Palmer-type soil modelling for evapotranspiration in different climatic regions of Kenya

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Abstract

Reference evapotranspiration (ET_0) and real evapotranspiration (ET) are vital components in hydrological processes and climate-related studies. Understanding their variability in estimation is equally crucial for micrometeorology and agricultural planning processes. The primary goal of this study was to analyze and compare estimates of (ET_0) and (ET) from two different climatic regions of Kenya using long-term quality controlled synoptic station datasets from 2000 to 2009 with 3-hour time resolution. One weather station (Voi, 63793) was sought from lowlands with an elevation of 579 m and characterized by tropical savannah climate while the other (Kitale, 63661) was sought from Kenya highlands with humid conditions and elevation of 1850 m above sea level. Reference evapotranspiration was calculated based on the FAO 56 standard methodology of a daily basis. One dimension Palmer-type soil model was used for estimating of real evapotranspiration using the wilting point, field capacity, and soil saturation point for each station at 1 m deep soil layer. The ratio of real and reference evapotranspiration dependent on the soil moisture stress linearly. Calculations of estimated evapotranspiration were made on daily and monthly basis. Applications of the site-specific crop coefficients (K_C) were also used. The result indicated that the differences among daily and monthly scale calculations of evapotranspiration (ET) were small without and with an application of crop coefficients (ET_{Kc}). This was due to high temperatures, global radiation, and also high soil moisture stress due to inadequate precipitation experienced in the tropics where Kenya lies. Results from Voi showed that mean monthly ET_0 ranged from 148.3±11.6 mm in November to 175.3±10.8 mm in March while ET was from 8.0±4.5 mm in September to 105.8±50.3 mm in January. From Kitale, ET_0 ranged from 121.5±8.5 mm/month in June to 157.1±8.5 mm/month in March while ET ranged from 41.7±32.6 mm/month in March to 126.6±12.2 mm/month in September. This was due to variability in temperature and precipitation between the two climatic regions. The study concludes that ET_0 and calculated evapotranspiration variability among the years on a monthly scale is slightly higher in arid and semi-arid climate regions than in humid regions. The study is important in strategizing viable means to enhance optimal crop water use and reduce ET losses estimates for optimal agricultural yields and production maximization in Kenya.

Keywords: crop coefficient, climatic regions, Kenya, reference evapotranspiration, real evapotranspiration, soil model

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Introduction

Kenya's mainstay of the economy is predominantly rainfed agriculture. Droughts of various severities, frequencies, timings, duration, intensity, and spatial extent vary from one climatic region to another and threaten food security in the country (Huho, J.M. and Mugalavai, M.E. 2010; Bowell, A. *et al.* 2021; Kipkemboi, K.B. *et al.* 2021). Therefore, a better understanding of hydrological processes and the distribution of water balance com-

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ponents is important (Okello, C. *et al.* 2020; Ferina, J. *et al.* 2021) to cushion inhabitants against extreme meteorological events. The components which include reference evapotranspiration (ET_0) and real evapotranspiration without and with an application of the crop coefficient (ET and ET_{Kc}), precipitation (P), soil moisture content (θ), soil recharge, soil surface runoff (R), and soil moisture loss coupled with other soil parameters should be given an in-depth insight to aid in operationalizing water management decisions.

Hydrological processes are crucial in plant developmental stages in times of water excess and/or stress. This is because crops have different rates of transpiration at different stages compounded by other factors such as environment and management practices (Zotarelli, L. *et al.* 2010; Ngetich, K.F. *et al.* 2012; Djaman, K. *et al.* 2017; Macharia, J.M. *et al.* 2021). For instance, during early crop developmental stages that is stages between vegetative emergence (VE) and vegetative tasseling (VT) (Ransom, J. *et al.* 2014) evaporation becomes the major process in water loss. For a fully grown crop, at reproductive stages (silking to physiological maturity) transpiration plays a major role and water stress causes more harm at the initial seedling stage and continued damage as crops near tasseling (Allen, R.G. *et at.* 1998). Soil water deficiency caused by unpredictable precipitation is an impediment to high yields in agriculturally potential areas. This prompts timely planting to ensure optimum utilization of available soil water during the rainy season (Ferina, J. *et al.* 2021). Since ET_0 and evapotranspiration are key determinants, long term modeling studies in Kenya and Africa are vital because of variations in water demand and soil characterization (Omondi, J.O. *et al.* 2017). A wide range of scientific methods have been used to estimate ET_0 (Penman, H.L. 1948) from different climatic components. This study used the FAO 56 standard methodology to estimate ET_0 on daily basis and one dimension Palmer-type soil model (Palmer, W.C. 1965; Ferina, J. *et al.* 2021) was used to estimate real evapotranspiration. The main aim of the study was to model ET_0, ET and ET_{Kc} in different climatic regions of Kenya. This was geared towards comparing changes in their estimates since they are influenced by climatic parameters and soil parameters which differ seasonally and from one climate region to another.

Recent studies (Hao, X. *et al.* 2018; McColl, K.A 2020) identified incorrectness of vital limiting cases and surface energy imbalances. This is due to the heterogeneity of regional characteristics in the Penman-Monteith evapotranspiration method. They provided a counter equation to correct the errors. McColl, K.A. (2020) suggests that it is more accurate in real-world conditions and it is not bound to additional assumptions, empiricism, or computational cost. This implies the complexity of the estimation of evapotranspiration since it relies on the heterogeneity nature of land surface features. As a key component of the hydrological cycle and its critical role in various sectors such as water resource management and agriculture (McColl, K.A. and Rigden, A.J. 2020), its study in various climate regions in Kenya which vary spatially resource-wise, is also very important in the current regime of climate change and variability. However, in our study, we relied on the standard and traditional Penman-Monteith method, because of its accuracy and ease of application to compute potential evapotranspiration.

The goal of this study is to evaluate estimates of reference (ET_0), and real evapotranspiration from two climatic regions of Kenya for proper planning and management of water resources using the traditional methodology (Zotarelli, L. *et al.* 2010; Ferina, J. *et al.* 2021) for present and future agricultural processes across water and agricultural sectors in daily and monthly time scale.

