Performance of Two Temperature-Based Reference Evapotranspiration Models in the Mkoji Sub-Catchment in Tanzania

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ABSTRACT

The performance of two temperature-based empirical models for computing reference evapotranspiration (ETo): the Hargreaves (HG) and the Jensen-Haise (J-H) models, were evaluated for the three: Upper, Middle, and Lower zones of the Mkoji sub-catchment of the Great Ruaha River Basin in Tanzania. Climatic data from the Mbeya, Igurusi, and Kapunga weather stations, representing the Upper, Middle, and Lower Mkoji respectively, were used to compute daily ETo in accordance with the two temperature-based models. A third model: the FAO-Penman-Monteith (F-P-M) model was used as a reference model for assessing the performance of the temperature-based models. The F-P-M model was used as a reference because it has been recommended as a universal model for computing ETo. The daily ETo calculated based on the temperature-based models were compared statistically with those of the F-P-M model. The results showed that daily ETo of the HG and J-H models were significantly different from the F-P-M model at $P<0.05$ in the three zones. In the Upper Mkoji, the ETo based on the HG and J-H models were significant different ($P<0.01$) from the F-P-M model for each month of the year. The absolute mean difference between the daily ETo by the F-P-M and the HG models was 0.32 mm/day, and between the F-P-M and J-H model was 0.38 mm/day. In the Middle Mkoji, ETo based on the HG and J-H models were also significant different ($P<0.01$) from the F-P-M model for each month of the year. The mean difference between the F-P-M and HG was 0.62 mm/day, and 0.60 mm/day between the F-P-M and J-H. In the Lower Mkoji, the ETo of the HG and J-H were significant different ($P<0.01$) from the F-P-M in the months of December to August, but in the other months of the year, the temperature-based models were not significantly different from the F-P-M model. The mean difference between the daily ETo of the F-P-M and the HG model, and between the F-P-M and J-H model were: 0.50 mm/day, and 0.62 mm/day, respectively. The coefficients of determination (r^2) of the linear regression equations between the F-P-M and the HG models, and between the F-P-M and J-H models for the three zones of the sub-catchment were found to be good (> 0.80 in the Upper and Middle zone, and >0.60 in the Lower zone). The equations can therefore be used to convert daily ETo from the temperature-based models to their equivalent in the F-P-M model.

Keywords: Evapotranspiration models, temperature-based ET models, reference evapotranspiration, dry season, rainy season

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1. INTRODUCTION

Quantitative information on evapotranspiration (ET), the movement of water from a cropped area to the atmosphere, is vital for estimating crop water requirement, proper planning of irrigation scheduling, irrigation system design, hydrological and drainage studies. The importance of evapotranspiration data in both agricultural and hydrological fields may have simulated the development of several approaches to quantifying the parameter. These approaches range from direct measurement of ET to empirical models that use climatic data as input variables. While direct measurement of evapotranspiration is tedious, time consuming and expensive if daily records of evapotranspiration are required, the use of weather data to estimate daily evapotranspiration offers an easy and very reliable alternative.

ET estimated from climatic data are always regarded as 'potential' because they effect of the energy balance and aerodynamic factors which influences the rate at which water leaves a wet surface. The ET estimated from climatic data is considered to be equivalent to the rate at which water is removed from a well-watered reference crop (either grass or alfalfa). It is therefore termed reference evapotranspiration represented by the symbol 'ETo' when grass is the reference crop and 'ETr when alfalfa is the reference crop (Burman et al., 1980). There are different renditions of the definition of the reference crop in the literature (Doorenbos and Pruitt, 1977; Burman et al., 1980; Jensen et al., 1990). But notable is the Allen et al. (1998) definition, which described the reference crop as a hypothetical crop with an assumed height of 0.12 m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling the evaporation from an extensive surface of green grass of uniform height, actively growing and adequately watered.

There are numerous models for estimating ETo. ETo models are generally classified according to the weather parameters that play the dominant role in the model. The generally classification include: the temperature-based models (e.g., Thornthwaite (1948); Blaney-Criddle (1950); Hargreaves and Samani (1985)); the mass-transfer models (based of vapour pressure or relative humidity, e.g., Rohwer (1931); Harbeck (1962)); the radiation models (based on solar radiation, e.g., Priestly-Taylor (1972), Makkink (1957)), and the combination models (based on the energy balance and mass transfer principles, e.g., the Penman (1948), modified Penman (Doorenbos and Puritt, 1977), and FAO-Penman-Montieth (Allen et al., 1998)).

The temperature-based ETo models are some of the earliest methods for estimating ET (Xu and Singh, 2002). According to Jensen et al. (1990), the relation of ET to air temperature dated back to the 1920s. Even today, the relations are still very attractive methods of estimating ETo because in many areas, especially in sub-Saharan African, air temperature data are more readily available compared to other weather data such as solar radiation; sunshine hours; relative humidity and wind speeds which are required by models of the other groups. Moreover, in places where the data for this other weather variables exist, they are always with wide range of missing data, making computation of daily ETo with those models difficult. For example, in the Mkoji sub-catchment of the Great Ruaha River Basin, though there are limited weather stations within and around the catchment (e.g., the Mbeya, The

Ministry of Agriculture Training Institute (MATI)-Uyole, MATI-Igurusi, Kapunga Rice farm, Mbarali weather stations), the commonest and most consistent records of weather parameters from these stations are the maximum and minimum air temperatures and rainfall. Although other data like wind speed, relative humidity or solar radiation are collected in some of the stations, they are always characterized by missing data ranging from few days in a month to several years in many of the stations.

Temperature-based model are simple to use and economical as they require less time and effort to apply them. There are list of temperature-based model, but Allen et al (1998) recommended the Hargreaves- Samani model (called the Hargreaves model) as the model that should be used to calculate ETo when only air temperatures data are available for computing ETo. Another temperature-based model that has been reported to be very convenient to use (James, 1988) and has better performance rating for semi-arid and arid conditions is the Jensen-Haise (1963) model (Hansen et al. 1979). The Jensen-Haise model was classified as a solar radiation model (e.g., Burman et al., 1980; Jensen et al., 1990). But air temperature plays a dominant role in the model expression. Therefore it can also be regarded as a temperature-based model. The Jensen-Haise model was formulated from 3000 measurements of evapotranspiration made over 35 years period from 20 locations in western United States (James, 1988).

Temperature-based models have some limitations in terms of the extent of use. According to James (1988), temperature based models are not as accurate as the Penman-type equations (the combination models) for period of less than 5 days. The American Society of Civil Engineers (ASCE) Irrigation Water Requirement Committee recommended the use of the Jensen-Haise method for estimating ETo for periods of 5 days to a month (Burman et al., 1980). The shortfall in accuracy if temperature-based models are used to compute daily ETo can be overcome if a simple conversion relationship is establishing between the daily ETo of the temperature-based models and the Penman-type models for the location in question. The work reported herein is aimed at comparing daily ETo computed using the Hargreaves and the Jensen-Haise models with those from the FAO-Penman-Monteith (F-P-M) model for the Mkoji sub-catchment, and to develop simple regression functions that can be used to convert daily ETo from the temperature-based models to its equivalent based on the F-P-M model.

