Calibration and ranking of Valiantzas reference evapotranspiration equations under the humid climate of northeast India
Vanita Pandey and P. K. Pandey

ABSTRACT
This study aims to compare and calibrate seven different types of Valiantzas (Valiz) ET$_0$ equations against FAO Penman–Monteith (P-M) equation at three sites under the humid climatic condition of northeast India. In the first stage, the different Valiantzas equations were ranked based on their original coefficient (OC) at each site. In the second stage, Valiz equations were assessed based on local calibrated coefficient (LCC). In the third stage, the selected Valiz equations were assessed based on global calibrated coefficient (GCC) considering pooled data for all the selected stations. The ranking of equations was done using a summative form of global positioning index (GPI). Different Valiantzas equations showed different performances relative to the sites having similar climate class (warm and temperate). With the OC, the Valiz 7 is ranked one at Dibrugarh and Shillong, and Valiz 2 for Aizawl. After local calibration, again, Valiz 7 is best at Dibrugarh and Shillong while Valiz 6 is best at Aizawl. With global calibration coefficient, Valiz 7 ranked best at all three selected stations. The suitable equations identified for the region are Valiz 7, Valiz 6 if full data are available, and Valiz 2 under limiting data conditions.

Key words | FAO56 P-M, GPI, humid, reference evapotranspiration, valiantzas equations

INTRODUCTION
For direct measurement of evapotranspiration, a lysimeter is the most reliable tool. However, from the physical and economical aspect, it is difficult to measure evapotranspiration in every area of interest. Also, the establishment and maintenance of a lysimeter for an extended period is tedious, expensive and time-consuming. Therefore, as an alternative, many empirical and physically based equations are developed where only the input of weather parameters is required (Alexandris et al. 2006).

In most cases, observed actual ET data are not available, and the ET$_0$ is often used in the estimation of the actual evapotranspiration (ET). Reference evapotranspiration (ET$_0$) is a variable that is mainly dependent on the climatic factors, and it can be computed using observed meteorological data at the site.

The FAO 56 Penman–Monteith (P-M) method was identified as the most suitable alternative to estimate reference evapotranspiration due to its proper and accurate estimation of ET$_0$ when compared to the results found by lysimeters in different types of climatic conditions at different locations (Jensen et al. 1990; Abtew & Obeysekera 1995; Razzaghi & Sepaskhah 2012; Ghamarnia et al. 2015; Nolz et al. 2016; Egbuikwem & Obiechefu 2017).

The P-M is a universally accepted method for the benchmarking of reference evapotranspiration (ET$_0$) (Allen et al. 1998) by the ICID, and ASCE-EWRI (2005). The application of P-M is limited in most of the developing countries due to an insufficient network of the meteorological observatory and proper maintenance (Pandey et al. 2016). Alternatively, numerous studies in different climatic conditions evaluated
the applicability of less data-demanding empirical $ET_0$ methods using sophisticated and straightforward techniques against FAO P-M (Pandey et al. 2009, 2014, 2016; Efthimiou et al. 2013; Djaman et al. 2015; Cadro et al. 2017) and others.

A simple algebraic explicit formula for estimating $ET_0$ based on commonly available meteorological site observed variables, namely, temperature ($T$), relative humidity (RH), solar radiation ($R_s$), and wind velocity ($u$) was presented by Valiantzas (2006). It depends on the methodical investigation and numerical interpretations of the ‘standardized’ calculation technique suggested by Shuttleworth (1993) and Allen et al. (1998). Valiantzas (2013, 2015) developed and recommended different equations for estimation of $ET_0$ that depend on simplification and interpretations made to the first Valiantzas equations (2006) $ET_0$ method. Moreover, proclaimed calculated values of $ET_0$ from the developed equations correlated well with the FAO 56 P-M.

The P-M equation is a shortened variant of the complicated process, which involves plenty of particular supporting conditions accepted to transform observed input parameters into various other in-between calculated parameters. These main secondary parameters that appear in FAO 56 P-M are slope vapor pressure curve, effective emissivity, the clear-sky radiation, the Stefan–Boltzman constant, and the degree of cloudiness, latent heat of vaporization, psychrometric coefficient, vapor pressure (saturation and actual) and others (Valiantzas 2013). Furthermore, the parameters mentioned above have different units of representation which increases the complexity of estimation. The conversion of units of secondary parameters to apply FAO methodology of $ET_0$ may not be wholly appropriate, which can result in an error in calculated $ET_0$ values. Also, the solar radiation and wind speed data are not always reliable as some old sensors report errors in observations. The availability of solar radiation data is always challenging in nations like India. Furthermore, measurement of net radiation requires a specific and sophisticated instrument, which requires regular maintenance by trained professionals limiting the availability of $R_n$ data, especially in developing countries. Available parameters at a well-maintained site are temperature ($T$), relative humidity (RH), solar radiation ($R_s$), and wind velocity ($u$) in India, at most sites long-term $R_n$ and $u$ data are also limited.