Geography and climate of Kenya

Kenya is geographically located at a longitude 34° E – 42° E, and latitude 5° S – 5° N. It has rich, diverse, and complex geomorphological features which are key modifiers of the climate system. The highest point is Mount Kenya (5,199 m) above sea level, while ranges, arid and semi-arid plains, and plateaus dominate the majority of the land. To the south, it is the Indian Ocean that regulates coastal climate (Ayugi, B. *et al.* 2020). In the western part of the country lies a complex rift valley lakes system. The climate varies from the modified tropical climate of the Kenya highlands to the desert climate of Central Northern Kenya (Obiero, J. and Onyando, J. 2013).

Study area and data sources

Different climatic regions of selected counties

The study was carried out in the different climatic regions of Kenya and from two counties *(Figure 1, Table 1)*. One, Trans-Nzoia County, is mountainous and climatically characterized by humid conditions, and the other, Taita-Taveta County, is lowland comprising of Taita, Mwambirwa and Sagalla hills with an altitude of 2,208 m a.s.l., and characterized by arid and semi-arid to tropical savannah climate. Trans-Nzoia County is humid, highland equatorial, mild, and generally warm and temperate. The Köppen-Geiger climate classification is Cfb (Peel, M.C. *et al.* 2007; Beck, H. *et al.* 2018). The annual average temperature is approximately 16 °C around Mount Elgon, and 28 °C in the lower areas. The diversity of agroecological factors coupled with agro-climatic zones has influenced spatial variation in the rainfed agriculturally productive region (Mbaisi, C.N. *et al.* 2016). Annual rainfall amount ranges between 1,267 mm to 1,808 mm while its elevation is between 1,800–2,000 m a.s.l. (Nyberg, J.M. *et al.* 2020).

Taita-Taveta is 89 percent arid and semi-arid. It is characterized by a tropical savannah climate (Aw). Mean monthly temperature is approximately 23 °C while the maximum and minimum are approximately 18 °C and 25 °C (Ogallo, L.A. *et al.* 2019). Its climate is influenced by south-easterly winds. On average, the county highlands receive 265 mm of precipitation, while the lowlands receive 157 mm during long rains between March, April, and May (MAM) while during short rains between October, November, and December (OND), rainfall amounts range from 341 mm in lowlands to 1,200 mm in highlands. Annual average precipitation amounts to 650 mm. The county is divided into three major topographical zones namely upper zone, comprising of Taita, Mwambirwa, and Sagalla hills region

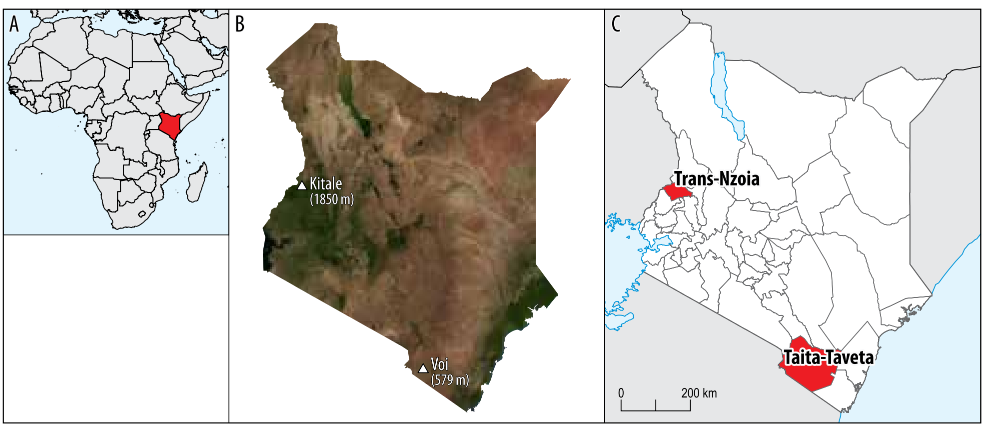

Fig. 1. Sketch map of Africa (a); Weather stations and their elevations (b); The two Kenyan counties under study: Trans-Nzoia, and Taita-Taveta in a sketch map of Kenya (c)

Table 1. Synoptic stations of counties under study, their geographical locations and duration of data set

County	Weather station	WMO-ID	Latitude	Longitude	Altitude, m	Duration of data set
			Highland			
Trans-Nzoia	Kitale	63661	0.9733°N	34.9588°E	1,850	2000–2009
			Lowland			
Taita-Taveta	Voi	63793	–3.3981°S	38.5581°E	579	2000–2009

with altitudes ranging between 304 and 2,208 m a.s.l., the lower zone consists of plains and the zone of national parks and mining areas (Government of Kenya, 2013; Mwakesi, I. *et al.* 2020). It is dominated agriculturally by maize, beans, and peas. Maize crop is the staple food from both counties as well as the whole of Kenya.

Dataset and quality control

Data with 3-hour time resolution was downloaded from Voi and Kitale synoptic weather stations and arranged into datasets from 2000–2009 (Meteomanz.com). Methodology of linear interpolation was used to check if the missing measurement periods were smaller than 12 hours. Mean daily course of the meteorological elements combined with the measured variables before and after the data gap was used for longer missing periods. If the lack of data was between half a day and 5 days, then the missing period was replaced with the average daily course from the data of the days (1 or 2 depending on the length of the data gap) before and after the missing period. If the data gap was even longer then we replaced the averages of 9 years for the given measuring period (8 measuring period each day). The measured and gap-filled time periods have been aligned during the initial and final 12 hours of the data-deficient period (5–5 data points) with a linear or exponential approximation.

Errors in the SYNOP messages (for instance bad digits) were also filtered in the temperature, relative humidity, pressure, wind speed, direction, and time series from the Meteomanz database based on a Visual Basic macro. 2.6 and 4.5 percent accounted for the missing data from Kitale and Voi SYNOP station daily data. The quality-assured database was arranged in Excel tables. After the data set was cleaned, step by step analysis of ET_0 (FAO 56 methodology, Zotarelli, L. *et al.* 2010; Lakatos, M. *et al.* 2020), calculated evapotranspiration using soil parameters ET and extended with maize coefficient, ET_{Kc} was undertaken using own Visual Basic Macro programmes developed in MS Excel.

