Comparison of Evapotranspiration Estimate using the Eddy Covariance Method and some Selected Empirical Models

by

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DECLARATION

We hereby declare that this thesis is our original work for the undergraduate degree and that, to the best of our knowledge, it does not contain any information that has been previously published by another person or information that has been acknowledged for the award of any other degree from the university, unless specifically noted in the text.

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Dedication

This research project is dedicated to God Almighty, who has provided grace and strength during the process. We also want to thank our parents for their support, wisdom, and drive, as well as everyone who helped make this effort a success.

Acknowledgement

To God Almighty be the glory, honour and praise for making it possible for us to attempt such a project and for a fruitful fulfillment. We would like to express our profound gratitude to our supervisor Dr.Emmanuel Quansah under whose valuable guidance we undertook this project. We also thank our parents for the unceasing encouragement, support and attention. We express our gratitude to the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) for providing the observed data used in this study. Finally, we are also grateful to Prof. Leonard K. Amekudzi and all lecturers in the Department of Meteorology and Climate Science, we are extremely thankful and indebted to them for sharing their expertise and encouragement.

And to all those who in one way or the other offered us a helping hand during the entire period of this work, We say thank you and God bless you all.

Abstract

The accurate estimation of evapotranspiration (ET) is crucial for applications in agricultural management and water resource engineering. Several empirical models have been devised to estimate ET in the absence of observational data. This study considered and evaluated four frequently used evapotranspiration models, namely the Priestley-Taylor (PT), Hargreaves (HG), Eddy Covariance (EC), and FAO Penman-Monteith models. Daily ET values were estimated and compared with the FAO ET estimates for a two-year period (2013 and 2014) over a grassland ecosystem in the Sudanian Savanna region of Ghana. This was carried out based on the correlation coefficient (R), Root Mean Square Error (RMSE), and the Mean Bias Error (MBE). The results of the comparison showed R of 0.81 and 0.51 for EC, 0.83 and 0.6 for Closed EC, 0.75 and 0.9 for HG, 0.98 and 0.99 for PT for 2013 and 2014 respectively. Similarly, the RMSE were 4.4 mm day^{-1}, 14.48 mm day^{-1} for the EC, 1.56 mm day^{-1} and 1.39 mm day^{-1} for Closed EC, 0.69 mm day^{-1} and 0.2 mm day^{-1} for HG and 0.76 mm day^{-1} and 0.71 mm day $^{-1}$ for PT. While the MBE of 5.0 mm day^{-1} and 11.3 mm day^{-1} for EC, 2.39 mm day^{-1} and 1.59 mm day^{-1} for Closed EC, 1.51 mm day^{-1} and 1.05 mm day^{-1} for HG, 1.67 mm day^{-1} and 1.78 mm day^{-1} for PT for 2013 and 2014 respectively. The result showed that the Priestley Taylor (PT) model performed well and was closer to the FAO Penman-Monteith approved equation than the HG and EC models.

Contents

List of Abbreviation

- ET — Evapotranspiration
- EC — Eddy Covariance
- ABL — Atmospheric Boundary Layer
- FAO — Food and Agriculture Organization
- PT — Priestley Taylor
- HG — Hargreaves
- BREB — Bowen ratio energy balance
- ETo — Reference evapotranspiration
- PM — Penman-Monteith
- PET — Potential Evapotranspiration
- ITCZ — Inter-Tropical Convergence Zone
- WASCAL — West African Science Service Centre on Climate Change and Adapted Land Use
- MBE — Mean Bias Error

- RMSE — Root Mean Square Error Zone
- R — correlation coefficient

Chapter 1

Introduction

1.1 Background to the study

Evapotranspiration (ET) is the amount of water lost from land surfaces to the atmosphere as a result of evaporation from soil and water surfaces, as well as plant transpiration. Evapotranspiration is a combination of two processes, namely evaporation and transpiration (Lum et al., 2017). Through evaporation, there is water lost from the soil or water surface, whereas water is also lost from plants through transpiration. Evaporation is the process by which liquid water turns into water vapour and leaves the surface where it was. From the earth's surface, evaporation can take place in the ocean, lakes, lagoons, and many more. Energy is required to convert liquid water to water vapour. Solar radiation from the sun serves as a heat source. When the surface of the body gets warm, molecular bonds begin to break, causing the liquid to change to gas. The water vapour then rises into the surrounding air. The force used to remove water vapour from the evaporating surface is equal to the water vapour pressure at the evaporating surface minus the surrounding atmosphere (Allen et al., 1998). Evaporation is affected in places with more plants because the plants form a canopy over the soil surface and block the sun from reaching the soil surface. Transpiration occurs when plant tissues release water into the atmosphere. The plant's leaves have tiny holes called stomata that let water vapour escape into the air. Stomata are microscopic openings on the plant's leaf that allow gases and water vapour to enter and exit. The stomata act as a plant's window. The plant's root collects water and other nutrients from the earth and delivers them to all other sections of the plant. Transpiration depends mainly on energy, the vapour pressure gradient, and wind. The transpiration rate can also be dependent on the ability of the plant's roots to access water in the soil. Crop characteristics also influence transpiration. The transpiration rate is different for different types of crops (Allen et al., 1998). Evapotranspiration (ET) is one of the primary sources of water vapour and latent heat that drive atmospheric processes (Wang et al., 2015). Evapotranspiration is an important component of the global climate system since it contributes to the energy balance, carbon cycle, and hydrological cycle and thus plays a huge role in the land-atmosphere interactions, i.e., the exchange of mass and energy (Liu et al., 2016). The amount and timing of evapotranspiration can have a huge effect on the atmosphere as well as surface and subsurface processes, such as cloud formation, river discharge (Koster and Milly, 1997), the ecosystem carbon and nitrogen cycles (Zaehle et al., 2014), surface albedo and temperature (Xiong and Qiu, 2014), and groundwater recharge (Renger et al., 1986). According to Wang et al. (2015), accurate ET calculations are critical for predicting climate and weather, understanding how the environment and ecology work, and managing water resources. An eddy is a circular movement of water causing a small whirlpool (a quick rotational mass of water) (Green et al., 2017). Covariance indicates the direction of the linear relationship between variables (Kim, 2018). Eddy Covariance (EC) also known as the eddy correlation or eddy flux. The EC is one of the most important ways to measure the atmosphere and figure out how turbulent the air is in the Atmospheric Boundary Layer (ABL). Evapotranspiration can be estimated at various scales by different approaches. At the site scale, the eddy covariance EC technique has been commonly used. From regional to global scales, ET is often estimated indirectly using the surface water balance or eddy covariance method (Paço et al., 2006). The EC method helps with the analysis of high-frequency wind and scalar atmospheric data series, gas, energy, and momentum, which yields values of fluxes of these properties. The food and agriculture organisation (FAO) developed an empirical formula which can be used to estimate energy requirements through transpiration. A large number of models have focused on the use of monthly techniques of calculation due to the high data requirements for daily calculations (McKenney and Rosenberg, 1993). Monthly estimates are a good place to start to understand something, but more advanced uses need the details collected every day. The Modified Penman-Monteith approach is now the most extensively used method for computing daily reference evapotranspiration (Allen et al., 1998). Unfortunately, this method is hard to use because it needs a lot of data. This is especially true in developing countries where data is scarce. This method doesn't work well with global databases, which usually only have a small number of variables because they need so much data. Moreover, the data demands of the modified Penman-Monteith technique are rarely met in all circumstances when working with climate data (Farmer et al., 2011). Furthermore, Hargreave also proposed an empirical formula which is used to estimate evapotranspiration. Hargreaves and Samani (1985), say that this method is easier to use because it depends more on the minimum and maximum air temperatures and the amount of radiation from space. Another method of estimating evapotranspiration from well-watered regions was put out by Priestley and Taylor in 1972. Net radiation, which can be computed, for a vegetated area was their primary data requirement. Accurate estimation of α is necessary for the PT model to be used successfully.

