Evaluation of Valiantzas ET_0 equations against FAO56-PM model in Indian semi-arid climatic conditions

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Abstract: In this study, the performance of three forms of Valiantzas ET_0 equations namely, (i) requiring full meteorological dataset, (ii) not requiring wind speed data, and (iii) not requiring both wind speed & relative humidity data for Indian semi-arid Hissar and Parbhani districts in comparison to widely accepted FAO-56 PM model was evaluated in terms of different statistical indices and their ranking based on Global Performance Indicator values. All Valiantzas ET_0 equations requiring full meteorological dataset under-estimated FAO56-PM estimates in the range of 9.10% to 21.84% at Hissar while they over-estimated it in the range of 0.98% to 8.32% at Parbhani district. Valiantzas equations not requiring wind speed data under-estimated FAO56-PM ET_0 values in the range of 3.90% to 34.56% at Hissar while, it over-estimated the same in the range of 11.55% to 41.28% at Parbhani. The Valiantzas equations not requiring both wind speed & relative humidity data under-estimated FAO56-PM ET_0 estimates in the range of 51.39% to 57.56% at Hissar and fluctuating trend in the range of -1.80% to 6.96% at Parbhani district. Among all 16 considered Valiantzas ET_0 equations, Val 7 and Val 2 (equations requiring full meteorological dataset) showed best performance at Hissar and Parbhani districts, respectively while Val 16 (equation not requiring both wind speed & relative humidity data) and Val 9 (representing Valiantzas equations not requiring wind speed data) were adjudged the worst at Indian semi-arid Hissar and Parbhani districts, respectively.

Keywords: Valiantzas equations, reference evapotranspiration, semi-arid, Hissar, Parbhani, India.

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1 Introduction

The process of evapotranspiration is the summation of evaporation from soil surface and transpiration from plant canopy (Shuttleworth, 1993). On one hand, direct evaporation accounts for the movement of water to vapour from source which may be soil, canopy capture, water bodies. On the other hand, transpiration accounts for the movement of water within a plant which is extracted by its root system from the soil and is successively lost as vapour through stomata present in plant leaves. The process of evaporation and transpiration happen concurrently and there is no easy way to separate these two processes individually. Apart from water availability in topsoil, evaporation from a cropped soil is mainly determined by the fraction of solar radiation which reaches to soil surface. This solar radiation fraction decreases with crop development over growing period as crop canopy shades

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more and more ground area with higher plant growth. When crop is small, water is mainly lost by soil evaporation, whereas transpiration dominates the process with well-established crop, as it fully covers soil surface. At sowing, almost 100% evapotranspiration comes from evaporation, while with full crop cover, more than 90% of it comes from the process of transpiration (Allen et al., 1998).

Evapotranspiration is a key constituent and its estimation is an important component in the irrigation and agricultural water research, management and its development (Chiew et al., 1995). As an imperative constituent of hydrosphere, atmosphere and biosphere, evapotranspiration plays an active role in determining exchange of energy and mass between them in the form of hydrologic cycle (Chen et al., 2005; Kumar et al., 2013). It can significantly affect the water budget of natural environment, i.e., about 65% of all precipitation falling on the earth’s surface evaporates back into the atmosphere (Kite, 2000; Trenberth et al., 2007; Ampas and Baltas, 2012). Evapotranspiration is a key element of water resource management which stimuluses water demands of agricultural and domestic sectors (Chen et al., 2005) and is widely used in agricultural & urban planning, agro-climatological zoning, irrigation scheduling, hydrological and irrigation engineering applications, regional water balance studies, global water budgets, sustainable water use etc. (Samani, 2000). It also assumes central role in a number of meteorological and hydrological applications, including climate change effects and impact assessment of droughts (Bandyopadhyay et al., 2009; El-Baroudy et al., 2010; Exner-Kittridge and Rains, 2010; Ladlani et al., 2012; Fisher and Pringle III, 2013; Tabari et al., 2013; Senatore et al., 2015), and is greatly influenced by climate as a vital part of regional hydrology (Ali and Shui, 2009; Huo et al., 2013). Having acquaintance on the level of ET_0 to determine water use is important for irrigation scheduling, agricultural research, management and development of water resources, especially in arid and semi-arid regions as it plays a key role in sustainable agriculture and environment (Chiew et al., 1995; Al-Ghobari, 2000; George et al., 2002; Ahmadi and Fooladmand, 2008; Askari et al., 2015; El-Wahed and Snyder, 2015). It is also important in planning economical uses of water resources (Zhao et al., 2004).

Allen et al. (1998) defined reference evapotranspiration as ‘the rate of evapotranspiration from a hypothetical grass reference crop with an assumed height of 0.12 m having a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23, in which the reference surface closely resembles an extensive surface of green grass of uniform height, actively growing, completely shading the ground and adequately watered. The FAO of the United Nations and the American Society of Civil Engineering (ASCE) recommended FAO56 Penman-Monteith combination equation (FAO56-PM) as, “index” or “reference” or “standard” method for estimating reference evapotranspiration (Allen et al., 1998, 2005).