The dominant ecosystem in northeast India is tropical wetland (Jhajharia et al. 2018). The region has vast potential for agricultural development. The study region soil and climate is best suited for farming of rice, tea, fruit crops, and medicinal crops. More than 60% of the crop area is under rainfed agriculture, and the study region is highly vulnerable to climate variability and climate change. The impact of climate change likely increases reference evapotranspiration due to increases in average daily temperature. The increased value of $ET_0$ results in an increased demand for crop water requirement.

The number of meteorological stations where the long-term historical required data to apply the FAO 56 Penman–Monteith model is insufficient in the study region due to remoteness, and low maintenance of observation sites. The selected sites, namely, Dibrugarh, Aizawl, and Shillong maintain long-term meteorological observations to apply the P-M model successfully.

There are a few reported studies that have applied Valiantzas equations in different regions (Gao et al. 2014; Valipour 2014; Ahooghalandari et al. 2017; Djaman et al. 2017). The above-cited studies reported good performance of Valiantzas equations under different climatic conditions, which may be further improved by site-specific calibration. In this study, the objective is to evaluate and calibrate different types of Valiantzas equations under the humid environment of northeast India. To the best of the authors’ knowledge, no such studies have been undertaken in Indian climatic conditions.

**METHODOLOGY**

**Study area and data**

The study region is described by diverse climate regimes, which are significantly subject to the southwest monsoon (June–September). The selected stations are in the warm and temperate climate class. The climate is classified as humid subtropical (Cwa) by the Köppen-Geiger system. The summer has much more rainfall when contrasted with winters. The long-term mean temperature, relative humidity, and total precipitation in Dibrugarh is 23.2 °C, 72.78%, and 2,372 mm, respectively. The average yearly temperature in
Aizawl is 24.15 °C, and 2,180 mm of total precipitation falls annually. The average annual relative humidity at Aizawl is 73.01% and ranges from 60% to 85%. The average yearly temperature, total precipitation, and relative humidity is 23.08 °C, 7,132 mm, and 80%, respectively, at the Shillong site.

The required meteorological data (daily scale) for the variables temperature, humidity, solar radiation, and wind speed for evaluating the Valiantzas ET₀ equations against P-M were collected at three weather stations across north-east India, from 2006 to 2016. These data were collected from the Indian Meteorological Department (IMD) Guwahati for Dibrugarh, Shillong, and Aizwal stations with the geographic coordinates presented in Table 1 and Figure 1.

FAO Penman–Monteith reference evapotranspiration equation

The FAO 56 Penman–Monteith (P-M) reference evapotranspiration equation was adopted for estimation of reference values (equivalent to observed) of ET₀ in the study. The P-M incorporates both physiological and aerodynamic components of the evapotranspiration process (Pandey et al. 2010) and is the most trusted equation globally under diverse climatic conditions. The P-M equation of ET₀ is as per

Table 1 | Geographical details of the study sites

<table>
<thead>
<tr>
<th>Stations</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dibrugarh</td>
<td>27.4728° N</td>
<td>94.9120° E</td>
<td>108</td>
</tr>
<tr>
<td>Shillong</td>
<td>25.5788° N</td>
<td>91.8133° E</td>
<td>1,500</td>
</tr>
<tr>
<td>Aizawl</td>
<td>23.1645° N</td>
<td>92.9376° E</td>
<td>1,132</td>
</tr>
</tbody>
</table>

Figure 1 | Location map of the study area.
Allen et al. (1998):

\[
\text{ET}_0 = \frac{0.408 \times \Delta \times (R_{\text{net}} - G) + \gamma (900/(T_m + 273))u \times (e_s - e_a)}{\Delta + \gamma \times (1 + 0.34u)}
\]  

(1)

where, \(\text{ET}_0\): grass reference evapotranspiration (mm d\(^{-1}\)), \(R_{\text{net}}\): net radiation (MJ m\(^{-2}\) d\(^{-1}\)), \(e_s, e_a\) are saturation and actual vapour pressure (kPa), respectively, \(\Delta\): slope of the saturation vapour pressure-temperature curve (kPa °C\(^{-1}\)), \(\gamma\): psychrometric constant (kPa °C\(^{-1}\)), \(u\): wind speed at 2 m height (m s\(^{-1}\)), \(T_m\): mean air temperature (°C), soil heat flux density (MJ m\(^{-2}\) d\(^{-1}\)).

Different types of Valiantzas reference evapotranspiration equations

Valiantzas derived a different equation for estimating \(\text{ET}_0\) for different weather parameter availability scenarios. The corrected version by Kisi (2014) of Valiantzas equations (Valiz 1, 2), along with other later revised versions of Valiantzas equations (references are given below) are selected for evaluation in the present study, keeping in view the objective to cover different limiting data scenarios.

