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Investigation of Valiantzas' simplified forms of FAO56 Penman-Monteith reference evapotranspiration models in a semi-arid region

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सार – भारत के तमिलनाडु में स्थित एक अर्ध-शुष्क क्षेत्र तिरुचिरापल्ली जिले के कृषि इंजीनियरिंग कॉलेज और अनुसंधान संस्थान, कुमुलूर, लालगुडी तालुका से प्राप्त मौसम संबंधी आंकड़ों का उपयोग करके सोलह वैलिएंटज़स संदर्भित वाष्पोत्सर्जन मॉडल के प्रदर्शन की जांच की गई। वैलिएंटज़स संदर्भित वाष्पोत्सर्जन की तुलना विश्व स्तर पर इस्तेमाल की जाने वाली FAO56 पेनमैन-मोंटिथ विधि से की गई थी। तुलना के लिए उपयोग किए जाने वाले सूचकांक निर्धारक गुणांक (R2), मानक त्रुटि अनुमान (SEE) और दीर्घकालिक औसत अनुपात (RT) के गुणांक हैं।इस स्टेशन में पूर्ण डेटासेट की आवश्यकता वाले वैलिएंटज़स के मॉडल ने उत्कृष्ट प्रदर्शन किया। जिन मॉडलों को वायु की गति के आंकड़ों की आवश्यकता नहीं थी, उन्होंने भी इस स्टेशन में समान रूप से अच्छा प्रदर्शन किया और FAO56-PM पद्धति के साथ काफी अच्छा संबंध प्रदर्शित किया। स्थानीय औसत वायु की स्थिति के लिए लेखांकन के अन्य सूत्र, केवल तापमान और सापेक्ष आर्द्रता डेटा के साथ न्यून सेट सूत्र और केवल तापमान और विकिरण डेटा के साथ न्यून सेट सूत्र भी इस स्टेशन में अच्छा प्रदर्शन करते हैं। जांच ने वैलिएंटज़स मॉडल की उचित सटीकता दिखाई। अतः इसलिए शोधकर्तापूर्ण डेटासेट की उपलब्धता के अभाव में इन मॉडलों का उपयोग कर सकते हैं।

ABSTRACT. The performance of sixteen Valiantzas' reference evapotranspiration models was investigated using the meteorological data obtained from Agricultural Engineering College and Research Institute, Kumulur, Lalgudi Taluk of Tiruchirapalli district, which is a semi-arid region located in Tamil Nadu, India. The Valiantzas' reference evapotranspiration was compared with the globally used FAO56 Penman-Monteith method. The indexes used for comparison are coefficient of determination (R2), Standard Error Estimate (SEE) and long-term average ratio (RT). The Valiantzas' models requiring complete dataset performed excellently in this station. The models not requiring wind speed data also performed equally well in this station and exhibited a fairly good correlation with FAO56-PM method. The other formulae accounting for local average wind conditions, reduced set formulae with temperature and relative humidity data alone and reduced set formulae with temperature and radiation data alone also performed well in this station. The investigation showed fair accuracy of Valiantzas' Models and hence researchers can use these models in the absence of availability of the complete dataset.

Key words – Evapotranspiration, FAO56 Penman-Monteith, Valiantzas' Models.

1. Introduction

Evapotranspiration is one of the most important parameters in agricultural water management. Precise estimation of reference evapotranspiration is to be done for planning and supply of optimal quantity of irrigation water. Reference evapotranspiration (ET_0) can be estimated using different methods like direct measurement from a reference crop (perennial grass or alfalfa), computation from weather data and energy balance models. Among the available physical and empirical models, FAO56 Penman-Monteith (FAO56-PM) (Allen *et al.*, 1998) method is a globally recommended method for estimation of ET_0. But the complication faced in

FAO56-PM method is, the inputs appear explicitly in the computation. Several calculations have to be done and handling of terms in different units is also complicated.

Valiantzas (2006, 2013a,b) developed algebraic formulae by simplifying Penman's equation, that compute ET_0 from a complete set of routinely measured meteorological variables, *e.g.*, wind speed, u (m/s); solar radiation, R_S (MJ/m^2/d); Relative Humidity, RH (%) and Temperature, T (°C). Valiantzas (2006, 2013a,b,c,d, 2014a,b, 2015, 2018a,b,c) proposed further simplifications ofFAO56-PM method under limited data conditions that has comparable accuracy to FAO56-PM method.

Valipour (2014) compared various full dataset formulations proposed by Valiantzas in Iran. Kisi (2016) reported that the recently developed Valiantzas' equation performs better than the soft computing regression methods for one of the two stations examined in Turkey and may be the best choice, where T and R_S data are only available. Djaman *et al*. (2017b) reported that Valiantzas full dataset formulation showed a good performance under humid, sub-humid and semiarid conditions across Africa. Djaman *et al*. (2017a) concluded that the performance of Valiantzas' equations depends on data requirements: the more meteorological inputs, the higher the ET_0 accuracy. According to Li *et al*. (2018) for full dataset, Valiantzas formulation on a daily timescale was the best alternative model for estimating the ET_0 in Eastern China. Several studies have provided valuable information on the accuracy of the Valiantzas' equations at different countries like Iran (Valipour, 2014); Mediterranean Climate (Kisi, 2014); Pilbara region of Western Australia (Ahooghalandari *et al*., 2016), Senegal (Djaman *et al*., 2015); Burkina Faso (Djaman *et al*., 2016).