The performance evaluation of various forms of Valiantzas ET_0 equations (Valiantzas, 2006, 2013a, 2013b, 2013c, 2013d, 2015) against standard FAO56-PM model undertaken by different researchers (Pan et al., 2011; Kisi, 2014; Gao et al., 2015; Valipour, 2015; Djaman et al., 2016a, 2016b; Peng et al., 2017; Djaman et al., 2017a, 2017b, 2017c; Akhavan et al., 2018; Djaman et al., 2018; Li et al., 2018) establish them as best alternate to FAO56-PM model across the world for calculating reference evapotranspiration values under different climatic conditions.

Considering the above, present study was conducted for two Indian semi-arid Hissar and Parbhani districts with specific aims as, (i) to evaluate performance of three forms of Valiantzas ET_0 equations in comparison to standard FAO56-PM model; and (ii) to identify most acceptable Valiantzas ET_0 equation on the basis of Global Performance Indicator (GPI) values.

2 Materials and methods

2.1 Study area and weather dataset

The study on performance evaluation of various forms of Valiantzas ET_0 equations against standard FAO56-PM model was carried out using daily meteorological dataset of semi-arid Hissar and Parbhani districts obtained from India Meteorological Department, Pune. The quality control of daily weather dataset was guaranteed by omitting days with at-least one meteorological variable missing from the analyses and removing those data that contained significant statistical deviation from the climatic averages were removed from the available dataset. The pertinent details of these two Indian semi-arid districts are:

Table 1 Details of study area

District	Longitude (°E)	Latitude (°N)	Height (m a.s.l.)	Period
Hissar	75.46	29.17	215.20	1992-2016
Parbhani	76.77	19.26	347.00	1990-2016

2.2 Estimation of reference evapotranspiration

2.2.1 FAO Penman Monteith method

In this study, FAO-56 PM model was chosen as index which was expressed mathematically (Smith et al., 1992; Allen et al., 1998) as Equation 1:

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

Where ET_0 is reference evapotranspiration, mm d^{-1}; R_n is net radiation at crop surface, MJ m^{-2} d^{-1}; G is soil heat influx density, MJ m^{-2} d^{-1}; T is mean daily air temperature, $^{\circ}C$; U_2 is wind speed at 2 m height, m s^{-1}; e_s is saturation vapour pressure, kPa; e_a is actual vapour pressure, kPa; e_s-e_a is saturation vapour pressure deficit, kPa; Δ is slope of vapour pressure curve, kPa $^{\circ}C^{-1}$, and γ is psychometric constant, kPa $^{\circ}C^{-1}$.

The computation of daily ET_0 using Equation 1 requires meteorological parameters consisting of air temperature (maximum and minimum), mean daily actual vapour pressure (e_a) derived from either dew point temperature or relative humidity (maximum and minimum), daily average of 24 h wind speed measured at two-meter height (U_2), and net radiation (R_n) measured or computed from solar and long wave radiation or from actual duration of sunshine hours (n). Since soil heat flux (G) has a relatively small value, therefore, it may be ignored when computation of ET_0 is done on daily basis (Allen et al., 1998).

2.2.2 Valiantzas ET_0 methods

Pertinent details of different forms of Valiantzas ET_0 equations considered in this study are presented in Table 2.

2.3 Tools used for statistical analysis and ranking

To ensure the rigorous comparison of different selected methods and evaluate performance of different Valiantzas ET_0 methods in comparison to standard FAO56-PM method, an extended analysis in terms of statistical indices, namely, Agreement Index (D), coefficient of determination (R^2), Mean Bias Error (MBE), Percentage Error of Estimate (PE) and Standard Error of Estimates (SEE) was undertaken with the help of Microsoft^{TM} Excel® as computing tool to analyse results. The D, R^2, MBE, PE, and SEE are defined as:

2.3.1 Agreement index (D)

The agreement index (D) measures degree with which observed variant is accurately estimated with the help of simulated variant. It varies in between “0.00” and “1.00”. The value “0.00” indicates complete disagreement, while “1.00” indicates perfect agreement. The D value can be obtained mathematically by Equation 18:

$$D = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (18)$$

2.3.2 Coefficient of determination (R²)

In statistics, coefficient of determination (R²) indicates how well the data points fit a statistical model. The value of R² ranges from 0 to 1. It measures variation in one factor caused by its relationship to another factor. It indicates “goodness of fit” of statistical model in the form of a line or curve and is expressed mathematically as Equation 19:

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sum_{i=1}^{n}(P_i - \bar{P})^2 \sum_{i=1}^{n}(O_i - \bar{O})^2}\right]^2 \quad (19)$$

The value of R^2 varies in between “0.00” and “1.00”. The value of R^2 greater than or equal to 0.90 is considered very satisfactory, whereas, its value lying between 0.80-0.90 is considered fairly good, and in between 0.60 and 0.80, it is considered unsatisfactory.