1.1. Description of the Study Area

The Mkoji sub-catchment lies between latitudes $7^0$48’ and $9^0$25’ South, and longitudes $33^0$40’ and $34^0$09’ East. It is a sub-catchment of the Great Ruaha River Basin, which is one of the four sub-basins of the largest and most prolific river basin in Tanzania - the Rufiji River Basin. The Mkoji sub-catchment covers an area of about 3400 km². Most of the catchment lies within Mbarali and Mbeya Rural districts, while smaller portions of the catchment lies within the Makete and Chunya districts in Iringa and Mbeya Regions, respectively. The sub-catchment was divided into three major zones based on topography, water resources availability and agricultural domain of the catchment by SWMRG (2004) as shown in Figure 1.

1.1.1. Zone A: Upper Zone (the highlands)

This zone lies in the Southwest highlands of Poroto and Chunya, with elevations rising from 1150m to over 2400m above sea level. The Poroto and Chunya escarpment forms the sources and tributaries of most of the major rivers in the Mkoji sub-catchment. Average annual rainfall in the zone is about 1070 mm. The rainy season is between the early November and early May. The extensive rainfall pattern in the zone and the type of soils allows for crop cultivation all year around.

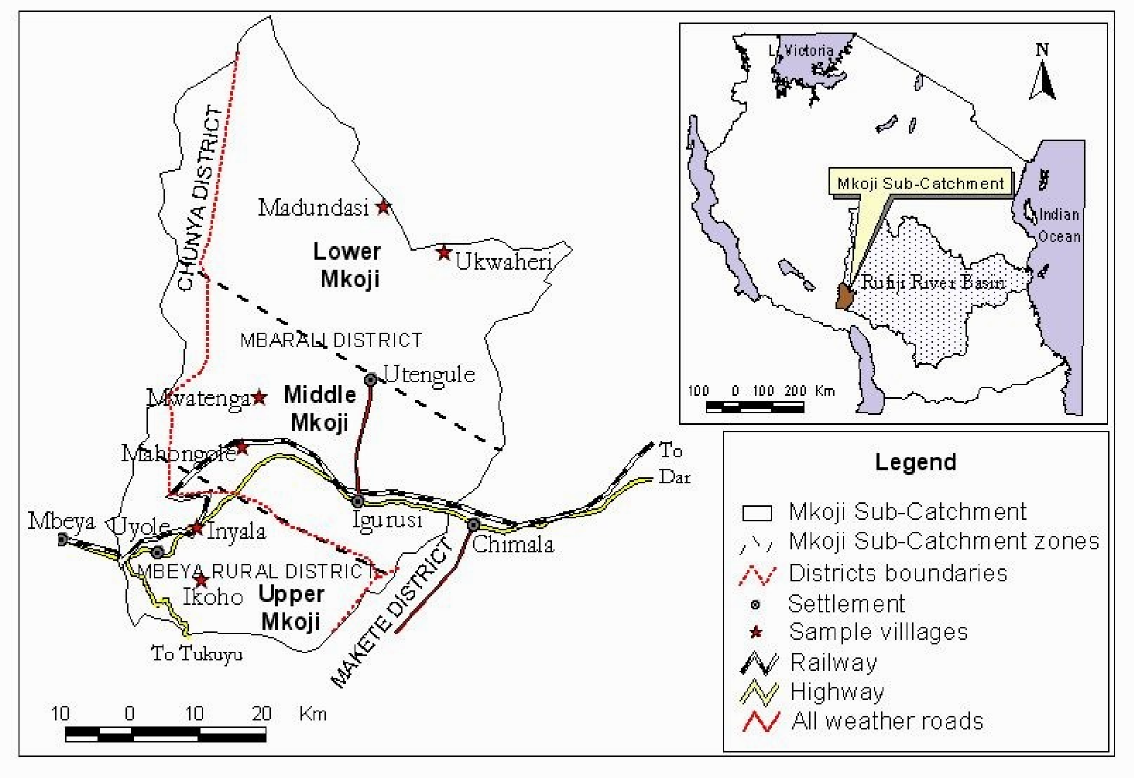


Figure 1. A map of Mkoji sub-catchment showing the Zones. Source: SWMRG (2004)

1.1.2. Zone B: Intermediate (Middle) Zone

This zone consists of the transitions between the highlands and the flat plains of Usangu. The average altitude of the zone is 1100m above sea level. The mean annual rainfall is about 800 mm. The rainy season is between the third decade of November and April. The zone is characterized by perennial and seasonal streams and rivers, which resulted from the runoff from the Poroto Mountains. The perennial water flows in the zone has led to a high concentration of irrigation schemes, both traditional as well as improved traditional irrigation systems.

1.1.3. Zone C: Lower Zone (the plains)

This zone is basically semi-arid, with a mean altitude of about 900m above sea level. The mean annual rainfall is about 520mm. The rainy season is between the third decade of

December and the first decade of April with frequently occurring dry spells of one to two weeks in the month of February and early March in the zone.

2. MATERIALS AND METHODS

2.1. The Reference Evapotranspiration Models

Only the main equations of the Hargreaves, Jensen-Haise, and the FAO-Penman-Monteith models are presented in this section. The detailed equations of the sub-units of the models may be found in the related references.

2.1.1. Hargreaves Models

The Hargreaves model as presented by Allen et al (1998) is given as:

$$ETo = 0.0023 * \left(T_{mean} + 17.8\right) * \left(T_{\max} - T_{\min}\right)^{0.5} * R_a \qquad (1)$$

Where:
ETo = reference evapotranspiration in MJ m^{-2} d^{-1},
T_{mean} = average air temperature expressed as: $T_{mean} = \dfrac{T_{\max} + T_{\min}}{2}$
T_{max} = maximum air temperature in ^{o}C;
T_{min}= Minimum air temperature in ^{o}C,
R_a= extraterrestrial radiation in MJ m^{-2} d^{-1}

ETo is converted to mm/day by a conversion factor of 0.408.

2.1.2. Jensen-Haise Model

The Jensen-Haise model for calculating grass reference evapotranspiration as described by James (1988) is given as:

$$ETo = C_T \left(T_{mean} - T_x\right) * R_a \qquad (2)$$

T_x and C_T are constants obtained as:

$$C_T = \frac{1}{\left[\left(45 - \dfrac{h}{137}\right) + \left(\dfrac{365}{es_{\max} - es_{mun}}\right)\right]} \qquad (3)$$

$$T_x = -2.5 - 0.14 * \left(es_{\max} - es_{\min}\right) - \frac{h}{500} \qquad (4)$$

Where: Rs is solar radiation (MJ m^{-2} d^{-1}); ‘h’ is altitude of the location (m); es_{max} and es_{min} are vapour pressures of the month with the mean maximum temperature and the month with the mean minimum temperature, respectively, expressed in mbar, ETo and T_{mean} is as previously defined.

