Estimation of Potential Evaporation Based on Penman Equation under Varying Climate, for Murang'a County, Kenya

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Abstract

Estimates of potential evaporation or evapotranspiration (ET) are essential input for rainfall-runoff modeling and water balance calculations. Rain-fed agriculture continues to be the backbone of Kenya's economic activities. This study focuses on the rainfall and ET regimes in Murang'a County. The variability of the elements may hinder agricultural development in the County and the country's ability to achieve sufficient food production, which is dependent on water management. The study utilizes meteorological controls on evaporation, and assesses the potential effects of climate change in mean monthly temperature, net radiation, vapour pressure, wind speed and rainfall for three climate models. The rainfall in the area depicts the equatorial bimodal regime, with ET closely mimicking it. The models show change in climate by the year 2050, relative to the 1961-1990 average. The climate models produce three different changes, implying some level of uncertainty for future agricultural production with various consequences on future food security for Murang'a residents. This could also be true for other regions in Kenya. Thus calls for intensive study on individual effect of each parameter on ET. This is necessary for appropriate climate and irrigation control that can lead to adjustment in the selection of crops for sowing in either of the rain seasons to maximize crop yield productivity.

Key Words: Evapotranspiration, Penman, Climate Change, Murang'a County

Introduction

Climate change is projected to result in an intensification of the global hydrological cycle (Huntington, 2006; IPCC, 2013).This necessitates research on how different methods of estimating evapotranspiration (ET) respond to it. The ET is an important hydrological process in the climate system (Lu et al., 2005) because it provides moisture to the atmosphere (Trenberth and Asrar, 2014), which is perceived to be the beginning of the hydrological cycle. It also consumes energy, contributing to water and energy transfer. However, it is difficult to measure ET directly from a large area, and as a result, many empirical relationships and equations have been developed to estimate ET using meteorological data (Arnell, 2002). According to some studies (e.g. Schwab et al., 1993; Stern, 1994), evapotranspiration estimates can be used to make many practical applications, but the principal use is to predict soil water deficit for irrigation. Given the present and likelihood of future change in climate (IPCC, 2013), there is need to understand the response of ET (Bates et al., 2008).

Kenya's economy is mainly dependent on rain fed agriculture (Ogallo, 2010), making rainfall the most important weather element in the country and the eastern Africa region at large. Kenya's Vision 2030, the country's long-term development agenda, identifies agriculture as a key sector for the realization of the vision's economic pillar (GoK, 2007). Thus, there is need for better understanding of the future state of the climate and its influences on Kenya's agricultural activities.

This study focused on rainfall distribution and the application of Penman equation to estimate ET and explore the effect of different climate models on estimated change in ET over Murang'a County. Murang'a County is located on the highlands east of the Great Rift Valley in Kenya (Figure 1).

The county lies between latitudes 0° 34' S and 1° 7' S and longitudes 36° E and 37°27' E, occupying a total area of 2,558.8 Km^2. The county's inhabitants mainly engage in crop farming, contributing largely to the food production to the central region as well as the whole country. The county lies between 914M above men sea level (ASML) in the east and 3,353m AMSL along the slopes of the Aberdare Mountains

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in the west. Landslides (Figure 2) are a common phenomenon in the County, especially during heavy rains (DMC, 2002).

