.3	3.4	5.2	2.7	4.0
PE		53.4	37.5	-99.4	25.4	27.0	64.6	-2.5	45.2

Table 1: Mean monthly daily ETo by various methods for Ranchi

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

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ETo method	Intercept	slope	R^2 (%)	F test
Pan evaporation (EP)	1.21	0.36	94.6	174.4
Thornthwaite (TW)	2.06	0.51	76.5	32.6
Hargreaves (HM))	-0.31	0.95	97.2	342.4
Turc (TC)	-1.99	0.43	73.6	27.9
Christiansen (CM)	-0.80	0.57	95.3	203.9
Modified Penman (MP)	-0.94	0.97	67.2	20.5
Makkink Radiation (MR)	1.41	0.94	85.4	58.6
FAO Blaney Criddle (FBC)	1.23	0.39	28.1	3.9

Table 2: Regression coefficients between Penman Monteith (PM) method and other methods

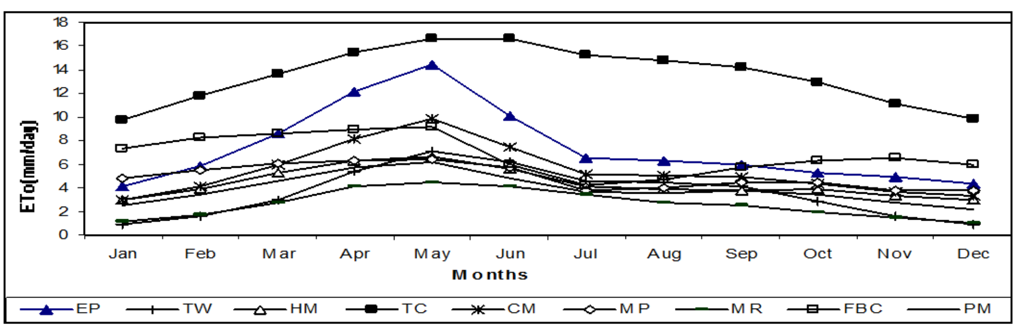

Figure1: Comparison of nine ET_0 methods for Ranchi

ISSN: 2319-8753

International Journal of Innovative Research in Science, Engineering and Technology

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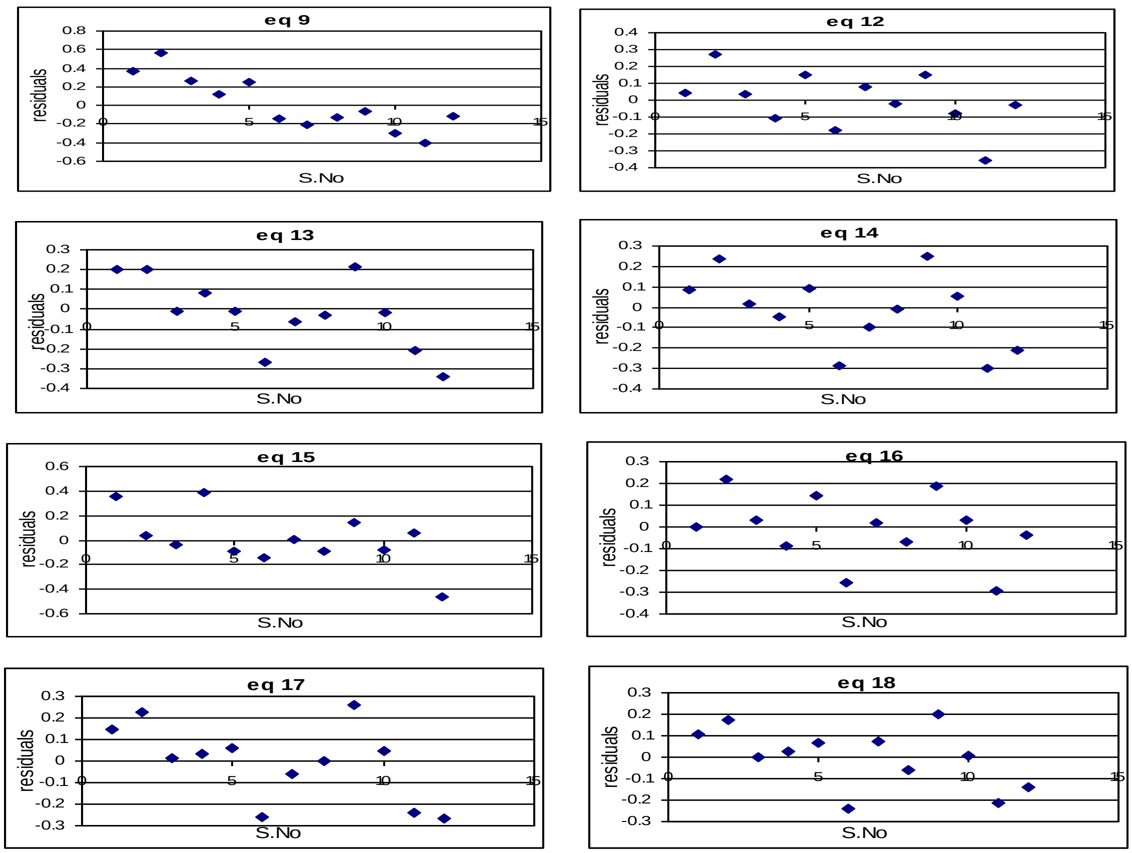