The es_{max} or es_{min} is expressed as:

$$es_i = EXP\left[\frac{19.08 * T_i + 429.41}{T_i + 237.3}\right] \qquad (5)$$

Where: T is air temperature, and ‘i’ represents maximum or the minimum term.

Solar radiation (R_s) is estimated from air temperature data using the equation (Allen et al., 1998):

$$R_s = K_{RS} * \left(T_{max} - T_{min}\right)^{0.5} * R_a \qquad (6)$$

Where: K_{Rs} is an empirical adjustment coefficient in the range of 0.16 to 0.19. 0.16 was recommended for interior locations where land mass dominates and air masses are not strongly influenced by a large water body, and 0.19 for coastal locations, situated on or adjacent to the coast of a large land mass and where air masses are influenced by a nearby water body (Allen et al., 1998). Other parameters in Eq.6 are as previously defined.

2.1.3. FAO-Penman-Monteith Model

The FAO Penman-Monteith (F-P-M) model as described by Allen et al. (1988) is given as:

$$ETo = \frac{0.408 * \Delta * \left(R_n - G\right) + \gamma * \left(\frac{900}{T + 273}\right) * U_2 * \left(e_s - e_a\right)}{\Delta + \gamma * \left(1 + 0.34 * U_2\right)} \qquad (7)$$

Where: ETo = Reference evapotranspiration (mm/day)
R_n = Net radiation at the crop surface (MJ m^{-2} d^{-1}),
G = Soil heat flux density (MJ m^{-2} d^{-1}),
T_{mean}= Mean air temperature at 2 m height (^oC),
U_2 = Wind speed at 2 m height (ms^{-1}),
es= Saturated vapour pressure (kPa),
ea = Actual vapour pressure (kPa),
(es-ea) = Saturated vapour pressure deficit (kPa),
Δ = Slope vapour pressure curve (kPa $^oC^{-1}$)
γ = Psychometric constant (kPa $^oC^{-1}$)

The F-P-M model requires air temperature, solar radiation (or sunshine hour), relative humidity, and wind speed data as input data. Where relative humidity, solar radiation or sunshine hours data are not available, Allen et al. (1998) gave details of how to go around the computation of ETo, estimating the data of the missing parameters from the available ones. For example, solar radiation and vapour pressure deficits can be estimated from air temperature differences. Therefore, the compulsory weather parameters that are required for calculating ETo using the F-P-M model are the maximum and minimum air temperatures and wind speed. When wind speed data are missing, Allen et al (1998) suggested that wind speed can be imported from a nearby station relying on the fact that air flow above a ‘homogenous’ region may have relatively large variations through the course of a day but small variations when referring to longer periods or the total for the day. So data from a nearby station where the air masses are of the same origin or where the same fronts govern air flow in the region and where the relief is similar can be used

2.2. Computing Daily Reference Evapotranspiration

Historical climatic data were obtained from the databanks of three weather stations: Mbeya, Igurusi, and Kapunga weather stations. The weather stations were under the management of the Tanzanian Meteorological Agency. Air temperatures were measured using thermometers kept in Stevenson screen at 2 m above ground surface. Wind speeds were also recorded at 2 m above ground surface. The Daily weather data for 16 years (1975-1990) from the Mbeya meteorological station were used to calculate daily ETo according to the Hargreaves, Jensen-Haise, and FAO-Penman-Monteith models for the Upper Mkoji sub-catchment. These years were considered because the weather parameters records for the station at these periods were consistent and sufficient for the F-P-M model. The weather parameters used were maximum and minimum air temperatures, wind speed and sunshine hour only. As a result of wide gaps in the relative humidity data, vapour pressure deficits were not computed from relative humidity data but from air-temperatures as recommended by Allen et al (1998) in the F-P-M model. The altitude of the meteorological station is 1707m above mean sea level.

Weather data for a period of 10 years (1984-1993) in the Igurusi weather station was used to calculate daily ETo for the middle zone of the sub-catchment Mkoji. The altitude of the meteorological station is 1100m above sea level. Weather parameters used in calculating ETo included maximum and minimum air temperatures, maximum relative humidity, wind speed and sunshine hours. There were no records of weather data before this period, and the data thereafter were not consistent and sufficient for the models under considerations. In the lower Mkoji, daily weather data for only a period of five years (1993-1997) in the Kapunga weather station, were consistent and sufficient were used to compute daily ETo. The altitude of the weather station is 1052m above sea level. The data from theses three weather stations: Mbeya, Igurusi, and Kapunga, were used to represent the three zones of the sub-catchment, respectively, in accordance with SWMRG (2004).

2.3. Method of Analysis of Results

ETo for the three models were first calculated for each day of the month for the years of data considered. The daily ETo values under each model were added together across the years to obtain an average for each day of the month. Then a statistical pair-test was used to compare the daily ETo for each month of the year for the three models. A comparison was made first between the ETo values of the two temperature-based models (Hargreaves and Jensen-Haise), and then a comparison was made between the pair of the temperature-based model and the FAO-Penman-Moneith model which was been used as a reference. Finally, a pair-test of the daily ETo for the entire year was also carried out between the pairs of models. A careful observation of the daily ETo for the year was made, and it was noticed that one linear expression could be fitted between the ETo of the F-P-M and HG, and between the F-P-M and J-H ETo data for the entire year in the middle and lower zones of the sub-catchment. But for the upper zone, separate linear expressions were used to fit the ETo data for the rainy season and the dry season, respectively.

3. RESULTS AND DISCUSSION

3.1. Trend of Weather Data

Tables 1, 2, and 3 show the monthly average of the weather data used for the calculation of ETo, for the three zones of the Mkoji sub-catchment, respectively. The maximum ambient temperature for the upper Mkoji varies from about 21°C during the cold-dry months of June and July to about 26°C in the warm-dry months of October and November. The maximum temperatures of the middle and lower zones are relatively the same, but the minimum temperatures of the cold-dry months (June and July) are slightly lower in the middle zone than the lower zone. The general pattern of the weather data is a reflection of the gradient in altitude from the upper to the lower zone. The average temperatures of the upper zone with higher altitude where lower than the middle and lower zones by about 30% in the cold-dry months (May to August) and about 20% for the other months of the year.