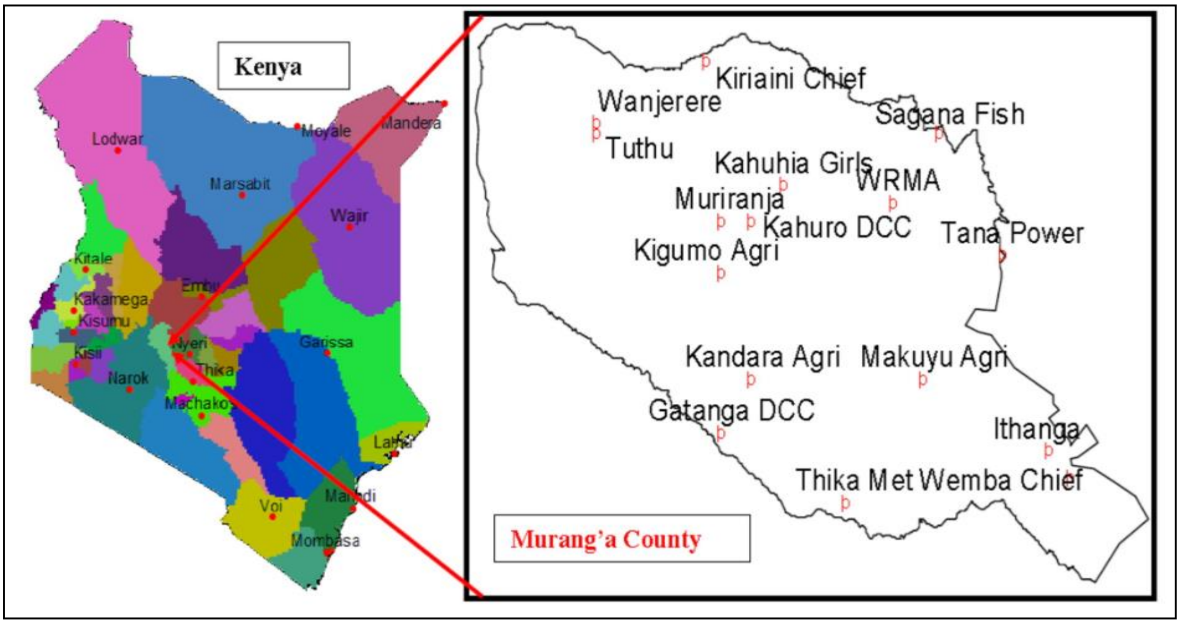

Figure 1: Area of study (left) Position of Murang'a Country in Kenya, (right) distribution of rainfall gauging stations in Murang'a County

Increases in temperature and changes in precipitation can have profound effects on regional hydrological resources (IPCC, 2013; Trenberth and Asrar, 2014). Due to climate variability and effects of climate change, adverse climatic effects are on the increase in Murang'a County. A steadily growing population in the area (KNBS, 2010) worsens the situation.

Figure 2: Rainfall induced landslide in Ichichi Village, Kangema Sub-County on 01.04.2014 where 200 tea bushes were destroyed (Picture by Murage)

The topography and geology of the county is both an asset and liability to the county's development (Simelton et al., 2013). The highest areas form the rain catchment areas from where most of rivers draining the county, originate. They generate down-flows during heavy storms resulting in landslides and gulley erosion.

Data and Methodology

The daily data used in the study are: temperature, evaporation, wind speed, solar radiation, and rainfall spanning 30 years; 1981 to 2011. The data was sourced from Kenya Meteorological Department (KMD).

The Penman method uses the combination of the energy-balance and aerodynamic equations. Penman developed the equation based on energy balance and mass transfer to compute the ET (Penman, 1948). This was based on the assumption that ET is affected by wind, radiation, temperature and humidity. The method was modified by Monteith to include cropped surfaces by introducing resistance factors (Monteith, 1965). According to studies (e.g., Lu et al., 2005; Douglas et al., 2009), more than 50 different methods exist by which ET can be estimated. Out of the many methods, Allen et al., (1998) and the Food and Agricultural Organization (FAO) recommend use of the Penman-Monteith equation. The equation directly incorporates the relevant meteorological variables, aerodynamic resistance of the vegetation, which control ET and gives the most accurate and satisfactory results (Doorenbos and Pruitt, 1977).

The Penman formula is described in most hydrological works (e.g. Valiantzas, 2006; Arnell, 2002; Ward and Robison, 2000; Shuttleworth, 1993; Shaw, 1993). However, each presents it in a slightly different way depending on the inputs. The formula version in Equation 1 used in this study is adopted from Arnell, (2002), due to the availability of the input data. This equation does not include heat exchange with the ground, water advected energy or change in heat storage. This assumption is acceptable for monthly or daily estimations in practical hydrological applications (Allan et al., 1998; Shuttleworth, 1993).

$$ET = \frac{\Delta Rn + \gamma Eap}{\Delta + \gamma} \qquad \text{……………………...…...…. (1)}$$

Where; ET is evapotranspiration, R_n is net radiation, Δ is slope of saturation vapour pressure and temperature at temperature T, γ is the psychometric constant (= 0.66 hPa ºC) and E_{ap} is the aerodynamic part.

The Eap is given by Equation 2,

$$Eap = 0.26(e_s - e)(1 + 0.536u) \qquad \text{………………………………. (2)}$$

Where; u is the wind speed, e is vapour pressure and e_s is saturation vapour pressure. The e_s is calculated from Teten's Equation 3,

$$e_s = 6.11e^{(\{17.27T\}/\{237.3+T\})} \qquad \text{…………………..…………. (3)}$$

The slope of the saturation vapour pressure/temperature relationship (Δ) at temperature T is given by Equation 4,

$$\Delta = \frac{4098e_s}{(237.3 + T)^2} \qquad \text{……………..…………………. (4)}$$

The study utilizes meteorological controls on ET, and assesses the potential effects of climate change in mean monthly temperature, net radiation, vapour pressure, wind speed and rainfall for three climate models, under the SRES A_1B emissions scenario. The three models are; Met Office Hadley Centre Coupled Model version 3 (HadCM3), Met Office Hadley Centre Global Environment Model version 2 (HadGEM2), and Fifth Generation Atmospheric General Circulation Model (ECHAM5). The models were used to show changes in climate in 2050 relative to the 1961-1990 averages.

