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Calibration of the Hargreaves and Priestley-Taylor equations for estimating reference evapotranspiration in the Densu River Basin in Ghana

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Reference evapotranspiration (ETo) defines the maximum evapotranspiration that can occur in a basin. Its accurate estimation is therefore very important in accurately estimating how much water is available in any Basin for use since the actual Evapotranspiration (AET) that occurs depends on the ETo estimated. AET is a parameter that is difficult to measure on the field and therefore is mostly estimated from ETo. Different empirical equations are used in estimating ETo with different levels of accuracy mostly defined by the set of input data. FAO-56 Penman-Monteith (FAO-56 PM), Priestley-Taylor, and 1985 Hargreaves equation were used in computing ETo for a station in Koforidua and Accra airport and the results were compared with a measured ETo estimated from pan evaporation data. When the FAO-56 PM ETo was compared with the ETo from Priestley-Taylor and 1985 Hargreaves, the average root-mean-square errors were 0.8659 and 1.1770 mm/d respectively. The Index of Agreement (d) between FAO-56 PM ETo values and ETo values from Priestley-Taylor and 1985 Hargreaves were 0.79 and 0.59 respectively. The estimated ETo values were however improved through local calibration of the Priestley-Taylor and 1985 Hargreaves equation. The results generally indicate that the Priestley-Taylor equation better estimates ETo values from the FAO-56 PM equation than the 1985 Hargreaves equation. When ETo values were estimated with FAO-56 PM, Priestley-Taylor and Hargreaves equations were compared to measured ETo values from pan evaporation data, FAO-56 PM equation performed better followed by the Priestley-Taylor and then the Hargreaves equation. This means that if enough data is available for ETo estimation then the FAO-56 PM equation is best in estimating ETo values followed by the Priestley-Taylor equation and then the Hargreaves equation. However, where only maximum and minimum temperature are the only available data, then Hargreaves is recommended for the estimation of the ETo values.

Key words: Evapotranspiration, Densu basin, Hargreaves, Priestley-Taylor, penman-monteith.

INTRODUCTION

Water is a basic necessity in healthy living, however, many people living in different Cities in Africa are facing serious challenges in accessing clean water and this poses serious public health challenges (Livingston, 2021). The problem of water scarcity in Africa can be attributed to population growth, land use changes, economic development, and climate change (African Climate Change Policy Centre report, 2011). In Ghana, anthropogenic water pollution activities such as illegal mining and inappropriate use of agrochemicals are creating challenges in accessing basic clean water (Bessah et al., 2021).

Some major factors influencing clean water availability and causing water scarcity in some cities are climate changes, increasing urbanization, and agricultural and water pollution activities (Wang et al., 2024). The climate change factors that are causing water scarcity are changes in rainfall patterns, decreases in precipitation and runoff, and increases in evapotranspiration (Leal Filho et al., 2021). The evidence of climate change in Ghana includes rising temperatures leading to higher evapotranspiration rates, vanishing rainy seasons, and increasing periods of dry season (Adjei et al., 2021). In Ghana currently, one of the major issues causing the closure of some drinking water treatment plants is due to the high levels of pollution and influencing water scarcity is illegal gold mining activities (Obiri-yeboah et al., 2021). Based on a Water Resources Commission of Ghana (WRC) report in 2017, about 60% of water bodies in Ghana are polluted because of illegal mining, industrial and household waste, farming, and other activities. Access to clean drinking water is however very essential in life.

United Nations Sustainable Development Goal Six however requires that everyone on earth must have access to safe and affordable drinking water by the year 2030. The worldwide problem of water scarcity must therefore be solved in creating access to safe and affordable drinking water. The continent of Africa is endowed with a lot of water resources, however, some cities in Africa are experiencing growing water scarcity mainly because of water resources management issues (Economic Commission for Africa report, (UNECA), 2011). Therefore, to solve the problem of water scarcity in Africa, the available water resources must be sustainably managed and these must include water resource conservation, environmentally friendly water usage, appropriateness of water used technologies, and efficient allocation of available water resources (Pereira, 2005).

Evapotranspiration (ET) is a process that combines evaporation and transpiration. ET is defined by meteorological variables, crop characteristics, and crop management practices (Pandey et al., 2016). The process of evaporation and transpiration occurs concurrently and therefore is very difficult to separate (Allien et al., 1998). ET and precipitation are the two most important components of the water cycle, and they play a very important role in the earth's surface water balance. In most cases, precipitation is the biggest component of the water cycle followed by evapotranspiration (Zhang et al., 2011). Precipitation is the major supplier of water to any basin while evapotranspiration is the major means by which water gets out of any basin. Accurate estimation of evapotranspiration is a requirement to accurately estimate how much-precipitated water is available in any catchment for use. Accurate estimation of ET is very essential in accurate water resources planning (Allen et al., 2011).

However, accurate ET in any basin is always a difficult parameter for hydrological scientists to measure directly or estimate (Fernandes et al., 2012). Lysimeters, which is a well-known apparatus used in measuring ET directly on the field are expensive and also require well-trained personnel for accurate ET measurement (Allen et al., 1998). Different empirical formulas are also available in estimating ET by first estimating Reference crop evapotranspiration (ETo) from different climate variables. Some of the developed methods for estimating ETo are Food and Agriculture Organization Penman-Monteith (FAO-56 PM), Camargo, Hargreaves-Samani, 1985 Hargreaves, Makkink, Jensen-Haise, Priestley-Taylor, Hargreaves, 1982-KinberlyPenman, FAO-Corrected–Penman, Penman-Monteith, Blanney-Criddle, FAO-Radiation and FAO-Blanney Criddle (Fernandes et al., 2012; Adeboye et al., 2009). The different equations for estimating ETo required different climate variables and hence resulted in different levels of accuracy.

FAO-56 Penman-Monteith (FAO-56 PM) has been accepted as the best equation in estimating ETo because of its accuracy in different parts of the world when it was compared with other equations (Allen et al., 1998). The FAO-56 PM equation was evaluated in different regions of the world such as in Iran (Bakhtiari et al., 2011), Spain (López-Urrea et al., 2006), USA (Irmak et al., 2002), and Nigeria (Adeboye et al., 2009) and the resultant estimated ETo was more accurate than other equations when the results were compared to measured values. However, the FAO-56 PM equation requires a lot of meteorological data such as maximum and minimum temperatures, wind speed, solar radiation, and relative humidity. These data are not always available, especially in most stations in a developing country like Ghana. The available limited data normally leads to the use of less accurate equations in estimating ETo. In most stations, readily available climate data are maximum and minimum temperature. When only temperature data are available then the best equation to use in estimating ETo is Hargreaves (Ejieji, 2011; Allen et al., 1998).