While several studies have provided valuable information on the accuracy of some of Valiantzas' equations elsewhere, very limited support data and information are available on the applicability of different Valiantzas equations in semi-arid regions of India. Hence this study aimed to evaluate sixteen Valiantzas' ET_0models by comparing them with the FAO56-PM modelin semi-arid regions of India. The evaluation is done on daily time steps and the best performing models have been identified to estimate the ET_0 under a semi-arid region in India for the first time.

2. Data, methodology and study area

Meteorological data required for FAO56-PM method and Valiantzas' models were collected from Agricultural Engineering College and Research Institute, Kumulur for a period of ten years (2005 to 2014) which has weather station corresponding to well-watered conditions. Kumulur is a village in Lalgudi Taluk of Tiruchirapalli district, located in Tamil Nadu, India. It is a Semi-Arid Region, located at 10.93°N Latitude; 79.82°E Longitude and 70m Elevation above MSL (Arunadevi *et al*., 2017). The long-term average relative humidity is 51% and long-term average wind speed is 1.9 m/s.

The FAO56-PM equation for estimating the daily grass-reference evapotranspiration is given by :

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

where, ET_0 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 [°C],u 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 of vapour pressure curve [kPa °C^{-1}], γ psychrometric constant [kPa °C^{-1}].

The sixteen models developed by Valiantzas are grouped into five categories *via*. C1) Formulae Requiring Full Set of Weather Data, C2) Reduced Set Formulae without Wind Data, C3) Formulae Accounting for Local Average Wind Conditions, C4) Reduced Set Formulae with Temperature and Relative Humidity Data Alone and C5) Reduced Set Formulae with Temperature and Radiation Data Alone. The formula of Turk (1961) with reduced wind data is also a common method for estimating ET_0 and is considered to be more efficient method for humid locations. The solar radiation-based equation of Hargreaves (1975) requiring only the R_S, *T*max and *T*min data is also considered for comparison in this paper. Therefore, eighteen models that are compared in this paper are listed below:

(C1) Formulae Requiring Full Set of Weather Data

Valiantzas (2006) : V^1 [R_s, T, RH, u]:

$$\begin{aligned} ET_0 = {} & 0.051(1-\alpha)R_s(T_{mean}+9.5)^{0.5} - 2.4\left(\frac{R_s}{R_a}\right) \\ & + 0.048(T_{mean}+20)\left(1-\frac{RH}{100}\right)(0.5+0.536u) \\ & + 0.00012z \end{aligned} \tag{2}$$

Valiantzas (2013b) : V^2 [R_s, T, RH, u]:

$$ET_0 = 0.0393 R_s \left(T_{mean} + 9.5\right)^{0.5} - 0.19 R_s^{0.6} \varphi^{0.15} + 0.048\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) u^{0.7} \tag{3}$$

Valiantzas (2013d) : V^3 [R_s, T, RH, u]:

$$\begin{aligned} ET_0 &= 0.051(1-\alpha) R_s \left(T_{mean} + 9.5\right)^{0.5} \\ &- 0.188\left(T_{mean} + 13\right)\left(\frac{R_s}{R_a} - 0.194\right) \\ &\left[1 - 0.00015\left(T_{mean} + 45\right)^2 \left(\frac{RH}{100}\right)^{0.5}\right] \\ &- 0.0165 R_s u^{0.7} + 0.0585\left(T_{mean} + 17\right) u^{0.75} \\ &\times \left\{\frac{\left[1 + 0.00043\left(T_{\max} - T_{\min}\right)^2\right]^2 - \frac{RH}{100}}{1 + 0.00043\left(T_{\max} - T_{\min}\right)^2}\right\} + 0.0001z \end{aligned} \tag{4}$$

Valiantzas (2013d) : V^4 [R_s, T, RH, u]:

$$\begin{aligned} ET_0 &= 0.051(1-\alpha) R_s \left(T_{mean} + 9.5\right)^{0.5} \\ &- 2.4\left(\frac{R_s}{R_a}\right) - 0.024\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \\ &- 0.0165 R_s u^{0.7} + 0.0585\left(T_{mean} + 17\right) u^{0.75} \\ &\times \left\{\left[1.03 + 0.00055\left(T_{\max} - T_{\min}\right)^2\right] - \frac{RH}{100}\right\} + 0.0001z \end{aligned} \tag{5}$$

Valiantzas (2013d) : V^5 [R_s, T, RH, u]:

$$\begin{aligned} ET_0 &= 0.051(1-\alpha) R_s \left(T_{mean} + 9.5\right)^{0.5} \\ &- \left\{22.46 \frac{R_s \varphi^{0.15}}{\left[4 \sin\left(2\pi J / 365 - 1.39\right)\varphi + 12\right]^2} + 0.92\right\}^2 \\ &- 0.024\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \\ &- 0.0165 R_s u^{0.7} + 0.0585\left(T_{mean} + 17\right) u^{0.75} \\ &\times \left\{\left[1.03 + 0.00055\left(T_{\max} - T_{\min}\right)^2\right] - \frac{RH}{100}\right\} + 0.0001z \end{aligned} \tag{6}$$

Valiantzas (2013a) : V^6 [R_s, T, RH, u]:

$$\begin{aligned} ET_0 &= 0.0393 R_s \left(T_{mean} + 9.5\right)^{0.5} - 2.4\left(\frac{R_s}{R_a}\right)^2 \\ &- 0.024\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \\ &+ W_{aero}\, 0.066 \left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) u^{0.6} \end{aligned} \tag{7}$$

When RH > 65%, W_{aero}= 0.78 and RH ≤ 65%, W_{aero}= 1.067, where W_{aero} is an empirical weighted factor.