The difference in ET at the two end extremes of each element perturbation was converted to percentages to estimate percentage change in ET. The error was estimated using the Chi- square method (Equation 5).

$$Error = \frac{1}{N}\sum(O - O_i)^2 \qquad \text{..} (5)$$

Where N total data set, O the observed values and Oi is the estimated values.

Results and Discussion

Estimation of the few missing data points was accomplished using the arithmetic mean method. Sample boxplots were produced to identify the outliers in the data set (Figure 3).

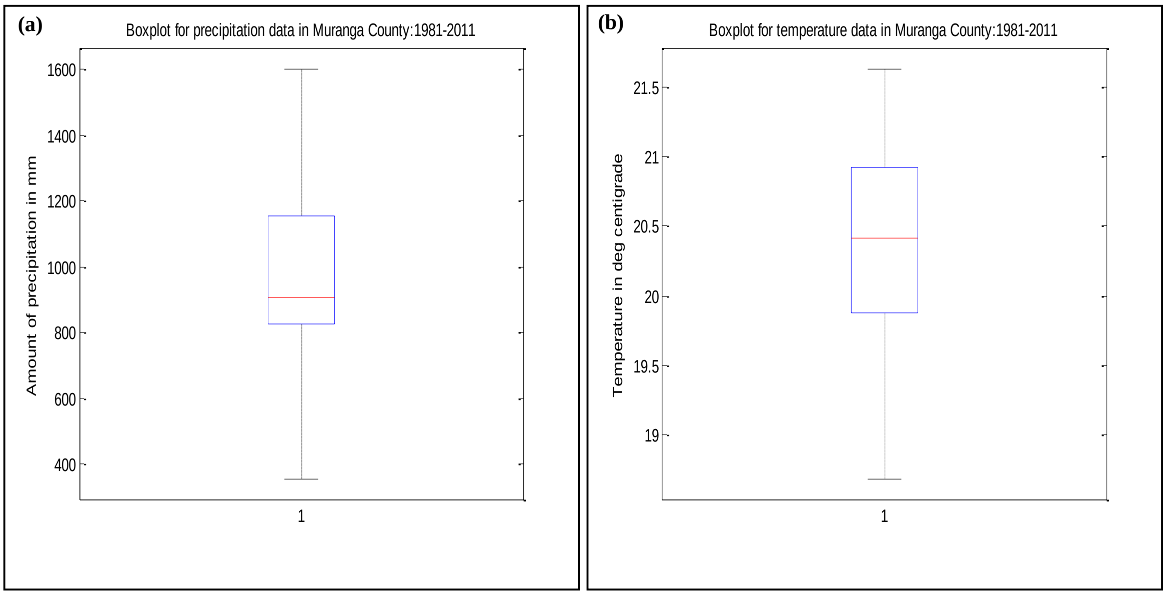

Figure 3: Boxplot **(a)** Precipitation, **(b)** Temperature

Precipitation is positively skewed with a higher frequency of small measurements, while temperature is normally distributed.

The County has a bimodal type of rainfall distribution. The long rain season occur in the months of March-May while the short season in October-December (Figure 4).The results are in agreement with many studies done over the entire country and the east Africa region at large (e.g., Ngetich et al., 2014; Funk et al., 2010 and Indeje et al., 2001).The major influence of the observed bimodal rainfall pattern is the inter-tropical convergence zone (ITCZ) while variation in space is attributed to local topography (Indeje et al., 2001). Figure 4 and 5 show that rainfall is observed to vary from one location to the other, implying need of different agricultural practices from one place to another.