1.2 Objectives

The aim of this study was to estimate daily evapotranspiration over grassland using the Eddy Covariance (EC) method, the Food and Agriculture Organisation (FAO) approved penman-

Monteith equation,Priestley-Taylor (PT) equation and the Hargreaves (HG) equation for the Sudanian Savanna of West Africa. The specific objectives were to:

i. validate the performance of the FAO-56 PM model against the EC as well as the other models; and

ii. test the variability of the estimated evapotranspiration during the wet and dry seasons.

1.3 Study Significance and Justification

Over the years, in-situ methods such as water balance and eddy covariance, which make use of lysimeters and eddy flux towers, have often been used to measure evapotranspiration over the globe. Unfortunately, due to installation cost and the lack of meteorological data, it is important to use empirical formulas to compute evapotranspiration estimates (Reuben, 2016; Lum et al., 2017). Evapotranspiration can be used to help model and manage agricultural and water resources, from choosing crops to figuring out how much water to use for irrigation and analysing streamflow and watersheds. The majority of global ET estimates are derived from monthly data. However, due to the significance of ET in various fields such as meteorology and agriculture, it is necessary to estimate ET on a daily scale.

1.4 Organization of Study

This study is divided into five (5) chapters, chapter 2 is devoted to a review of the literature. The third chapter is a discussion of the methodology used in the study, which includes a description of the study area, the climate of the study area, data and instrumentation, a description of the model and bias estimation methods. The fourth chapter discusses the analysis and results obtained, while the last chapter, chapter 5, offers a summary and conclusion of the findings, as well as highlights the study's contribution and recommendations.

Chapter 2

Literature Review

2.1 Methods for Estimating Evapotranspiration

The modern understanding of evapotranspiration microclimatology dates back to 1802 when Dalton established a mass transport equation for estimating evaporation (Guo et al., 2016). Since then, several in-situ, remote sensing-based methods and empirical models for estimating evapotranspiration have been proposed (Asare et al., 2011; Domec et al., 2012; Ding et al., 2013; Reuben, 2016; Rashid Niaghi and Jia, 2019; Denager et al., 2020). This study will address some of the well-known methods for estimating evapotranspiration such as the Eddy Covariance, the Food and Agriculture Organization Penman-Monteith method, the Hargreaves method, and the Priestley–Taylor method. The Weighing lysimeters and eddy covariance methods are two approaches for measuring evapotranspiration directly. Implementing and managing these strategies can be difficult, as well as costly to install, maintain, and run (Allen et al., 1998; Shi et al., 2008; Gebler et al., 2015). Due to their high costs and time-consuming tasks, these methods are unsuitable for routine measurements (Allen et al., 1998). However, they are useful for evaluating ET estimated from indirect methods such as the residual energy balance, Bowen ratio energy balance (BREB) (Fritschen, 1965; Angus and Watts, 1984), soil water balance (Dugas et al., 1985), and other predictive mathematical models such as the FAO Penman-Monteith, Hargreaves, and Priestley-Taylor.

2.2 Estimation of Evapotranspiration Based on the FAO Penman-Monteith Method

Modeling water usage, agricultural/ecological applications, natural resource management, and other planning activities all require an accurate estimation of evapotranspiration (ET) (Chiew et al., 1995; Tilahun, 2006; Fooladmand and Haghighat, 2007; Mu et al., 2007; Suleiman and Hoogenboom, 2009). ET is essential on heat energy supply, vapour pressure gradient, and movement of air, Allen et al. (1998); Xu and Singh (1998); Jensen et al. (1997); Samani (2000); Moeletsi et al. (2013); Berengena and Gavilán (2005); Bautista et al. (2009) used earth-atmosphere energy balance aerodynamic principles or experimentally established models to evaluate ET. The Food and Agriculture Organization (FAO) of the United Nations (UN) suggests the use of the Penman-Monteith equation to estimate ET using meteorological data. The Penman-Monteith (PM) equation is one of the most meaningful ET models based on theory. In this regards, the FAO recommends it as the standard method for calculating the evapotranspiration in the absence of observed data. The PM model, created by Allen et al. (1998), is a hybrid model that calculates energy and moisture fluxes between the atmosphere, land, and water surfaces (Lee et al., 2004). The FAO 56 PM method consists of the processes that estimate meteorological data using other, more frequently recorded variables, such as minimum and maximum temperatures (Allen et al., 1998). The method estimates evapotranspiration by taking into account the temperature, the relative humidity, the amount of sunshine, the height of the site, and the speed of the wind. Although this method is widely recognized due to its accuracy, its applicability is limited due to its reliance on several variables, including maximum and lowest temperatures, vapour pressure, net radiation, and wind speed (Allen et al., 1998; Annandale et al., 2002; Tilahun, 2006; Fooladmand et al., 2008). This constraint has significant ramifications for locations with limited data, such as developing countries, which must rely on other approaches to estimate ET. In addition, Allen et al. (1998) found that the data requirements of the modified Penman-Monteith technique are rarely met in all cases when working with climate change using a group of general circulation models (GCMs). Furthermore, under low evaporative circumstances, the modified Penman was regularly found to overestimate ET by up to 20 percent. Nonetheless, some European studies prove that the Penman-Monteith technique performs pretty accurately and consistently in both arid and humid climates (Allen et al., 1998). In Ghana,Asare et al. (2011) estimated daily potential evapotranspiration (PET) at Atomic-Kwabenya in the coastal savanna. It was observed that the Penman-Monteith model generated daily PET values that correlated satisfactorily with the Hargreaves-Samani model PET data. Reuben (2016), also estimated daily evapotranspiration in Sumbrungu in the upper east region of Ghana. It was observed that the PM model performs better under wet conditions compared to dry conditions.