Methodology

Due to complexity of the climate parameters required, FAO 56 standard methodology (Equation 1) of the daily base was used to estimate reference evapotranspiration, ET_0 (Allen, R.G. *et al.* 1998). There are also many methods for the estimation of potential evapotranspiration (E_{pot}), for instance, temperature as well as both temperature and terrestrial radiation-based methods (McMahon, T.A. *et al.* 2013; Lang, D. *et al.* 2017; Musyimi, P.K. *et al.* 2021). The definition of potential evapotranspiration is that from a surface of unlimited water but in this definition of potential evapotranspiration, the evapotranspiration rate does not relate to a specific crop while for the definition of reference evapotranspiration is that from a well-watered grass surface (Irmak, S. and Haman, D.Z. 2003).

Penman-Monteith reference evapotranspiration method is accepted as accurate, adopted, and recommended worldwide as a standardized method for ET_0 estimation across various climatic characterization for instance in Muranga County of Kenya (Shilenje, Z.W. *et al.* 2015). One dimension Palmer-type soil model (Equations 2–7) was used for estimating evapotranspiration using site-specific soil parameters *(Table 2)* which included wilting point, field capacity, and soil saturation point for each station at 1 m deep soil layer (Ács, F. and Breuer, H. 2006; Ács, F. *et al.* 2007; Dy, C.Y. and Fung, J.C.-H. 2016; Ferina, J. *et al.* 2021). This is obviously a rough approach since this study did not take into account the areal variability of the depth of the root zone. Therefore, the most commonly used 1 m depth value was applied.

The Palmer-type evapotranspiration model has also been applied in Kenya in previous studies to compute climate-based indices and evaluate meteorological and agricultural droughts (Marshall, M.T. *et al.* 2012). The soil types with the parameters were obtained from a soil map of Kenya with a 5 km space resolution which was taken using the Weather Research and Forecasting (WRF) model due to the scarcity of soil data parameters (Dy, C.Y. and Fung, J.C.-H. 2016) (see *Table 2*). The integration of the two models in the methodology was applied because the use of evapotranspiration-driven models in agricultural studies is still in its initial stages due to data scarcity in sub-Saharan Africa (Marshall, M.T. *et al.* 2012). Ratio of real and reference evapotranspiration dependent on the region-specific soil moisture stress. Application of the site-specific crop coefficients (K_C) were also applied in the model (Equation 3). This study used the maize coefficient as specified by FAO (Allen, R.G. *et al.* 1998; Tyagi, N.K. *et al.* 2003), because it is the staple food of Kenya and widely grown in the counties under study (Luciani, R. *et al.* 2019). The parameters used in Equation (1) are for daily time step by step in which analysis of each station climate data was done using Visual Basic Macro programmes developed in MS Excel.

Considering the i^{th} day of the year. The reference evapotranspiration for the i^{th} day of the year is [mm day^{-1}]:

$$ET_{0i} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}, \quad (1)$$

Meteorological variables for the given day of the year (without the notation i) are: R_n = net radiation at the crop surface [MJ m^{-2} day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = mean daily air temperature at 2 m height [°C], u_2 = wind speed at 2 m height [m s^{-1}], calculated from the reference wind measurement in 10 m height (Zotarelli, L. *et al.* 2010; Lakatos, M. *et al.* 2020), e_s = saturation water vapour pressure [kPa], e_a = actual water vapour pressure [kPa], $e_s - e_a$ = saturation water vapour pressure deficit [kPa], Δ = slope of the water vapour pressure curve [kPa °C^{-1}], γ = psychrometric constant [kPa °C^{-1}].

The daily evapotranspiration without (LE) and with the crop coefficients (LE_{Kc}) calculated by the 1D Palmer model for the i^{th} day of the year is determined by the soil type (see *Table 2*), the plant constant (Kc_i) and the parameterization of β_{i-1} function respectively. The latter is considered a simple linear function of the available soil moisture ($\theta_{i-1} - WLT$) (see Equation 4). There are other approaches as an exponential form of parametrization of function (Mintz, Y. and Walker, G.K. 1993). During the test calculations, no significant differences were observed among the different methodologies, so we kept the linear approximation. The initial soil moisture [in mm] in the upper 1 m deep soil layer is the previous daily (i – 1) value, θ_{i-1}

$$ET_i = \beta_{i-1} \cdot ET_{0i}, \quad (2)$$

$$(ET_{Kc})_i = Kc_i \cdot ET_i, \quad (3)$$

$$\beta_{i-1} = \begin{cases} 1 & if \;\; FC \leq \theta_{i-1} \\ \frac{\theta_{i-1} - WLT}{FC - WLT}) & if \; WLT \leq \theta_{i-1} \leq FC, \\ 0 & if \; \theta_{i-1} \leq WLT \end{cases} \quad (4)$$

where ET_i = real evapotranspiration, β_{i-1} = soil moisture availability parameter in a one-meter-deep layer of soil, WLT = wilting point, FC = field capacity, and Kc_i = specific crop coefficient for a given day. Parameterization knowing the amount of daily precipitation (P_i), of Runoff (R_i) provide the base on the daily water balance equation. (Units are mm in our cases.)

Table 2. Soil characteristics of synoptic stations in regions under investigation*

Stations	Soil type for WRF model	Saturation point (SAT), % v/v	Field capacity (FC), % v/v	Wilting point (WLT), % v/v
		Lowland		
Voi	Sandy clay loam (7)	40.4	31.5	6.9
		Highland		
Kitale	Loam (6)	43.9	32.9	6.6

*According to Dy, C.Y. and Fung, J.C.-H. 2016.