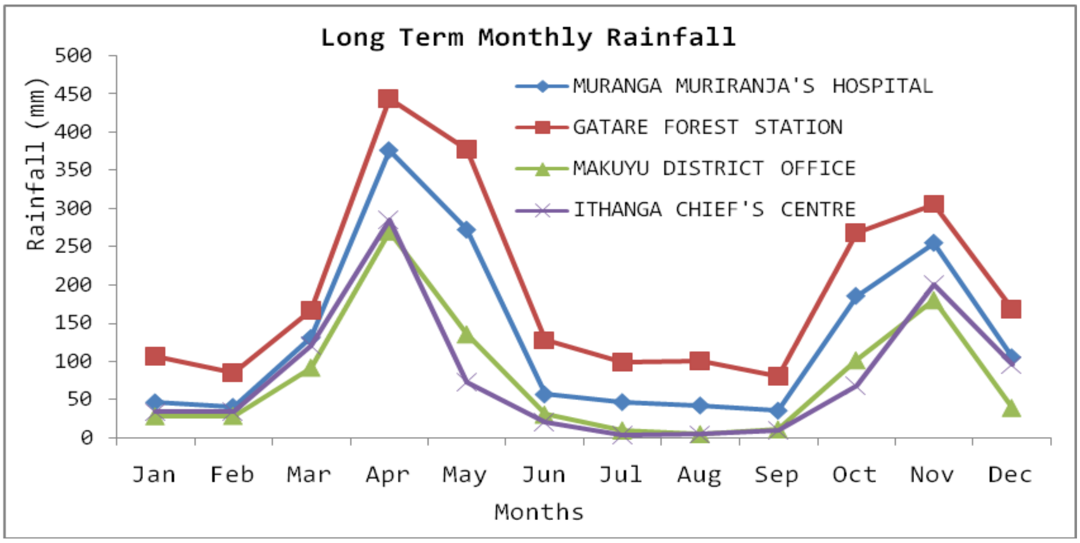

Figure 4: Rainfall distribution in Murang'a County.

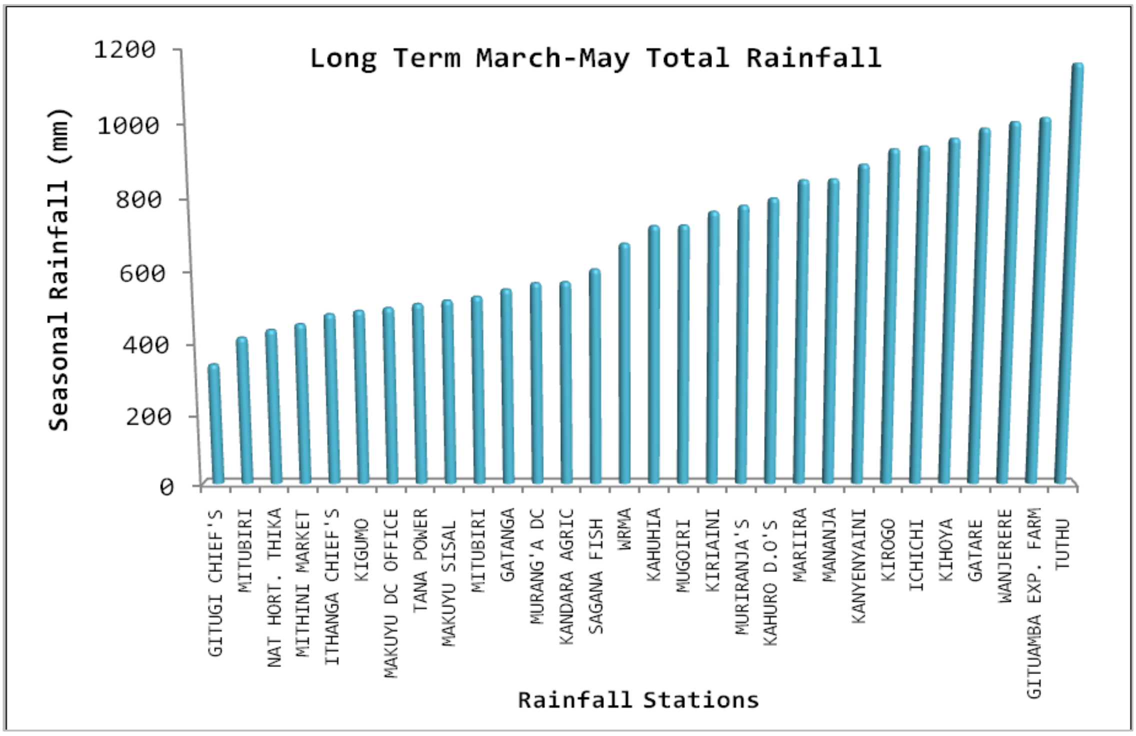

Figure 5: Long term rains spatial variation.

