Research Paper

An evaluation of the performance and subsequent calibration of two reference evapotranspiration estimation models for Gweru, Zimbabwe

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ABSTRACT

This study evaluated the performances and subsequently calibrated the Hargreaves and Blanney Criddle reference evapotranspiration \( \text{(ET}_0 \text{)} \) estimation models for the semi arid Gweru climate in Zimbabwe. The FAO – 56 Penman Monteith model was used as the standard method for the evaluation. The \( \text{ET}_0 \) calculator (Version 2.3) was used for the computation of daily \( \text{ET}_0 \) for all models using observed maximum temperatures, minimum temperatures, mean temperatures, mean relative humidity and wind speed at 2 m height as input data. The Hargreaves and Blanney Criddle models were evaluated using the Model Efficiency (EF), the Bias (B), the Root Mean Square Error (RMSE), the Mean Absolute Prediction Error (Err) and the coefficient of determination \( (R^2) \). The Blanney Criddle model was found to be highly accurate (Err of 6.807\%), a B of -0.303 mm day\(^{-1}\), a RMSE of 0.404 mm day\(^{-1}\), an EF of 0.926 and an \( R^2 \) of 0.970. The Hargreaves mode had a less accurate but rather good performance as evidenced by an Err of 12.06\%, a RMSE of 0.855 mm day\(^{-1}\), a B value of -0.211 mm day\(^{-1}\), EF of 0.66 and an \( R^2 \) of 0.751. After calibration, the performance of the Blanney Criddle model was within acceptable limits of the evaluation methods used. The Err dropped to only 3.925\%, the RMSE to 0.269 mm day\(^{-1}\) and the B value to -0.00012 mm day\(^{-1}\). The EF also increased to 0.965. There was little change in the performance of the Hargreaves model even after calibration. The EF increased to 0.703 and the B value decreased to -0.081 mm day\(^{-1}\). The Err, RMSE and the \( R^2 \) remained largely unchanged. From these observations, it can be concluded that the Blanney Criddle model is the best method to use for daily \( \text{ET}_0 \) estimation for the semi arid region of Gweru because of its highly accurate prediction accuracy. For this site, it is highly recommended to use 0.303 as the value of the constant \( a \) in the equation instead of the default 0 value. The site specific \( k \) value of the Hargreaves model is 0.0025 instead of the default 0.0023.

Key words: Reference evapotranspiration, FAO -56 Penman Monteith, Hargreaves model, Blanney Criddle model.

INTRODUCTION

The quantification of evapotranspiration is a very important aspect of water management, determination of crop water requirements, irrigation designs and land use planning (Orang et al., 1995; Yoder et al., 2005; ElNesr et al., 2011; Umara et al., 2012). Evapotranspiration (evaporation and transpiration) may be quantified from soil surfaces, open water surfaces as well as vegetation surfaces for those applications to be achieved. This quantification can be done through direct measurement or through estimation using established equations. The direct measurement of evapotranspiration is complex, expensive and time consuming (Ejieji, 2011) thus the estimation of evapotranspiration is usually done indirectly using the reference evapotranspiration \( (\text{ET}_0) \). Integrating \( \text{ET}_0 \) with the respective surface or crop factors will give the evapotranspiration. \( \text{ET}_0 \)is the evapotranspiration rate from
a reference surface, not short of water (Allen et al., 1998). A reference surface is a hypothetical grass closely representing an extensive surface of 8 – 15 cm tall, green grass cover of uniform height, actively growing and completely shading the ground (Allen et al., 1998).

Evapotranspiration consists of two components, that is, the energy component and the aerodynamic component. The energy component is responsible for conversion of liquid water to water vapour and the aerodynamic (mass transfer) component is responsible for vapour removal from the evaporating surface into the atmosphere. Radiation and temperature provide the energy required to break water bonds to form vapour. Humidity (especially vapour pressure) and wind speed constitute the aerodynamic component (vapour removal from the surface). The quantification of ET$_o$ requires the evaluation of both components and this is done by using combination methods. The standard method for estimating ET$_o$ is the FAO 56 – Penman Monteith model (Allen et al., 1998) which is a combination method, that is, has an energy component as well as the aerodynamic / mass transfer component.