Table 2 Different forms of Valiantzas ET_0 equations considered in the study

S. No.	Valiantzas ET_0 equations	Symbol	Eq. No.
	Equations requiring full meteorological dataset		
1.	$ET_0 = 0.051 \times (1-\alpha)R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + 0.048 \times (T+20)(1-0.01RH)(0.5+0.536U_2) + 0.00012Z$	Val 1	(2)
2.	$ET_0 = 0.051 \times (1-\alpha)R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + 0.052 \times (T+20)(1-0.01RH)(a_u - 0.38 + 0.54U_2)$	Val 2	(3)
3.	$ET_0 = 0.051 \times (1-\alpha)R_S\sqrt{T+9.5} - 0.188 \times (T+13)\left(\frac{R_S}{R_a} - 0.194\right)\left(1 - 0.00014 \times (0.7 \times T_{max} + 0.3 \times T_{min} + 46)^2 \times \sqrt{0.01RH}\right) +$ $0.049 \times (T_{max} + 16.3)(1-0.01RH)(a_u + 0.536U_2)$	Val 3	(4)
4.	$ET_0 = 0.051 \times (1-\alpha)R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + 0.048 \times (T+20)(1-0.01RH)(0.5+0.536U_2)$	Val 4	(5)
5.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 - 0.024 \times (T+20)(1-0.01RH) + 0.066 \times W_{aero} \times (T+20) \times$ $(1-0.01RH){U_2}^{0.6}$ $W_{aero} = 0.78$, when $RH > 65\%$; and $W_{aero} = 1.067$, when $RH \leq 65\%$	Val 5	(6)
6.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 0.19 \times {R_S}^{0.6}\varphi^{0.15} + 0.048 \times (T+20)(1-0.01RH){U_2}^{0.7}$	Val 6	(7)
7.	$ET_0 = 0.051 \times (1-\alpha)R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 - 0.024 \times (T+20)(1-0.01RH) - 0.0165 \times R_S{U_2}^{0.7} + 0.0585 \times (T+17) \times {U_2}^{0.75}$ $\times [(1.03 + 0.00055TR^2) - 0.01RH] + 0.0001Z$	Val 7	(8)
	Equations not requiring wind speed data		
8.	$ET_0 = 0.038 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + 0.075(T+20)(1-0.01RH)$	Val 8	(9)
9.	$ET_0 = 0.047 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + 0.09(T+20)(1-0.01RH)$	Val 9	(10)
10.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + C_u \times (T+20)(1-0.01RH)$ $C_u = 0.054$ when $RH > 65\%$; and $C_u = 0.083$ when $RH \leq 65\%$	Val 10	(11)
11.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 0.19 \times {R_S}^{0.6}\varphi^{0.15} + 0.078 \times (T+20)(1-0.01RH)$	Val 11	(12)
12.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 - 0.024 \times (T+20)(1-0.01RH) + 0.1W_{aero}(T+20) \times (1-0.01RH)$ $W_{aero} = 0.78$, when $RH > 65\%$; and $W_{aero} = 1.067$, when $RH \leq 65\%$	Val 12	(13)
13.	$ET_0 =$ $0.00668 \times R_a\sqrt{(T+9.5)(T_{max} - T_{dew})} + 0.0696 \times (T_{max} - T_{dew}) - 0.024 \times (T+20) \times (1-0.01RH) - 0.00455 \times R_a\sqrt{(T_{max} - T_{dew})} +$ $0.0984 \times (T+17)(1.03 + 0.00055TR^2 - 0.01RH)$ where $T_{dew} = T_{min} - 0.12T + 2$	Val 13	(14)
14.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 2.4 \times \left(\frac{R_S}{R_a}\right)^2 + C_u \times (T+20)(1-0.01RH)$ $C_u = 0.076 - 0.0119(RH - 50)^{0.2}$, when $RH > 50\%$; and $C_u = 0.076 + 0.0084(50 - RH)^{0.2}$, when $RH \leq 50\%$.	Val 14	(15)
	Equations not requiring both wind speed & relative humidity data		
15.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 0.19 \times {R_S}^{0.6}\varphi^{0.15} + 0.0061 \times (T+20)(1.12T - T_{min} - 2)^{0.7}$	Val 15	(16)
16.	$ET_0 = 0.0393 \times R_S\sqrt{T+9.5} - 0.19 \times {R_S}^{0.6}\varphi^{0.15} + 0.0059 \times (T+20)(T - T_{min} - 0.45TR + 3.45)^{0.8}$	Val 16	(17)

Note: ET_0 = reference evapotranspiration (mm d^{-1}), α = albedo, R_s = solar radiation (MJ m^{-2} d^{-1}), R_a = extra-terrestrial radiation (MJ m^{-2} d^{-1}), T = mean air temperature (°C), RH = relative humidity (%), U_2 = wind speed at 2 m height (m s^{-1}), TR = temperature difference (°C), Z = altitude above mean sea level (m), T_{dew} = dew point temperature (°C), T_{max} = maximum air temperature (°C), T_{min} = minimum air temperature (°C), φ = latitude (radian), and U_{av} = long-term average wind speed (m s^{-1}).