Valiantzas Equation (1) (Valiz 1) (Valiantzas 2013; Kisi 2014):

\[
\text{ET}_0 = 0.0393T_s(T_m + 9.5)^{1/2} - 0.19R_s0.6\varphi^{0.15} \\
+ 0.0061(T_m + 20)(1.127T_m - T_{\text{min}} - 2)^{0.7}
\]  

(2)

Valiantzas Equation (2) (Valiz 2) (Valiantzas 2013; Kisi 2014):

\[
\text{ET}_0 = 0.0393T_s(T_m + 9.5)^{1/2} - 0.19R_s0.6\varphi^{0.15} \\
+ 0.0061(T_m + 20)(1 - \frac{RH}{100})
\]  

(3)

Valiantzas Equation (3) (Valiz 3) (Valiantzas 2015):

\[
\text{ET}_0 = 0.0393T_s(T_m + 9.5)^{1/2} - 2.4\frac{R_s}{Ra}^2 + C_u(T_m + 20)\left(1 - \frac{RH}{100}\right)
\]  

(4)

where \(C_u = 0.076 - 0.0119(\text{RH} - 50)^{0.2}\) when RH ≥ 50%, \(C_u = 0.076 + 0.0084(50 - \text{RH})^{0.2}\) when RH ≤ 50%

Valiantzas Equation (4) (Valiz 4) (Valiantzas 2006):

\[
\text{ET}_0 = 0.051(1 - \alpha)R_s(T_m + 9.5)^{1/2} - 2.4\left(\frac{R_s}{Ra}\right)^2 \\
- 0.048(T_m + 20)\left(1 - \frac{RH}{100}\right)(0.5 + 0.5564u) + 0.00012z
\]  

(5)

Valiantzas Equation (5) (Valiz 5) (Valiantzas 2013, 2015):

\[
\text{ET}_0 = 0.00668R_s\sqrt{(T_m + 9.5)(T_{\text{max}} - T_{\text{dew}})} \\
- 0.0969(T_{\text{max}} - T_{\text{dew}}) - 0.024(T + 20)\left(1 - \frac{RH}{100}\right) \\
+ 0.00455R_s\sqrt{(T_{\text{max}} - T_{\text{dew}})} + 0.0984(T_m + 17) \\
\left(1.03 + 0.0005TR^2 - \frac{RH}{100}\right)
\]  

where \(T_{\text{dew}} = T_{\text{min}} + 0.45TR - 3.45; TR = (T_{\text{max}} - T_{\text{min}})
\]

Valiantzas Equation (6) (Valiz 6) (Valiantzas 2013):

\[
\text{ET}_0 = 0.051(1 - \alpha)R_s(T_m + 9.5)^{1/2} \\
- 2.4\frac{R_s}{Ra}^2 - 0.024(T_m + 20)\left(1 - \frac{RH}{100}\right) - 0.0165R_s u^{0.7} \\
+ 0.0585(T_m + 17)u^{0.75}\left[1.03 + 0.00043TR^2\right] - \frac{RH}{100} \\
+ 0.0001z
\]  

(7)

Valiantzas Equation (7) (Valiz 7) (Valiantzas 2013):

\[
\text{ET}_0 = 0.051(1 - \alpha)R_s(T_m + 9.5)^{1/2} - 2.4\frac{R_s}{Ra}^2 \\
- 0.024(T_m + 20)\left(1 - \frac{RH}{100}\right) - 0.0165Rsu^{0.7} \\
+ 0.0585(T_m + 17)u^{0.75}\left[1.03 + 0.0005TR^2\right] - \frac{RH}{100} \\
+ 0.0001z
\]  

(8)

Note: In Equations (2)–(8), abbreviations are as follows: \(\text{ET}_0, R_s, \Delta, \gamma, u, T_m\) are already defined in Equation (1), \(T_{\text{max}}\): air temperature (maximum) (°C), \(T_{\text{min}}\): air temperature (minimum) (°C), \(TR\): \(T_{\text{max}} - T_{\text{min}}\) (°C), \(z\): elevation (m), \(RH\): mean relative humidity (%), \(\varphi\): latitude (rad), \(R_s\): extra-terrestrial radiation (MJ m\(^{-2}\) d\(^{-1}\)), albedo (\(\alpha\)) = 0.25, \(C_u\) is coefficients.
Performance evaluation and ranking

Performance of the estimated ET0 different Valiantzas equations were tested using statistical measures such as coefficient of determination ($R^2$), index of agreement (D), mean absolute error (MAE), mean bias error (MBE), and weighted root mean square error (WRMSE).

$$R^2 = 1 - \frac{\sum_{j=1}^{n} (ET_{P-M,j} - ET_{Valiz,j})^2}{\sum_{j=1}^{n} ((ET_{P-M} - \sum_{j=1}^{n} ET_{P-M,j})/n)^2}$$  \hspace{1cm} (9)

where $ET_{P-M} = ET_0$ estimated using P-M (mm d$^{-1}$); $ET_{Valiz} = ET_0$ values estimated with different forms of Valiantzas equations (mm d$^{-1}$), and $n$ = the total number of observations.