A simple 1D bucket model was applied. If, at the end of the day, the estimated soil moisture value exceeds the saturation point ($\theta_i > FC$), then the remainder is considered as a runoff (R_i). The model does not take into account the terrain conditions nor the depth of groundwater and the surface water movement:

$$R_i = \begin{cases} 0 & if\ (\theta_{i-1} - ET_i + P_i) \leq SAT \\ (\theta_{i-1} - ET_i + P_i) - SAT & if\ (\theta_{i-1} - ET_i + P_i) > SAT \end{cases}, \quad (5)$$

The value of soil moisture, θ_i and corrected evaporation ET_i (practically near zero) can also be easily calculated at the end of the i^{th} day, when the soil moisture is near wilting point, as we know that: $WLT \leq \theta_{i-1} \leq SAT$:

$$\theta_i = \begin{cases} WLT & if & (\theta_{i-1} - ET_i + P_i) \leq WLT \\ (\theta_{i-1} + ET_i + P_i) & if & WLT > (\theta_{i-1} - ET_i + P_i) \leq SAT \\ SAT & if & (\theta_{i-1} - ET_i + P_i) > SAT \end{cases}, \quad (6)$$

$$ET_i = \begin{cases} ET_i & if\ (\theta_{i-1} - ET_i + P_i) \geq WLT \\ (\theta_{i-1} + P_i - WLT) & if\ (\theta_{i-1} - ET_i + P_i) < WLT \end{cases}, \quad (7)$$

Although the Palmer-type soil model is globally and regionally used for its suitability in the analysis of hydrological processes, it has a limitation in that it does not consider the application and use of other soil properties such as textural variation among soils, physical and chemical composition of various soils which vary from one region to the other (Ferina, J. *et al.* 2021). This study also did not put into consideration such inputs due to a range of issues such as scarcity, uncertainty, and unavailability of the properties of soil data from Kenya. However, the model is useful as it forms a basis for future studies of other soil properties as well as provides room for its improvement.

A normality and hypothesis test

The methods to analyze the normality of the time series used in the study are Kolmogorov-Smirnov (K-S) test, and Shapiro-Wilk test (Ghasemi, A. and Zahediasl, S. 2012). The importance of the normality test was to help decide the statistical significance test for mean and standard deviation from the two counties. This study relied on the Shapiro-Wilk test as it is recommended for small samples. The distribution of 10-year rainfall data portrayed a normal distribution while monthly precipitation between the two counties showed variation in normality among the months regardless of the season. A simple F-test was used to compare the standard deviation of annual precipitation, ET, ET_0, ET_{Kc}, from the two counties while the T-test (was used when the distribution between the months was normal) and Mann-Whitney U-test (was used when the distribution between months was skewed) were used to compare the monthly mean of precipitation. This was due to its applicability in determining the stability of time series data, its ease, and simplicity of use (Lim, G.-K. *et al.* 2020). The following four hypotheses were tested based on the normality of the data:

– H_0: There is no statistical significant difference of annual precipitation, ET, ET_0, ET_{Kc}, between the two climatic regions of the two counties.
– H_1: There is statistical significant difference of annual precipitation, ET, ET_0, ET_{Kc}, between the two climatic regions of the two counties.
– H_0: There is no statistically significant difference between the two climatic regions of

the two counties based on mean monthly precipitation data.

– H_1: There is statistically significant difference between the two climatic regions of the two counties based on mean monthly precipitation data.

Results and discussion

This section describes the pattern of temperature and precipitation and compares spatial variation of the mean monthly ET_0 and estimates ET without crop coefficient ($Kc_i \equiv 1$) and evapotranspiration with crop (maize) coefficient, ET_{Kc} from arid and semi-arid Taita-Taveta and humid Trans-Nzoia counties of Kenya. It also examines decadal and annual means (x) and standard deviations (σ_X) of precipitation (P), reference and estimated real evapotranspiration (ET_0, ET, ET_{Kc}), ET/ET_0 and ET_{Kc}/ET_0 ratios. The importance of analyzing ratios of the regions under study was to determine evaporative stress indices which are also synonymous with drought index, a reflection of temperature properties on the surface. Evaporative stress indices have been previously used to examine droughts of various durations more so short-term, crop growth and irrigation demands as well as water stress (Yao, A.Y.M. 1974; Choi, M. *et al.* 2013; Anderson, M.C. *et al.* 2016; Liu, Y. *et al.* 2019). It was also important to compare the evaporative index using ET with and without the application of the maize coefficient.

Temperature and rainfall pattern of the counties under study

Results indicated that the mean monthly temperature ranged from 22.7 to 28.4 °C in Taita-Taveta County while in Trans-Nzoia County the range was between 17.8 to 21.9 °C. (There are tropical regions.) Mean annual precipitation in Taita-Taveta was 574.2±205.8 mm while absolute minimum and maximum were 212.3 mm in the year 2003, and 801.4 mm in the year 2004 respectively. The rainfall amount of 212.3 mm was too low compared to the mean of 574.2 mm, indicating drought. Similar droughts were experienced across Kenya in the 2000s. Arid and semi-arid regions which cover 80 percent of land mass were highly affected (Nyaoro, D. *et al.* 2016; Venton, C.C. 2018).

In Trans-Nzoia County, the mean annual precipitation was 1,200±174 mm while maximum and minimum absolute values were 1,014.2 mm in the year 2000 and 1,460.3 mm in the year 2001 respectively. There was a noticeable variation in precipitation in the two regions under study *(Figure 2)*. This conforms to the results of Huho,

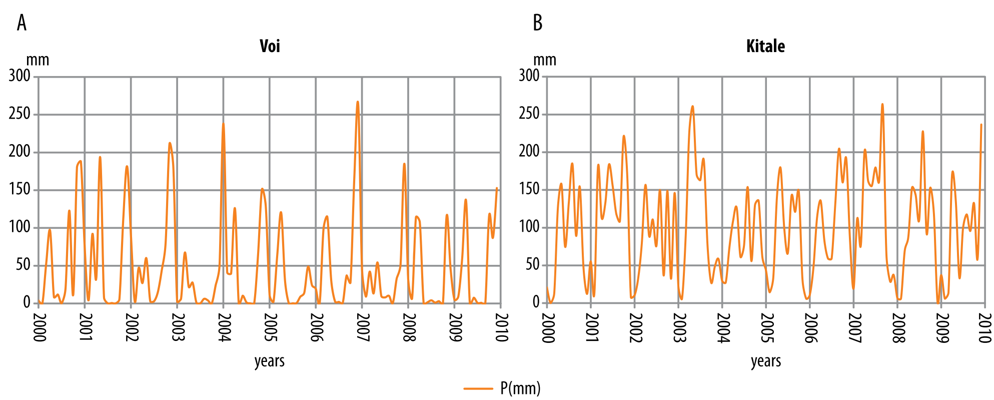

Fig. 2. Monthly precipitation variation (2000–2009) in Voi synoptic station, Taita-Taveta County (a), and in Kitale synoptic station, Trans-Nzoia County (b)