Priestley-Taylor equation requires fewer data sets than the FAO-56 PM equation but requires more data sets

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than the Hargreaves equation. The Priestley and Taylor was developed from the 1948 Penman equation with an assumption that the component of advection is very small and hence the aerodynamic component of the 1948 Penman equation is reduced to a coefficient (Tabari and Talaee, 2011). Priestley-Taylor equation has been evaluated with the FAO-56 PM equation in different regions of the world and was found to be less accurate when their results were compared to measured data (Fernandes et al., 2012; Suleiman and Hoogenboom, 2007; Utset et al., 2004; Gunston and Batchelor, 1983). Both Priestley-Taylor and Hargreaves equations required fewer data sets in estimating ETo as compared to that required by the FAO-56 PM equation. The result is that both Priestley-Taylor and Hargreaves equation are able to accurately the ETo as compared to the FAO-56 PM equation. To be able to reduce the error between the values from the Priestley-Taylor and Hargreaves equation and that from the FAO-56 PM equation, Priestley-Taylor and Hargreaves equation ETo must be locally calibrated (Tabari and Talaee, 2011; Allen et al., 1998). These local calibrations can be done by developing a relationship between the Priestley-Taylor and Hargreaves equation ETo values and the values from the FAO-56 PM equation. Several researchers have done local calibration of both Priestley-Taylor and Hargreaves equation ETo by developing a relationship between FAO-56 PM ETo values and the values from Priestley-Taylor and Hargreaves equation (Fernandes et al., 2012; Tabari and Talaee, 2011).

Ghana is a developing country with limited climate data. In all the meteorological stations within the Densu River Basin in Ghana, there was only one station with enough data to estimate the ETo using the FAO-56 PM equation. Hence it was not possible to obtain enough data to calculate a good distribution of accurate ET data within the basin. However, there was enough data to estimate ET using the Priestley-Taylor and Hargreaves equation. The ET estimated using the Priestley-Taylor and Hargreaves equation was not as accurate as the ET estimated using the FAO-56 PM equation. To improve the accuracy of the ET estimated using Priestley-Taylor and Hargreaves equation, a local relationship was developed between Priestley-Taylor and 1985 Hargreaves equation ETo and the ETo values from FAO-56 PM equation. Several researchers have done local calibration of ETo equation values with limited data input and ended up improving their estimated ETo values when they were compared with measured values. Tabari and Talaee (2011) did a local calibration of Hargreaves and Priestley–Taylor equations and ended up with more accurate ETo values in Kordestan and Kerman provinces in Iran. Rahimikhoob et al. (2012) also did a local calibration for Hargreaves and Priestley–Taylor equations on the southern coast of the Caspian Sea (SCCS) in the north of Iran which resulted in the improvement of the estimated ETo values. Niranjan and Nandagiri (2021) did a local calibration of Hargreaves equations in Karnataka State, India, and ended up with more accurate ETo values. There is therefore the need to investigate if a local calibration can be used to improve the ETo values obtained in a limited data Densu basin in Ghana.

The objective of this study therefore are as follows:

1) Compare the performance of well-accepted ETo values estimated with the FAO-56 PM equation to ETo values estimated with Priestley-Taylor and 1985 Hargreaves equations in the Densu River Basin in Ghana
2) Develop and test the accuracy of the developed empirical linear equation relating Priestley-Taylor and 1985 Hargreaves estimated ETo values to FAO-56 PM estimated ETo values for the Densu River Basin in Ghana.

Meteorological data for stations within the Densu River Basin (Koforidua), Meteorological data for Kotoka International Airport, Accra, and Pan Evaporation Data derived from reference evapotranspiration data from the premises of Water Research Institute (CSIR-WRI) in Accra were used. The meteorological station in Koforidua is the only station within the Densu Basin with enough data to estimate ETo values using the FAO-56 PM equation. The station at Kotoka International Airport, Accra is outside the Densu River Basin but was used because it is the closest station to the Densu River Basin with enough data to estimate FAO-56 PM ETo equation values. No station within the Densu River basin had measured ETo or evaporation data. The closest station with ETo values estimated from pan evaporation data was the station within the premises of CSIR-WRI at airport area in Accra.

Data and Study Area

Study area: Densu River basin

The River Basin is part of the Coastal River System in Ghana with an estimated total area of about 2,600 km^2. The basin is located within latitude 5°30-6°17'N and longitude 0°10-0°37'W. The river covers a distance of about 116 km and it flows from the Atiwa Mountains in the Eastern Region of Ghana to the Weija Dam in the Greater Accra region in Ghana then it enters the sea through the Densu Delta Ramsar site also known as Sakumo I Lagoon at Bortianor in the Ga Municipality. The population density within the Basin is very high and this has resulted in the over-exploitation of the Densu River (WRC, 2007).

Most of the communities within the Densu River basin and even some communities outside the basin depend on the Densu River for their drinking water supply. The Densu Basin has eight drinking supply schemes that supply water to the communities within and outside the basin. Five of these water supply schemes rely directly on the Densu River while 3 of the schemes are groundwater supply systems.

MATERIALS AND METHODS

In this analysis, FAO-56 PM, Priestley-Taylor, and Hargreaves equations were used in estimating ETo for stations within the Densu River basin. Each of the equations requires different sets of meteorological station data. The station in Koforidua is the only station within the Densu basin with enough data to estimate the ETo values using the FAO-56 PM equation. Priestley-Taylor and Hargreaves equations that require lesser sets of data as compared to the FAO-56 PM equation were also ETo values.

ETo values estimated using the FAO-56 PM equation were used as the reference values in estimating ETo (Allen et al., 1998). An empirical linear relationship was developed between the ETo values obtained from the FAO-56 PM equation and that obtained from Priestley-Taylor and 1985-Hargreaves. These developed empirical linear relationships were then tested with data from a station in Accra (which is closer to the Basin) to verify how applicable the linear equations were outside the station from which they were developed.

The ETo values obtained from the Priestley-Taylor and 1985-Hargreaves equation were compared to the ETo values obtained using the FAO-56 PM equation. The analysis was done using statistical tools such as Root Mean Square Error (RMSE), relative error (RelRMSE), and index of agreement (d).