$$D = 1 - \frac{\sum_{j=1}^{n} (ET_{Valiz,j} - ET_{P-M,j})^2}{\sum_{j=1}^{n} (|ET_{Valiz,j} - ET_{P-M,j}| + |ET_{P-M,j} - ET_{P-M,j}|)^2}$$  \hspace{1cm} (10)

$MAE$ (Mean absolute error):

$$MAE = \frac{\sum_{j=1}^{n} |ET_{P-M,j} - ET_{Valiz,j}|}{n}$$  \hspace{1cm} (11)

$MBE$ (Mean bias error):

$$MBE = \frac{\sum_{j=1}^{n} |ET_{Valiz,j} - ET_{P-M,j}|}{n}$$  \hspace{1cm} (12)

Weighted root mean square error (WRMSE)

The weighted RMSE judges the reliability of different Valiantzas equations at each data point and is also useful to understand the degree of linear adjustment possible to reference value. WRMSE is calculated based on the combined influence of both RMSE and adjusted RMSE (ARMSE). ARMSE indicates precision in assessing ET0 without a consistent bias. A combination these two is used to evaluate the predictive power of unadjusted ET0, and ease of revising the coefficients of the specific comparison equation to a reference value to improve statistical fitness. Weighted RMSE (WRMSE) may be formulated based on a weighted average of RMSE and ARMSE (Pandey et al. 2016):

$$WRMSE = 0.67 \times RMSE + 0.33 \times ARMSE$$  \hspace{1cm} (13)

The RMSE and ARMSE are calculated as follows.

$RMSE$ (root mean square error)

$$RMSE = \sqrt{\frac{\sum_{j=1}^{n} (ET_{P-M,j} - ET_{Valiz,j})^2}{n}}$$  \hspace{1cm} (14)

$ARMSE$ (adjusted RMSE)

The ARMSE statistic fits the regression line through the origin by assuming zero mean residual, and is advantageous in evaluating both (reference and predicting) equations, theoretically approaching the origin simultaneously when actual values of ET0 are zero (Pandey et al. 2016). This approach was used for an examination of the reliability of fit between ET0 estimates, by different types of Valiantzas equations, and the P-M. The regression line slope (m) was used for bias correction in ET0 estimates. Afterwards, ARMSE was calculated as (Pandey et al. 2016):

$$ARMSE = \sqrt{\frac{\sum_{j=1}^{n} (ET_{P-M,j} - m \times ET_{Valiz,j})^2}{n}}$$  \hspace{1cm} (15)

Ranking of different Valiantzas equations

Global performance index (GPI) was used for final ranking of different Valiantzas equations. The GPI is based on the assumption that if the value of the indicator is higher than the median, then the higher the difference between the two reduces the accuracy of the equation (Despotovic et al. 2015). We used a summative form of GPI; it has an advantage over the multiplicative form in that, if any index value is zero
then the value of GPI automatically becomes zero, irrespective of the values of another indicator entirely. Additionally, in additive form, the individual indicator cannot fully influence the GPI values, also, it allows comparison of negative R² values, which is not possible in another form of GPI.

Furthermore, all the selected indices were normalized between 0 and 1 to avoid the potent stimulus of any particular index. Due to this, maxima value of any index is scaled to 1 and minima value to 0. Thus, the GPI may be formulated as (Despotovic et al. 2015):

\[
GPI = \sum_{i=1}^{n} a_i (X_i - X_{ij}) \tag{16}
\]

where \(X_i\) are median values of scaled indicator \(i\), \(X_{ij}\) value of indicator \(i\) for equation \(j\), and \(a_i = -1\) for \(R^2\), and 1 for all other indices.

RESULTS

Evaluation of performance of Valiantzas equations based on original coefficient

The Valiz 7 equation performed better across the sites concerning the P-M with \(R^2\) and D varying between 0.84 and 0.99, WRMSE varying between 0.173 and 0.278 mm d\(^{-1}\), MBE varying between \(-0.065\) and \(-0.161\) mm d\(^{-1}\), and MAE varying between \(0.146\) mm d\(^{-1}\) and \(0.259\) mm d\(^{-1}\). Valiz 7 yielded positive GPI values at sites, varying between 0.16 and 0.379, and secured the rank of 1 and 2 across the sites. Valiz 7 showed the most accurate daily ET\(_0\) estimation method against the P-M equation with \(R^2\) obtaining approximate unity at each of the sites (Table 2).

The Valiz 2 equation also performed well across the sites with \(R^2\) and D varying between 0.98 and 1.00, WRMSE varying between 0.262 and 0.425 mm d\(^{-1}\), MBE varying between \(-0.105\) and \(-0.237\) mm d\(^{-1}\), and MAE varying between 0.268 and 0.349 mm d\(^{-1}\). Valiz 2 showed the highest positive GPI value (0.403) at Aizawl and almost similar values at the other two sites (Table 2). The ranking details are depicted in Table 2.