2.3.3 Mean bias error (MBE)

MBE is difference between the mean of predicted and observed values, usually intended to measure average model bias. The MBE may take positive or negative values and is calculated by mathematical expression presented in Equation 20:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - O_i) \qquad (20)$$

2.3.4 Percentage error of estimate (PE)

The PE expresses difference between a predicted value and observed value. The value of percentage error close to zero indicates its closeness to resultant value and is considered good. It is expressed mathematically as Equation 21:

$$PE = \left|\frac{\bar{P} - \bar{O}}{\bar{O}}\right| \times 100 \qquad (21)$$

2.3.5 Standard error of estimates (SEE)

The SEE measures variation of an observation made around the computed regression line between the standard and comparison methods. If standard error is zero, then there is no variation corresponding to computed line and correlation is considered perfect. The SEE is expressed mathematically as Equation 22:

$$\mathrm{SEE} = \sqrt{\left[\frac{1}{\mathrm{n(n-2)}}\right]\left[\mathrm{n}\sum \mathrm{P_i}^2 - \left(\sum \mathrm{P_i}\right)^2 \frac{[\mathrm{n}\sum \mathrm{O_i P_i}]-(\sum \mathrm{O_i})(\sum \mathrm{P_i})}{\mathrm{n}\sum \mathrm{O_i}^2-(\sum \mathrm{O_i})^2}\right]^2} \tag{22}$$

In Equation 18, Equation 19, Equation 20, Equation 21 and Equation 22, $\mathrm{P_i}$ and $\mathrm{O_i}$ are predicted and observed values of $\mathrm{ET_0}$ (mm $\mathrm{d^{-1}}$) by different Valiantzas methods and FAO56-PM model respectively, $\overline{\mathrm{P}}$ and $\overline{\mathrm{O}}$ are corresponding mean values of $\mathrm{ET_0}$ (mm $\mathrm{d^{-1}}$), and n is total number of observations.

2.3.6 Global performance indicator (GPI)

Each statistical index has its own strength and weakness. The comparison or ranking of large number of models is very difficult and this problem was resolved by using Global Performance Indicator (GPI) as a tool. If value of some statistical index is found less than the median value of a particular model in comparison to model, the results will be most accurate than other models and vice-versa. GPI has an important advantage that it ranks different models and thereby, classification of models becomes easier and more realistic. In order to avoid predominant influence of any particular indicator, they have to be normalized between "0.00" and "1.00". The maximum and minimum values of individual scaled statistical indicator are "1.00" and "0.00", respectively (Behar et al., 2015; Despotovic et al., 2015). The summative form of GPI is mathematically expressed as Equation 23:

$$\mathrm{GPI} = \sum_{i=1}^{n}(\overline{\mathrm{X}}_\mathrm{i} - \mathrm{X_{ij}}) \times a_\mathrm{i} \tag{23}$$

Where $\overline{\mathrm{X}}_\mathrm{i}$ is median value of scaled indicator i, $\mathrm{X_{ij}}$ is of indicator i for method j, a_i = (-)1 for $\mathrm{R^2}$ and (+)1 for all other statistical indicators.

The more accurate model will have higher GPI value. There are several advantages of summative form of GPI in comparison to its productive form as in later case, if value of one indicator is 0.00 then the product of all indicators will automatically be 0.00, regardless of value of other indicators that could be rather high. Moreover, making simple product of all indicators could lead to very wide range of GPI values, which makes comparison of models more difficult (Despotovic et al., 2015).

3 Results and discussion

3.1 Performance of Valiantzas equations requiring full meteorological dataset

The comparison of average values of $\mathrm{ET_0}$ obtained with FAO56-PM model and different Valiantzas equations requiring full meteorological dataset (Table 3) showed that at Hissar district, these equations under-estimated FAO56-PM estimated in the range of 9.10%-21.84%, whereas they over-estimated FAO56-PM $\mathrm{ET_0}$ values in the range of 0.98%-8.32% at Parbhani district.

Table 3 Average $\mathrm{ET_0}$ values obtained with different Valiantzas equations requiring full meteorological data against FAO56-PM model

FAO56-PM model	Average $\mathrm{ET_0}$ values (mm $\mathrm{day^{-1}}$) obtained with Valiantzas equations						
	Val 1	Val 2	Val 3	Val 4	Val 5	Val 6	Val 7
				Hissar district			
6.0281	5.1202 (-15.06%)	4.8035 (-20.31%)	5.1705 (-14.23%)	5.0944 (-15.49%)	5.2603 (-12.74%)	4.7114 (-21.84%)	5.4796 (-9.10%)
				Parbhani district			
4.7533	5.1490 (+8.32%)	4.7999 (+0.98%)	4.838 (+1.82%)	5.1074 (+7.45%)	5.0281 (+5.78%)	5.0307 (+5.83%)	4.9085 (+3.27%)

Note: Figures in parathesis shows change in comparison to FAO56-PM model estimates. Negative (-) sign shows decrement while positive (+) sign shows increment.