Table 3. Decadal mean monthly ET_0 in Lowland, Voi station, Taita-Taveta County (Aw)

Year/Month	1	2	3	4	5	6	7	8	9	10	11	12	Mean ($\bar{x}$)	SDev. (σ_X)
2000	162.9	176.1	166.4	158.2	147.3	135.7	143.6	155.9	157.8	178.1	144.2	150.5	*156.4*	*13.0*
2001	146.3	158.6	180.2	154.2	162.8	143.8	149.0	170.4	178.1	191.0	153.1	139.6	*160.6*	*16.2*
2002	144.4	159.8	165.3	157.3	169.9	177.7	177.3	157.7	156.4	164.8	157.7	151.0	*161.6*	*10.0*
2003	170.1	164.6	198.3	177.4	164.7	167.3	182.2	175.3	175.3	191.2	170.4	182.4	*176.6*	*10.5*
2004	152.7	149.6	183.0	160.6	188.2	160.2	177.1	172.9	179.2	167.6	151.6	147.4	*165.8*	*14.1*
2005	161.2	169.3	176.4	165.0	182.3	174.8	165.5	164.4	169.4	181.5	148.5	172.9	*169.3*	*9.4*
2006	182.3	173.4	169.4	153.6	165.8	166.8	167.6	174.9	162.2	156.4	133.1	137.3	*161.9*	*14.1*
2007	144.5	155.9	170.9	173.8	157.3	167.0	167.3	157.2	166.7	174.4	151.1	150.1	*161.4*	*10.1*
2008	150.8	156.0	162.1	147.8	154.4	150.3	152.3	152.8	162.4	183.4	130.3	140.9	*153.6*	*12.8*
2009	164.4	149.1	181.3	168.8	170.7	154.8	160.1	152.2	172.0	154.4	143.5	140.2	*159.3*	*12.5*
Mean (x)	*157.9*	*161.2*	*175.3*	*161.7*	*166.3*	*159.9*	*164.2*	*163.4*	*167.9*	*174.3*	*148.3*	*151.2*	–	
SDev. (σ_X)	*12.5*	*9.4*	*10.8*	*9.4*	*12.3*	*13.6*	*12.9*	*9.3*	*8.2*	*13.2*	*11.6*	*15.0*		

Table 4. Decadal mean monthly ET_0 in Highland, Kitale station, Trans-Nzoia County (Cfa)

Year/Month	1	2	3	4	5	6	7	8	9	10	11	12	Mean (x)	SDev. (σ_X)
2000	158.0	162.7	166.0	128.4	124.7	119.7	111.0	122.7	138.8	127.0	117.4	136.5	*134.4*	*18.5*
2001	128.4	147.7	136.8	123.3	123.3	112.0	113.9	123.2	131.9	125.0	110.4	139.3	*126.3*	*11.3*
2002	134.3	151.4	140.8	129.6	128.0	123.5	133.7	134.6	144.2	134.6	128.1	129.8	*134.4*	*7.8*
2003	150.7	155.4	164.4	131.1	128.5	119.5	125.2	124.9	143.0	142.2	129.1	150.1	*138.7*	*14.3*
2004	151.1	152.6	165.8	125.9	139.4	126.8	133.5	134.8	134.8	146.3	127.3	143.4	*140.1*	*12.2*
2005	157.3	163.2	159.9	146.3	120.4	124.3	128.7	136.7	132.8	141.4	143.9	166.3	*143.4*	*15.6*
2006	164.4	156.9	151.9	139.8	139.3	129.6	130.8	132.4	144.8	150.3	118.2	123.4	*140.2*	*14.0*
2007	150.3	135.1	162.7	141.8	135.4	104.2	119.1	128.9	129.4	143.5	137.0	151.3	*136.5*	*15.4*
2008	155.8	155.1	149.9	141.8	129.2	121.4	122.6	123.7	136.9	132.5	139.7	153.9	*138.5*	*12.9*
2009	152.5	165.0	173.2	123.4	125.5	133.6	133.0	141.3	144.9	140.6	146.1	134.5	*142.8*	*14.3*
Mean (x)	*150.2*	*154.5*	*157.1*	*133.1*	*129.4*	*121.5*	*125.1*	*130.3*	*138.1*	*138.4*	*129.7*	*143.8*	–	
SDev. (σ_X)	*11.0*	*8.8*	*11.8*	*8.5*	*6.6*	*8.5*	*8.3*	*6.6*	*5.9*	*8.3*	*12.0*	*12.8*		

J.M. (2017) who mentioned that the amount of rainfall received in a given region differs from year-to-year. For instance, in Machakos County, the coefficient of variation of 42 and 41 percent for MAM and OND rainfall seasons respectively for KARI Katumani station and 39 and 54 percent for Mutisya Mango Farm station respectively were experienced (Huho, J.M. 2017). Similarly, Ghaedi, S. (2021) noted that patterns of precipitation variability were evident across Iran from one year to another. Consequently, higher variability dominates the arid and semi-arid climatic regions across the world, which are characterized by low, unpredictable, and erratic rainfall amounts.

Spatial variation of mean monthly ET_0 in lowland, Taita-Taveta County (Aw)

Reference evapotranspiration (ET_0) was estimated using FAO 56 standard methodology (Equation 1). Results indicated that decadal mean monthly reference evapotranspiration varied from one year to the other and from one month to the other. This variation was dependent on the seasons of the year since a greater percentage of Kenya exhibits two major rainy seasons, the MAM long rain season and OND, short rain season, both related to the influence of the ITCZ, but differing in the amount of precipitation received and its interannual and inter-seasonal variability (Camberlin, P. and Wairoto, J.G. 1997). For instance, Taita-Taveta experiences two rainy seasons, MAM and OND. The precipitation climatology of countries near the Equator where Kenya lies is heterogeneous due to influences of topography, lakes, and seasonal dynamics of tropical winds (Nicholson, S.E. 2017).