The Valiz 4 equation is another good choice for the region as it performed closely to Valiz 2 across the sites with \(R^2\) and D varying between 0.63 and 0.996, WRMSE varying between 0.262 and 0.425 mm d\(^{-1}\), MBE varying between \(-0.101\) and \(-0.237\) mm d\(^{-1}\), and MAE varying between 0.268 and 0.349 mm d\(^{-1}\). The Valiz 4 showed a positive value of GPI (0.311, 0.108) at Shillong and Dibrugarh. However, the GPI value is negative at Aizawl (Table 2).

Another good equation is Valiz 6 which performed satisfactorily in the region. The values of accuracy measures (\(R^2\), D) vary between 0.92 and 0.99, 0.639 and 0.99, respectively. The WRMSE value varies between 0.52 and 0.853 mm d\(^{-1}\), MBE and MAE vary between 0.384 and 1.054 mm d\(^{-1}\). The Valiz 6 scored a similar rank at two sites (Aizawl and Shillong), but performs worst at Dibrugarh (Table 2).

The Valiantzas ET\(_0\) equations with limited data (Valiz 1, 3, 5) yielded average results across the region, with \(R^2\) and D varying between 0.42 and 0.97, WRMSE varying between 0.278 and 1.819 mm d\(^{-1}\), MBE varying between \(-0.065\) and \(-1.948\) mm d\(^{-1}\), and MAE varying between 0.249 and 1.852 mm d\(^{-1}\) (Table 2).

There is large variability of evaluation statistics and rank among the sites for these equations. The GPI varies between \(-1.039\) and 0.564, which represents low reliability, and inconsistency of the performance of Valiz 1, 2, 3 equations. However, Valiz 1 is a little superior compared to Valiz 3 and Valiz 5 (Table 2).

The analysis of results revealed that performance of Valiantzas equations changes across the sites within the same climatic region, due to the large variability in topographic conditions across northeast India, which necessitates calibration of equations to improve the consistency of performance across the sites in particular climatic regions.

Improvement in performance of Valiantzas equations after calibration

The improvement in performance of the equations was evaluated under two scenarios: the local calibration coefficient (LCC) and global calibration coefficient (GCC) with pooled data set.

Performance under LCC scenario at different sites

After local calibration, both the error statistics and accuracy estimators indicate an appreciable improvement in
performance of all selected Valiantzas equations across the site. The highest improvement was observed in Valiz 5 compared to OC at Dibrugarh, Shillong, and Aizawl (Table 2). There was a significant reduction in error indices of Valiz 5 after local calibration (WRMSE reduced from 1.819 to 0.092 mm d⁻¹, MBE from −1.948 to 0.015 mm d⁻¹, and MAE from 1.965 to 0.065 mm d⁻¹). Similarly, accuracy estimators also improved (R² from 0.42 to 0.987 and D from 0.616 to 0.997). The GPI shows improvement from −1.039 to −0.071. Furthermore, the Valiz 7 equation showed remarkable improvement with an index of agreement as 1 and R² as 0.99. The highest consistency in performance