2.3 Estimation of Evapotranspiration Based on the Eddy Covariance Method

The Eddy Covariance (EC) technique is one of the most well-known methods for estimating evapotranspiration. In this approach, evapotranspiration is modelled using latent heat flux. These long-term fluxes above the canopy can be measured in a way that is continuous and at high temporal resolution. Concurrent measurements of sensible heat flow and other trace gas fluxes, such as carbon dioxide (CO_2) and methane (CH_4) (Wilson et al., 2001). This method could be used to investigate key connections between hydrological and other biogeochemical processes. When atmospheric turbulence is weak, as it usually is at night (Lee et al., 2004; Wilson et al., 2001), the measurements can be difficult to interpret (Lee et al., 2004; Wilson et al., 2001). Furthermore, ET is minor during dew and rain events, when the air humidity above the smooth surface of the observed field is close to saturation and dew formation and raindrops on the equipment cause the instruments to become disordered. However, evaporation of intercepted water immediately after rain events can be significant, resulting in an underestimation of ET (Ringgaard et al., 2011; Denager et al., 2020). The main weakness of the EC approach is the energy balance closure problem, which is the imbalance between the land surface energy output and input. This imbalance means that the EC method may underestimate actual evapotranspiration (Denager et al., 2020). Since the closure problem is usually characterised by low turbulent fluxes, either the sensible and latent heat flux are underestimated or the net radiation and ground heat flux are overestimated.

2.4 Estimation of Evapotranspiration Based on the Hargreaves Method

The Hargreaves (HG) equation was recommended by Jensen et al. (1997) as one of the most basic and accurate empirical approaches. This empirical approach only requires measured mean air temperature and temperature range as well as computed extraterrestrial radiation (Hargreaves and Samani, 1985). The HG equation, according to Allen et al. (1998), gives reasonable evapotranspiration estimations with universal validity. Since the Hagreaves-Samani (HS) method was developed using data from arid to sub-humid environments, it may not work well in places that are very different from those used for testing, such as humid regions.

Temesgen et al. (2005), also concluded that the Hagreaves-Samani (HS) technique understates evapotranspiration in dry and windy regions due to the lack of a wind factor and that it is more accurate when applied to 5 or 7 day averages rather than daily periods. Although the Hagreaves-Samani (HS) equation performs admirably in most applications, especially when used for irrigation scheduling, numerous authors have tried to recalibrate the Hargreaves-Samani coefficients or parameters to improve performance e.g., (Droogers and Allen, 2002; Trajkovic, 2007) with Fooladmand et al. (2008), or to modify the equation Diodato and Bellocchi (2007). In comparison to other more sophisticated equations, the HS technique is frequently favoured because it is reasonably adequate and simply requires the maximum and lowest air temperatures (Hargreaves and Allen, 2003). This is especially important in areas where solar radiation, air humidity, and wind speed data are scarce or of poor quality, but maximum and minimum air temperatures are readily available in most agro-climatic and weather stations, as air temperature can be measured with fewer errors and by less-trained individuals than the other climate variables used in combination equations. According to Popova et al. (2006), it tends to overstate ET over grassland.

2.5 Estimation of Evapotranspiration Based on the Priestley Taylor Method

Priestley and Taylor presented an equation for evapotranspiration (ET) in 1972 that requires less data as compared to the well-established Penman-Monteith model (Gunston and Batchelor, 1983), which estimates evapotranspiration under low advective conditions (Stannard, 1993). The Priestley-Taylor (PT) equation was simplified by reducing the vapour deficit and convection terms into a constant, α the Taylor coefficient, on which the model's accuracy is dependent

(Priestley and Taylor, 1972; Gunston and Batchelor, 1983). The Priestly-Taylor coefficient (α) varies greatly, with values as low as 1 for any saturated surface surrounded by water bodies, as high as 1.3 for well-watered grasslands, and as high as 3 for saturated woodland surrounded by forest (Priestley and Taylor, 1972) and has been confirmed by a number of research, including Tanner and Jury (1976);Flint and Childs (1991);Lhomme (1997); Castellvi et al. (2001); Pereira (2004); Agam et al. (2010); Baldocchi and Xu (2007). Gunston and Batchelor (1983), demonstrated the bulk system's application to the PT model, the Penman-Monteith (PM) and Priestley-Taylor (PT) models had high agreement for 86 station-months , showing that either PM or PT may be used to estimate ET in humid tropical climates. The agreement between PM and PT breaks down in low humidity. The PT technique has a restriction in that it was developed for saturated conditions and open water sites where wind speed impacts were insignificant (McAneney and Itier, 1996; Cristea et al., 2013; Alblewi et al., 2015). Tongwane et al. (2017) investigated the seasonal variation of evapotranspiration (ET), the PT coefficient, in South Africa's eastern Free State. Their mean PT coefficient was lowest in autumn and largest in spring, with lowest and largest values of 1.30 and 2.61, respectively, and the variation of the PT coefficient is large in winter and spring, but is small in summer and autumn. Variation of the PT coefficient depends on land cover, meteorological factors, and site conditions. In addition, they proved that the PT approach for calculating ET underestimates evapotranspiration when the standard coefficient of 1.26 is used in the mountainous semi-arid environments. Asare et al. (2011), estimated daily potential evapotranspiration in Ghana's coastal savanna at Atomic-Kwabenya. When the PT and PM methods were compared, they found a reasonable correlation of 0.82 and a high correlation of 0.96 when compared to the Hargreaves and Samani model and other methods used in their research. As a result, they concluded that the PT model can be used instead of the PM model to estimate potential evapotranspiration at their study site. In addition, Reuben (2016), estimated daily evapotranspiration in Sumbrungu, Ghana's upper east region.

They observed that the PT model struggled to simulate observed values across the seasons but did particularly well in wet conditions.

Chapter 3

Methodology

3.1 Study Area

The study area is Sumbrungu in the Upper East Region of Ghana, at latitude $10.846^{o}N$ and longitude $0.917^{o}W$ Figure 3.1, at an elevation of 200 m above sea level (Quansah et al., 2015). Bolgatanga and Sumbrungu are separated by a distance of approximately 35 kilometers. The landscape is typical of the Southern Sudanese Savanna, with grasslands and drought-resistant trees interspersed. The site's soil texture is a mix of loamy and sandy soil, with an average grass height of 0.10 meters (Quansah et al., 2015).The most important economic activity among the natives is agriculture. Their principal crops include millet, guinea corn, maize, peanuts, beans, sorghum, and tomatoes and onions in the dry season. They also raise animals such as cows, sheep, goats, and poultry such as guinea fowl.