The County can thus be divided into three climatic regions; the western region with an equatorial type of climate, the central region with a sub-tropical climate and the eastern part with semi-arid conditions. This is because; to the east it borders Embu County which sits to the lee side of the giant Mt. Kenya making it dry. The Western region is generally wet and humid due to the influence of the windward effect of the Aberdares and Mt. Kenya.

The ET is observed to vary month by month in the County (Figure 6). The ET pattern mimics the rainfall pattern with ET generally being less than rainfall throughout the year.

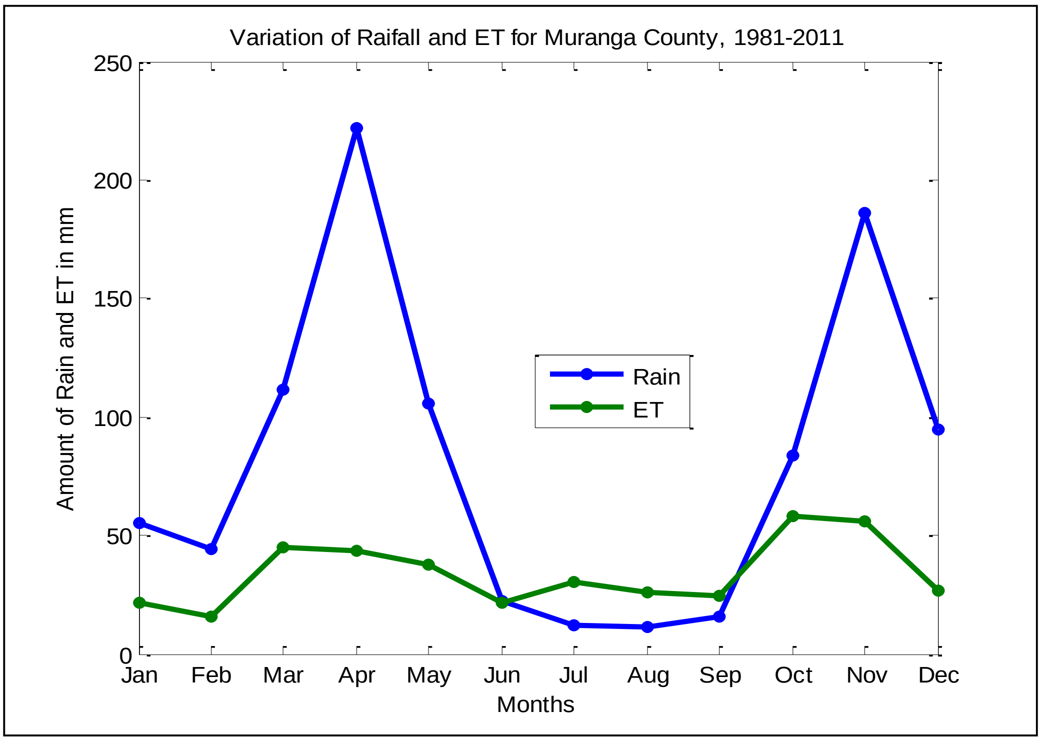

Figure 6: Average total monthly ET and rainfall.

The rain recharges the groundwater, which in turn supplies water for ET, explaining the observed pattern. The ET is controlled by the characteristics of the catchments like vegetation, land use and management; this may explain the observed pattern in the months of June to September.

Figures 7 a, b, c, d and e show the relationship between ET and the other variables that drives ET; rain, wind, temperature vapour pressure and radiation.