The FAO-56 penman-monteith equation

The FAO-56 PM equation for estimating reference ETo is expressed as:

$$\mathrm{ETo} = \frac{0.408\,\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.034\,U_2)} \qquad (1)$$

where ETo is the reference Evapotranspiration $\left(\frac{mm}{d}\right)$, Δ is the slope of the vapor pressure curve $(\mathrm{kPa\,°C^{-1}})$, Rn is the net radiation $(\mathrm{MJ\ m^{-2}d^{-1}})$, G is the Soil heat flux density $(\mathrm{MJ\ m^{-2}d^{-1}})$, T is the mean daily air temperature at 2 m height $(°\mathrm{C})$, U_2 is the wind speed at 2 m height, e_s is the saturated vapor pressure (kPa), e_a, actual vapor pressure, γ is psychrometric constant $(\mathrm{kPa\,°C^{-1}})$, and $e_s - e_a$ is saturated vapor pressure deficit (kPa)

The FAO-56 PM equation (Equation 1) requires maximum and minimum air temperature, and wind speed at 2 m height, solar radiation (calculated using sunshine duration), and relative humidity in estimating ETo. The step-by-step calculation of the ETo using the required meteorological data is defined in a publication by Zotarelli et al. (2015). Some of the parameters in the procedure are summarized as follows:

Mean air temperature (Tmean)

$$\mathrm{Tmean} = \frac{\mathrm{Tmin} + \mathrm{Tmax}}{2} \qquad (2)$$

where Tmin is the minimum air temperature and Tmax is the maximum air temperature.

Atmospheric pressure (P)

$$P = 101.3\left(\frac{293 - 0.006Z}{293}\right)^{5.26} \qquad (3)$$

where Z is elevated (m)

Actual vapor pressure (e_a)

$$e_a = e_{\mathrm{Tmin}} = 0.06108\exp^{\left(\frac{17.27\mathrm{Tmin}}{\mathrm{Tmin} - 237.3}\right)} \qquad (4)$$

where Tmin is the minimum air temperature (°C)

Saturated vapor pressure (e_5)

$$e_s = \frac{e_{\mathrm{Tmax}} + e_{\mathrm{Tmin}}}{2} \qquad (5)$$

The slope of the vapor pressure curve (Δ)

$$\Delta = \frac{2504\exp^{\left(\frac{17.27\,\mathrm{Tmean}}{\mathrm{Tmean} + 237.3}\right)}}{(\mathrm{Tmean} + 237.3)^2} \qquad (6)$$

Psychrometric constant (γ)

$$\gamma = 0.000665P \qquad (7)$$

The inverse relative distance earth-sun (dr)

$$dr = 1 + 0.33\mathrm{Cos}\left(\frac{2\pi}{365}j\right) \qquad (8)$$

where j is the number of the day in the year between 1 (1 January) and 365 or 366 (31 December)

solar declination (δ)

$$\delta = 0.409\mathrm{Sin}\left(\frac{2\pi}{365}j - 1.39\right) \qquad (9)$$

Sunset hour angle ($\mathbf{w_s}$)

$$w_s = \arccos(-\tan(\varphi)\tan(\delta)) \qquad (10)$$

where φ is the latitude of the station in decimal radians

Extraterrestrial radiation for daily periods (Ra)

$$\mathrm{Ra} = \frac{24(60)}{\pi}G_{sc}\,dr(w_s\sin(\varphi)\sin(dr) + \cos(\varphi)\cos(\delta)\sin(w_s)) \qquad (11)$$

where G_{sc} = solar constant = 0.0820 MJ m^{-2} min^{-1}

Possible daylight hours (N)

$$= \frac{24}{\pi}w_s \qquad (12)$$

Solar radiation (Rs)

$$\mathrm{Rs} = \left(a_s + b_s \frac{n}{N}\right) \mathrm{Ra} \tag{13}$$

where n is the sunshine duration and a_s, b_s is the coefficient and most literature define

$$a_s = 0.25 \text{ and } b_s = 0.5$$

Priestley-Taylor

Pereira et al. (1997) defined the Priestley-Taylor equation in estimating ETo as

$$\mathrm{ETo} = \alpha W(\mathrm{Rn} - G) \tag{14}$$

where W is an index which is defined as

$$W = \frac{\Delta}{\Delta + \gamma} \tag{15}$$

and Rn is the net radiation which is defined as

$$R_n = (1 - A)R_s - [(0.1 + 0.9n)(0.34 - 0.14e^{0.5})\sigma(T_{mean} + 273)^4] \tag{16}$$

where A is the albedo or canopy reflection coefficient, n is the actual duration of sunshine (hours), σ is the Stefan-Boltzmann constant, which is equal to $5.67\mathrm{x}10^{-8}\ \mathrm{W.m^{-2}.K^{-4}}$.

σ is the calibration constant, which is equal to 1.26 and G is the soil heat flux density (MJ.m^{-2}.day^{-1})

1985 Hargreaves

Hargreaves and Allen (2003) defined 1985-Hargreaves reference Evapotranspiration as:

$$\mathrm{ETo} = 0.0023\mathrm{Ra}(\mathrm{Tmean} + 17.8)\left((\mathrm{Tmax} - \mathrm{Tmin})^{0.5}\right) \tag{17}$$

Conversion of pan evaporation to reference evapotranspiration

The pan evaporation (ETc) values were converted to reference evapotranspiration (ET$_o$) using the pan coefficient (Kp).

The reference evapotranspiration is defined by Snyder et al. (2005) as:

$$\mathrm{ETo} = K_p \times \mathrm{ETc} \tag{18}$$

The values of Kp range from 0.35 to 0.85 and it depends on the local environment (Grismer et al., 2002). Kp depends on upwind fetch distance, wind run, and relative humidity at the pan site. The pan evaporation (ETc) data from the premise of CSIR-Water Research Institute (CSIR-WRI) were converted to ETo values using equation 18.

Statistical analysis

Priestley-Taylor and 1985-Hargreaves equation was used in estimating ETo and compared to ETo estimated with FAO-56 PM equation. These comparisons were done using five (5) goodness-of-fit statistical tools, namely, (i) Correlation Coefficient (R), (ii) Root Mean Square Error (RMSE), (iii) Relative error (RelRMSE), (iv) R-squared (R^2) and (v) Index of Agreement (IA). Because there are no measured ETo data within the Densu River basin, the recommended FAO56-PM equation ETo values were used as a reference ETo for comparison (Allen et al., 1998).

The RMSE is defined as:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \tag{19}$$

where P_i is ETo calculated with Priestly-Taylor and 1985-Hargreaves, equation (mmd^{-1}), and O_i is ETo calculated with FAO56 PM equation (mmd^{-1}), and N is the number of observations.

The Relative error ($\mathrm{RelRMSE}$) is expressed as a percentage and is defined as:

$$\mathrm{RelRMSE} = \frac{\mathrm{RMSE}}{O_{Average}} \tag{20}$$

where O $_{Average}$ is the Average of ETo values calculated using FAO56 PM equation (mmd^{-1}).