There are many methods (models) that can be used for ET$_o$ estimation but their performances are evaluated based on the FAO 56 – Penman Monteith model. Some of these models are temperature based, radiation based and aerodynamic / mass transfer based (Ejieji, 2011). Examples include the Penman, Blanney – Cridde, Hargreaves, Jensen – Haise, Thornthwaite and Makkink models. Although the FAO 56 – Penman Monteith model is usually considered the most accurate method to use for all conditions, its practical applicability is very limited especially in developing countries. This is because the model is complex and requires many input data (ElNesr et al., 2011; Sheikh and Mohammadi, 2013). There is generally a serious shortage of standard meteorological stations that can provide all the required standard input data to be used by the model (Jensen et al., 1997; Sheikh and Mohammadi, 2013). The problem of input data shortage is also prevalent in developed countries (Kra, 2010) because many weather stations across the world collect mostly temperature data. This data deficiency resulted in the development of empirical models which use less input variables and are much simpler and reliable (ElNesr et al., 2011; Umara et al., 2012; Sheikh and Mohammadi, 2013).

These empirical models shorten the computational procedures that are in the FAO 56 – Penman Monteith model (Kra, 2010). The use of these empirical models however, must be treated with caution because they are usually less accurate and the results may be misleading. These errors are found because the models were developed for specific regions and hence have no universal application (Sheikh and Mohammadi, 2013). Most empirical models are best suited for humid conditions where the aerodynamic term is relatively small (FAO, 1998). Empirical models are however less accurate in arid and semi arid conditions (aerodynamic component is significant) (FAO, 1998).

Empirical models are, most fittingly, used after local calibrations for them to be reliable (Kra, 2010; ElNesr et al., 2011; Sheikh and Mohammadi, 2013). The main objective of this study was to calibrate the Blaney – Cridde and the Hargreaves models for use in the semi arid area of Gweru in Zimbabwe.

**MATERIALS AND METHODS**

**Study area and data used**

The study was conducted in Gweru (19.45°S, 29.817°E, and 1400 m above mean sea level) in central Zimbabwe. The area has a hot and dry climate for a greater part of the year with the average annual length of the dry season being 232 days (FAO, 2005). The net primary production is precipitation limited. The climate class is semi arid with an aridity index of 0.43 and an evaporation ratio of up to 92.6% (FAO, 2005). The area is hence vulnerable to droughts and irrigation is required to alleviate crop water stress.

Meteorological data used for this study ranged from 1963 to 2012 (Tutimeno network, 2013). It must be noted, however, that the data records were not continuous. There are some years where observed data were missing and in some cases, some missing days within a recorded year. The following observed meteorological variables with a daily temporal resolution were used for this study: Maximum temperature, minimum temperature, means temperature, mean relative humidity and wind speed at 2 m height.

**Procedure**

The FAO – 56 Penman Monteith model (Equation 1) was used as the standard method for evaluation of the Hargreaves (Equation 2) and the Blaney Cridde (Equation 3) models. The performances of the Hargreaves and Blaney Criddle methods were therefore assessed basing on the FAO – 56 Penman Monteith method. Calculations of ET$_o$ on a daily time step were done using the ET$_o$ calculator (Version 2.3). The calculations by the ET$_o$ calculator are as outlined in the FAO – 56 guidelines (Raes, 2007).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} U_z (e_a - e_d)}{\Delta + \gamma (1 + 0.34U_z^2)}$$  \hspace{1cm} (Equation 1)

Where: $ET_o$ is the reference crop evapotranspiration (mm day$^{-1}$), $R_n$ is net radiation at the crop surface (MJ m$^{-2}$ day$^{-1}$), $G$ is the soil heat flux (MJ m$^{-2}$ day$^{-1}$), $T$ is the average air temperature ($^\circ$C), $U_z$ is wind speed measured at 2 m height (m s$^{-1}$), ($e_a - e_d$) is the vapour pressure deficit (KPa), $\Delta$ is the...
Table 1. Interpretation of the mean absolute prediction error values.