The performance of Valiantzas $\mathrm{ET_0}$ equations requiring full meteorological dataset compared against standard FAO56-PM model (Table 4) showed that at Hissar, Val 7 equation produced the maximum value of D, followed by Val 5 and Val 3 with values of 0.9858, 0.9697 and 0.9627, respectively, whereas, Val 6 yielded its lowest value (0.9073). The highest value of $\mathrm{R^2}$ was obtained with Val 3 (0.9963), followed by Val 7 (0.9932) and Val 5 (0.9919) while its lowest value (0.9831) was obtained with Val 2. The value of MBE was found the lowest with Val 6 as -1.3167 mm d^{-1}. The lowest value of PE was observed with Val 7 (9.0996%) while its highest value (21.8431%) was observed with Val 6. From Table 4, it was also clear that Val 3 ranked the first with highest GPI value (0.5694). The lowest value of GPI was obtained with Val 2 (-0.4036) and was ranked the last among all seven Valiantzas equations requiring full meteorological dataset.

Table 4 Performance of Valiantzas ET_0 equations requiring full meteorological data against FAO56-PM model and their ranking

Valiantzas equations	Statistical indices					GPI	Rank
	D	R²	MBE	PE	SEE		
				Hissar district			
Val 1	0.9485	0.9886	-0.9079	15.0607	1.2988	-0.0020	5
Val 2	0.9263	0.9831	-1.2246	20.3143	1.5651	-0.4036	7
Val 3	0.9627	0.9963	-0.8576	14.2262	1.1349	0.5694	1
Val 4	0.9471	0.9886	-0.9337	15.4894	1.3171	-0.0010	4
Val 5	0.9697	0.9919	-0.7678	12.7373	1.0341	0.2450	3
Val 6	0.9073	0.9867	-1.3167	21.8431	1.7185	-0.0469	6
Val 7	0.9858	0.9932	-0.5485	9.0996	0.7319	0.4501	2
				Parbhani district			
Val 1	0.9783	0.9858	0.3956	8.3234	0.4328	-0.5403	6
Val 2	0.9973	0.9934	0.0466	0.9795	0.1475	1.6265	1
Val 3	0.9970	0.9963	0.0864	1.8181	0.1537	1.4526	2
Val 4	0.9819	0.9858	0.3541	7.4489	0.3951	-0.3580	5
Val 5	0.9859	0.9832	0.2748	5.7802	0.3624	-0.0568	4
Val 6	0.9782	0.9499	0.2773	5.8343	0.4316	-0.6288	7
Val 7	0.9948	0.9912	0.1552	3.2650	0.2145	0.8541	3

Note: D = Agreement index, R^2 = coefficient of determination, MBE = Mean bias error (mm d^{-1}), PE = Percent error of estimate (%), SEE = Standard error of estimate (mm d^{-1}), GPI = Global performance indicator, and Rank = Ranking of Valiantzas ET_0 equations.

At Parbhani, Val 2 produced the maximum value of D, followed by Val 3 and Val 7 with values of 0.9973, 0.9970 and 0.9948, respectively, whereas Val 6 yielded its lowest value (0.9782). The highest value of R^2 was obtained with Val 3 (0.9963), followed by Val 2 (0.9934) and Val 7 (0.9912) while its lowest value (0.9499) was obtained with Val 6 equation. The values of MBE, PE and SEE were found the lowest with Val 2 equation as 0.0466 mm d^{-1}, 0.9795% and 0.1475 mm d^{-1}, respectively, followed by Val 3 (0.0864 mm d^{-1}, 1.8181% and 0.1537 mm d^{-1}) and Val 7 equation (0.1552 mm d^{-1}, 3.2650% and 0.2145 mm d^{-1}), respectively. It was also clear from Table 4 that Val 2 with the highest GPI value (1.6265) performed the best among all the equations while Val 6 with the lowest GPI value (-0.6288) ranked the last.

3.2 Performance of Valiantzas ET_0 equations not requiring wind speed data

The comparative evaluation of seven Valiantzas ET_0 equations not requiring wind speed data against full dataset requiring FAO56-PM model for semi-arid Hissar and Parbhani districts (Table 5) revealed that Valiantzas equations extended lower ET_0 values (3.90%-34.56%) at Hissar and yielded significantly higher values (11.55%-41.28%) in comparison to FAO56-PM model estimates at Parbhani.

Table 5 Average ET_0 values obtained with different Valiantzas equations not requiring wind speed data against FAO56-PM model

FAO56-PM model	Average ET_0 values (mm d^{-1}) obtained with						
	Val 8	Val 9	Val 10	Val 11	Val 12	Val 13	Val 14
				Hissar district			
6.0281	4.1477 (-31.19%)	5.1336 (-14.84%)	4.3966 (-27.07%)	3.9446 (-34.56%)	4.3890 (-27.19%)	5.7931 (-3.90%)	4.5936 (-23.80%)
				Parbhani district			
4.7533	5.3024 (+11.55%)	6.7154 (+41.28%)	5.5240 (+16.21%)	5.4506 (+14.67%)	5.5190 (+16.11%)	5.7976 (+21.97%)	5.4885 (+15.47%)

Note: Figures in parathesis shows change in comparison to FAO56-PM model estimates. Negative (-) sign shows decrement while positive (+) sign shows increment.