Table 2 | Error statistics and accuracy estimates of Valiantzas equations with OC, and LCC, and ranking based on GPI at individual sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Valiz Eqs</th>
<th>Mean ET₀ (mm d⁻¹)</th>
<th>Error estimates (mm d⁻¹)</th>
<th>Accuracy estimates</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM Valiz</td>
<td>MAE</td>
<td>MBE</td>
<td>WRMSE</td>
<td>R²</td>
</tr>
<tr>
<td>DIBRUGARH</td>
<td>OC Valiz</td>
<td>2.96</td>
<td>3.148</td>
<td>0.249</td>
<td>0.940</td>
</tr>
<tr>
<td>OC Valiz 2</td>
<td>3.286</td>
<td>−0.178</td>
<td>0.370</td>
<td>0.925</td>
<td>0.995</td>
</tr>
<tr>
<td>OC Valiz 3</td>
<td>3.956</td>
<td>−0.986</td>
<td>0.784</td>
<td>0.940</td>
<td>0.964</td>
</tr>
<tr>
<td>OC Valiz 4</td>
<td>3.310</td>
<td>−0.339</td>
<td>0.320</td>
<td>0.980</td>
<td>0.996</td>
</tr>
<tr>
<td>OC Valiz 5</td>
<td>4.822</td>
<td>1.852</td>
<td>1.648</td>
<td>0.510</td>
<td>0.810</td>
</tr>
<tr>
<td>OC Valiz 6</td>
<td>2.567</td>
<td>0.403</td>
<td>0.340</td>
<td>0.980</td>
<td>0.996</td>
</tr>
<tr>
<td>OC Valiz 7</td>
<td>3.034</td>
<td>0.156</td>
<td>0.191</td>
<td>0.980</td>
<td>0.999</td>
</tr>
<tr>
<td>LCC Valiz 1</td>
<td>3.008</td>
<td>−0.038</td>
<td>0.143</td>
<td>0.980</td>
<td>0.995</td>
</tr>
<tr>
<td>LCC Valiz 2</td>
<td>2.963</td>
<td>0.007</td>
<td>0.180</td>
<td>0.967</td>
<td>0.992</td>
</tr>
<tr>
<td>LCC Valiz 3</td>
<td>2.966</td>
<td>0.004</td>
<td>0.150</td>
<td>0.976</td>
<td>0.994</td>
</tr>
<tr>
<td>LCC Valiz 4</td>
<td>2.918</td>
<td>0.052</td>
<td>0.083</td>
<td>0.995</td>
<td>0.998</td>
</tr>
<tr>
<td>LCC Valiz 5</td>
<td>2.932</td>
<td>0.038</td>
<td>0.152</td>
<td>0.976</td>
<td>0.994</td>
</tr>
<tr>
<td>LCC Valiz 6</td>
<td>2.962</td>
<td>0.008</td>
<td>0.060</td>
<td>0.996</td>
<td>0.999</td>
</tr>
<tr>
<td>LCC Valiz 7</td>
<td>2.980</td>
<td>−0.010</td>
<td>0.097</td>
<td>0.999</td>
<td>1.000</td>
</tr>
<tr>
<td>SHILLONG</td>
<td>OC Valiz 1</td>
<td>3.21</td>
<td>3.317</td>
<td>0.321</td>
<td>0.820</td>
</tr>
<tr>
<td>OC Valiz 2</td>
<td>3.320</td>
<td>−0.015</td>
<td>0.425</td>
<td>0.840</td>
<td>0.957</td>
</tr>
<tr>
<td>OC Valiz 3</td>
<td>3.991</td>
<td>−0.775</td>
<td>0.695</td>
<td>0.870</td>
<td>0.823</td>
</tr>
<tr>
<td>OC Valiz 4</td>
<td>3.596</td>
<td>−0.580</td>
<td>0.331</td>
<td>0.970</td>
<td>0.966</td>
</tr>
<tr>
<td>OC Valiz 5</td>
<td>3.163</td>
<td>−1.948</td>
<td>1.819</td>
<td>0.420</td>
<td>0.616</td>
</tr>
<tr>
<td>OC Valiz 6</td>
<td>2.832</td>
<td>0.384</td>
<td>0.320</td>
<td>0.990</td>
<td>0.961</td>
</tr>
<tr>
<td>OC Valiz 7</td>
<td>3.347</td>
<td>−0.132</td>
<td>0.173</td>
<td>0.980</td>
<td>0.992</td>
</tr>
<tr>
<td>LCC Valiz 1</td>
<td>3.235</td>
<td>−0.016</td>
<td>0.326</td>
<td>0.880</td>
<td>0.969</td>
</tr>
<tr>
<td>LCC Valiz 2</td>
<td>3.221</td>
<td>−0.005</td>
<td>0.224</td>
<td>0.946</td>
<td>0.986</td>
</tr>
<tr>
<td>LCC Valiz 3</td>
<td>3.221</td>
<td>−0.004</td>
<td>0.197</td>
<td>0.959</td>
<td>0.989</td>
</tr>
<tr>
<td>LCC Valiz 4</td>
<td>3.212</td>
<td>0.005</td>
<td>0.072</td>
<td>0.995</td>
<td>0.999</td>
</tr>
<tr>
<td>LCC Valiz 5</td>
<td>3.186</td>
<td>0.031</td>
<td>0.222</td>
<td>0.946</td>
<td>0.986</td>
</tr>
<tr>
<td>LCC Valiz 6</td>
<td>2.946</td>
<td>0.270</td>
<td>0.208</td>
<td>0.998</td>
<td>0.980</td>
</tr>
<tr>
<td>LCC Valiz 7</td>
<td>3.212</td>
<td>0.005</td>
<td>0.048</td>
<td>0.998</td>
<td>1.000</td>
</tr>
<tr>
<td>AIZWAL</td>
<td>OC Valiz 1</td>
<td>3.65</td>
<td>2.927</td>
<td>0.702</td>
<td>0.670</td>
</tr>
<tr>
<td>OC Valiz 2</td>
<td>2.867</td>
<td>−0.237</td>
<td>0.262</td>
<td>0.967</td>
<td>0.967</td>
</tr>
<tr>
<td>OC Valiz 3</td>
<td>4.287</td>
<td>−0.656</td>
<td>0.574</td>
<td>0.890</td>
<td>0.85</td>
</tr>
<tr>
<td>OC Valiz 4</td>
<td>3.239</td>
<td>0.391</td>
<td>0.583</td>
<td>0.630</td>
<td>0.825</td>
</tr>
<tr>
<td>OC Valiz 5</td>
<td>4.73</td>
<td>1.439</td>
<td>−1.098</td>
<td>1.613</td>
<td>0.830</td>
</tr>
<tr>
<td>OC Valiz 6</td>
<td>2.574</td>
<td>1.053</td>
<td>1.054</td>
<td>0.920</td>
<td>0.639</td>
</tr>
<tr>
<td>OC Valiz 7</td>
<td>3.792</td>
<td>−0.161</td>
<td>0.278</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>LCC Valiz 1</td>
<td>3.653</td>
<td>−0.027</td>
<td>0.101</td>
<td>0.980</td>
<td>0.995</td>
</tr>
<tr>
<td>LCC Valiz 2</td>
<td>3.658</td>
<td>−0.031</td>
<td>0.106</td>
<td>0.981</td>
<td>0.995</td>
</tr>
<tr>
<td>LCC Valiz 3</td>
<td>3.622</td>
<td>0.004</td>
<td>0.138</td>
<td>0.967</td>
<td>0.992</td>
</tr>
<tr>
<td>LCC Valiz 4</td>
<td>3.626</td>
<td>0.001</td>
<td>0.104</td>
<td>0.981</td>
<td>0.995</td>
</tr>
<tr>
<td>LCC Valiz 5</td>
<td>3.612</td>
<td>0.015</td>
<td>0.092</td>
<td>0.987</td>
<td>0.997</td>
</tr>
<tr>
<td>LCC Valiz 6</td>
<td>3.629</td>
<td>−0.002</td>
<td>0.033</td>
<td>0.99</td>
<td>1.00</td>
</tr>
<tr>
<td>LCC Valiz 7</td>
<td>3.599</td>
<td>0.028</td>
<td>0.031</td>
<td>0.999</td>
<td>0.999</td>
</tr>
</tbody>
</table>
was observed in the case of Valiz 7 as it retains a similar ranking after local calibration as well. Other equations also result in improvement after local calibration (Table 2).