<table>
<thead>
<tr>
<th>Values</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10</td>
<td>Highly accurate</td>
</tr>
<tr>
<td>11 - 20</td>
<td>Good</td>
</tr>
<tr>
<td>21 - 50</td>
<td>Reasonable</td>
</tr>
<tr>
<td>51+</td>
<td>Inaccurate</td>
</tr>
</tbody>
</table>

Slope of the vapour pressure curve (KPa °C⁻¹), γ is the psychrometric constant (KPa °C⁻¹).

The Hargreaves equation used is as given by Hargreaves (1994):

$$ET_o = K (T_{mean} + 17.8) \sqrt{(T_{max} - T_{min})} (0.408 R_o)$$

Where: $K$ is a coefficient (default value is 0.0023), $T_{mean}$ is the mean daily air temperature (°C), $T_{max}$ is the mean daily maximum air temperature (°C), $T_{min}$ is the mean daily minimum air temperature (°C) and $R_o$ is the extraterrestrial radiation (MJ m⁻² day⁻¹).

The Blaney-Criddle equation used as given by Doorenbos and Pruitt (1977) is:

$$ET_o = a + b \left[ p (0.46 T_{mean} + 8.13) \right]$$

(Equation 3)

Where: $p$ is the mean daily percentage of total annual daytime hours (%), $T_{mean}$ is as previously defined and $a$ and $b$ are calibration factors for minimum relative humidity, ratio of actual to possible sunshine hours and daytime wind speed. Default values for $a$ and $b$ factors are 0 and 1 respectively.

Evaluation of the ET₀ estimation methods

The performances of the Hargreaves and the Blanney Criddle models were evaluated using the Model Efficiency (EF), Bias (B) in mm day⁻¹, Root Mean Square Error (RMSE) in mm day⁻¹, Mean Absolute Prediction Error (Err) as a percentage and the coefficient of determination ($R^2$). These tests were calculated using Equations 4 to 7.

$$EF = 1 - \frac{\sum_{i=1}^{n} (EPM_i - EM_i)^2}{\sum_{i=1}^{n} (EPM_i - EPM)^2}$$

(Equation 4)

$$B = \frac{1}{n} \sum_{i=1}^{n} (EM_i - EPM_i)$$

(Equation 5)

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (EM_i - EPM_i)^2}$$

(Equation 6)

$$Err = \frac{1}{n} \sum_{i=1}^{n} \left| \frac{100 (EM_i - EPM_i)}{EPM_i} \right|$$

(Equation 7)

Where: $EM_i$ and $EPM_i$ are the corresponding ET₀ predictions of either the Hargreaves or Blaney Criddle models and the FAO – 56 Penman Monteith (mm day⁻¹) respectively. $n$ is the number of paired comparisons.

For this study, an error of ± 5% was acceptable as regarded by other researchers (Irmark et al., 2003; Noori Mohammadieh et al., 2009). The Mean Absolute Prediction Error was interpreted using Lewis (1982) guidelines (Table 1) in Gundalia and Dholakia (2013). EF values between 0 and 1 were regarded as acceptable but values closer to 1 are highly acceptable (Gundalia and Dholakia, 2013). EF values less than 0 were unacceptable. Model calibration was done to ensure that the prediction errors would be within acceptable limits.

RESULTS AND DISCUSSION

The Blaney Criddle model generally performed better compared to the Hargreaves model (Table 2). A Mean Absolute Prediction error of 6.807% reflects that the Blaney Criddle's prediction accuracy is highly accurate. A model efficiency of 0.926 is also highly acceptable. An average Bias of -0.303 mm day⁻¹ is rather worrying and is an indication that the model is generally underestimating ET₀ (Figure 1a).