The Index of Agreement (IA) was developed by Willmott (1981) and is used as a standardized measurement of the degree of model prediction error. D values range from 0 to 1. A value of 1 indicates a perfect match, and a value of 0 indicates no agreement at all. The Index of Agreement (d) is defined as

$$\mathrm{IA} = 1 - \frac{\Sigma(P_i - O_i)^2}{\Sigma(|P_i - O_{average}| + |O_i - O_{average}|)^2} \tag{21}$$

The correlation coefficient (r) measures the strength and direction of a linear relationship between two variables (Taylor, 1990). The value of r is always between +1 and –1. A perfect negative linear relationship has a value of –1 while a +1 indicates a perfect positive linear relationship. When r is 0 then there is no linear relationship between the two parameters. The correlation coefficient (r) is defined as

$$\mathbf{r} = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{N\sum x^2 - (\sum x)^2(\sum y)^2 - (\sum y)^2}} \tag{22}$$

where, N is the number of pairs of ETo parameters, $\sum x$ is the sum of the ETo parameter calculated with the FAO-56 PM equation, $\sum y$ is the sum of ETo calculated with Priestley-Taylor or 1985-Hargreaves empirical equation.

R-squared (R^2) simply determines the proportion of variance in the dependent variable that can be explained by the independent variable or it explains how well the data fit the regression model, whereas correlation explains the strength of the relationship between an independent and dependent variable, R-squared explains to what extent the variance of one variable explains the variance of the second variable.

$$\boldsymbol{R^2} = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{(N\sum x^2 - (\sum x)^2)(N\sum y^2 - (\sum y)^2)}} \tag{23}$$

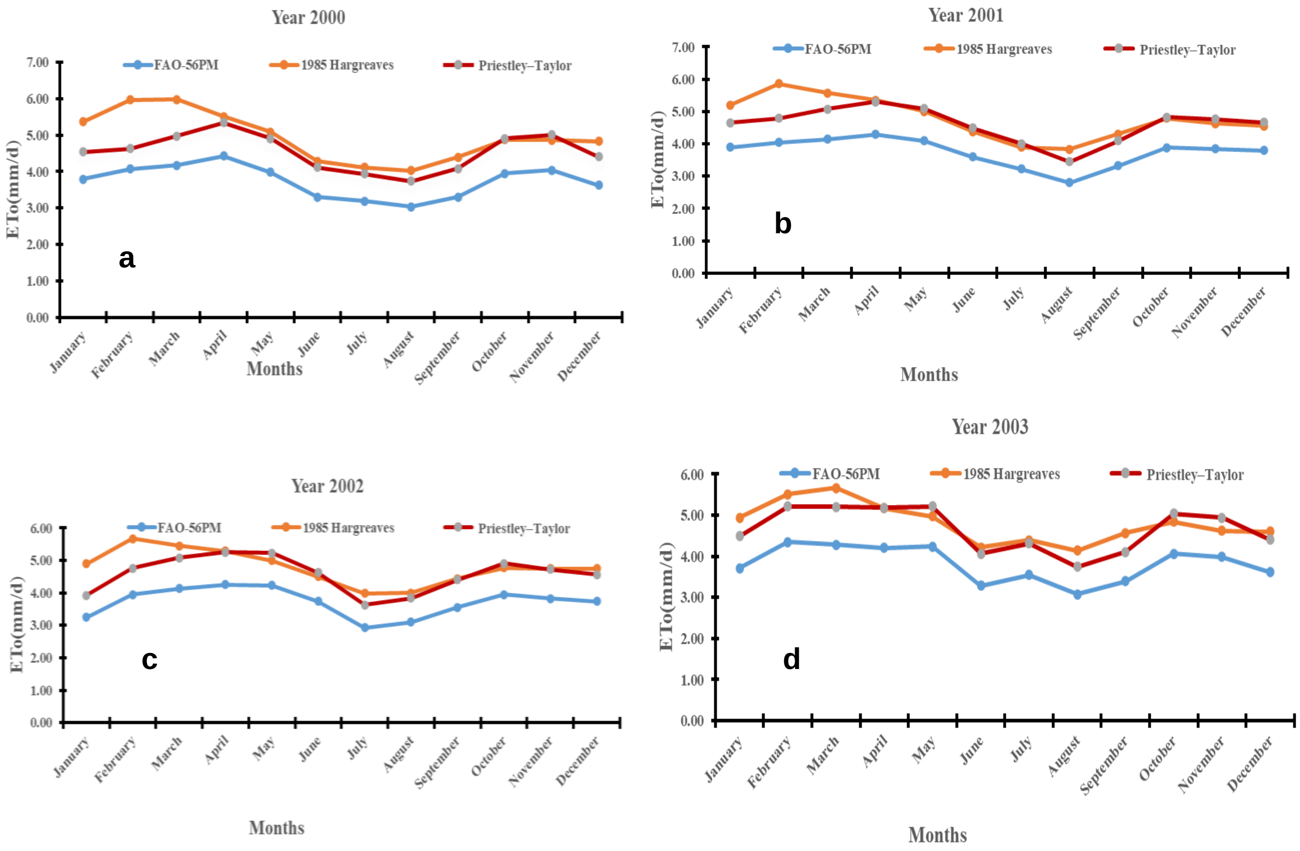

Figure 1. Monthly average ETo values from 2000 to 2003 calculated with FAO-56 PM, Priestley-Taylor, and 1985-Hargreaves equations.

RESULTS AND DISCUSSION

The analysis was conducted with data from 1st January 2000 to 31st December 2003 for the meteorological station in Koforidua which is within the Densu river basin. Figure 1 a, b, c and d shows plots of average daily ETo values for each month from 2000 to 2003 estimated with Priestley-Taylor, 1985-Hargreaves, and FAO-56 PM equations.

The ETo values from the FAO56-PM equation were then compared with the ETo values estimated with Priestley-Taylor and 1985-Hargreaves equations. The summary of the results obtained is shown in Table 1.