(C2) Reduced Set Formulae without Wind Data

Valiantzas (2006) : V^7 [R_s, T, RH]:

$$ET_0 = 0.051(1-\alpha) R_s \left(T_{mean} + 9.5\right)^{0.5} - 2.4\left(\frac{R_s}{R_a}\right)^2 + 0.075 \left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \tag{8}$$

Valiantzas (2013b) : V^8 [R_s, T, RH]:

$$ET_0 = 0.0393 R_s \left(T_{mean} + 9.5\right)^{0.5} - 0.19 R_s^{0.6} \varphi^{0.15} + 0.078 \left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \tag{9}$$

Valiantzas (2013d) : V^9 [R_s, T, RH]:

$$\begin{aligned} ET_0 &= 0.0393 R_s \left(T_{mean} + 9.5\right)^{0.5} \\ &- \left\{22.46 \frac{R_s \varphi^{0.15}}{\left[4 \sin\left(2\pi J / 365 - 1.39\right)\varphi + 12\right]^2} + 0.92\right\}^2 \\ &- 0.024\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \end{aligned} \tag{10}$$

Valiantzas (2013a) : V^{10} [R_s, T, RH]:

$$ET_0 = 0.0393 R_s \left(T_{mean} + 9.5\right)^{0.5} - 2.4\left(\frac{R_s}{R_a}\right) - C_u \left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \tag{11}$$

When RH > 65%, C_u = 0.054 and RH ≤ 65%, C_u= 0.083, where C_u is an empirical weighted factor.

Turk (1961) : Turk [R_s, T, RH]:

$$ET_0 = \left(23.89R_s + 50\right)\left(\frac{0.013T_{mean}}{T_{mean} + 15}\right)\left[1 - W_{RH}\left(0.71 - \frac{1.43RH}{100}\right)\right] \tag{12}$$

Where W_{RH} = 1 when RH < 50% and W_{RH} = 0 when RH > 50%.

(C3) Formulae Accounting for Local Average Wind Conditions

Valiantzas (2013b) : V^{11} [Rs, T, U]:

$$ET_0 = 0.0393R_s\left(T_{mean} + 9.5\right)^{0.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.0037\left(T_{mean} + 20\right)\left(1.12T_{mean} - T_{\min} - 2\right)^{0.7}U^{0.7} \tag{13}$$

Valiantzas (2018a) : V^{12} [Rs, T, RH, U]:

$$ET_0 = 0.0393R_s\left(T_{mean} + 9.5\right)^{0.5} - 2.4\left(\frac{R_s}{R_a}\right)^2 - 0.024\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) + W_{aero}0.066\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right)U^{0.6} \tag{14}$$

When RH > 65%, W_{aero}= 0.78 and RH ≤ 65%, W_{aero}= 1.067, where W_{aero} is an empirical weighted factor.

Valiantzas (2018b) : V^{13} [T, RH, U]:

$$ET_0 = 0.0118\left(1 - \frac{RH}{100}\right)^{0.2}\left(T_{\max} - T_{\min}\right)^{0.3}\left[R_a\left(T_{mean} + 10\right)^{0.5} - 40\right] + 0.1\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right)\left(\frac{U}{2}\right)^{0.6} \tag{15}$$

(C4) Reduced Set Formulae with Temperature and Relative Humidity Data Alone

Valiantzas (2013d) : V^{14} [T and RH]:

$$ET_0 = 0.00668R_a\left[\left(T_{mean} + 9.5\right)\left(T_{\max} - T_{dew}\right)\right]^{0.5} - 0.0696\left(T_{\max} - T_{dew}\right) - 0.024\times\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) - 0.00455R_a\left(T_{\max} - T_{dew}\right)^{0.5} + 0.0984\times\left(T_{mean} + 17\right)\left\{\left[1.03 + 0.0055\left(T_{\max} - T_{\min}\right)^2\right] - \frac{RH}{100}\right\} \tag{16}$$

Valiantzas (2018b) : V^{15} [T and RH]:

$$ET_0 = 0.0118\left(1 - \frac{RH}{100}\right)^{0.2}\left(T_{\max} - T_{\min}\right)^{0.3}\left[R_a\left(T_{mean} + 10\right)^{0.5} - 40\right] + 0.1\left(T_{mean} + 20\right)\left(1 - \frac{RH}{100}\right) \tag{17}$$

(C5) Reduced Set Formulae with Temperature and Radiation Data Alone

Valiantzas (2013b) : V^{16} [T and R_s]:

$$ET_0 = 0.0393R_s\left(T_{mean} + 9.5\right)^{0.5} - 0.19R_s^{0.6}\varphi^{0.15} + 0.0061\left(T_{mean} + 20\right)\left(1.12T_{mean} - T_{\min} - 2\right)^{0.7} \tag{18}$$