The Hargreaves model had a lower prediction accuracy as evidenced by the higher Mean Absolute Prediction Error (12.06%) and a RMSE of 0.855 mm day⁻¹. The EF is acceptable although it is lower. The Hargreaves model also
Table 2. Performance evaluation results for the Hargreaves and Blaney Criddle models.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Err (%)</td>
<td>12.060</td>
</tr>
<tr>
<td>RMSE (mm day(^{-1}))</td>
<td>0.855</td>
</tr>
<tr>
<td>EF</td>
<td>0.660</td>
</tr>
<tr>
<td>Bias (mm day(^{-1}))</td>
<td>-0.211</td>
</tr>
<tr>
<td>R(^2)</td>
<td>0.751</td>
</tr>
</tbody>
</table>

Figure 1. A comparison of the FAO – 56 Penman Monteith model with the Blaney Criddle model (a) before calibration and (b) after calibration.

generally underestimates \( ET_o \) (Figure 2a) with an average Bias of -0.211 mm day\(^{-1}\). A comparison of the performances of these two models is also outlined in Appendix 1. The reduced performance of the Hargreaves model may be attributed to the fact that the model was not specifically designed for daily estimates of \( ET_o \) (Raes, 2007). The model is subject to errors caused by fluctuation of temperature ranges caused by the movement of weather fronts and by large variations in wind speed and cloud cover (Raes, 2007).

The calibration of the Blaney Criddle model enhanced its performance (Table 2). An \( EF \) of 0.965 and a very low Bias of -0.00012 mm day\(^{-1}\) reflects that the model prediction highly matches that of the FAO – 56 Penman Monteith method. The Blaney Criddle model however exhibits very low prediction errors (Table 2). There is slight underprediction especially for \( ET_o \) values above 8 mm day\(^{-1}\) (Figure 1b) and almost no errors for values below 8 mm day\(^{-1}\). There were no significant changes that were noted after the calibration of the Hargreaves model (Table 2). The only notable observation was an improvement in the model efficiency to 0.703. The errors, however, remained the same and the deviation from the standard method is still large (Figure 2b).

The site specific Blaney Criddle model is as follows:

\[
ET_o = 0.303 + b \left[ p \left( 0.46 T_{\text{mean}} + 8.13 \right) \right]
\]

(Equation 8)

The \( a \) value has been changed from the default 0 to 0.303 to cater for the general underestimation of the model. The site specific \( k \) value of the Hargreaves model (Equation 2) is 0.0025 instead of the default 0.0023.

Conclusion

The Blaney Criddle model is highly recommended for the estimation of daily \( ET_o \) in the semi arid region of Gweru.
This model is very simple and requires less input data (only mean temperature and daily day time hours) but has proved to be highly accurate. For this site, it is highly recommended to use $0.303$ as the value of the constant $a$ in the Blaney Criddle equation instead of the default $0$ value. The Hargreaves model is less accurate although its performance is satisfactory. The site specific $k$ value of the Hargreaves model is $0.0025$ instead of the default $0.0023$.

REFERENCES


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Figure 2. A comparison of the FAO – 56 Penman Monteith model with the Hargreaves model (a) before calibration and (b) after calibration.
Appendix 1: A comparison of the performances of the Hargreaves model and the Blaney Criddle model for the outlined time periods.
Appendix 1: Cont.
Appendix 1: Cont.

2004

\[ y = 1.098x - 0.644 \]
\[ R^2 = 0.781 \]

2004

\[ y = 1x - 0.222 \]
\[ R^2 = 0.968 \]

2011

\[ y = 1.158x - 0.881 \]
\[ R^2 = 0.769 \]

2011

\[ y = 1.006x - 0.258 \]
\[ R^2 = 0.967 \]