Figure 2: The residual plots of some of the regression equations in time order sequence.

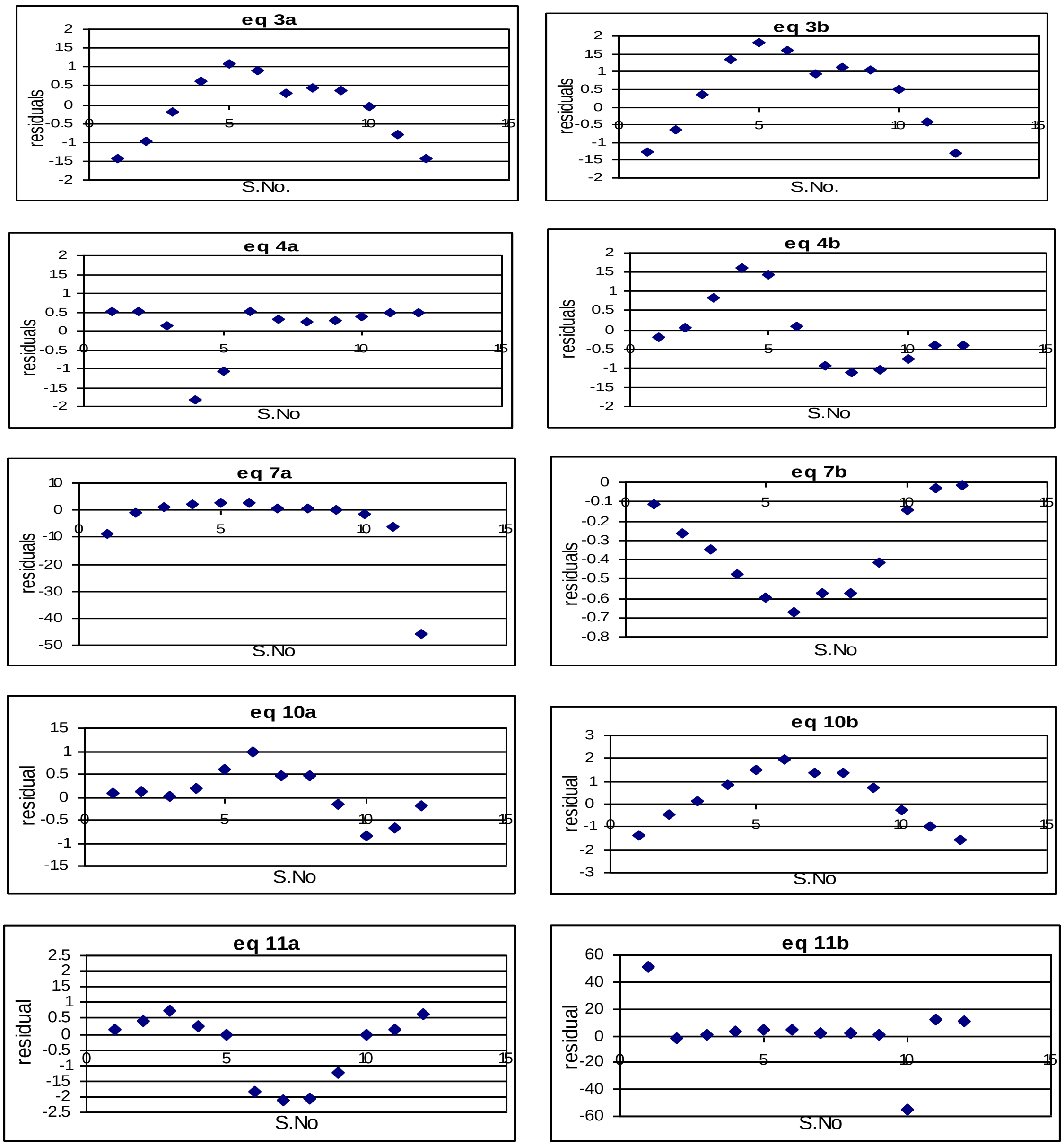

Figure 3: The residual plots of selected regression models after transformation in time order sequence.