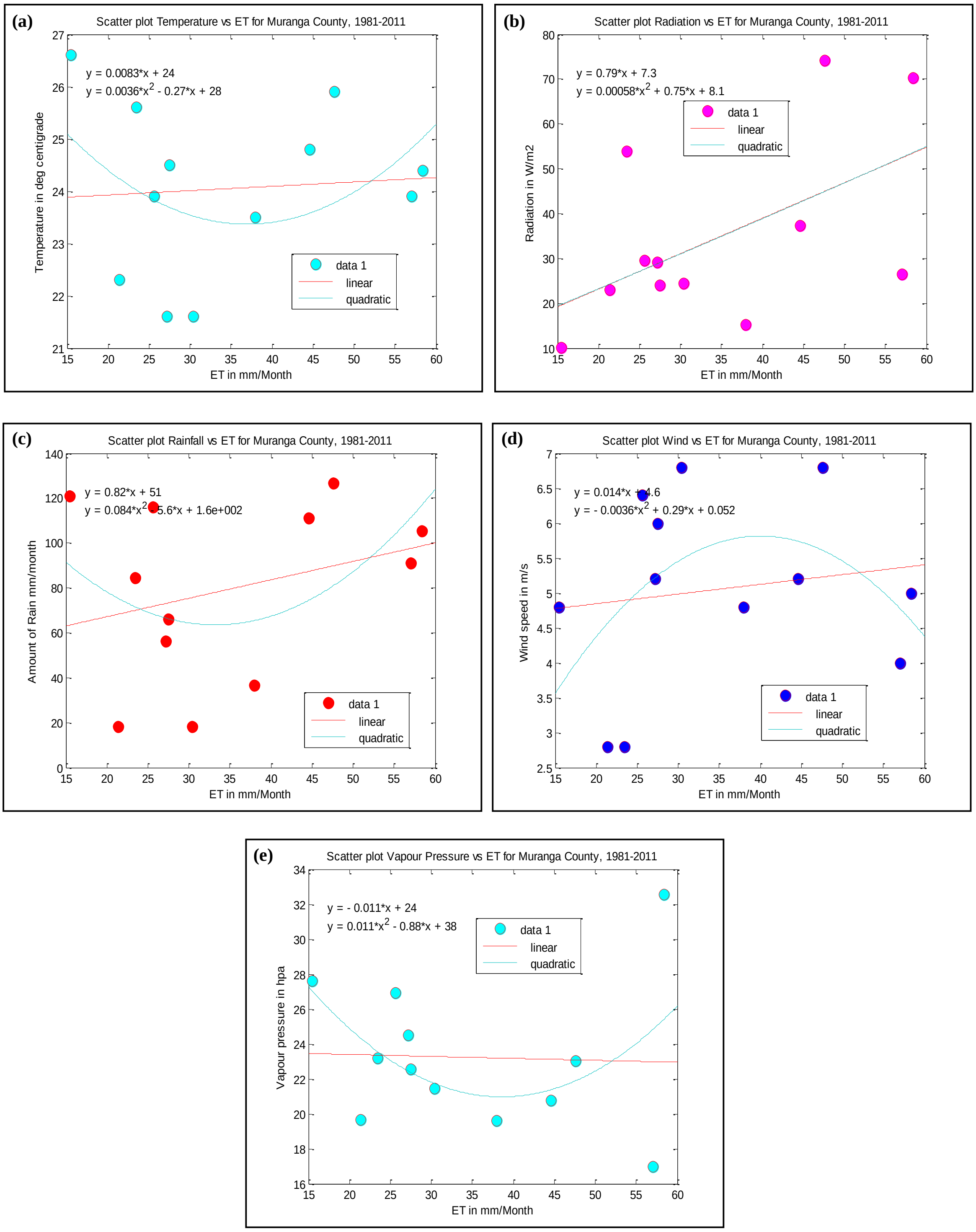

Figure 7: Scatter of average daily ET and **(a)** Temperature, **(b)** Radiation, **(c)** Rainfall, **(d)** Wind speed **(e)** Vapour pressure.

There is observed strong positive relationship between ET with radiation and rainfall at coefficients of 0.82 and 0.79 respectively (Figures 7b and c). The least relationship exists between ET and vapour pressure at negative 0.011 (Figure 7e). This implies that on the factors considered, rainfall and radiation play a key role on the variation of ET in Murang'a County. However, there are other factors beyond meteorological ones such as; type of soils, seasons, land use practices, crop type and cover that equally affect ET.

A sensitivity analysis was undertaken on the raw input data, one variable at a time, to test the effect of instrumental errors on the data set on the calculated ET. The instruments at the weather stations have the following levels of accuracy; temperature ± 0.2°C, vapour pressure ± 2%, radiation ± 5% and wind speed ± 0.1m/s. The calculation and measurements errors of the parameters translate to uncertainty in the estimated values of the ET, this was tested and summarised in Table 1.

Table 1: Accuracy levels in percentage depending on the changes in the drivers of ET in Murang'a, 1981 – 2011.