The Priestley-Taylor and 1985-Hargreaves equation ETo values were higher than the values obtained from the FAO56-PM equation (Table 1). In general, the highest values of ETo were from the 1985-Hargreaves equation followed by Priestley-Taylor. This is similar to the results by Chen et al. (2005) in Taiwan which concluded that Priestley-Taylor and 1985-Hargreaves mostly overestimate ETo values. This overestimation of ETo values results in a higher error when values from the Priestley-Taylor and 1985-Hargreaves equation are compared to measured values. However, the Priestley-Taylor equation generally produced a better result when it is compared to the results from the FAO56-PM equation, with an RMSE of 0.87 mmd^{-1} and RelRMSE of 23.08%. The ETo values from the 1985-Hargreaves equation were higher than the values from the Priestley-Taylor equation. 1985-Hargreaves equation produced an average RMSE of 1.20 mmd^{-1} and RelRMSE of 31.90%. The Index of Agreement produced by Priestley-Taylor and 1985-Hargreaves equations relative to the FAO56-PM estimates were 0.79 and 0.59 respectively. The index of Agreement from both Priestley-Taylor and 1985-Hargreaves equations was greater than 0.5, which indicates that their level of agreement with values from the FAO56-PM equation was above average and hence were good. This result is similar to what was observed by Tukimat al., (2012) in a study at Muda Irrigation Scheme in Malaysia, where they concluded that radiation-based methods like Priestley-Taylor always perform better than temperature-based methods like 1985-Hargreaves when compared to the result from FAO56-PM equation. However, in Semi-arid Regions in Northeast Iran and in the Campos dos Goytacazes region, in Rio de Janeiro State, the 1985-Hargreaves equation performed better than the Priestley-

Table 1. Summary of ETo estimates for Koforidua, Ghana (2000 -2003) calculated with Priestley-Taylor, 1985-Hargreaves and FAO-56 PM methods.

Methods	Average Yearly ETo (mm/d)				Overall Average ETo (mm/d)	RMSE (mm/d)	RelRMSE (%)	IA
	2000	2001	2002	2003				
1985-Hargreaves	4.9393	4.7726	4.7843	4.7985	4.8240	1.1970	31.90	0.59
Priestley–Taylor	4.5490	4.5992	4.5748	4.6554	4.5946	0.8659	23.08	0.79
The FAO-56 PM	3.7373	3.7413	3.7186	3.8095	3.7518	-	-	-

Table 2. Linear equations for adjusting ETo estimates calculated with Priestley-Taylor and 1985-Hargreaves equations to match ETo estimates from FAO-56 PM equation at the Koforidua meteorological station

Methods	Equations
Priestley-Taylor	0.8088x + 0.0357
1985-Hargreaves	0.7506x + 0.1309

Taylor equation when their results were compared to the results from FAO56-PM equation (Sheikh and Mohammadi, 2013; Fernandes et al., 2012).

Figure 2 shows a plot of ETo values estimated with the FAO56-PM equation against the ETo values from Priestley-Taylor and 1985-Hargreaves equations. The coefficients of determination (R^2) obtained from a graph of FAO56-PM equation values against the values from Priestley-Taylor and 1985-Hargreaves equations are 0.98 and 0.54, respectively.

The ETo values estimated from the Priestley-Taylor equation show a higher agreement to ETo values estimated from the FAO-56 PM equation. This means that the ETo values from the Priestley-Taylor equation agree better with the ETo values from the FAO-56 PM equation than the ETo values estimated from the 1985-Hargreaves equation.

A linear relationship between ETo values was estimated with FAO56-PM equation and that estimated with Priestley-Taylor and 1985-Hargreaves equations were established and evaluated. The ETo values estimated with the FAO56-PM equation were used as the reference ETo values because there were no measured ETo data within the Densu River basin. The linear equation established between the ETo values estimated from the FAO-56 PM equation and the values estimated with Priestley-Taylor and 1985-Hargreaves equations is shown in Table 2.

These linear relationships were applied to climate station data in Koforidua from 2010 to 2013. This was to determine if the linear equation can be used to estimate the FAO-PM equation values at the same station using values from Priestley-Taylor and 1985-Hargreaves equations for a period other than the one used in developing the equations. The results from the linear equation and ETo values from Priestley-Taylor and 1985-Hargreaves equations were then compared to the values calculated with the FAO-PM equation. A summary of these results is shown in Table 3.

The results show that when the linear equation together with the Priestley-Taylor and 1985-Hargreaves equations were used, the ETo values estimated were better with less error than when only the Priestley-Taylor and 1985-Hargreaves equations were used if the results are compared to the ETo values estimated from FAO-56 PM equation. The adjusted Priestley-Taylor and 1985-Hargreaves ETo values with the linear equations were much closer to the ETo values from the FAO-56 PM equation than the unadjusted Priestley-Taylor and 1985-Hargreaves estimates. The RMSE obtained in this situation for Priestley-Taylor and 1985-Hargreaves equations were 0.1150 and 0.5373 mm/d, respectively. This means that by using the Priestley-Taylor and 1985-Hargreaves equations together with the established linear equation, the FAO-56 PM ETo values can be better estimated.

A similar local calibration was done by Gao et al. (2015) in Guizhou Province in the Southwestern region of China and they concluded that when ETo equations are calibrated locally, they perform

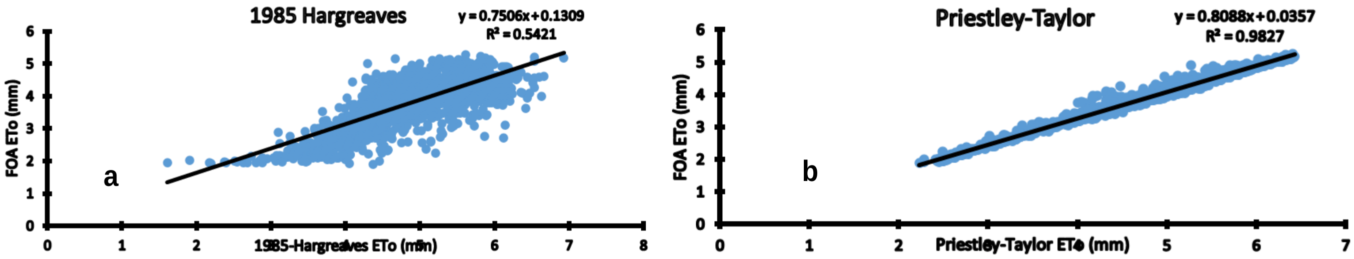

Figure 2. A graph of ETo values estimated by FAO PM equation against those estimated from 1985-Hargreaves and Priestley-Taylor equation.