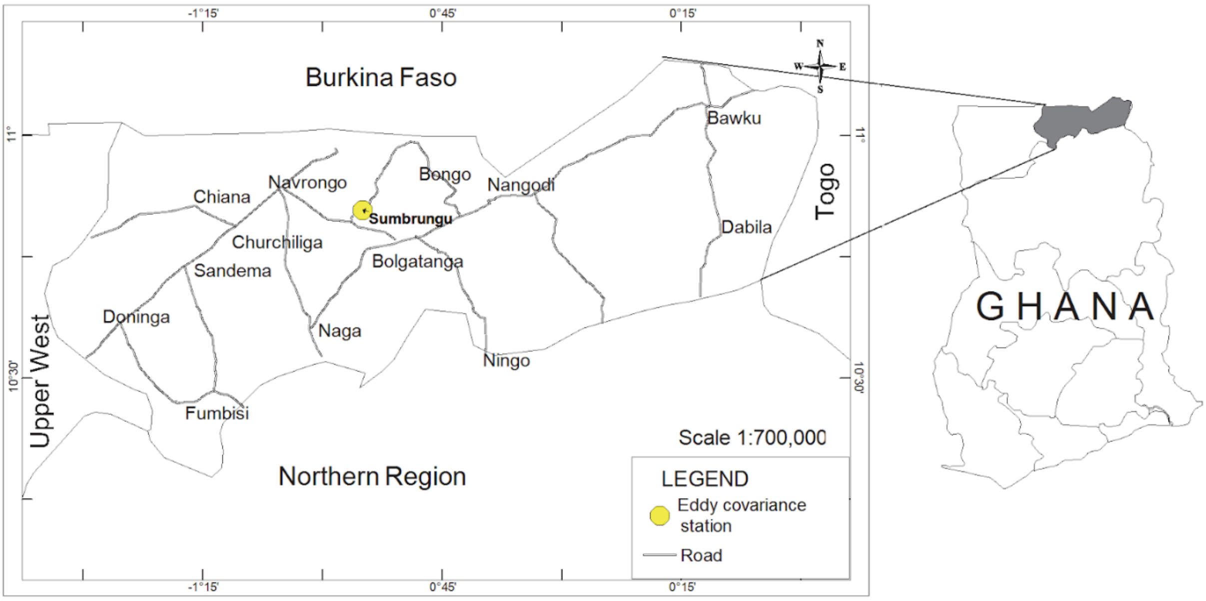

Figure 3.1: depicts the location of the study site in Ghana's Upper East Region Quansah et al. (2017)

3.2 Climate of the Study Area

The climate of the study is the Sudanian Savanna vegetation, with the dry season falling between November and April each year. The rainfall pattern is monomodal, beginning in May and ending in October each year. The migration of the Inter-Tropical Convergence Zone (ITCZ), northeast trade winds from the Sahara, and southwest winds across the seas cause climate fluctuations in the northern region of Ghana. Due to an enhanced north east trade wind, the dry season, also known as the Harmattan, is marked by dryness and dust-laden winds coming from the Sahara. During the wet season, there is prolonged rainfall due to the relaxation of the north east trade winds and the intensification of the south west trade winds blowing from the Atlantic Ocean. This fuels the laden winds with moisture, resulting in an increase in humidity, which leads to an increase in the amount of rainfall received during the wet season (Quansah et al., 2015).

3.3 Data Acquisition

The data collection was gathered from a meteorological station in the Upper East Region of Ghana under the WASCAL (West African Science Service Centre on Climate Change and Adapted Land Use) WRAP 1.0 Project. The data is a secondary data set span from January to December 2013 and 2014. The data is made up of net solar radiation, latent heat, sensible heat, ground heat, ground heat, date and time and temperature were all included in the data set. The data were determine at half-hourly, but were integrated into daily values.

3.4 Description of the Eddy Covariance Method

The Eddy covariance method is a remote sensing method. This technique is a statistical method that measures and calculates H_2O, CO_2, momentum, latent heat and sensible heat fluxes i.e. turbulent energy fluxes within the atmospheric boundary layer (Quansah et al., 2015; Denager et al., 2020). The latent heat flux was estimated based on Equation (3.1) (Quansah et al., 2015):

$$H = \rho_a \overline{C_p \omega' T_a'} \tag{3.1}$$

where $\rho a is the density of dry air at a given air temperature (kgm^{-3})$, C_p is the specific heat capacity of dry air at constant pressure (Jkg^{-1}), T_a is the air temperature derived from the ultrasonic anemometer (), λ is the latent heat of evaporation (Jkg^{-1}), ω is the vertical component of the wind velocity (ms^{-1}). From 3.1, the daily ET values were estimated based on 3.2

$$ET_{EcDaily} = \frac{1}{\rho_w} \sum_{i=0}^{n} \frac{LE_{30min}^{i}}{\lambda(T)} \tag{3.2}$$

where $\rho_w(kgm^{-3})$ is the density of water, n is the number of values for a given day. $\lambda(MJkg^{-1})$

is the heat of vaporization as a function of the temperature T (°C) given by the equation:

$$\lambda = (2.501 - 0.00236T) \tag{3.3}$$

3.5 Description of the Model Equations

The FAO Penman Monteith equation (Allen et al., 1998), the Hargreaves model (Hargreaves and Samani, 1985), and the Priestly Taylor model (Priestley and Taylor, 1972), were all employed in this study to estimate evapotranspiration (mm day^{-1}). These are shown in Equations 3.4 -3.6 respectively as:

$$ET_O = \frac{0.408\delta(R_n - G) + \gamma\frac{900}{T+273} \times \mu(e_s - e_n)}{\delta + \gamma(1 + 0.34\mu_2)} \tag{3.4}$$

$$ET_H = 0.0023 \times [(T + 17.8)(T_x - T_n)]^{0.05} \times \frac{R_a}{\lambda} \tag{3.5}$$

$$ET_{TP} = \alpha \times \frac{\delta \times (R_n - G)}{\lambda_V} \times 1000 \tag{3.6}$$

where R_n is the net radiation at crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the air temperature at 2 m height (°C), μ_2 is the wind speed at 2 m height (ms^{-1}),e_s is the saturation vapor pressure (kPa), e_n is the actual vapor pressure (kPa), (e_s - e_n) is the saturation vapor deficit (kPa), δ is the slope of vapor pressure curve (kPa °C) and γ – psychometric constant (kPa °C^{-1}) = 0.4 (g_w / kg $_w$) K^{-1}, the coefficient α is 1.26 (water bodies), more than 1 in humid conditions and almost 2 in arid condition, λ is latent heat (evapotranspiration) mm day^{-1} and λ_V is the latent heat of vaporization of water .

3.6 Model Validation Schemes

This study makes use of the mean bias error and the root mean squared error analysis in order to estimate the error bias of different models. The Mean Bias Error (MBE) can determine whether a model is suitable or not. Closer MBE values have a propensity to under-or over-predict, with MBE values near to zero are preferred. As a result, the Root Mean Squared Error (RMSE) provides a comparison of the actual variation between terms on a term-by-term basis, with a lower RMSE value between the expected and actual values, suggesting a more accurate model in terms of absolute deviation (Quansah et al., 2014).The following formulae are used to calculate the mean bias error (MBE) and root mean square error (RMSE):

$$MBE = \frac{1}{N}\sum_{i=0}^{n}(H_{ip} - H_{im}) \tag{3.7}$$

$$RMSE = \sqrt{\frac{1}{N}[\sum_{i=0}^{n}(H_{ip} - H_{im})^2]} \tag{3.8}$$

where H_{im} represents the i^{th} observed value, H_{ip} represents the i^{th} estimated or forecast value, and n represents the total number of observations

The degree to which the modelled and observed values vary together was measured using a simple linear correlation. The correlation coefficient (R), which has a range of -1 to 1, is used to estimate the modelled evapotranspiration (ET). R does not depend on the units of measurement. R is given by the formula ;

$$R = \frac{\sum XY - \frac{\sum X \sum Y}{n}}{\sqrt{\sum(X - \bar{x})^2 \times \sum(Y - \overline{Y})^2}} \tag{3.9}$$

where R_n denotes the total number of daily values, The X and Y in the equation to calculate R might not always correspond to the modelled and observed values, respectively. $\overline{X}$ and

$\overline{Y}$ means of X and Y, respectively. In the test for significance, the association between two evapotranspiration estimates is tested using the correlation coefficient, R, which ranges between -1 and 1. When R is close to 1.0, the model is said to be accurate.