	Evapotranspiration as the other parameters change								
Month	Observed ET	ET@ T^1 +0.2	ET@ T-0.2	ET@ vp^2+2%	ET@ vp-2%	ET@ Rad^3+5%	ET@ Rad-5%	ET@ wind +0.1	ET@ wind -0.1
Jan	21.6	23.1	20.1	10.4	32.9	21.9	21.4	22.1	21.2
Feb	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
Mar	44.9	47.7	42.1	24.2	65.7	45.2	44.7	45.4	44.4
Apr	43.3	45.5	41.1	26.0	60.6	43.5	43.0	43.9	42.7
May	37.5	39.5	35.6	20.7	54.4	37.8	37.3	38.1	37.0
Jun	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4	21.4
Jul	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4	30.4
Aug	26.3	26.2	26.5	26.3	26.3	26.6	26.1	26.3	26.3
Sep	24.6	24.5	24.8	24.6	24.6	24.9	24.4	24.6	24.6
Oct	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4	58.4
Nov	56.1	57.8	54.4	41.4	70.8	56.3	55.8	57.0	55.1
Dec	26.7	29.2	24.2	7.3	46.1	27.0	26.4	27.0	26.4

T^1 –Observed temperature, vp^2 – Vapour pressure, Rad^3 – Radiation figures

The parameters have some uncertainty if they change but the greatest source of uncertainty is in the perturbed vapour pressure (Table 1). Although the vapour pressure has a weak direct relationship with ET (Figure. 7e), any change in vapour pressure greatly influences temperature. The vapor pressure varies with its temperature. This has implications in the future climate as studies show increasing trends of temperature over Kenya, particularly central Kenya where Murang'a is located (Funk et al., 2010). Figure 8 shows the three scenarios of observed, increased and reduced temperature.

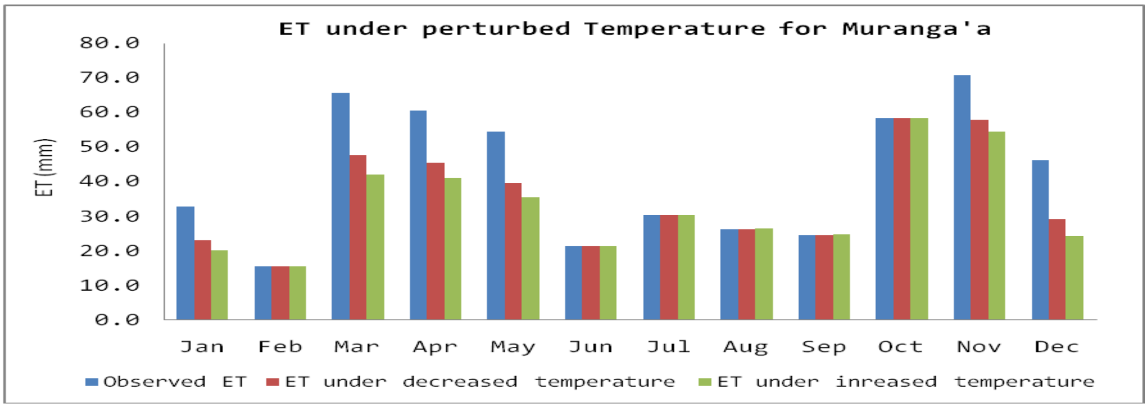

Figure 8: Evapotranspiration with perturbed temperature.

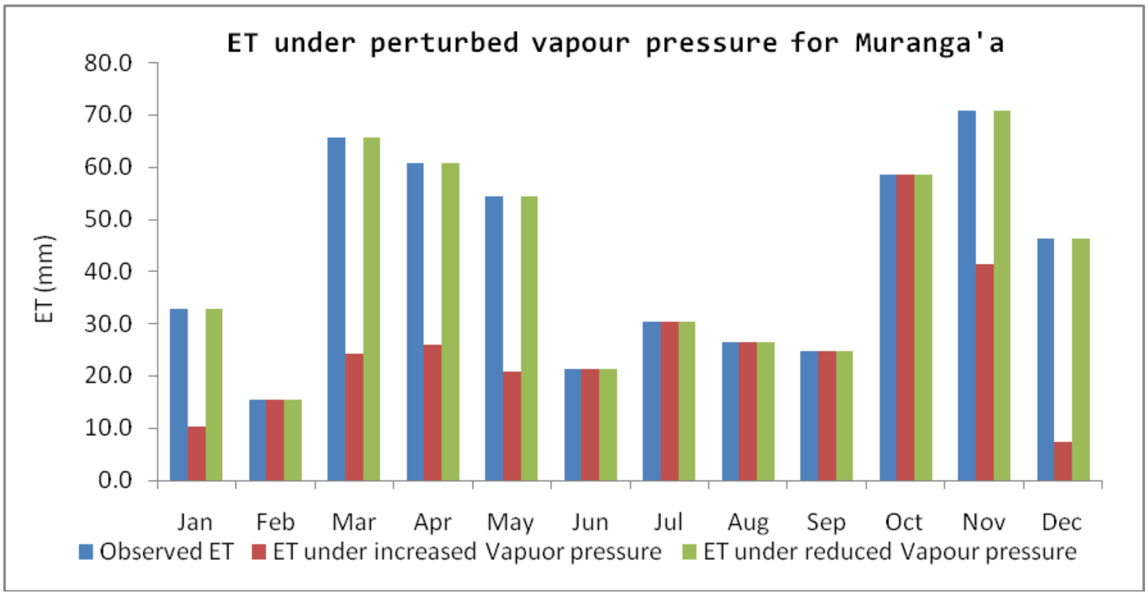

Figure 9: Evapotranspiration with perturbed vapour pressure.