The highest decadal mean monthly value of the reference evapotranspiration was 175.3 ±10.8 mm in March, while the lowest decadal mean monthly value was 148.3±11.6 mm in November for the 10 years of analysis *(Table 3)* during the two rainy seasons. The highest annual mean value was 176.6±10.5 mm/year in 2003, while the lowest was 153.6±12.8 mm/year in 2008 (see *Table 3*). During dry seasons, which have its peak from July to September and December to February experience no precipitation or very little amounts, there were relatively small differences of ET_0 among months and high values of ET_0 as shown in *Table 3.* This implies that ET_0 estimates depend mostly on high temperatures and solar insolation but in cases where ET_0 is larger than precipitation more so in the dry months irrigation is an option to substitute the insufficient amount of precipitation and evaporative requirements by crops (Sadick, A. *et al.* 2015).

Spatial variation of mean monthly ET_0 in highland Trans-Nzoia County (Cfa)

Results from humid Trans-Nzoia County indicated that the decadal mean monthly ET_0 varied from one year to the other and from one month to the other but the estimates were lower than in Taita-Taveta County. This was because of lower temperatures experienced in Trans-Nzoia than in Taita-Taveta County. The highest mean value was 157.1±11.8 mm/month in March while the lowest mean monthly value was 121.5±8.5 mm/month in June *(Table 4).* It was also evident that there were moderate differences among the months.

The mean differences among the months were also moderate with the largest mean difference of 11.1 mm/month between November and December (see *Table 4*). Similar variations were observed by Djaman, K. *et al.* (2018) who stated that there were temporal and spatial variations in the monthly average ET_0 from January to December across Madagascar with January average ET_0 (less than 5 mm/day), the highest more so in regions characterized by hot and dry climates while the lowest ET_0, ranging from 3.27 to 3.70 mm/day, evident in the central-eastern humid region of Madagascar.

Mean monthly reference and real evapotranspiration estimation using soil parameters from the two counties

Results of the estimates indicated variation in ET_0 and ET from two counties. In Taita-Taveta County the differences in mean monthly ET estimates were small and almost followed the same trend varying from month to month and year to year *(Figure 3*, a*)*. Mean monthly ET estimates ranged from 8.0±4.5 mm/month in September to 105.8±50.3 mm/month in January. This was due to varying precipitation amounts and simultaneously soil moisture contents. In Trans-Nzoia County, the differences in estimates were slightly high and indicated a noticeable difference (see *Figure 2*, b). Mean monthly ET (without application of plant constant, *Kc*) estimates ranged from 41.7±32.6 mm/month in March to 126.6±12.2 mm/month in September. Mean monthly ET dependent on the season of the year and varied from one climatic region to the other but greater variation was experienced in arid and semi-arid climates. However, in long and short rainy seasons real evapotranspiration is nearly independent of soil textural characteristics because of adequate precipitation. For instance, in Trans-Nzoia County, precipitation ranges from 1,267 mm to 1,808 mm (Nyberg, J.M. *et al.* 2020) while Taita-Taveta County receives 265 mm in the highlands and 157 mm in the lowlands during long rains (MAM); while during short rains (OND) the range is from 341 mm in lowlands to 1,200 mm in highlands (Mwakesi, I. *et al.* 2020).

Textural characteristics vary greatly from one soil type to the other as stated by Mugo, J.W. *et al.* (2016) in a study in Kitui County of Kenya. During dry spells ET mostly depends on both soil texture and amount of precipitation which vary across different climatic regions (Ács, F. *et al.* 2007). For instance, in Taita-Taveta County, the type of soil was sandy clay loam while in Kitale it was loam (see *Table 2*). This implies that the amount of precipitation received in the lowlands is not sufficient enough to meet the requirements of ET_0 and ET unlike in highlands or mountainous regions where rainfall is reliable. There were some few cases where small differences or equal estimates of ET_0 and ET were equal, for example in January 2001, 2003, and 2007. In this month temperatures as well as precipitation were low. These results concur with Ferina, J. *et al.* (2021) who stated that differences in ET_0 and ET are small when precipitation is adequate and equally large when precipitation decreases. The variability in ET_0 and ET is dependent on soil moisture, recharging of lost soil moisture through precipitation, nature, and type of land cover among other heterogeneous land character-

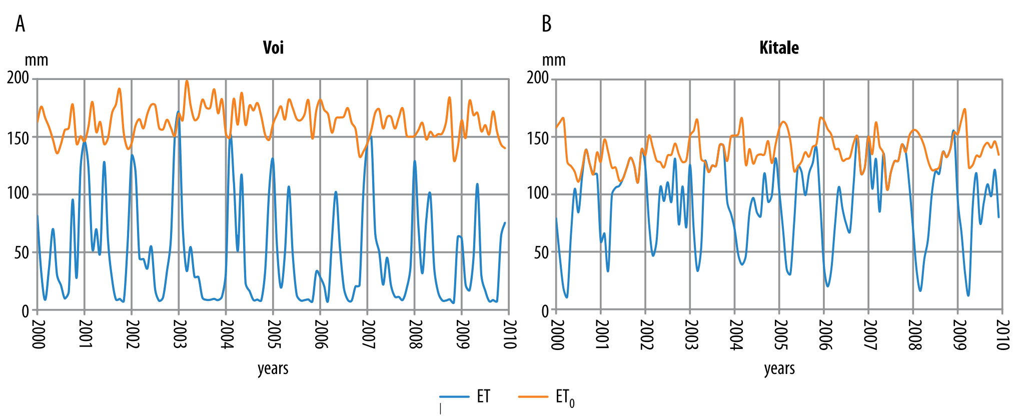

Fig. 3. Mean monthly variability of ET_0 and ET in Voi synoptic station, Taita-Taveta County (a), and in Kitale synoptic station, Trans-Nzoia County (b)

istics. However, its estimation is of greater importance to water and agricultural sectors as well as ecosystem stability and well-being (McColl, K.A. and Rigden, A.J. 2020).