Performance of GCC under pooled data scenario

The analysis of Table 3 and Figure 2 resulted in the consistently high performance of all seven Valiantzas equations with regression slope varying from 0.98 to 1. The $R^2$ values vary from 0.92 to 0.99. Furthermore, the effect of global calibration based on pooled data set resulted in improvement, especially in Valiz 2, Valiz 5, and Valiz 6 at all the sites, which do not predict well with the OC (Tables 2 and 3). The findings of the study revealed that global calibration has better generalization ability compared to local calibration, as this resulted in Valiz 7 being most suitable at all three sites. The first four ranked equations for the region are Valiz 7, Valiz 6, Valiz 2, and Valiz 5, in order of superiority. Therefore, depending on the availability of data, any of the identified equations can be used for a selected station in particular, and in general at the regional scale with GCC, as the performance of GCC is more consistent compared to LCC, and can be seen for all three selected sites in Tables 2 and 3.

DISCUSSION

The particularity of those methods is the similar climate data requirements (mean temperature ($T_m$), relative humidity (RH) solar radiation ($R_s$), and wind speed (u)) as the P-M method and their simplicity of use relative to the P-M equation, which necessitates several intermediate calculations exposed to errors and slips. The Valiz 7 is the best reported in this study concurrent with the findings of Djaman et al. (2015), who concluded that Valiz 7 could serve as an alternative method to the standard P-M equation in the Senegal River basin. The findings of the research are additionally in agreement with Kisi (2014), who revealed that Valiantzas 7 (Valiz 7) with complete data of P-M performed superior to other limiting data equations at the majority of sites in Turkey. Pandey et al. (2017), in a comparative study of different data-driven techniques for estimation of $ET_0$ in the study region, reported the highest performance of ($T_m$, $R_s$, RH, u) input in $ET_0$ estimation. Valipour (2015) also reported a similar conclusion for Valiz 7 under the climatic conditions of Iran. Valiz 6 could also be used for accurate estimation of daily $ET_0$ across the region (regression slope of 1.001 and $R^2$ of 0.995) (Figure 2). However, Valiz 2 could be the first choice for its simplicity and depending on the level of professional expertise and the technical ability of the user.

The Valiz 2 performed better compared to the other Valiantzas $ET_0$ equations with limited data, with $R^2$ of 0.95, WRMSE of 0.206 mm d$^{-1}$, MBE of $-0.026$ mm d$^{-1}$, and MAE of 0.151 mm d$^{-1}$ (Table 3). Among the three best Valiantzas equations, Valiz 2 was the simplest and also performed well across northeast India, with a regression slope of 1.004 (Figure 2). Djaman et al. (2016a, 2016b) also reported similar findings in Burkina Faso. These results, in general, confirmed the findings of previous studies by Djaman et al. (2015, 2016a, 2016b), who reported full agreement between the Valiantzas $ET_0$