Hargreaves (1975) : HG [T and R_s]:

$$ET_0 = 0.0135 * 0.408R_s\left(T_{mean} + 17.8\right) \tag{19}$$

where, $T_{\max}$, $T_{\min}$ and T_{mean} are daily maximum, minimum and mean air temperature (°C) respectively; RH is the daily average relative humidity (%); R_s is the solar radiation [MJ m^{-2} day^{-1}]; R_a is the extraterrestrial radiation [MJ m^{-2} day^{-1}]; α = 0.25 for V^{1} [R_s, T, RH, u] and V^{7} [R_s, T, RH, u]; α = 0.23 for remaining models; U is long-term average annual wind speed (ms^{-1});φ is latitude of the weather station in radians and z is elevation of weather station in meters. The reference evapotranspiration estimated from eighteen models are compared with FAO56-PMequation. The indexes used for comparison are traditional co-efficient of determination (R^2), standard error estimate (SEE) and long term average ratio (rt).

$$SEE = \sqrt{\frac{\sum_1^n \left(Y_i - X_i\right)^2}{n - 1}} \tag{20}$$

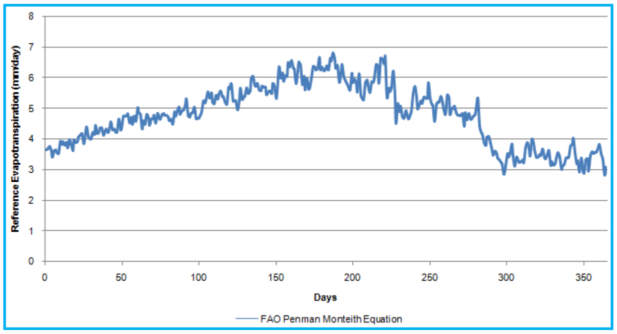


Fig. 1. ET_0 estimated from FAO56-PM Model for Kumulur Station

$$rt = \frac{X_{av}}{Y_{av}} \tag{21}$$

where, X_i = estimated ET_0using Valiantzas ET_0 models; Y_i = ET_0 estimated using FAO56-PM model with full dataset, at i^{th} data point; n = total number of observations; X_{av} and Y_{av} are the long term average values of Valiantzas ET_0 models and FAO56-PM model respectively.

3. Results and discussion

From the ten years data, reference evapotranspiration was estimated for Kumulur station. It was found that reference evapotranspiration varies from 2.8 to 6.8mm day^{-1}. The variation of reference evapotranspiration using FAO-PM method is shown in Fig. 1.

The simple linear regression analysis for Valiantzas' models and FAO56-PM model was carried out for daily weather data of Kumulur station is presented in figures along with R^2 value, standard error estimate and long-term average ratio for each model.

The Valiantzas' models requiring full dataset performed excellently at this station. The SEE of V^1 [R_s, T, RH, u] is 0.426 mm/day [Fig. 2(a)] and also it falls within the maximum value of SEE (0.466 mm/day) reported by Valiantzas (2013a) for V^1 [R_s, T, RH, u] model estimated at twelve stations.

The SEE (0.332 mm/day) [Fig. 2(b)] of V^2 [R_s, T, RH, u] model was almost near to average value of SEE (0.323 mm/day) reported by Valiantzas (2013c) for V^2 [R_s, T, RH, u] model estimated at seventeen stations.

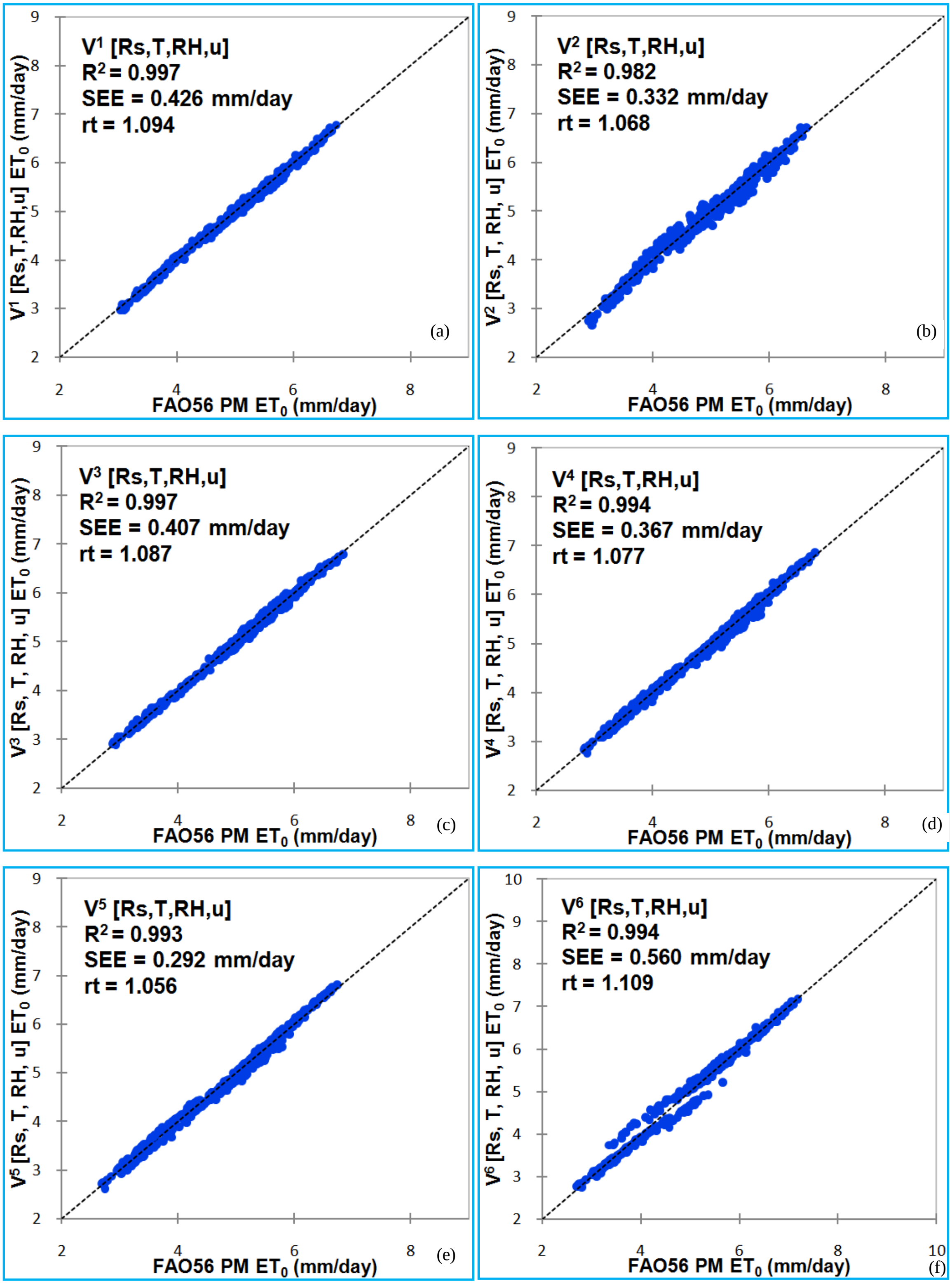
V^3 [R_s, T, RH, u] and V^4 [R_s, T, RH, u] had little higher SEE compared to maximum SEE reported by Valiantzas (2013d) [Figs. 2(c&d)]. The seven stations maximum value of SEE for V^3 [R_s, T, RH, u] obtained by Valiantzas (2013d) was 0.217 mm/day and SEE for V^3 [R_s, T, RH, u] at Kumulur station was 0.407 mm/day. Also when V^4 [R_s, T, RH, u] is used, the SEE is less compared to the SEE of V^3 [R_s, T, RH, u].