In Taita-Taveta County, Voi station *(Figure 3*, a*)*, in many instances, *ET* was too low compared to *ET* estimates of Trans-Nzoia County *(Figure 3*, b*)*. For instance, *ET* ranged from 8.0±4.5 mm/month in September to 105.8±50.3 mm/ month in January. This was because of high temperatures and unreliable precipitation amounts. This increased soil moisture content stress brings a deficit due to aridity conditions of the region and this impacts agriculture and brings potentially adverse effects to the yields hence food insecurity. Contrary to this, in Kitale station (see *Figure 2*, b), Trans-Nzoia County, *ET* was relatively higher and ranged from 41.7±32.6 mm/month in March to 126.6±12.2 mm/month in September and varying annually which also influence maize yield. According to Marshall, M.T. *et al.* (2012), variability in *ET* and maize yield correlations and incompatibility with the awaited growing season are highest in Western Kenya where Trans-Nzoia County lies geographically. There were some few cases where small differences or equal estimates of ET_0 and *ET* were equal, for example in January 2007 because the region receives an adequate amount of precipitation, and the temperatures are usually low. These results are in tandem with Ferina, J. *et al.* (2021) who stated that different climatic regions vary significantly in terms of agricultural essentials, more importantly, soil moisture content, precipitation amount, temperature, and sufficient water. Therefore, the estimation of ET_0 and *ET* is of fundamental importance in the agricultural potential region as well as the other sectors considering their variability.

Daily reference evapotranspiration, real evapotranspiration without and with maize coefficient (ET_{Kc})

Daily results in Taita-Taveta County indicated that, daily averages, ET_0, *ET* and evapotranspiration with maize coefficient, ET_{Kc} was 5.3±0.9 mm/day, 1.6±1.2 mm/day and 1.6±1.2 mm/day respectively. There was practically no significant difference between evapotranspiration without and with maize coefficient as their estimates were almost the same but ET_0 was higher in Taita-Taveta County (*Figure 4*, a) than in Trans-Nzoia (*Figure 4*, b) because of the high temperatures experienced in lowland Taita-Taveta County. The daily maximum value of ET_0 was 8.5 mm/day and was observed on 13 January 2006, while the daily minimum absolute estimate was 1.7 mm/day and recorded on 31 May 2003 in Taita-Taveta County. This was because January is among the hottest months in the dry season of January and February, while May is a month of the long rainy season, hence the variations among values in Taita-Taveta County.

Similarly, in Trans-Nzoia County, the daily maximum absolute estimate of *ET* was 6.2 mm/day on 29 May 2001, whilst the absolute minimum value was 0.0 mm/day on three days: 19, 20 and 21 October 2003. On the other hand, daily evapotranspiration with modified maize coefficients, ET_{Kc} Kc_{ini} (initial period, Kc_{mid} mid-season, the crop growth development period and Kc_{end}, late season period) of 0.3, 0.75, 1.2, and 0.4 and 0.3, 0.8, 1.2, and 0.6 (Allen, R.G. *et al.* 1998) in Taita-Taveta and Trans-Nzoia County respectively. For the Kc_{end}, the modification was done in this study as the average between crop development period and Kc_{end} that was 0.8 and 0.9 in Taita-Taveta and Trans-Nzoia County respectively *(Figure 5)* were used to compute the estimations. As stated by Guerra, E. *et al.* (2011), crop coefficients are fundamentally vital for estimating the evapotranspiration of crops. They computed approximately similar maize coefficients in Kenya of Kc_{ini} of 0.5, Kc_{mid} of 1.0 and Kc_{end} of 0.8. These values were computed for three crop stages, initial, mid-season, and end-season without consideration of the development stage.

The reason for using the maize crop coefficient is because of the importance of soil moisture content to crop growth and development and its deficiency can highly impact the yield of maize crop hence food insecurity in Kenya.

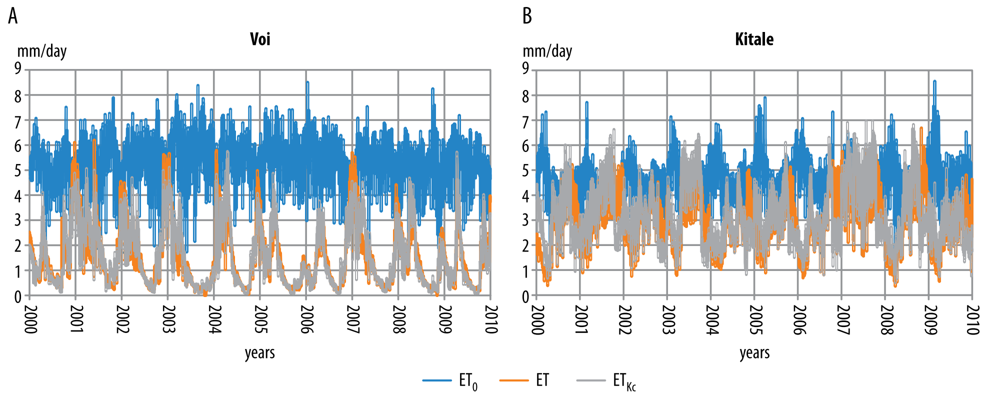

Fig. 4. Daily variability of ET_0, ET and ET_{Kc} in Voi synoptic station, Taita-Taveta County (a), and in Kitale synoptic station, Trans-Nzoia County (b)

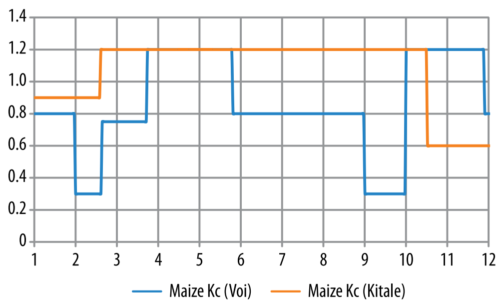

Fig. 5. Maize coefficients in Voi (two rainy seasons), and Kitale (single rainy season) annually

The government's food security depends on the availability of enough quantity of maize to meet food demands. Further, it is the most important and staple food for over 90 percent of population, grown on 1.6 million hectares of land and 80 percent of its farming is practiced by small-scale farmers (Wambugu, P.W. *et al.* 2012). As stated by Shanahan, J.F. and Nielsen, D.C. (1987), despite water availability's importance in every stage of crop development, from germination to harvest, many crops are most sensitive to moisture deficits during the reproductive stages. This occurs mostly during the duration of tasseling, silking, and pollination since water stress during the reproductive stages revitalizes deeper root growth (Mayaki, W.C. *et al.* 1976).