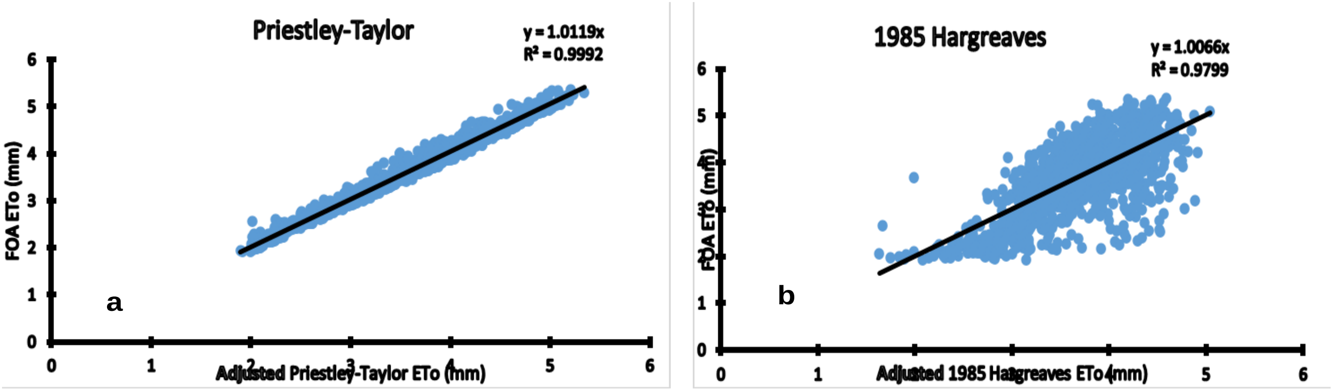

Figure 3. A graph of FAO-56 PM estimated ETo values against Priestley-Taylor and 1985-Hargreaves equations estimated ETo.

better than the original equation in estimating ETo values. The RelRMSE for ETo was estimated from Priestley-Taylor and 1985-Hargreaves equations together with the linear equation and compared to the FAO-56 PM estimated ETo is 3.10 and 14.50% respectively. The Index of the agreement produced by Priestley-Taylor and 1985-Hargreaves equations relative to the FAO56-PM equation were 0.99 and 0.81 respectively. This means that the FAO56-PM estimated ETo values are nearly perfectly estimated from Priestley-Taylor and 1985-Hargreaves equations with the help of the locally calibrated linear equations.

Figure 3a and b show a graph of the FAO-PM estimated ETo values when plotted against the adjusted Priestley-Taylor and 1985-Hargreaves estimates of ETo values.

The linear equation therefore can be used to predict the FAO-56 PM ETo values at the station in Koforidua even when there is limited data available for ETo values estimation using Priestley-Taylor and 1985-Hargreaves equations.

The same linear equations were then applied to a station at kotoka International Airport, Accra to determine whether the linear equation could be applied at a station outside Koforidua where the equations were established. This station in Accra was chosen because it is the closest station to the Densu basin with enough data to estimate the FOA-56 PM Eto values. The summary of the results when the equation was applied at the station in Accra is shown in Table 4.

The trend in ETo values for the station at the Kotoka International Airport, Accra, is similar to the results obtained from the station in Koforidua. When the results of the ETo values from the FAO-56 PM equation were compared to the values from the Priestley-Taylor and 1985-Hargreaves equations, the Priestley-Taylor equation performed better than the 1985-Hargreaves equation. These results are shown in Table 5. The RMSE for Priestley-Taylor and 1985-Hargreaves equations were 0.7522 and 0.5622 mmm/d respectively. The Index of Agreement produced by Priestley-Taylor and 1985-Hargreaves equations with the ETo values from the FAO-56 PM equation were 0.91 and 0.73 respectively.

When the linear equations were applied to the station at Kotoka International Airport, Accra, 1985 Hargreaves, and Priestley-Taylor together with their established linear equations underestimated the FAO-56 PM ETo. However, the Priestley-Taylor equation performed better

Table 3. Summary of comparing FAO-56 PM ETo equation and that estimated with Priestley-Taylor and 1985-Hargreaves and adjusted with station developed linear equation for the Koforidua meteorological station (2010-2013).

Methods	Average Yearly ETo (mm/d)				Overall Average ETo (mm/d)	RMSE (mm/d)	RelRMSE (%)	IA
	2010	2011	2012	2013				
1985-Hargreaves	3.6647	3.7437	3.6788	3.6891	3.6891	0.5373	14.50	0.81
Priestley–Taylor	3.6964	3.6248	3.6790	3.6683	3.6684	0.1150	3.10	0.99
The FAO-56 PM	3.7330	3.6760	3.7414	3.7034	3.7133	-	-	-

Table 4. Summary of ETo estimates for Kotoka International Airport, Accra, Ghana (2000 -2003) calculated with Priestley-Taylor, 1985-Hargreaves and FAO-56 PM methods.

Methods	Average Yearly Adjusted ETo (mm/d)				Overall Average ETo (mm/d)	RMSE (mm/d)	RelRMSE (%)	IA
	2000	2001	2002	2003				
1985-Hargreaves	4.1173	3.9362	4.0267	4.0135	4.0235	0.7522	17.15	0.73
Priestley–Taylor	4.7100	4.8650	4.8237	4.9401	4.8346	0.5622	12.82	0.91
The FAO-56 PM	4.3766	4.3199	4.3490	4.4910	4.3857	-	-	-

Table 5. Summary of yearly FAO-56 PM ETo value for Accra (2000 - 2003) calculated using linear correction method developed for Priestley-Taylor and 1985-Hargreaves methods for Koforidua for a station in Accra Airport.

Methods	Average Yearly Adjusted ETo (mm/d)				Overall Average ETo (mm/d)	RMSE (mm/d)	RelRMSE (%)	AI
	2000	2001	2002	2003				
1985-Hargreaves	3.2213	3.0854	3.1533	3.1434	3.1509	1.4111	32.18	0.54
Priestley–Taylor	3.8451	3.9705	3.9371	4.0313	3.9460	0.5180	11.81	0.91
The FAO-56 PM	4.3766	4.3199	4.3490	4.4910	4.3857	-	-	-

than the 1985-Hargreaves equation which is similar to the results in Koforidua. The relative error for both Priestley-Taylor and 1985-Hargreaves equations were all less than 50% while their Index of Agreement was also greater than 0.5. The values of ETo calculated with the original 1985-Hargreaves equation were better than the ETo values calculated with the linear equation and 1985-Hargreaves equation. The values from the original Priestley-Taylor equation were not that different from those calculated with the linear and Priestley-Taylor equation.

Comparing results with ETo estimated from measured pan evaporation data

Since there were no available measured ETo data within the Densu river basin, data from Kotoka International Airport, Accra were analyzed to verify which of the equations give a better estimation of ETo values compared to ETo estimated from pan evaporation data. Climate data was obtained from the station at Kotoka International Airport, Accra together with ETo estimated from pan evaporation data measured at the premises of CSIR-Water Research Institute

Table 6. Summary of correlation of Pan Evaporation values and ETo from FAO-56 PM, Priestley-Taylor and 1985 Hargreaves equations for Accra (2000 - 2003).