Chapter 4

Results and Discussion

4.1 Analysis of Daily-Average Modelled Evapotranspiration Estimates for the year 2013

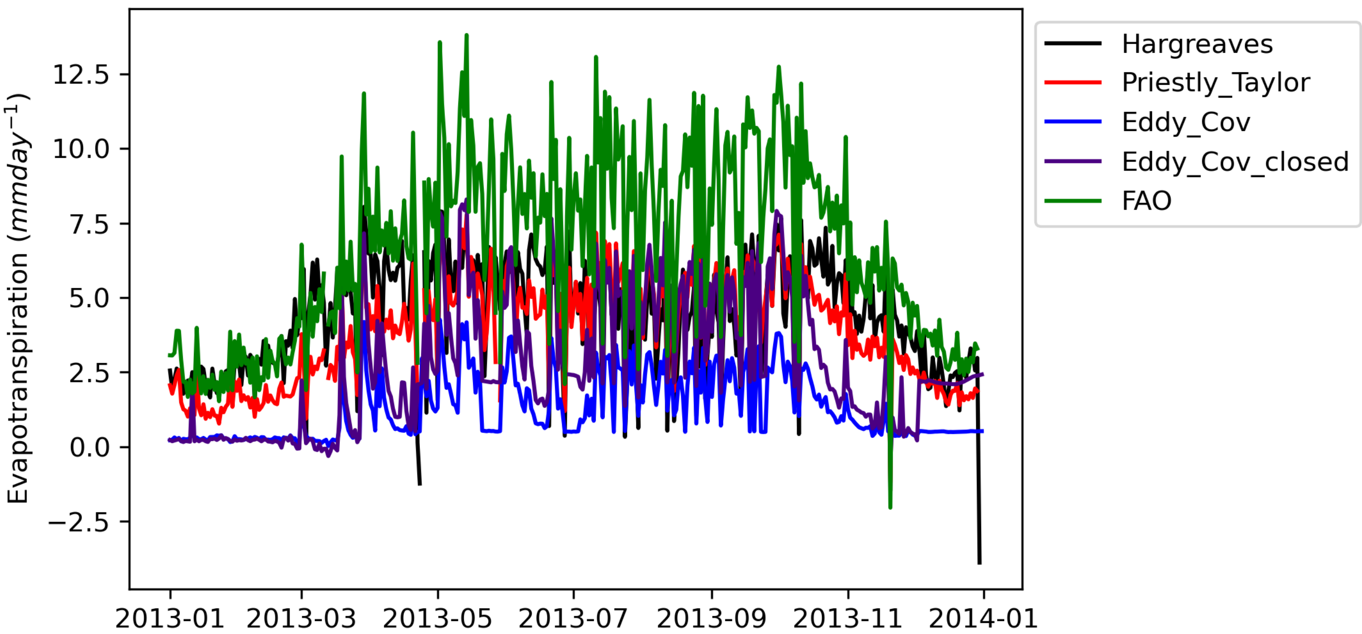

Figure 4.1: Time series plot of daily modelled ET for the year 2013.

Figure 4.1 illustrates the daily variation of evapotranspiration for Priestley Taylor (PT), FAO Penman Monteith, Eddy Covariance (EC), Closed EC and Hargreaves (HG) in 2013.

Evapotranspiration is low in January, February, and March and starts to rise in April, peaks in May, and slightly falls in July, which usually has high amounts of rainfall and humidity. ET then rises again in August to November and then recedes in December. This is due to the decrease in soil moisture content and the withering of leaves that retain plant moisture. The negative values of ET on the graph show surface condensation, but they are cut off at zero for practical application (Ringgaard et al., 2011). Furthermore, it can also be observed that the Priestley Taylor and the Hargreaves models, to some degree of accuracy, conform to the FAO Penman-Monteith model with the exception of the eddy covariance, which underestimates ET. This can be attributed to the non-closure in which the total of the turbulence fluxes (sensible heat (H) and latent heat (LE)) is less than the available energy (ground heat fluxes and net radiation). This has been ascribed to the inability of frequent EC tower measurements to capture some eddies, as well as flaws in individual instrument data. Nonetheless, this energy imbalance may be addressed by dividing the leftover energy into H and LE using the measured Bowen ratio. On an annual time scale, the maximum observed ET was 13.81 mm day^{-1} , 7.77 mm day^{-1}, 4.26 mm day^{-1}, 8.29 mm day^{-1},and 8.04 mm day^{-1} for FAO, PT, EC, Closed EC, and HG, respectively. The minimum ET observed was -2.04 mm day^{-1}, -1.19 mm day^{-1}, 0.03 mm day^{-1}, -0.53 mm day^{-1}, and -3.88 mm day^{-1} for FAO, PT, EC, Closed EC, and HG, respectively.