The sunshine hours for the three zones in the catchment were relatively the same, varying for about 5 h/day to about 10 h/day. The lower values in the range occur in the rainy seasons, and the higher values occur in the dry seasons. The wind speeds in the upper zone were higher compared to the middle and the lower zones. The difference may be attributed to difference in altitude. Wind speeds in the upper zone were about 20 –30% higher than the middle and lower zones during the months that precede the onset of rains (October and November), and increased to between 50 and 70% during the rain and the cold-dry months of December to May.

Table 1: Monthly mean of weather data of the Upper Mkoji sub-catchment

Average of 16 years data (1975-1990) from the Mbeya Weather Station

Month	Max. Temp (°C)	Min. Temp (°C)	Wind Speed (m/sec)	Sun shine (hr)
Jan	23.1	13.9	1.8	4.4
Feb	23.5	13.7	1.8	5.1
Mar	23.7	13.5	1.8	5.2
Apr	23.1	12.4	2.0	6.7
May	22.3	9.3	2.4	8.5
Jun	21.5	5.7	2.6	10.0
Jul	21.8	5.0	2.9	10.2
Aug	23.1	7.0	3.2	10.0
Sep	25.4	9.6	3.4	9.4
Oct	26.6	12.5	3.6	8.5
Nov	26.1	13.3	3.1	7.3
Dec	23.9	13.9	2.3	5.1

Table 2: Monthly mean of weather data of the middle Mkoji sub-catchment

Average of 10 years data (1984-1993) from the Igurusi Weather Station					
	Max. Temp (°C)	Min. Temp (°C)	Max. Rel. humidity (%)	Wind speed (m/sec)	Sun Shine (hr)
Jan	27.5	17.6	79.9	0.9	4.9
Feb	27.7	17.8	81.0	0.7	5.3
Mar	28.0	17.4	81.2	0.8	5.9
Apr	28.1	16.6	78.6	0.8	7.0
May	26.8	15.9	72.4	0.9	8.1
Jun	27.6	12.1	68.5	1.0	9.4
Jul	26.8	10.7	61.1	1.1	9.3
Aug	28.3	12.2	60.0	1.3	9.0
Sep	30.0	13.3	59.6	1.4	8.5
Oct	31.2	15.6	57.6	1.4	7.1
Nov	31.2	17.0	58.9	1.3	6.7
Dec	29.8	18.5	70.1	1.0	6.1

Table 3: Monthly mean of weather data of the lower Mkoji sub-catchment

Average of 5 years data (1993-1997) from the Kapunga Weather Station				
	Max. Temp (°C)	Min. Temp (°C)	Wind speed m/sec)	Sun Shine (hr)
Jan	28.2	17.8	0.9	5.7
Feb	28.2	17.6	0.6	4.8
Mar	28.4	17.5	0.8	7.6
Apr	28.3	16.9	0.9	8.1
May	28.0	15.3	1.0	8.9
Jun	27.0	13.6	1.1	9.3
Jul	26.7	13.3	1.4	10.1
Aug	27.4	14.4	1.8	9.9
Sep	29.2	16.4	1.9	9.8
Oct	31.0	18.3	2.5	9.7
Nov	31.1	19.1	2.5	9.5
Dec	29.5	18.5	1.8	8.9

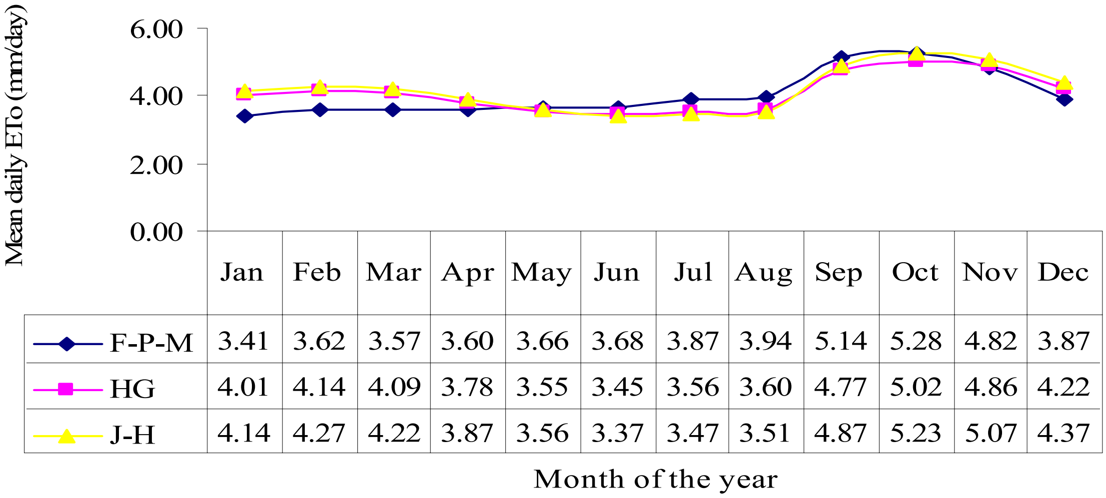
3.2. Reference Evapotranspiration (ETo)

The results of the computed ETo are discussed separately for each zone.

3.2.1. Upper Zone

Figure 2 presents the mean daily ETo for the upper zone of the Mkoji sub-catchment based on the Hargreaves (HG), Jensen-Haise (J-H), and the FAO-Penman-Moneith (F-P-M) models. The trend shows a similar pattern for the three models. However, the ETo values of the temperature-based models were higher than the F-P-M models during the months of rainfall (November to April), and lower during the cold-dry (May to July) and warm-dry months (August to October) of the year. Using the F-P-M model as a reference, the temperature-based models over-estimated ETo during the rainy season, but underestimate ETo during the dry season in the upper zone of the sub-catchment. The temperature-based models underestimated ETo during the dry season because they not capture the influence of wind on evaporation. The high wind speeds recorded during the dry season should largely influence evaporation.

The pair-comparison of the models performance for each month of the year showed that the ETo values by the Hargreaves models were not significantly different ($P<0.05$) from the Jensen-Haise. But the Hargreaves versus F-P-M, and Jensen-Haise versus F-P-M were found to be highly significant different ($P<0.01$) in each month of the year. The absolute mean difference between the daily ETo by the F-P-M and the HG models and between the F-P-M and J-H model was 0.32 and 0.38 mm/day, respectively, while the absolute difference in mean between HG and J-H model was 0.02 mm/day.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ F-P-M	3.41	3.62	3.57	3.60	3.66	3.68	3.87	3.94	5.14	5.28	4.82	3.87
■ HG	4.01	4.14	4.09	3.78	3.55	3.45	3.56	3.60	4.77	5.02	4.86	4.22
▲ J-H	4.14	4.27	4.22	3.87	3.56	3.37	3.47	3.51	4.87	5.23	5.07	4.37