V^5 [R_s, T, RH, u] had little higher values of SEE around 0.292 mm/day compared to the maximum SEE reported by Valiantzas (2013d) which was 0.248 mm/day. Performance of V^5 [R_s, T, RH, u] with less SEE (0.292 mm/day) and rt (1.056), was identified as the best model when compared to all the other full dataset models (C1) [Fig. 2(e)].

V^6 [R_s, T, RH, u] had little higher SEE [Fig. 2(f)] compared to the maximum SEE reported by Valiantzas (2013a), *i.e.*, around 0.466 mm/day. Overall all the models requiring full dataset showed a very good correlation. Djaman *et al.* (2017b) reported that Valiantzas full-set of data formulation showed a good performance under humid, sub-humid and semiarid conditions across Africa. Li *et al.* (2018) also reported that full set of data Valiantzas model on a daily timescale was the best alternative model for estimating the ET_0 in Eastern China. Djaman *et al.* (2017a) also concluded that the performance of Valiantzas' equations depends on data requirements: the more meteorological inputs, the higher the ET_0 accuracy.

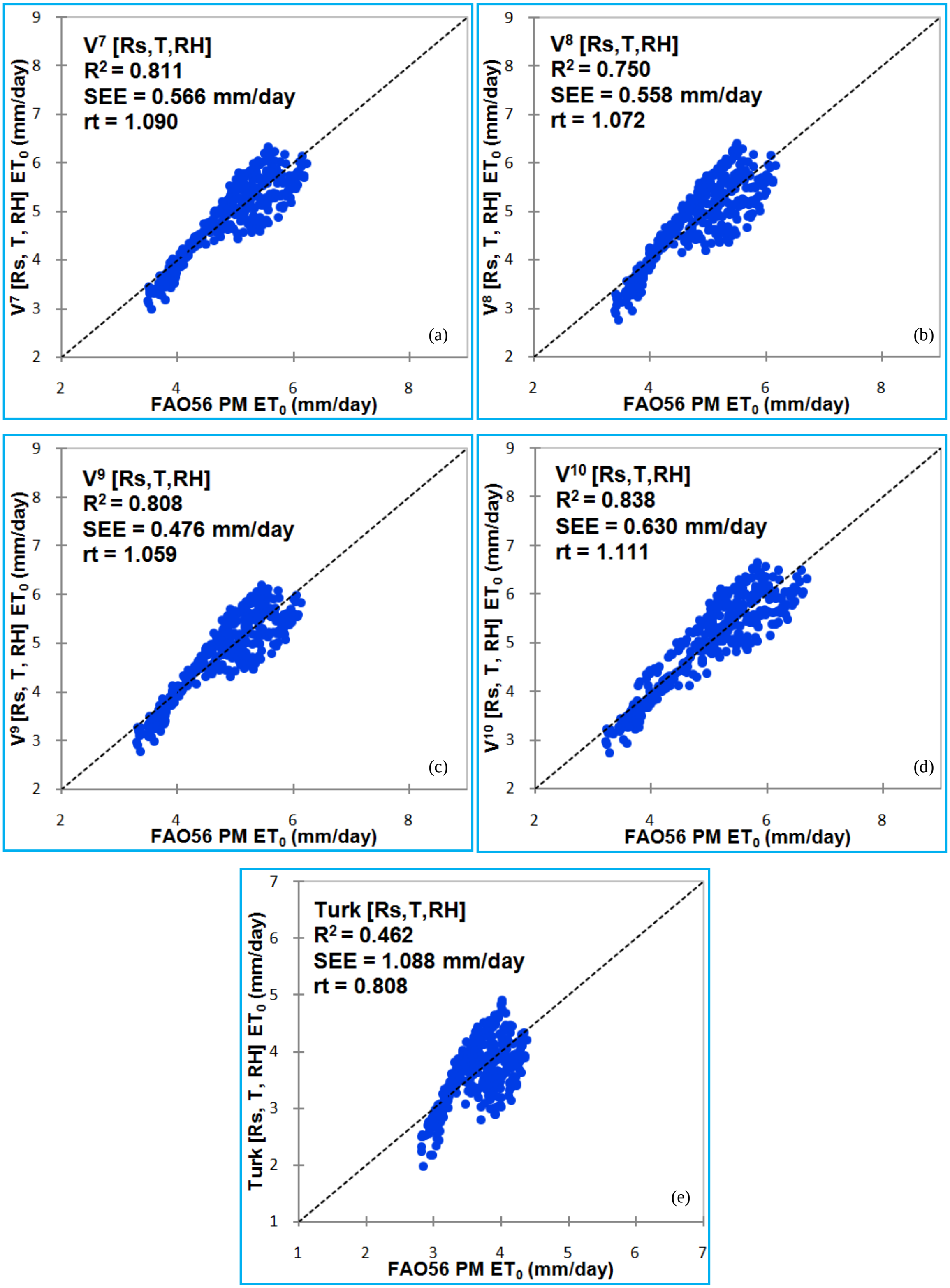
The models not requiring wind speed data (C2) also performed equally well in this station and there is a fairly good correlation between these Valiantzas [R_s, T, RH] models and FAO56-PM model. The SEE of V^7 [R_s, T, RH] was 0.566 mm/day [Fig. 3(a)] which is less than the maximum SEE (0.897 mm/day) reported by Valiantzas (2013a) for twelve stations. Similarly the SEE of V^8 [R_s, T, RH] was 0.558 mm/day [Fig. 3(b)] and almost near to the average value of SEE (0.548 mm/day) reported by Valiantzas (2013c) that was estimated for seventeen stations.