There is observed decrease in ET under the two scenarios; increase and decrease in temperature as compared to the observed. The decrease in evapotranspiration in plants however reduces chances of plant stress, increasing its viability and consequently increase food production. Figure 9 shows the uncertainty in ET variation with vapour pressure.

An analysis of changing all the other parameters was undertaken and the results show the greatest uncertainty comes from vapour pressure and temperature as its deviations from the observed ET. An error of 3.4% was obtained for vapour pressure using equation 5.

Figure 10 presents the scenario produced using the three different models. Generally, the three models closely resemble the observed ET. From the month of April to June, the models show an increased ET.

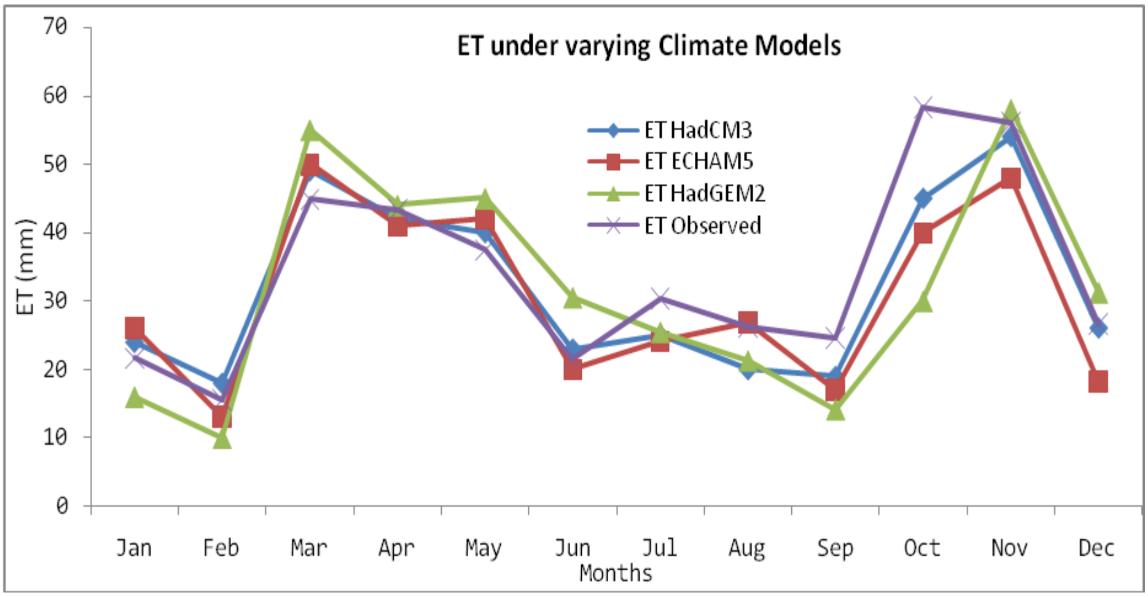

Figure 10: Mean monthly total ET for the 3climate models.

Increased ET due to increased temperatures means an increase in water vapour in the atmosphere, creating a feedback and slightly lowering the overall evaporation. The HadGEM2 shows both the highest increase and lowest decrease in the ET. Parameter uncertainty makes models to vary slightly giving a wide range of possibilities.

Conclusion and Recommendations

All the meteorological conditions vary in space and in time and hence the evapotranspiration. Evapotranspiration is higher in summers and the tropics, depending on the availability of moisture, provided by rainfall. Precipitation over Murang'a County is variable in space and time. The county experiences bimodal rainfall regime. Temperature and vapour pressure are observed to be the meteorological factors with significant impact of ET in the region. The increase in evaporation potential may increase crop stress, reducing crop production. The changes in ET are important in irrigation determination and control. This thus calls for intensive study on individual effect of each parameter on evapotranspiration. This is necessary for appropriate adjustment in the selection crops to plant in either of the rain seasons to maximize crop yield productivity since in future, country's ability to achieve sufficient food production may be greatly dependent on water management.

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