Figure 2. Mean daily ETo for Upper Mkoji Sub-catchment

Figures 3a and 3b show the linear relationship between the ETo of the F-P-M and HG models, and the F-P-M and J-H models, respectively for the rainy season; and Figs. 4a and 4b show the relationship between the ETo of the F-P-M and HG models, and the F-P-M and J-H models, respectively, during the dry season. The regression of the relationship between the F-P-M and HG models in the rainy season was obtained as:

$$FPM = 1.1952 * HG - 1.2171 \qquad r^2 = 0.8009;$$

And the regression of the relationship between the F-P-M and J-H models for the rainy season was obtained as:

$$FPM = 1.0937 * JH - 0.9454 \qquad r^2 = 0.7983$$

The regression of the relationship between the F-P-M and HG models in the dry season was also obtained as:

$$FPM = 0.981 * HG + 0.3159 \qquad r^2 = 0.9517;$$

and the regression of the relationship between the F-P-M and J-H models for the dry season was:

$$FPM = 0.8404 * JH + 0.8715 \qquad r^2 = 0.933$$

The coefficients of determination (r^2) for each pair of relationship were good (> 0.75). The dry season is characterized by two distinct phases of cold and warm periods. Hence ETo values during the dry season formed two separate clusters at the lower and upper ends of Figs.4a and 4b. The clusters at the lower ends of the figures are values of ETo for the cold period of the dry season (May to July) while the clusters at the upper end of the figures are the ETo values for the warm period of the dry season (August to October).

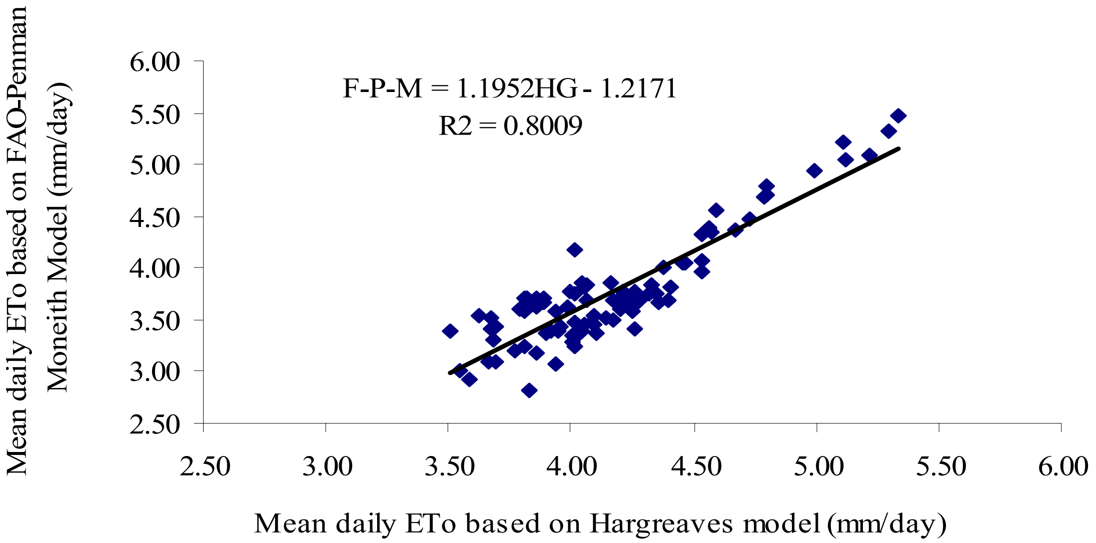


Figure 3a. Relationship between FAO-Penman-Monteith and Hargreaves models for the rainy season in Upper Mkoji sub-catchment

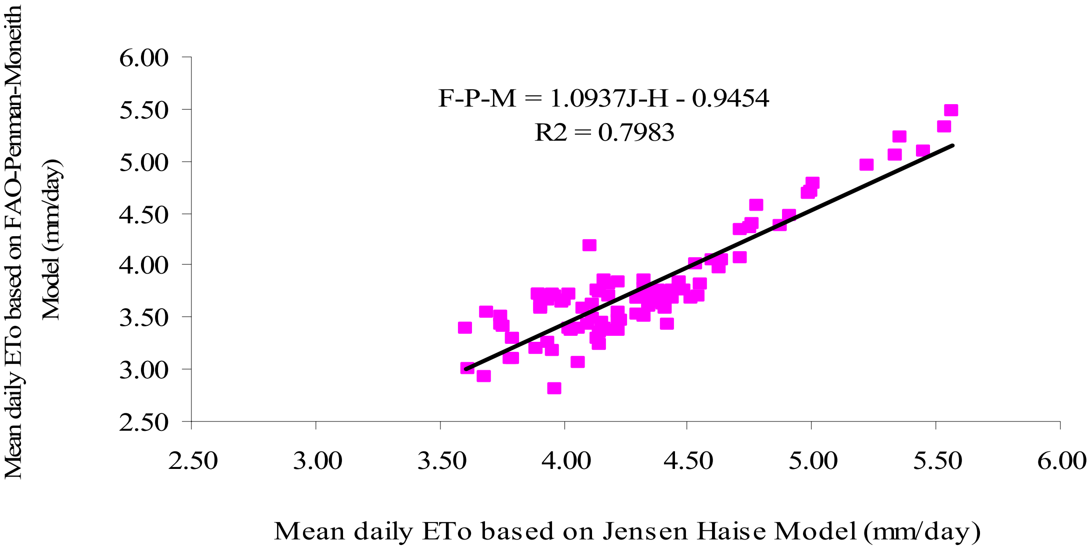


Figure 3b. Relationship between FAO-Penman-Monteith (F-P-M) and Jensen-Haise (J-H) models for the rainy season in Upper Mkoji sub-catchment

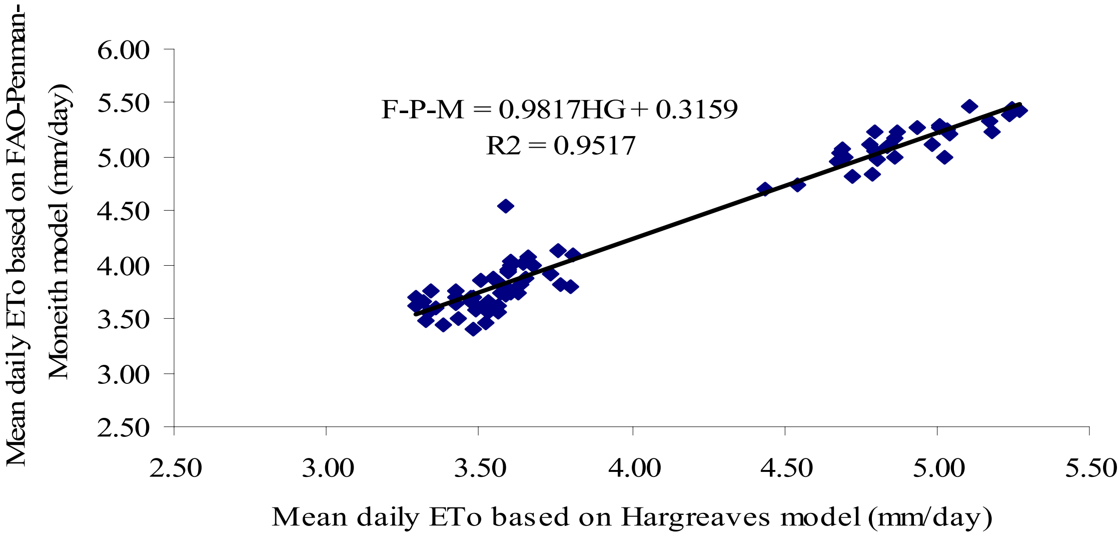


Figure 4a. Relationship between FAO-Penman-Monteith (F-P-M) and Hargreaves (HG) models for the dry season in Upper Mkoji sub-catchment