4.2 Analysis of Daily-Averaged Modelled Evapotranspiration Estimates for the year 2014

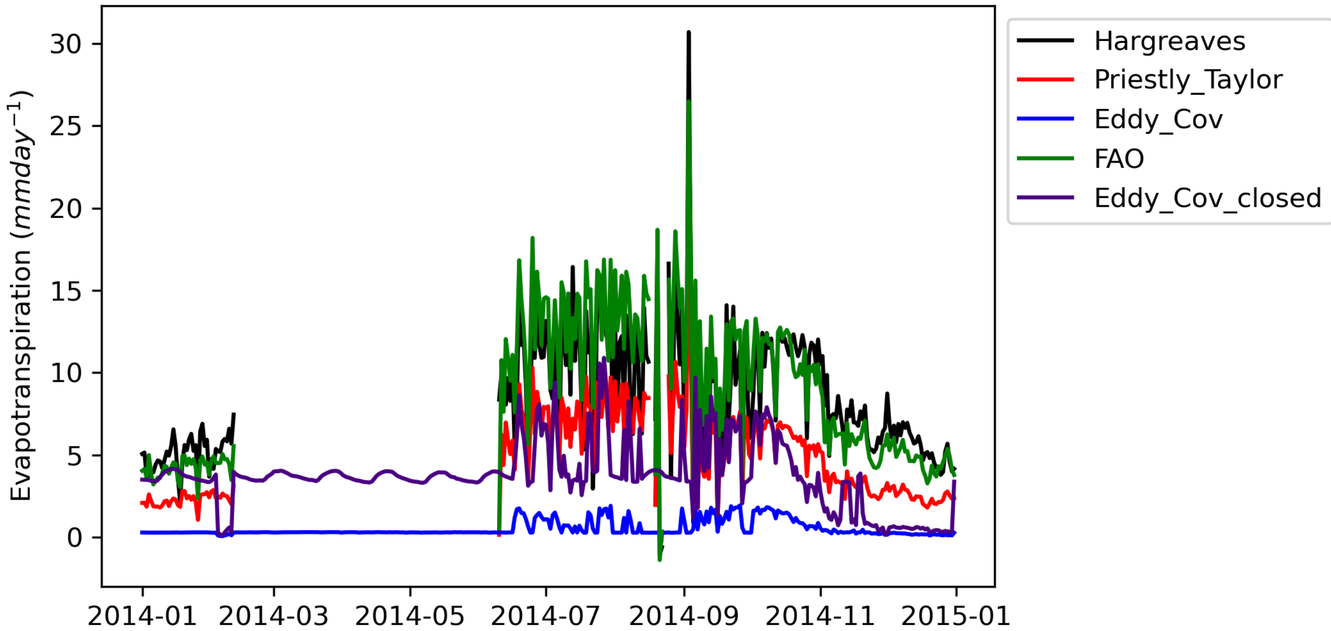

Figure 4.2: Time series plot of daily modelled ET for the year 2014.

Figure 4.2 presents a daily time series of evapotranspiration estimates for Priestley Taylor, FAO Penman Monteith, Eddy Covariance, and Hargreaves in 2014. A data gap in the data can be observed from February to June, and that was as a result of a malfunction of a device on the Eddy flux tower. This was not the case for the eddy covariance technique, which is reliant on latent heat flux. ET is low in January and starts to rise in July and peaks in September and slightly falls in October as a result of increased humidity, then rises again in November and then recedes in December. On an annual time scale, the maximum observed ET was 26.48 mm day^{-1}, 18.69 mm day^{-1}, 1.94 mm day^{-1}, 10.90 mm day^{-1}, and 30.69 mm day^{-1} for FAO, PT, EC, Closed EC, and HG, respectively. The minimum ET observed was -1.39 mm day^{-1}, -1.08 mm day^{-1}, 0.06 mm day^{-1}, 0.09 mm day^{-1}, and -1.08 mm day^{-1} for FAO, PT, EC, Closed EC, and HG, respectively. The Priestley-Taylor and the Hargreaves models have some degree of accuracy conforming to that of the FAO Penman-Monteith model. with the exception of the EC model, which underpredicted ET estimates throughout the year.

4.2.1 Analysis of Monthly-Averaged Modelled Evapotranspiration Estimates for the year 2013

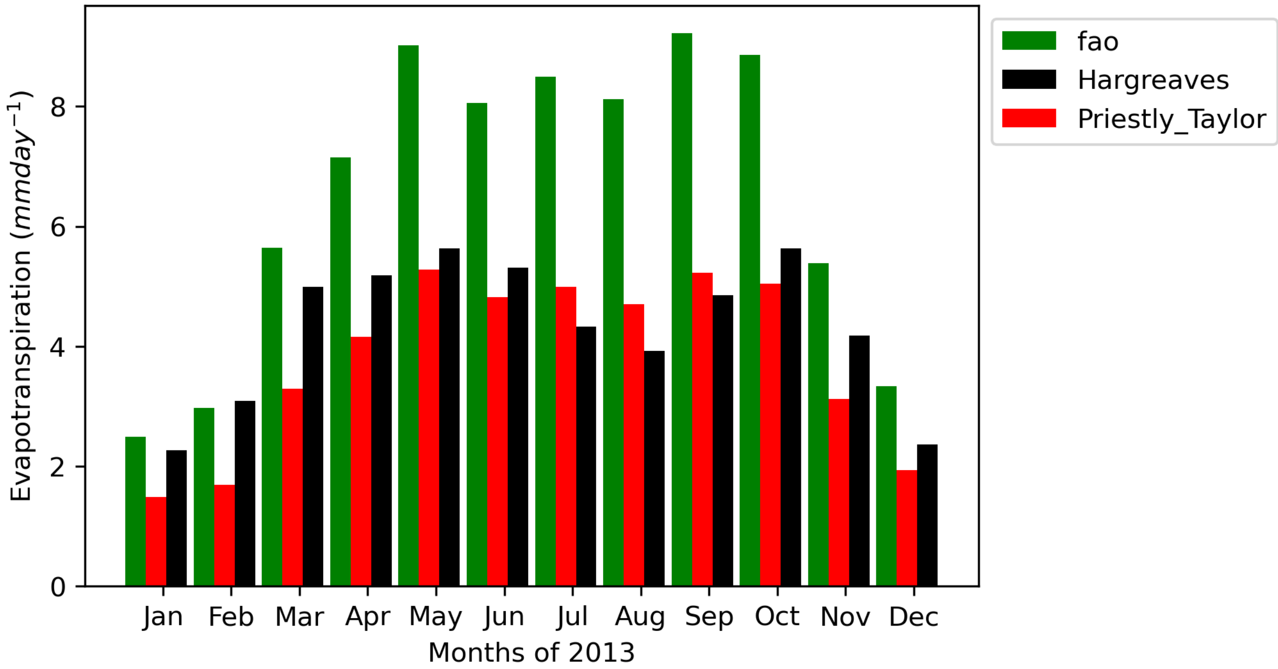

Figure 4.2.1: Monthly-Averaged Evapotranspiration from the FAO, Hargreaves, and Priestly-Taylor Models for 2013.