| Table 3 | Error statistics and accuracy estimates of Valiantzas equations with GCC at three weather sites’ pooled data set |
|----------|---------------------------------|-----------------|------------------|-----------------|-----------------|--------------------|
| Valiz Eqs | Mean $ET_0$ (mm d$^{-1}$) | Error estimates (mm d$^{-1}$) | Accuracy estimates | Ranking |
| PM | Valiz | MAE | MBE | WRMSE | $R^2$ | D | GPI | Rank |
| Valiz 1 | 3.206 | 3.160 | 0.151 | 0.045 | 0.238 | 0.944 | 0.985 | −0.654 | 7 |
| Valiz 2 | 3.233 | 3.150 | 0.151 | 0.026 | 0.206 | 0.950 | 0.988 | 0.020 | 3 |
| Valiz 3 | 3.285 | 3.222 | 0.222 | −0.081 | 0.291 | 0.920 | 0.975 | −0.324 | 6 |
| Valiz 4 | 3.212 | 3.166 | 0.166 | −0.005 | 0.196 | 0.960 | 0.989 | −0.087 | 5 |
| Valiz 5 | 3.208 | 3.246 | 0.146 | −0.022 | 0.198 | 0.960 | 0.989 | 0.008 | 4 |
| Valiz 6 | 3.218 | 3.098 | 0.098 | −0.012 | 0.132 | 0.981 | 0.995 | 0.779 | 2 |
| Valiz 7 | 3.163 | 3.066 | 0.066 | 0.044 | 0.101 | 0.990 | 0.998 | 0.882 | 1 |
Figure 2 | Comparison of estimated ET₀ by different Valiantzas equations and P-M equation at three sites’ pooled data set.
estimates and the P-M estimates with full climatic data sets in the semi-arid climate of the Senegal River basin and across Burkina Faso. The results also confirm the study of Valipour (2015), who reported Valiz 2 (T, Rs, RH) as the best method among limited data methods in Iran. However, the findings of this study contrast with the findings of Djaman et al. (2016a), who reported poor performance by Valiz 6 across Burkina Faso.

The Valiantzas ET∞ equations with limited data (Valiz 1, 3, 5) yielded poor results across the region (Table 3). Among these, Valiz 1 presented the worst results, as it scored seven ranks on pooled data set (Table 3). This result is similar to Djaman et al.’s (2016b) findings in Sahelian climatic conditions for missing Rs and u scenario, that the Valiantzas equation performed worst.

The findings of this study additionally confirm the study of Ahooghalandari et al. (2017), who reported that Valiz 1 and 2 were suitable in their original forms for ET∞ estimation in Western Australia and showed better performance after local calibration. The Valiantzas method also produced the best results among six temperature-based ET∞ equations in the southeast U.S., showing a higher correlation and lower error at 92 automated weather stations in Florida, Georgia, and North Carolina (Gelcer et al. 2010). Pandey & Pandey (2016) in a study over northeast India reported that temperature only P-M (TPM) equation performed significantly well after calibration. Pandey et al. (2009, 2014) reported excellent performance of Hargreaves & Samani (1985) ET∞ equation after calibration in northeast India. Gao et al. (2014) reported that Valiantzas methods T, RH, and Rs based performed reasonably well at humid sites in south-western China. However, Peng et al. (2017) reported the worst performance by Valiz 1 and 2 in different sub-regions of mainland China.

CONCLUSIONS

This study was undertaken with the objective to evaluate the performance of different Valiantzas equations in the northeastern region of India. Different Valiantzas equations were evaluated and calibrated based on LCC at individual sites, and with GCC on pooled data set. There was a remarkable improvement in the performance of equations. Additionally, findings revealed that the global calibration approach is better compared to local calibration to improve the reliability and consistency of different Valiantzas equations. Thus, we can say that local conditions affect the estimation capacity of the equation, so it is always better to go for calibration of equation based on local climatic conditions. The GPI is better to index ranking of equations as it takes into account the integrated approach of all the selected evaluation statistics.

In light of these results, in the context of limited data, Valiz 2 can be recommended for daily ET∞ estimation under conditions of missing data in northeast India. If full climatic data are available, then Valiz 7, 6, and 5 could be the first choice owing to their simplicity and accuracy. However, under limited data conditions, and if at all possible, Valiantzas ET∞ equations should be compared to using the standard FAO56 P-M equation.

REFERENCES


Kisi, O. 2014 Discussion of simple ET0 forms of Penman’s equation without wind and/or humidity data. I: theoretical development by John D. Valiantzas. Journal of Irrigation and Drainage Engineering 140 (7), 07014016-1.


Valiantzas, J. D. 2013 Simple ET0 forms of Penman’s equation without wind and/or humidity data. II: comparisons with reduced set-FAO and other methodologies. Journal of Irrigation and Drainage Engineering 139 (1), 9–19.


Valipour, M. 2014 Investigation of Valiantzas’ evapotranspiration equation in Iran. Theoretical and Applied Climatology 121 (1–2), 267–278.


First received 14 April 2018; accepted in revised form 25 August 2018. Available online 19 September 2018