At Hissar, Val 13 equation extended best value of D as 0.9409, followed by Val 9 and Val 14 equations with values of D as 0.8032 and 0.7912, respectively while Val 11 yielded the poorest results with the lowest value of D as 0.6797 (Table 6). From Table 6, it was clear that Val 13 produced the highest R^2 value, followed by Val 14 and Val

8 equations with corresponding values of 0.8948, 0.8911 and 0.8787 while Val 11 produced its lowest value as 0.8620. Best result in terms of lowest MBE (-2.0834 mm d^{-1}) was obtained with Val 11, while Val 13 resulted in the highest MBE value of -0.2350 mm d^{-1}.

Table 6 Performance of Valiantzas ET_0 equations not requiring wind speed data against FAO56-PM estimates and their ranking

Valiantzas equations	Statistical indices					GPI	Rank
	D	R^2	MBE	PE	SEE		
			Hissar district				
Val 8	0.7095	0.8787	-1.8804	31.1946	2.8389	0.2365	3
Val 9	0.8032	0.8709	-0.8945	14.8386	2.1389	0.0469	4
Val 10	0.7503	0.8705	-1.6315	27.0650	2.5693	-0.0129	5
Val 11	0.6797	0.8620	-2.0834	34.5622	3.0653	-0.2874	7
Val 12	0.7492	0.8705	-1.6391	27.1915	2.5769	-0.0138	6
Val 13	0.9409	0.8948	-0.2350	3.8989	1.3378	0.7126	1
Val 14	0.7912	0.8911	-1.4345	23.7966	2.3394	0.5910	2
			Parbhani district				
Val 8	0.9405	0.9125	0.5491	11.5519	0.6991	0.6246	1
Val 9	0.7259	0.8988	1.9621	41.2776	2.0444	-1.5279	7
Val 10	0.9041	0.8703	0.7707	16.2137	0.9507	-0.1769	4
Val 11	0.8989	0.8228	0.6973	14.6688	0.9382	-0.5689	6
Val 12	0.9049	0.8709	0.7657	16.1076	0.9453	-0.1631	3
Val 13	0.8660	0.8997	1.0442	21.9688	1.1500	-0.2073	5
Val 14	0.9134	0.8852	0.7351	15.4659	0.9437	0.0013	2

Note: D = Agreement index, R^2 = coefficient of determination, MBE = Mean bias error (mm d^{-1}), PE = Percent error of estimate (%), SEE = Standard error of estimate (mm d^{-1}), GPI = Global performance indicator, and Rank = Ranking of Valiantzas ET_0 equations.

The lowest accepted values of PE and SEE were obtained with Val 13 equation as 3.8989% and 1.3378 mm d^{-1}, respectively while their highest values as 34.5622% and 3.0653 mm d^{-1} were obtained with Val 11 equation. On the basis of GPI values, Val 13 showed the best performance with the highest GPI (0.7126), followed by Val 14 and Val 8 equations with GPI as 0.5910 and 0.2365, respectively while Val 11 was ranked the last with the lowest GPI value of -0.2874.

It was found that at Parbhani, Val 8 extended the best value of D as 0.9405, followed by Val 14 (0.9134) and Val 12 (0.9049) while Val 9 yielded the poorest results with value of D as 0.7259. From Table 6, it was also evident that Val 8 produced the highest value of R^2, followed by Val 13 and Val 9 equations with corresponding values as 0.9125, 0.8997 and 0.8988 while the lowest R^2 value of 0.8228 was obtained with Val 11 equation.

Similarly, Val 8 produced best results with the lowest values of MBE, PE and SEE as 0.5491 mm d^{-1}, 11.5519% and 0.6991 mm d^{-1} while Val 9 resulted in the highest values of MBE, PE and SEE as 1.9621 mm d^{-1}, 41.2779% and 2.0444 mm d^{-1}, respectively. The ranking of different Valiantzas ET_0 equations on the basis of GPI values showed that Val 8 showed the best performance with the highest value (0.6246) followed by Val 14 and Val 12 equations with corresponding values as 0.0013 and -0.1631, respectively. Among seven Valiantzas equations not requiring wind speed data, the Val 9 equation ranked the last with the lowest GPI value of -1.5279.

3.3 Performance of Valiantzas ET_0 equations not requiring both wind speed & relative humidity

The two Valiantzas ET_0 equations not requiring both wind speed & relative humidity data at Hissar under-estimated FAO56-PM ET_0 values to the tune of 51.39% to 57.56% while at Parbhani, Val 15 and Val 16 under-estimated and over-estimated FAO56-PM ET_0 estimates to the tune of 1.80% and 6.96%, respectively (Table 7).