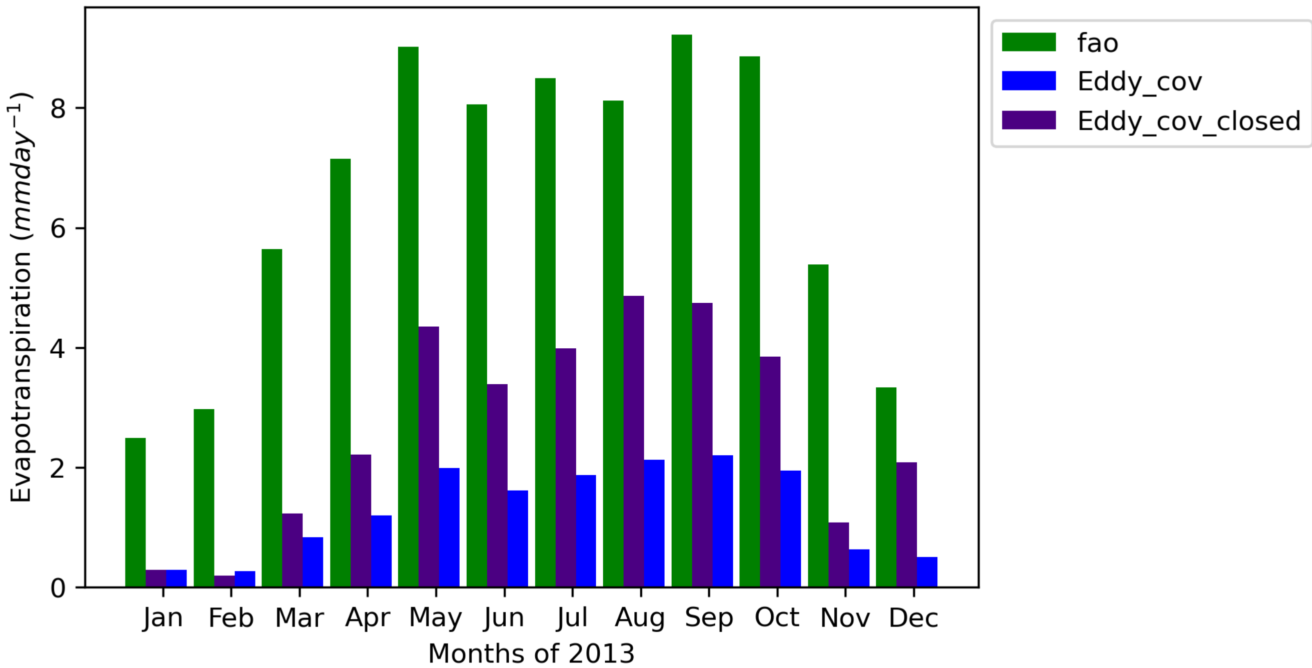

Figure 4.2.1: Monthly-Averaged Evapotranspiration from the FAO, Eddy Covariance, and Closed Eddy covariance Models for 2013.

Evapotranspiration shows highly seasonal behavior with very low values in the dry season (January, February, March, November, December) and peaks in the rainy season (April, June, July, August, September, October). When compared to the FAO model, the PT model performed very well. Likewise, the Hargreaves model also performed well during the dry season but under predicted ET during the wet season. On the other hand, the EC method under predicted ET in both the wet and dry seasons for the year 2013.

4.3 Model Validation for 2013

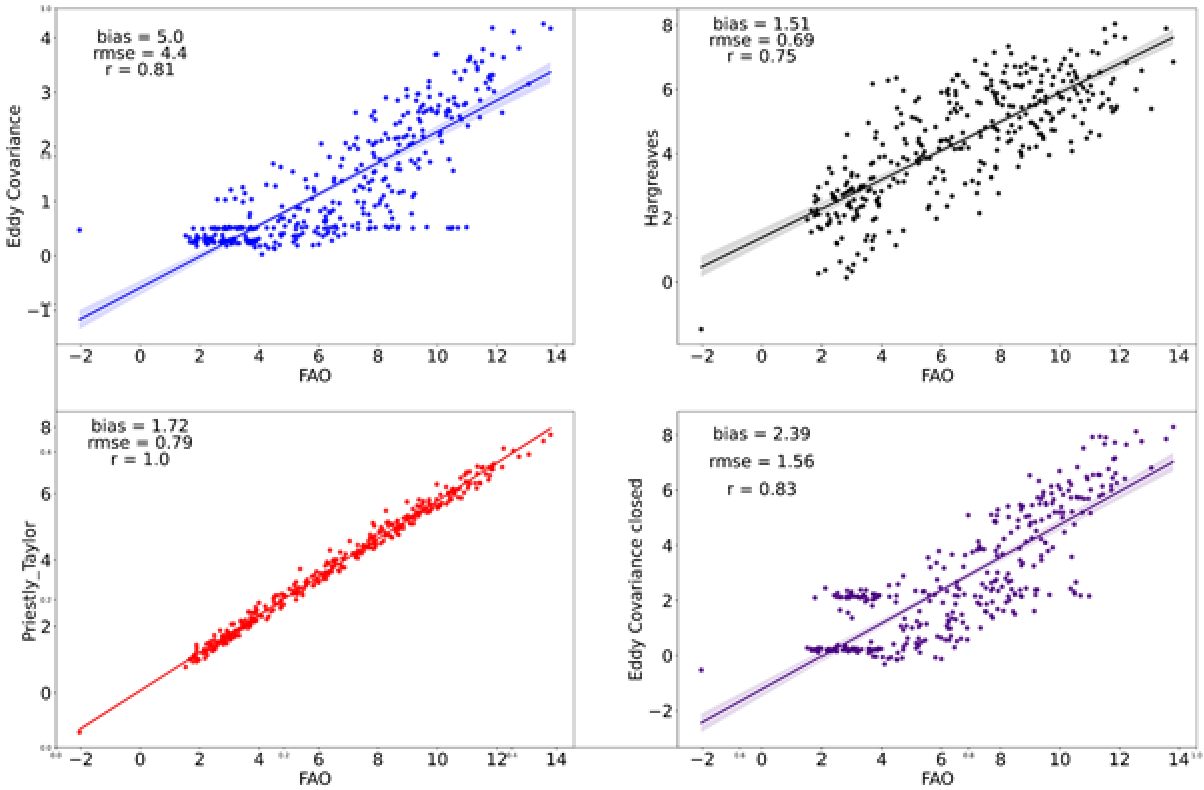

Figure 4.4: Comparison of the Observed ET (FAO) and the other Models for 2013.

When the ET estimations of each model were compared to the FAO model, PT was able to predict ET with a very good correlation coefficient (R) of 0.98, mean bias error (MBE), and root mean square error (RMSE) of 1.72 mm day^{-1} and 0.97 mm day^{-1}, respectively. The EC model had a R, MBE, and RMSE of 0.81, 5.00 mm day^{-1}, and 4.40 mm day^{-1}, respectively. Closed EC had R, MBE, and RMSE of 0.81, 2.39 mm day^{-1}, and 1.56 mm day^{-1}, respectively. For HG, the observed R, MBE, and RMSE were 0.75, 1.51 mm day^{-1}, and 0.69 mm day^{-1}, respectively.