Methods	Correlation Coefficient (r) of Pan Evaporation
1985-Hargreaves	0.3336
Priestley-Taylor	0.5023
The FAO-56 PM	0.5414

Table 7. Summary of yearly pan evaporation and values with FAO-56 PM, Priestley-Taylor, and 1985-Hargreaves equations from 2010 to 2013 for the Kotoka International Airport, Accra.

Methods	Average Yearly ETo (mm/d)				Overall Average ETo (mm/d)	RMSE (mm/d)	RelRMSE (%)	IA
	2010	2011	2012	2013				
1985-Hargreaves	3.9941	4.6185	4.1141	4.0366	4.1898	1.4913	34.37	0.4247
Priestley-Taylor	4.8659	4.7588	4.6702	4.8182	4.7780	1.4552	33.54	0.6604
FAO-56 PM	4.4909	4.5601	4.4924	4.6028	4.5313	1.3386	30.88	0.6639
ETo From Pan Evaporation	4.2735	4.3330	4.2911	4.3573	4.3386	-	-	-

(CSIR-WRI) which is located close to the Kotoka International Airport. FAO56-PM, Priestley-Taylor, and 1985-Hargreaves equation were used to estimate the ETo values and then compared to the ETo estimated from pan evaporation data. The correlation between the ETo estimated from pan evaporation data and the ETo values calculated with FAO-56 PM, Priestley-Taylor, and 1985-Hargreaves equations were estimated and are shown in Table 6.

The values of ETo from the FAO-56 PM equation had a better correlation with the ETo estimated from Pan evaporation data than ETo from Priestley-Taylor and 1985-Hargreaves equations. In general, when ETo from FAO-56 PM, Priestley-Taylor and 1985-Hargreaves equations were compared to ETo estimated from pan evaporation data, ETo from FAO-56 PM had a better correlation with ETo estimated from pan evaporation data with a correlation value of 0.54, followed by the Priestley-Taylor equation with a correlation value of 0.50, and then the 1985-Hargreaves equation with a value of 0.33. Both FAO-56 PM and Priestley-Taylor equations ETo had a correlation coefficient higher than 0.5 which was good, while the 1985-Hargreaves equation ETo correlation coefficient with the ETo estimated from pan evaporation was less than 0.5 indicating poor results.

The ETo values calculated with FAO-56 PM, Priestley-Taylor, and 1985-Hargreaves equations were compared with the ETo estimated from pan evaporation values, and the summary of the results is shown in Table 7.

The FAO-56 PM equation performed better than all the other equations when the results were compared with the ETo estimated from pan evaporation data. When the ETo estimated from pan evaporation values were compared to the values from the FAO-56 PM equation, the RMSE was 1.3386 mm/d, the RelRMSE was 30.88% and the Index of Agreement was 0.6639. In the case of the Priestley-Taylor equation, the RMSE was 1.4552 mm/d**,** the RelRMSE was 33.54% and the Index of Agreement was 0.6604 which is greater than 0.5. The worst performance came from the 1985-Hargreaves equation with an RMSE of 1.4913 mm/d, RelRMSE of 34.37%, and Index of Agreement of 0.4247.

These results are similar to those reported by Temeepattanapongsa and Thepprasit (2015), where the FAO-56 PM equation performed better, followed by the Priestley-Taylor equation and 1985-Hargreaves when their results were compared to ETo estimated from pan evaporation data in Thailand.

However, studies by Adeboye et al. (2009) in Nigeria stated that 1985-Hargreaves performed better than the FAO-56 PM equation when their results were compared to ETo estimated from pan evaporation data.

Conclusion

The results show that the relative error when ETo values from 1985-Hargreaves equations were compared with ETo values from the FAO-56 PM equation was about 32%. When the ETo values from the Priestley-Taylor equation were compared with ETo values from the FAO-56 PM equation, the relative error was 23%. The Priestley-Taylor equation therefore better estimates the ETo values than the 1985-Hargreaves equations when their results were compared to the ETo values from the FAO-56 PM equation. The results also showed that even though empirical linear relations can be established between FAO-56 PM equation ETo values and that from Priestley-Taylor and 1985-Hargreaves equations, the empirical linear relationships are station specific or localized and hence cannot be transferred to other stations. The empirical relationship developed for a station can therefore only be used to estimate FAO-56 PM ETo values for that station. Once the station changes, a new empirical linear relationship is required to estimate the FAO-56 PM ETo values.

In the absence of enough data to estimate the FAO-56 PM ETo values in the Densu basin, Priestley-Taylor and 1985-Hargreaves equations can be used, with some adjustments using an established linear equation.

When the values from FAO-56 PM, Priestley-Taylor and 1985-Hargreaves were compared to an ETo estimated from pan evaporation values from Kotoka International Airport, Accra, FAO-56 PM performed better than the rest. This means that in the absence of measured ETo data, FAO-56 PM ETo values better represent the measured ETo values, followed by Priestley-Taylor and 1985-Hargreaves equations.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Adeboye OB, Osunbitan JA, Adekalu KO, Okunade D (2009). Evaluation of FAO-56 Penman-Monteith and Temperature Based Models in Estimating Reference Evapotranspiration Using Complete and Limited Data, Application to Nigeria. Agricultural Engineering International: CIGR.

Adjei V, Amoning EF, Adjokatse IT (2021). The Evil Couple: Illegal Mining in Water Bodies and Climate Change - A Case Study of Ghana. 10(2):90-101.

African Climate Change Policy Centre. (2011). Climate Change and Water Resources of Africa: Challenges, Opportunities and Impacts. United Nations Economic Commission for Africa.

Allen RG, Pereira LS, Raes D, Smith M (1998). FAO Irrigation and drainage paper No. 56. Rome: food and agriculture organization of the United Nations 56(97):e156. http://www.climasouth.eu/sites/default/files/FAO%2056.pdf

Allen R, Irmak A, Trezza R, Hendrickx JM, Bastiaanssen W, Kjaersgaard J (2011). Satellite-based ET estimation in agriculture using SEBAL and METRIC. Hydrological Processes 25(26):4011-4027.

Bakhtiari B, Ghahreman,N, Liaghat AM, Hoogenboom G (2011). Evaluation of reference evapotranspiration models for a semiarid environment using lysimeter measurements. Journal of Agricultural Science and Technology 13(2):223-237.

Bessah E, Raji AO, Taiwo OJ, Agodzo SK, Ololade OO, Strapasson A, Donkor E (2021). Assessment of surface waters and pollution impacts in Southern Ghana. Hydrology Research 52(6):1423-1435.

Chen JF, Yeh HF, Lee CH, Lo WC (2005). Optimal comparison of empirical equations for estimating potential evapotranspiration in Taiwan. 31st IAHR Congress 2005: Water Engineering for the Future, Choices and Challenges pp. 3687-3697.