Table 7 Average ET_0 values obtained with different Valiantzas equations not requiring both wind speed & relative humidity data against FAO56-PM model

FAO56-PM model	Average ET_0 values (mm d^{-1}) obtained with Valiantzas equations	
	Val 15	Val 16
	Hissar district	
6.0281	2.9301 (-51.39%)	2.5583 (-57.56%)
	Parbhani district	
4.7533	5.0842 (+6.96%)	4.6677 (-1.80%)

Note: Figures in parathesis shows change in comparison to FAO56-PM model estimates. Negative (-) sign shows decrement while positive (+) sign shows increment.

The performance of two Valiantzas equations not requiring both wind speed & relative humidity against FAO56-PM estimates (Table 8) reveals that the performance of Val 15 at Hissar district was the best in terms of the highest values of D (0.5461) and R^2 (0.4492) with GPI value as 0.5000 and the lowest values of MBE, PE and SEE with their respective values as -3.0980 mm d^{-1}, 51.3928% and 4.2219 mm d^{-1}, respectively. At Parbhani district, Val 16 extended the highest value of D (0.9252) and R^2 (0.8900) with the best results in terms of the lowest acceptable values of MBE, PE and SEE as -0.0857 mm d^{-1}, 1.8026% and 0.6510 mm d^{-1}, respectively. The analysis revealed that Val 16 ranked the first with GPI value of 1.5000.

Table 8 Performance of Valiantzas ET_0 equations not requiring both wind speed & relative humidity data against FAO56-PM estimates and their ranking

Valiantzas equations	Statistical indices					GPI	Rank
	D	R²	MBE	PE	SEE		
			Hissar district				
Val 15	0.5461	0.4492	-3.0980	51.3928	4.2219	0.5000	1
Val 16	0.5258	0.3363	-3.4698	57.5607	4.5603	-0.5000	2
			Parbhani district				
Val 15	0.9205	0.8402	0.3309	6.9615	0.7139	-1.5000	2
Val 16	0.9252	0.8900	- 0.0857	1.8026	0.6510	1.5000	1

Note: D = Agreement index, R^2 = coefficient of determination, MBE = Mean bias error (mm d^{-1}), PE = Percent error of estimate (%), SEE = Standard error of estimate (mm d^{-1}), GPI = Global performance indicator, and Rank = Ranking of Valiantzas ET_0 equations.

3.4 Overall Ranking of Valiantzas Equations against FAO56-PM Estimates

The overall ranking of 16 Valiantzas ET_0 equations based on GPI values revealed that for Hissar (Table 9), the first rank was assigned to Val 7 (requiring full meteorological dataset) as it produced the highest GPI of 0.1808 while Val 5 and Val 3 equations were ranked the second and third with corresponding GPI values of 0.1348 and 0.1304, respectively. The last rank was assigned to Val 16 equation (representing Valiantzas equations not requiring both wind speed & relative humidity data) as it produced the lowest GPI value of -0.8146.

Table 9 Normalized value of statistical indices and overall ranking of Valiantzas ET_0 equations for Indian semi-arid Hissar district

S. No.	Valiantzas equations	Statistical indices					GPI	Rank
		D	R²	MBE	PE	SEE		
				Equations requiring full meteorological data				
1	Val 1	0.9190	0.9883	0.7920	0.2080	0.1481	0.1067	4
2	Val 2	0.8708	0.9800	0.6941	0.3059	0.2176	0.0771	7
3	Val 3	0.9497	1.0000	0.8075	0.1925	0.1053	0.1304	3
4	Val 4	0.9160	0.9883	0.7840	0.2160	0.1529	0.1050	5
5	Val 5	0.9650	0.9933	0.8353	0.1647	0.0789	0.1348	2
6	Val 6	0.8294	0.9854	0.6656	0.3344	0.2577	0.0837	6
7	Val 7	1.0000	0.9953	0.9031	0.0969	0.0000	0.1808	1
				Equations not requiring wind speed data				
8	Val 8	0.3992	0.8217	0.4913	0.5087	0.5504	0.0576	8
9	Val 9	0.6030	0.8100	0.7961	0.2039	0.3675	0.0249	13
10	Val 10	0.4881	0.8094	0.5683	0.4317	0.4799	0.0267	12
11	Val 11	0.3345	0.7966	0.4286	0.5714	0.6095	0.0379	9
12	Val 12	0.4856	0.8093	0.5659	0.4341	0.4819	0.0272	11
13	Val 13	0.9025	0.8462	1.0000	0.0000	0.1583	-0.0291	14
14	Val 14	0.5769	0.8405	0.6292	0.3708	0.4199	0.0292	10
				Equations not requiring both wind speed & relative humidity data				
15	Val 15	0.0440	0.1710	0.1149	0.8851	0.9116	-0.5992	15
16	Val 16	0.0000	0.0000	0.0000	1.0000	1.0000	-0.8146	16

Note: D = Agreement index, R^2 = coefficient of determination, MBE = Mean bias error (mm d^{-1}), PE = Percent error of estimate (%), SEE = Standard error of estimate (mm d^{-1}), GPI = Global performance indicator, and Rank = Ranking of Valiantzas ET_0 equations.