4.4 Model Validation for 2014

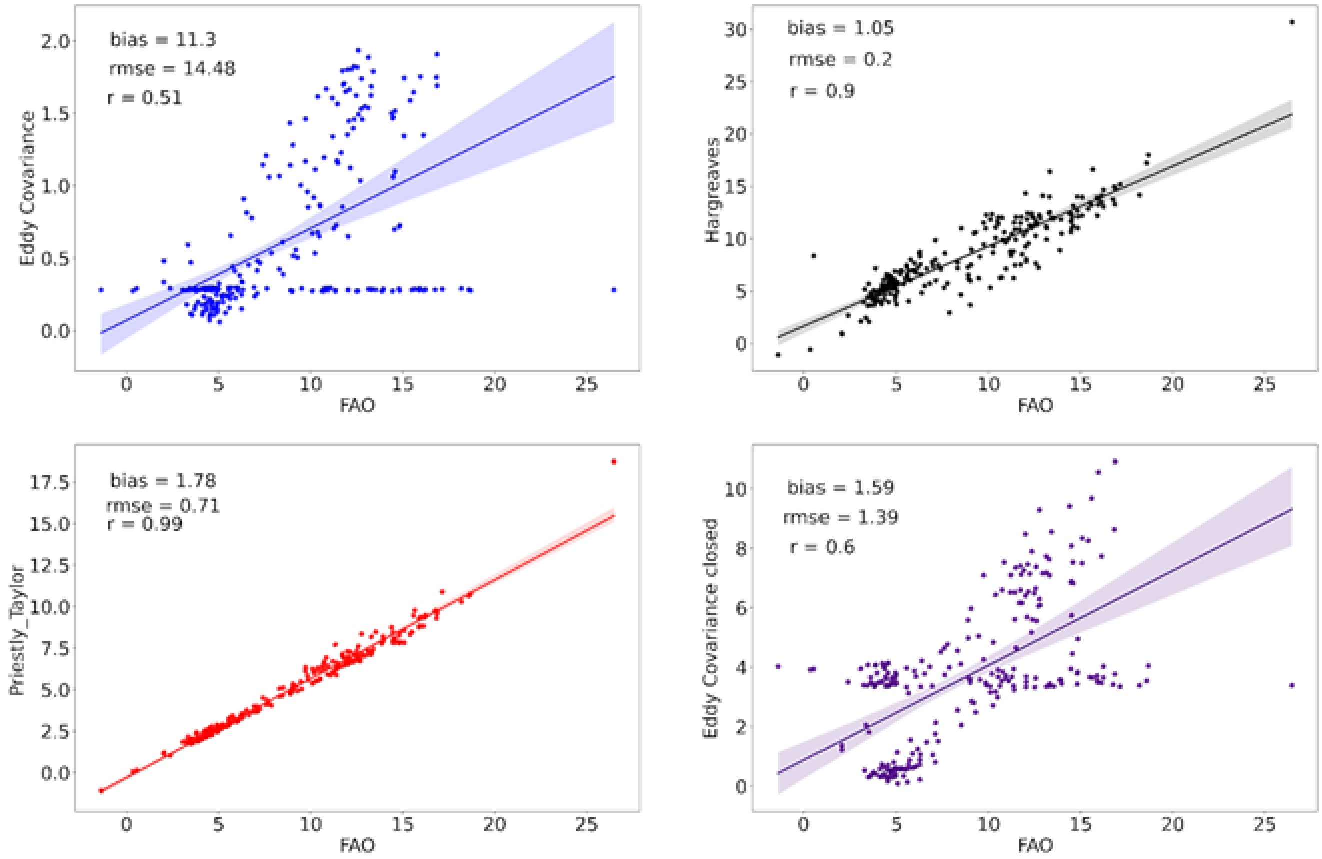

Figure 4.4: Comparison of the Observed ET (FAO) and the other Models for 2014.

PT was able to predict ET with a very good correlation coefficient (R) of 0.99, mean bias error (MBE), and root mean square error (RMSE), which were 1.78 mm day^{-1} and 0.71 mm day^{-1}, respectively. The R, MBE, and RMSE of the EC model were 0.51, 11.30 mm day^{-1}, and 14.48 mm day^{-1}, respectively. R, MBE, and RMSE for Closed EC were 0.60, 1.50 mm day^{-1}, and 1.39 mm day^{-1}, respectively. The R, MBE, and RMSE for HG were observed to be 0.97, 1.59 mm day^{-1}, and 0.20 mm day^{-1}, respectively, when the ET estimations of each model were compared to the FAO model. Summary of the statistics gleaned from the model assessment is given in Tables 4.1 and 4.2:

Table 4.1: Summary of model validation for 2013

Models	**MBE** (mm day^{-1})	**RMSE** (mm day^{-1})	**R**
Eddy Covariance	5.00	4.40	0.81
Closed Eddy Covariance	2.39	1.56	0.83
Hargreaves	1.51	0.69	0.75
Priestley-Taylor	1.72	0.79	0.98

Table 4.2: Summary of model validation for 2014

Models	**MBE** (mm day^{-1})	**RMSE** (mm day^{-1})	**R**
Eddy Covariance	11.30	14.48	0.51
Closed Eddy Covariance	1.59	1.39	0.60
Hargreaves	1.05	0.20	0.90
Priestley-Taylor	1.78	0.71	0.99

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

For the years 2013 and 2014, evapotranspiration was calculated using the Priestley-Taylor (PT), FAO Penman Monteith, Eddy covariance (EC), and Hargreaves (HG) models over a grassland ecosystem at Sumbrungu in the Upper East Region of Ghana. The data was obtained from a meteorological station in the Upper East Region of Ghana under the WASCAL WRAP 1.0 Project provided the data for this study. In addition, the effectiveness of the closed EC, EC, PT, and HG models was assessed in comparison to the FAO. The results of the comparison showed R of 0.81 and 0.51 for EC, 0.83 and 0.6 for closed EC, 0.75 and 0.9 for HG, 0.98 and 0.99 for PT for 2013 and 2014 respectively. Similarly, the RMSE were 4.4 mm day^{-1}, 14.48 mm day^{-1} for the EC, 1.56 mm day^{-1} and 1.39 mm day^{-1} for closed EC, 0.69 mm day^{-1} and 0.2 mm day^{-1} for HG and 0.76 mm day^{-1} and 0.71 mm day^{-1} for PT. While the MBE of 5.0 mm day^{-1} and 11.3 mm day^{-1} for EC, 2.39 mm day^{-1} and 1.59 mm day^{-1} for closed EC, 1.51 mm day^{-1} and 1.05 mm day^{-1} for HG, 1.67 mm day^{-1} and 1.78 mm day^{-1} for PT for 2013 and 2014 respectively. The results showed that the EC model struggled to simulate the observed values over the two-year study period, whereas the HG and closed EC models were able to moderately simulate values close to those of the FAO. However, the PT performed very well, close to the FAO. The PT model only incorporates two climatic factors, which are net radiation and ground heat flux, in the estimation of ET, whereas the PM model incorporates both the aerodynamic and the energy balance technique in the estimation. In order to estimate ET, the HG model uses both air temperature and net radiation, whereas the EC model only uses latent heat fluxes (LE). The estimation of ET using the EC model is improved when LE is closed using the Bowen ratio. The obtained results and statistics from the error evaluation schemes revealed that during the dry season, the PT model estimated ET close to the FAO model. The HG, EC, and closed EC models underestimated ET during the wet season, but the PT model estimated ET quite well in 2013. During the dry season, the PT model estimated ET close to the FAO model, while the HG, EC, and EC-closed models underestimated it. The HG and EC closed models predicted ET well during the wet season, but the PT model estimated ET fairly well, while the EC model underestimated ET throughout the year 2014. It is observed that the PT model performs far better under wet conditions than the HG, EC, and Closed EC models. On an annual basis, the PT model outperforms the HG, EC, and Closed EC models. According to the findings, the PT model can be used to estimate ET over the region. However, because the FAO model is typically used, this must be done with caution, preferably on watered grassland.

5.2 Recommendation from this study

In the absence of observed data or FAO-derived data, it is recommended that the Priestley Taylor (PT) model, which requires less meteorological data be used.

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