Economic Commission for Africa report (UNECA) (2011). New and Emerging Challenges in Africa Summary Report. https://archive.uneca.org/sites/default/files/uploaded-documents/CFSSD/CFSSD7/4AfricaNewEmergingChallengesSummaryReportEN.pdf#:~:text=On%20average%2C%20Africa%20has%20about%20100m3%20per,the%20global%20average%20of%201%2C000m3%20per%20capita.&text=It%20is%20projected%20that%20many%20countries%20in,increases%20in%20water%20demand%20(see%20figure%201).

Ejieji CJ (2011). Performance of three empirical reference evapotranspiration models under three sky conditions using two solar radiation estimation methods at Ilorin, Nigeria. Agricultural Engineering International: CIGR Journal 13(3):1-21.

Fernandes LC, Paiva CM, Rotunno Filho OC (2012). Evaluation of six empirical evapotranspiration equations-case study: Campos dos Goytacazes/RJ. Revista Brasileira de Meteorologia *27*(3):272-280.

Gao X, Peng S, Xu J, Yang S, Wang W (2015). Proper methods and its calibration for estimating reference evapotranspiration using limited climatic data in Southwestern China. Archives of Agronomy and Soil Science 61(3):415-426.

Grismer ME, Orang M, Snyder R, Matyac R (2002). Pan evaporation to reference evapotranspiration conversion methods. Journal of Irrigation and Drainage Engineering 128(3):180-184.

Gunston H, Batchelor CH (1983). A comparison of the Priestley-Taylor and Penman methods for estimating reference crop evapotranspiration in tropical countries. Agricultural Water Management 6(1):65-77.

Hargreaves GH, Allen RG (2003). History and evaluation of hargreaves evapotranspiration equation. Journal of Irrigation and Drainage Engineering 129(1):53-63.

Irmak S, Haman DZ, Jones JW (2002). Evaluation of Class A pan coefficients for estimating reference evapotranspiration in humid location. Journal of Irrigation and Drainage Engineering 128(3):153-159.

Leal Filho W, Totin E, Franke JA, Andrew SM, Abubakar IR, Azadi H, Nunn PD, Ouweneel B, Williams PA, Simpson NP (2021). Global Adaptation Mapping Initiative Team. Understanding responses to climate-related water scarcity in Africa. Science of the Total Environment 806:150420.

Livingston J (2021). Water scarcity and health in urban Africa. Daedalus 150(4):85-102.

Lopez-Urrea R, de Santa Olalla FM, Fabeiro C, Moratalla A (2006). An evaluation of two hourly reference evapotranspiration equations for semiarid conditions. Agricultural Water Management 86(3):277-282.

Niranjan S, Nandagiri L (2021). Effect of local calibration on the performance of the hargreaves reference crop evapotranspiration equation. Journal of Water and Climate Change 12(6):2654-2673.

Obiri-Yeboah A, Nyantakyi EK, Mohammed AR, Yeboah SI, Domfeh MK, Abokyi E (2021). Assessing potential health effect of lead and mercury and the impact of illegal mining activities in the Bonsa river, Tarkwa Nsuaem, Ghana. Scientific African 13:e00876.

Pandey PK, Dabral PP, Pandey V (2016). Evaluation of reference evapotranspiration methods for the northeastern region of India. International Soil and Water Conservation Research 4(1):52-63.

Pereira A, Villa Nova NA, Sedyama G (1997). Evapo (transpira) cão. Piracicaba. ESALQ/USP 183 p.

Pereira LS (2005). Water and agriculture: facing water scarcity and environmental challenges. Agricultural Engineering International: CIGR Journal.

Rahimikhoob A, Behbahani MR, Fakheri J (2012). An Evaluation of Four Reference Evapotranspiration Models in a Subtropical Climate. Water Resources Management 26(10):2867-2881.

Sheikh V, Mohammadi M (2013). Evaluation of Reference Evapotranspiration Equations in Semi-arid Regions of Northeast of Iran. International Journal of Agriculture and Crop Sciences 5(5):450.

Snyder RL, Orang M, Matyac S, Grismer ME (2005). Simplified estimation of reference evapotranspiration from pan evaporation data in California. Journal of Irrigation and Drainage Engineering 131(3):249-253.

Suleiman AA, Hoogenboom G (2007). Comparison of priestley-taylor and FAO-56 penman-monteith for daily reference evapotranspiration estimation in Georgia. Journal of Irrigation and Drainage Engineering 133(2):175-182.

Tabari H, Talaee PH (2011). Local Calibration of the Hargreaves and Priestley-Taylor Equations for Estimating Reference Evapotranspiration in Arid and Cold Climates of Iran Based on the Penman-Monteith Model. Journal of Hydrologic Engineering 16(10):837-845.

Taylor R (1990). Interpretation of the Correlation Coefficient: A Basic Review. Journal of diagnostic medical sonography 6(1):35-39.

Temeepattanapongsa S, Thepprasit C (2015). Comparison and recalibration of equations for estimating reference crop evapotranspiration in Thailand. Kasetsart Journal - Natural Science 49(5):772-784.

Tukimat NNA, Harun S, Shahid S (2012). Comparison of different methods in estimating potential évapotranspiration at Muda Irrigation Scheme of Malaysia. Journal of Agriculture and Rural Development in the Tropics and Subtropics 113(1):77-85.

Utset A, Farré I, Martínez-Cob A, Cavero J (2004). Comparing Penman-Monteith and Priestley-Taylor approaches as reference-evapotranspiration inputs for modeling maize water-use under Mediterranean conditions. Agricultural Water Management 66(3):205-219.

Wang M, Bodirsky BL, Rijneveld R, Beier F, Bak MP, Batool M, Droppers B, Popp A, van Vliet MT, Strokal M (2024). A triple increase in global river basins with water scarcity due to future pollution. Nature Communications 15(1):880.

WRC (2007). Densu river basin: Integrated water resources management plan. Water Resources Commission: Accra, Ghana, 90. https://scholar.google.com/scholar?q=WRC%2C%202007.%20Densu%20River%20Basin%20%E2%80%93%20Integrated%20Water%20Resources%20Management%20Plan.

Water Resources Commission of Ghana (WRC) (2017). https://winrock.org/wp-content/uploads/2021/08/Ghana_Country_Profile_Final.pdf

Zhang XC, Wu JW, Wu HY, Li Y (2011). Simplified SEBAL method for estimating vast areal evapotranspiration with MODIS data. Water Science and Engineering 4(1):24-35.

Zotarelli MF, Carciofi BAM, Laurindo JB (2015). Effect of process variables on the drying rate of mango pulp by Refractance Window. Food Research International 69:410-417.