For V^9 [R_s, T, RH], the SEE calculated was 0.476 [Fig. 3(c)] and is lesser compared to the average value reported by Valiantzas (2013d) for the same method at different locations (SEE = 0.649 mm/day). The SEE of V^{10} [R_s, T, RH] [Fig. 3(d)] was within the maximum value of SEE (0.897 mm/day) obtained by Valiantzas (2013a) for twelve station. Higher SEE (1.088 mm/day) was obtained for Turk [R_s, T, RH] model compared to Valiantzas [R_s, T, RH] models [Fig. 3(e)]. Valiantzas (2013c) also reported a maximum SEE of 1.242 mm/day while using Turk method. Hence V^9 [R_s, T, RH] was identified as the best model compared to all the other models not requiring wind speed data (C2) with less SEE (0.0.476 mm/day) and rt (1.059) [Fig. 3(c)].



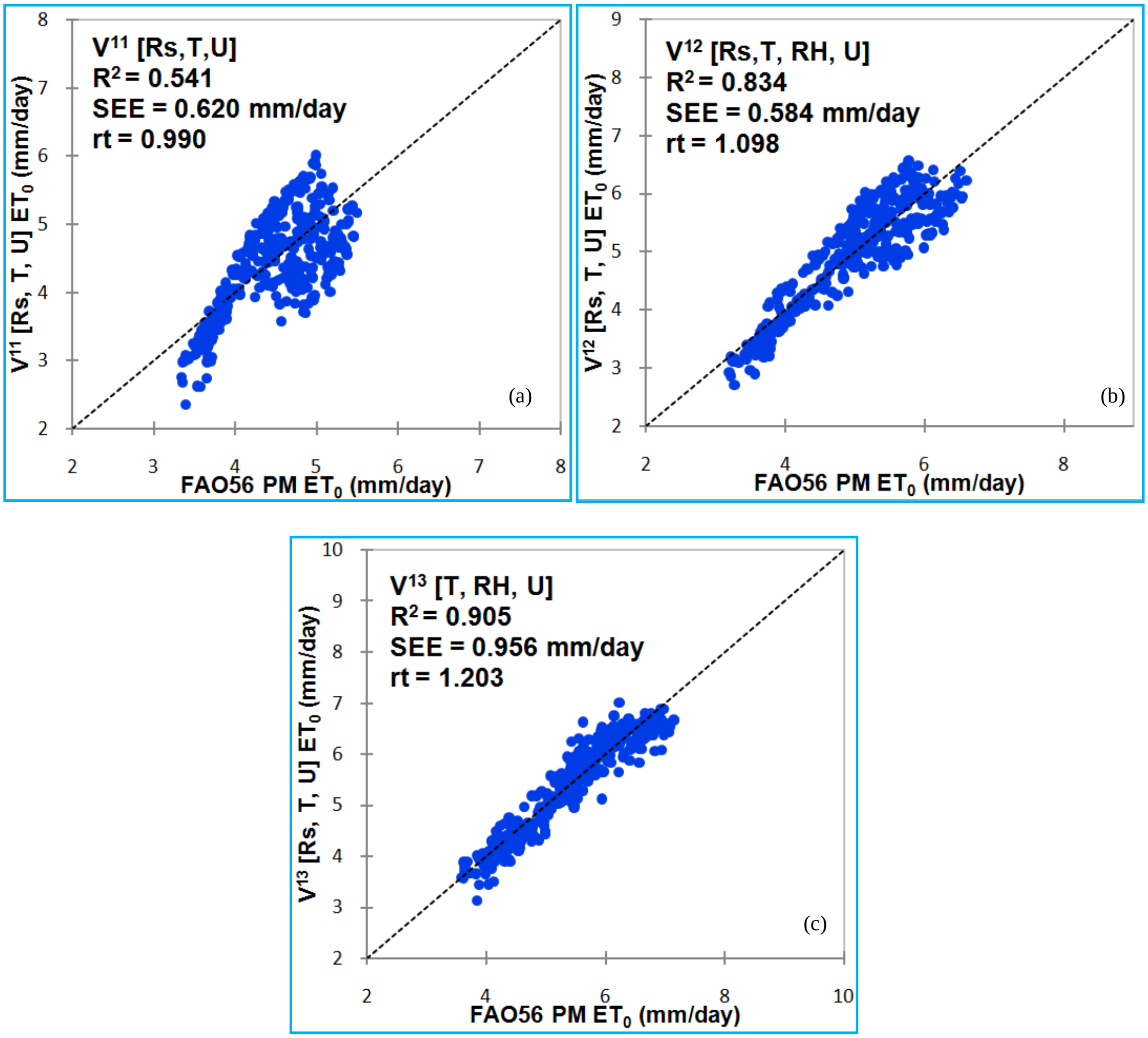
Figs. 2(a-f). Comparison of daily ET_0 estimated by Valiantzas' Model *versus* FAO PM model for Full Dataset