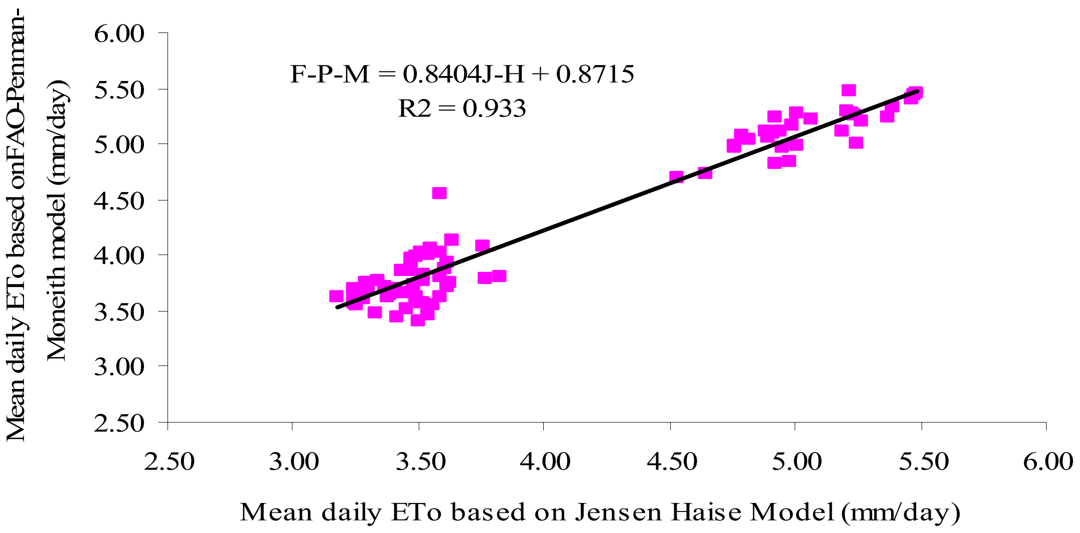


Figure 4b. Relationship between FAO-Penman-Monteith (F-P-M) and Jensen-Haise (J-H) models for the dry season in Upper Mkoji sub-catchment

3.2.2. Middle Zone

The trends of mean ETo for the middle zone of the Mkoji sub-catchment are presented in Fig. 5. The trend pattern was the same for the three models. However, the temperature-based models overestimated ETo with reference to the F-P-M model in all the months of the year. The comparison of the models showed that for all the months of the year, the ETo values of the HG and the J-H models were highly significantly different ($P<0.01$) from the FPM models. But the ETo of the HG versus J-H models were not significantly different. The absolute mean difference between the F-P-M and HG models, and between the F-P-M and J-H models was 0.62 mm/day and 0.60 mm/day, respectively. The absolute mean difference between the HG and J-H model was 0.05 mm/day.

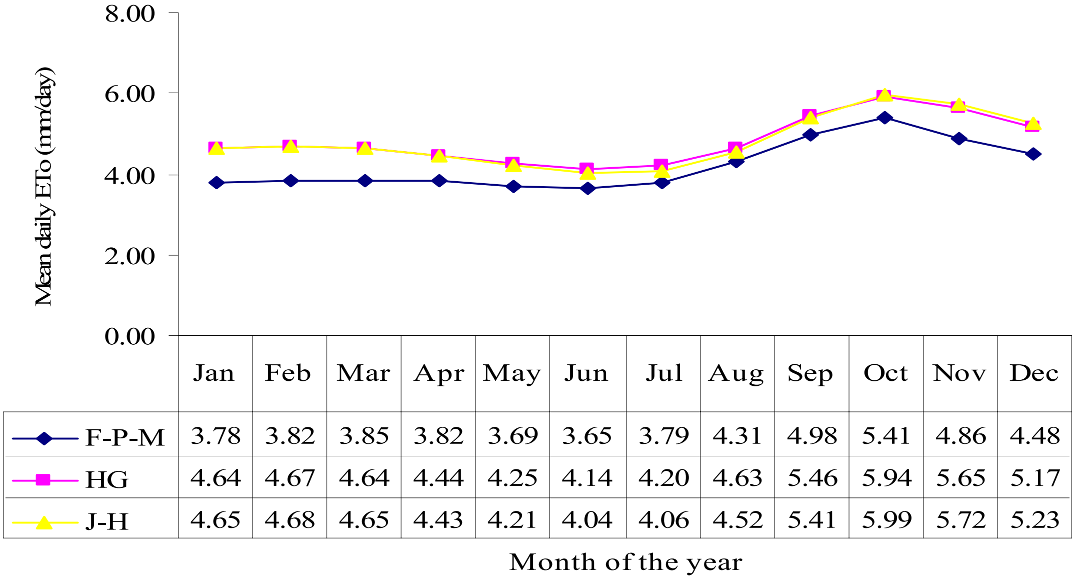
Figures 6a and 6b shows the linear relationships between the F-P-M and HG models, and the F-P-M and J-H models respectively. The trend of the ETo values for both the wet and dry seasons did not necessitate splitting the year into two seasons, hence only one regression equation was used to define the relationship between models for the wet and dry seasons in the middle zone of the sub-catchment. The regression of the relationship between the F-P-M and HG models was obtained as:

$$FPM = 0.964 * HG - 0.4306 \qquad r^2 = 0.846;$$

While the regression of the relationship between the F-P-M and J-H model was obtained as:

$$FPM = 0.880 * JH - 0.0088 \qquad r^2 = 0.8177$$

The coefficients of determination for both regressions were good. The regressions equations can be use to covert the temperature-based models ETo to their equivalent in F-P-M.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ F-P-M	3.78	3.82	3.85	3.82	3.69	3.65	3.79	4.31	4.98	5.41	4.86	4.48
■ HG	4.64	4.67	4.64	4.44	4.25	4.14	4.20	4.63	5.46	5.94	5.65	5.17
▲ J-H	4.65	4.68	4.65	4.43	4.21	4.04	4.06	4.52	5.41	5.99	5.72	5.23