At Parbhani district (Table 10), Val 2 (representing Valiantzas equations requiring full meteorological dataset) ranked the first with highest GPI value of 0.8759 while Val 3 and Val 7 equations were ranked the second and third with GPI values of 0.8501 and 0.7274, respectively. The last rank was assigned to Val 9 (representing equations not requiring wind speed data) as it produced the lowest GPI value of -0.16049, while Val 15 and Val 16 equations (representing equations not requiring both wind speed & relative humidity data) were ranked 10th and 7th, respectively at Parbhani district.

Table 10 Normalized value of statistical indices and overall ranking of Valiantzas ET_0 equations for Indian semi-arid Parbhani district

S. No.	Valiantzas equations	Statistical indices					GPI	Rank
		D	R²	MBE	PE	SEE		
		Equations requiring full meteorological data						
1	Val 1	0.9300	0.9393	0.2350	0.1822	0.1504	0.3989	6
2	Val 2	1.0000	0.9832	0.0646	0.0000	0.0000	0.8759	1
3	Val 3	0.9991	1.0000	0.0840	0.0208	0.0032	0.8501	2
4	Val 4	0.9432	0.9391	0.2147	0.1605	0.1305	0.4474	5
5	Val 5	0.9580	0.9241	0.1760	0.1191	0.1132	0.5149	4
6	Val 6	0.9298	0.7321	0.1773	0.1205	0.1497	0.3120	8
7	Val 7	0.9907	0.9706	0.1176	0.0567	0.0353	0.7274	3
		Equations not requiring wind speed data						
8	Val 8	0.7908	0.5167	0.3100	0.2624	0.2908	-0.1800	9
9	Val 9	0.0000	0.4379	1.0000	1.0000	1.0000	-1.6049	16
10	Val 10	0.6567	0.2736	0.4182	0.3780	0.4234	-0.6454	13
11	Val 11	0.6373	0.0000	0.3823	0.3397	0.4168	-0.8190	15
12	Val 12	0.6597	0.2770	0.4158	0.3754	0.4206	-0.6372	12
13	Val 13	0.5165	0.4430	0.5518	0.5208	0.5285	-0.7174	14
14	Val 14	0.6908	0.3593	0.4008	0.3595	0.4197	-0.5543	11
		Equations not requiring both wind speed & relative humidity data						
15	Val 15	0.7171	0.0998	0.2034	0.1484	0.2986	-0.3105	10
16	Val 16	0.7345	0.3873	0.0000	0.0204	0.2654	0.3241	7

Note: D = Agreement index, R^2 = coefficient of determination, MBE = Mean bias error (mm d^{-1}), PE = Percent error of estimate (%), SEE = Standard error of estimate (mm d^{-1}), GPI = Global performance indicator, and Rank = Ranking of Valiantzas ET_0 equations.

4 Conclusions

The performance of three forms of Valiantzas ET_0 equations namely, (i) equations requiring full meteorological dataset, (ii) equations not requiring wind speed data, and (iii) equations not requiring both wind speed & relative humidity data for semi-arid districts of Hissar and Parbhani in comparison to widely accepted FAO-56 PM model in terms of D, R^2, MBE, PE and SEE along with their ranking based on GPI values revealed that:

(1) All Valiantzas ET_0 equations requiring full meteorological dataset under-estimated FAO56-PM estimates in the range of 9.10%-21.84% at Hissar, while they over-estimated FAO56-PM ET_0 values in the range of 0.98%-8.32% at Parbhani. These equations showed the excellent performance in terms of the highest values of D and R^2 with the lowest errors. The Val 3 equation ranked the first at Hissar district, whereas Val 2 equation performed the best at Parbhani district. The Val 2 performed the worst at Hissar while Val 6 yielded the worst results at Parbhani.

(2) Valiantzas ET_0 equations not requiring wind speed data yielded 3.90%-34.56% lower ET_0 values in comparison to FAO56-PM estimates at Hissar and over-estimated them in the range of 11.55%-41.28% at Parbhani. Val 13 and Val 8 equations performed the best at Hissar and Parbhani districts, respectively as they produced better ET_0 estimates with D and R^2 values in the range of 0.6797-0.9409 and 0.8620-0.8948, respectively at Hissar while at Parbhani district, values of D and R^2 were observed in the range of 0.7259-0.9405 and 0.8228-0.9125, respectively.

(3) Valiantzas ET_0 equations not requiring both wind speed & relative humidity data (Val 15 and Val 16) under-estimated FAO56-PM ET_0 values at Hissar in the range of 51.39% to 57.56% while at Parbhani, fluctuating trend in the range of -1.80% to 6.96% in comparison to FAO56-PM ET_0 estimates was observed. The Val 15 equation showed the best performance at Hissar with value of D and R^2 in the range of 0.5248-0.5461 and 0.3363-0.4492, respectively.

Among all 16 Valiantzas ET_0 equations, Val 7 and Val 2 showed the best performance at Hissar and Parbhani districts, respectively while Val 16 and Val 9 equations extended the worst results at Indian semi-arid districts of Hissar and Parbhani, respectively.

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