Though R^2 value is lesser for V^{11} [R_s, T, U], the SEE is lesser compared to the maximum value of SEE (0.916 mm/day) reported by Valiantzas (2013c) [Fig. 4(a)]. V^{12} [R_s, T, U] model also performed better while comparing



Figs. 3(a-e). Comparison of daily ET_0 estimated by Valiantzas' Model *versus* FAO PM model for No wind data

with SEE obtained by Valiantzas (2018a) for Or land station daily data [Fig. 4(b)]. A lesser value of SEE (0.956 mm/day) was obtained for V^{13} [*T*, RH, *U*] compared to the maximum value of SEE (1.62 mm/day)

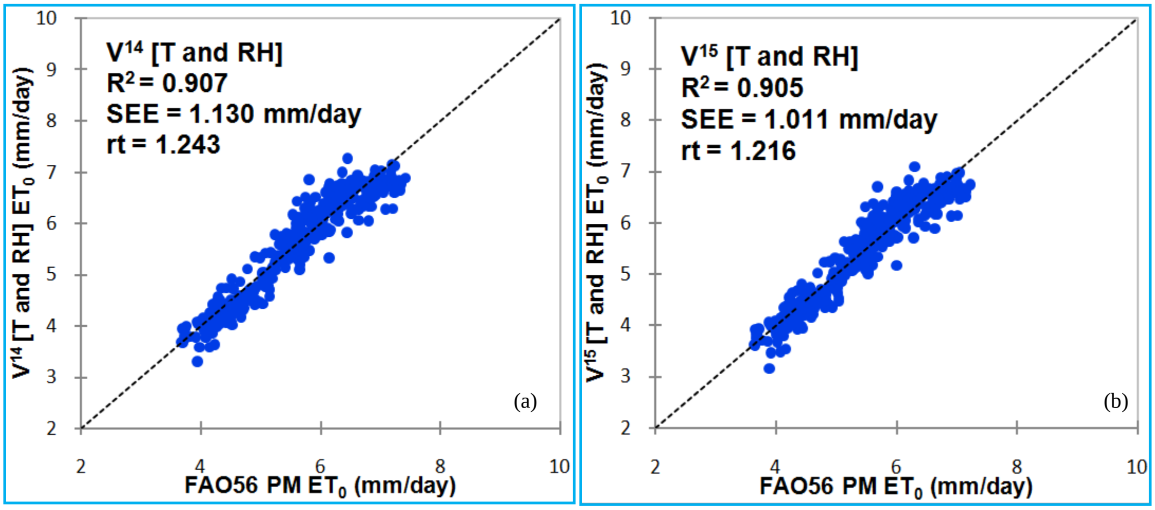


Figs. 4(a-c). Comparison of daily ET_0 estimated by Valiantzas' Model *versus* FAO PM model for Long Term Average Wind Data