Figure 5. Mean daily ETo for Middle Mkoji Sub-catchment

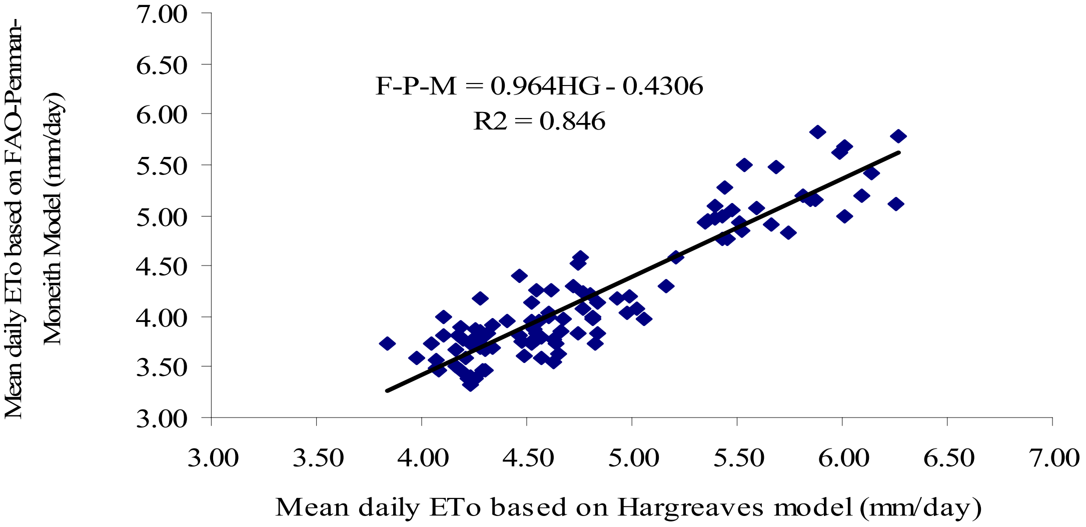


Figure 6a. Relationship between FAO-Penman-Monteith (F-P-M) and Hargreaves (HG) models for the year in Upper Mkoji sub-catchment

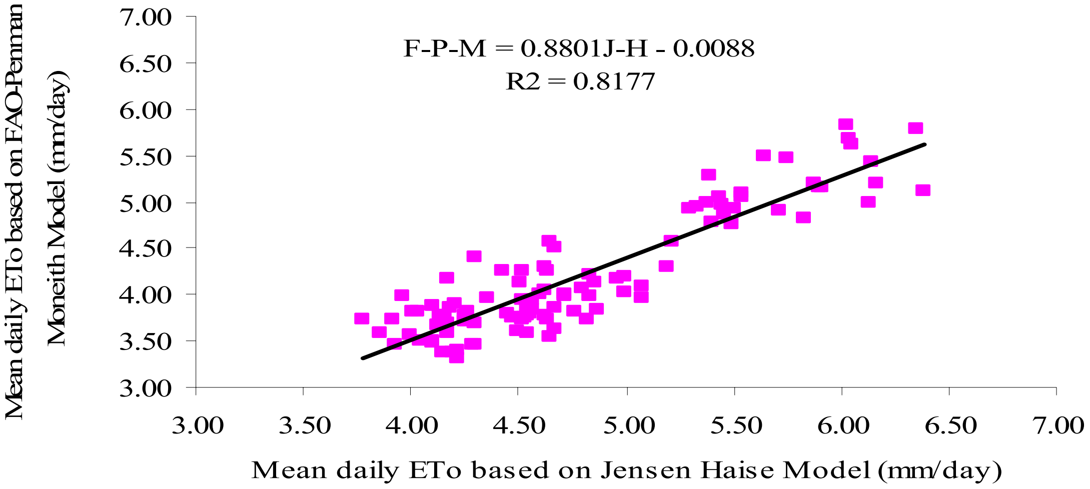


Figure 6b. Relationship between FAO-Penman-Monteith (F-P-M) and Jensen-Haise (J-H) models for the rainy season in Upper Mkoji sub-catchment

3.2.3. Lower Zone

Figure 7 shows the trends of mean ETo for the lower zone of the Mkoji sub-catchment. The ETo trends for the three models were similar. The temperature-based models overestimated ETo (with reference to the F-P-M model) only from January to August. The daily ETo of the HG and J-H were highly significantly different from the F-P-M in those months. ETo values from September to December were not significantly different among the three models. The absolute mean difference between the daily ETo of the F-P-M and the HG models, the F-P-M and J-H models, and the HG and J-H models were: 0.50, 0.62, and 0.19 mm/day, respectively.

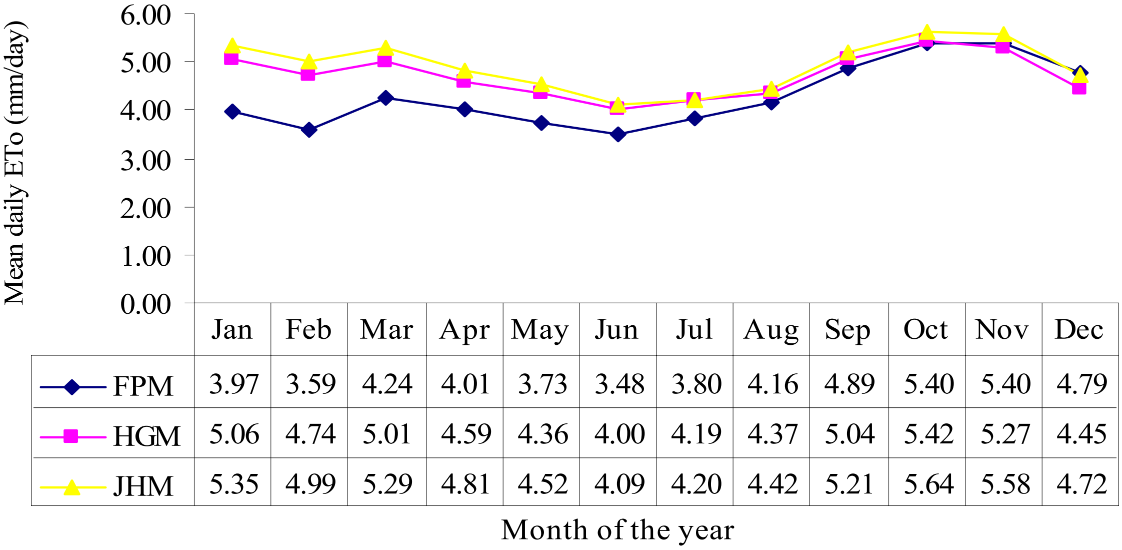
Figures 8a and 8b show the linear relationship between the F-P-M and HG models, and the F-P-M and J-H models, respectively for the lower zone. The regression of the relationship between the F-P-M and HG models was obtained as:

$$FPM = 0.9092 * HG - 0.0027 \qquad r^2 = 0.686;$$

While the regression of the relationship between the F-P-M and J-H model was obtained as:

$$FPM = 0.7501 * JH + 0.6213 \qquad r^2 = 0.6329$$

The coefficients of determination for both regressions were fair ($r^2>0.6$). The lack of a good fit between the temperature-based models and the reference F-P-M may be due to the fewer number of years of data analysed for the zone. However, the regression equations can still be used to convert temperature-based models ETo values to their equivalent in F-P-M.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
◆ FPM	3.97	3.59	4.24	4.01	3.73	3.48	3.80	4.16	4.89	5.40	5.40	4.79
■ HGM	5.06	4.74	5.01	4.59	4.36	4.00	4.19	4.37	5.04	5.42	5.27	4.45
▲ JHM	5.35	4.99	5.29	4.81	4.52	4.09	4.20	4.42	5.21	5.64	5.58	4.72

Figure 7. Mean daily ETo for Lower Mkoji Sub-catchment

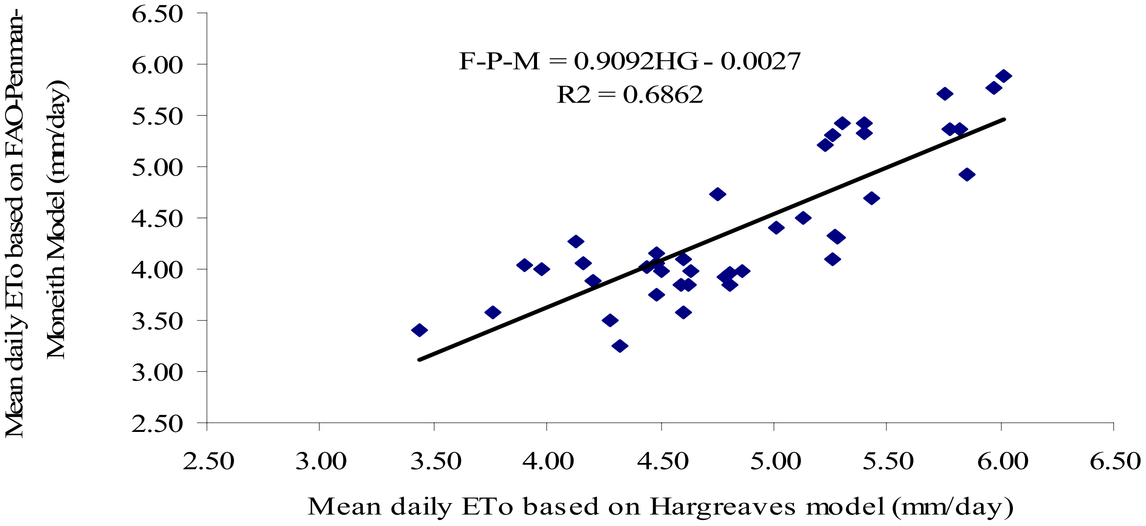


Figure 8a. Relationship between FAO-Penman-Monteith and Hargreaves models for the year in Lower Mkoji sub-catchment

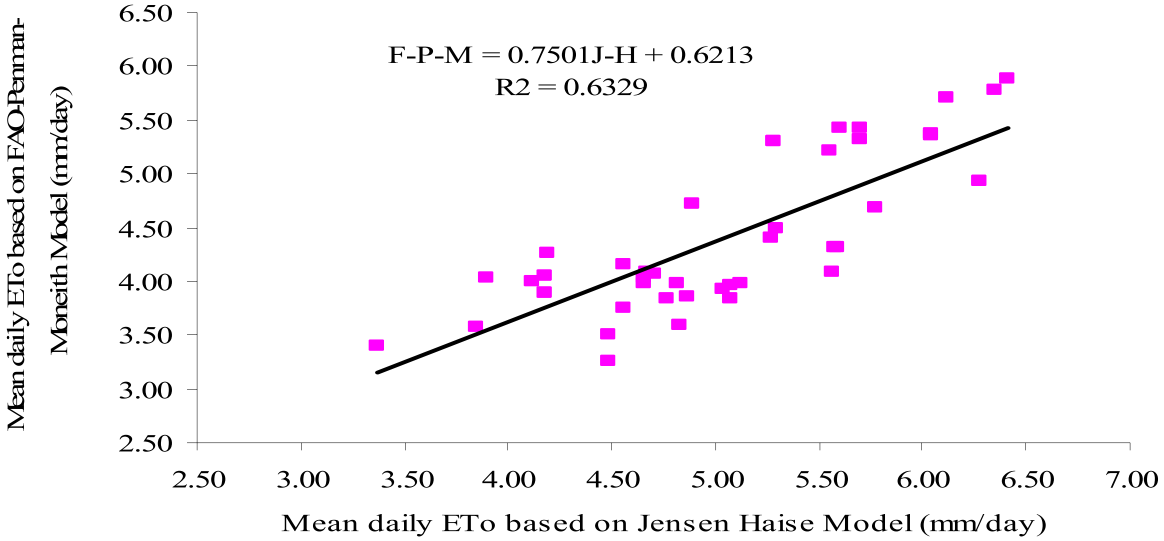


Figure 8b. Relationship between FAO-Penman-Monteith and Jensen-Haise models for the rainy season in Upper Mkoji sub-catchment

4. CONCLUSION

The performance of two temperature-based empirical models for computing reference evapotranspiration (ETo): the Hargreaves (HG) and the Jensen-Haise (J-H) models have been evaluated for the three: Upper, Middle, and Lower zones of the Mkoji sub-catchment of the Great Ruaha River Basin in Tanzania. The daily ETo estimated using the HG and J-H models were significantly different from the F-P-M model ($P< 0.05$) in the three zones of the catchment. In the Upper Mkoji, the ETo based on the HG and J-H models were significantly different ($P<0.01$) from the F-P-M model for each month of the year. In the Middle Mkoji, ETo based on the HG and J-H models were also significantly different ($P<0.01$) from the F-P-M model for each month of the year. In the Lower Mkoji, the ETo of the HG and J-H were significant different ($P<0.01$) from the F-P-M in the months of December to August, but in the other months of the year, the temperature-based models were not significantly different from the F-P-M model. The coefficients of determination (r^2) of the linear regression equations between the F-P-M and the HG models, and between the F-P-M and J-H models for the three zones of the sub-catchment were found to be good (> 0.80 in the Upper and Middle zone, and >0.60 in the Lower zone). The equations can therefore be used to convert daily ETo from the temperature-based models to their equivalent in the F-P-M model.

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