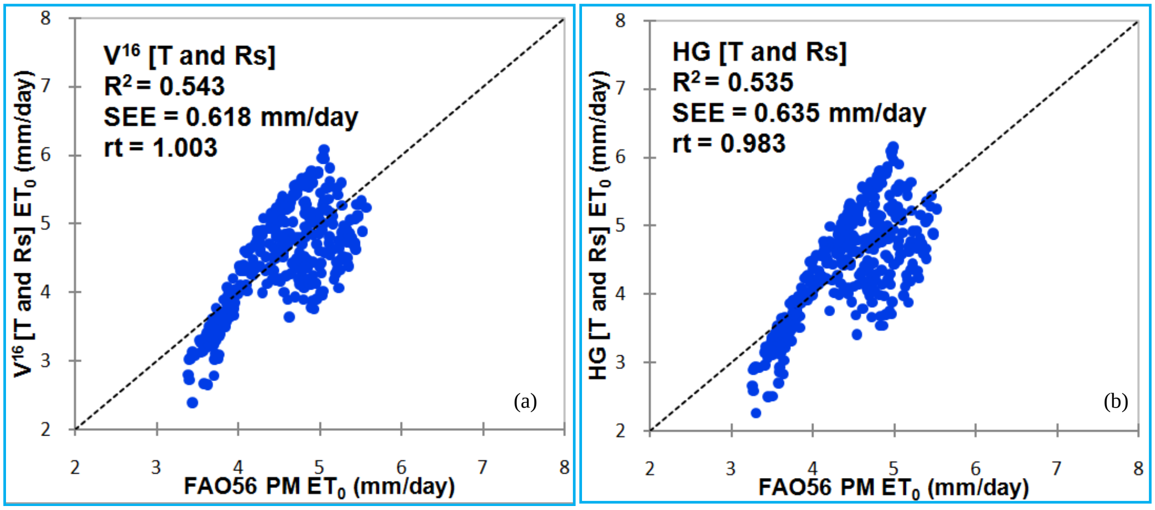
obtained by Valiantzas (2018b) for Andravida station and it was higher than the average value (0.603 mm/day) [Fig. 4(c)]. Though all the above three models performed well, V^{12} [R_s, *T*, *U*] model with SEE = 0.584 mm/day and *rt* = 1.098 was identitfied as the best model for calculation of ET_0 when long-term average wind speed and the remaining parameters are available (C3).

A nearer value of SEE (1.130 mm/day) was obtained for V^{14} [*T* and RH] model while comparing with the maximum value of SEE (1.105 mm/day) obtained by Valiantzas (2013d) for seven stations. The SEE (1.01 mm/day) of V^{15} [*T* and RH] is lesser compared to the maximum value (1.12 mm/day) of SEE reported by Valiantzas (2018b) for around thirty two stations. Though both the methods exhibited a good correlation with FAO56-PM method having R^2 value of 0.907 and 0.905 respectively [Figs. 5(a&b)], V^{15} [T and RH] with SEE = 1.011 mm/day and *rt* = 1.216, was identified as the best model for calculation of ET_0 when long-term average wind speed and the remaining parameters are available (C4).

While comparing V^5 [R_s, *T*, RH, *u*] and V^9 [R_s, *T*, RH], it was found that, the SEE was higher when wind speed is not available. When long-term average wind speed is used instead of missing wind speed, *i.e.*, V^{12} [R_s, *T*, RH, *U*] model, the SEE is reduced compared to no wind speed data modelV^{10} [R_s, *T*, RH]. Similarly while using the long-term average wind speed in Valiantzas [*T* and RH] model, the standard error estimate is reduced. So when wind speed data is not available for particular station, the long term average wind speed can be used for estimation of reference evapotranspiration.



Figs. 5(a&b). Comparison of daily ET_0 estimated by Valiantzas' Model *versus* FAO PM model for Temperature and Relative Humidity Data



Figs. 6(a&b). Comparison of daily ET_0 estimated by Valiantzas' Model *versus* FAO PM model for Temperature and Radiation Data

The value of SEE (0.618 mm/day) obtained for V^{16} [T and R_s] model for Kumulur station is lesser compared to the average value of SEE (0.693 mm/day) obtained by Valiantzas (2013c) for seventeen stations. While comparing V^{16} [T and R_s] with HG [T and R_s], V^{16} [T and R_s] performed better with lesser SEE [Figs. 6(a&b)]. Hence when relative humidity and wind speed data is not available (C5), V^{16} [T and R_s], was identified as the best model for calculation of $ET_{0.}$

4. Conclusions

The FAO56 standardized Penman-Monteith equation is globally used for estimation of reference evapotranspiration. A disadvantage in using the FAO56 Penman-Monteith is that the main weather variables appearing directly in the equation are net radiation at the surface (R_n), temperature, slope of saturation vapor pressure curve, vapour pressure deficit (D), psychrometric constant and wind velocity. Though there are specific instruments to measure R_n and D, the usually available weather records in the standard meteorological stations are maximum and minimum air temperatures, solar radiation; maximum and minimum relative humidity and wind speed (Shuttleworth, 1993). The Valiantzas models requiring full dataset performed excellently in Kumulur station among which V^5 [R_s, T, RH, u] was best. The Valiantzas models requiring no wind data also performed well in this station. It is noted that that newly developed Valiantzas [R_s, T, RH] models performed better compared to the old Turk model under no wind speed data condition. Similarly Valiantzas [T and R_s] models performed better compared to Hargreaves [*T* and R_s] model. The three Valiantzas models using long-term average wind speed also performed better in this station. Hence, in the five categories, C1) Formulae Requiring Full Set of Weather Data - V^5 [R_s, *T*, RH, *u*], C2) Reduced Set Formulae without Wind Data - V^9 [R_s, *T*, RH], C3) Formulae Accounting for Local Average Wind Conditions - V^{12} [R_s, *T*, *U*], C4) Reduced Set Formulae with Temperature and Relative Humidity Data Alone - V^{15} [*T* and RH] and C5) Reduced Set Formulae with Temperature and Radiation Data Alone - V^{16} [*T* and R_s], the respective simplified models proposed by Valiantzas had good accuracy in this station and can be used for ET_0 calculations under full dataset and limited data conditions.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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