Similarly, soil moisture distress can highly influence real evapotranspiration since if there is a moisture deficiency, evapotranspiration requirements are not satisfied. For instance, Stegman, E.C. (1982) noted that a 1 percent decrease in seasonal real evapotranspiration led to an average loss of 1.5 percent in maize yield, whereas water stress more so during the reproductive stages more so the blister stage (10–14 days after silking) led to a 2.6 percent decline in maize crop yield. This can as well proportionately explain the reduction in maize yield in Taita-Taveta County which experiences two growing seasons (MAM and OND). Daily maximum estimate of ET_{Kc} was 5.7 mm/day on 10 April 2009 while the daily absolute minimum estimate was 0.1 mm/day from 29 August to 28 of September 2003, 2005 and 2006 respectively. This was because April is a month of the long rainy season of Kenya while July, August, and September (JAS) are dry seasons with August and September recording high temperatures in the arid and semi-arid climatic region of Kenya. Daily estimates of Trans-Nzoia County showed that the mean daily average of, ET_0 and ET was 4.5±0.9 mm/day, 3.1±1.1 mm/day and 3.2±1.2 mm/day respectively. These averages were moderately low as compared to Taita Taveta County (see *Figure 3*, b) because these regions received a high amount of precipitation and low temperatures hence meeting the requirements of *ET*. The daily absolute maximum ET_0 for the 10 years (2000–2009) was 8.5 mm/day on 21 February 2009 whilst the minimum absolute value was 1.6 mm/day on 4 July 2007. Similarly, evapotranspiration without and with maize coefficient maximum absolute daily estimates was 7.0 mm/day and 6.6 mm/day on 1 November 2008 and 27 July 2007 respectively. These results are in tandem with those reported by Hobeichi, S. *et al.* (2018) who indicated that evapotranspiration had higher values in the Sahel from September to November.

The analysis also showed the daily absolute minimum values of *ET* without, and with *Kc* were 0.51 mm/day and 0.36 mm/day on the same day (27 March 2008) respectively. The daily, monthly, and annual variations of ET_0, *ET* and ET_{Kc} was due to varying daily, monthly and annual precipitation amounts (see *Figure 2*) and deficiency of precipitation mean soil moisture content and evapotranspiration deficiency hence agricultural drought. This concurs with Marshall, M.T. *et al.* (2012) who indicated that deficits in estimated real evapotranspiration are a direct measure of crop stress and can be integrated into agricultural drought monitoring systems.

Annual comparison of trends of P, ET, ET_0, ET_{Kc} from the two counties

Analysis also shows an annual variation of ET_0 in the two climate regions, with a range of 1,837.6 mm/year to 2,119 mm/year in Taita-Taveta and 1,515.1 mm/year to 1,721.1 mm/year in Trans-Nzoia, and a decadal average of 1,950.7 mm/year in Taita-Taveta County and 1,650.3 mm/year in Trans-Nzoia County. These results are in agreement with Djaman, K. *et al.* (2018) who observed that across Madagascar, annual ET_0 varied from 1,081 mm/year to 2,239 mm/year and averaged 1,620 mm/year. The highest value range of the long-term average annual ET_0 was between 1,891 and 2,111 mm/year on the western coast and northwestern coast (Djaman, K. *et al.* 2018). Further, from *Table 5*, it was evident that higher annual precipitation (*P*) amounts led to higher *ET* and lower annual precipitation amounts led to lower. For instance, in 2003, in Taita-Taveta County, the annual precipitation amount was 212.3 mm and the same year had the lowest *ET* estimate of 447.4 mm/year. This was due to the 2003 drought which was experienced across the whole lower eastern. This result conforms with Yang, Z. *et al.* (2016) who mentioned that the decrease in *ET* is attributed to a decrease in precipitation amounts, and regions with less annual precipitation depict less.

Analysis based on standard deviation (σ) from the annual mean precipitation, *ET*, ET_0, ET_{Kc} was carried out for the whole decade (10 years) for the two counties. A simple F-test (Lim, G. *et al.* 2020) was used to determine whether the standard deviation between the two counties was statistically different. At a significance level (α) of 0.05, results showed that p values of precipitation, *ET*, ET_0, ET_{Kc} from the two counties were greater than 0.05. This means we do not reject the null hypothesis and there is no statistically significant difference between the standard deviation of precipitation, of the two counties. Contrary to the expected results, this outcome implies a similarity of tropical annual precipitation cycles between the two counties and from the two climatic regions (Ilyés, C. *et al.* 2021). A further test of significance by T-test and Mann-Whitney U-test showed that there is no statistically significant difference between the monthly mean precipitation of January, February, March, and November. There exist a statistically significant difference between the monthly mean precipitation of April, May, June, July, August, September, October, and December. These differences and similarities may be attributed to climate variability and change which causes shifts in air and ocean currents circulation linked to ITCZ hence the anomalies (Ayugi, B. *et al.* 2016; Obwocha, E.B. *et al.* 2022) hence change in monthly weather pattern since precipitation distribution is mostly irregular Kenya in time and space. The

Table 5. *Decadal annual mean and standard deviation of annual precipitation (P), reference evapotranspiration (ET_0) and the estimated evapotranspiration (ET) without and with plant (maize) coefficient (ET_{Kc}) from the two counties*

Counties	Indicator	Years 2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Mean ($\bar{x}$)	SDev. (σ_X)
Taita-Taveta (Tropical savannah, arid and semiarid)	*P**	696.4	704.8	763.8	212.3	801.4	326.2	765.5	463.0	432.7	576.0	*574.2*	*205.8*
	ET_0	1876.5	1927.1	1939.4	2119.0	1985.5	2031.1	1942.8	1936.2	1837.6	1911.4	*1950.7*	*79.4*
	ET	598.7	737.3	675.9	447.4	677.7	450.8	507.0	604.1	505.4	466.1	*567.0*	*105.9*
	ET_{Kc}	669.9	748.8	667.8	467.2	665.0	461.6	494.2	598.4	510.8	469.9	*575.4*	*106.8*
	ET/ET_0	0.32	0.38	0.35	0.21	0.34	0.22	0.26	0.31	0.28	0.24	*0.29*	*0.06*
	ET_{Kc}/ET_0	0.36	0.38	0.34	0.22	0.33	0.22	0.25	0.31	0.27	0.25	*0.29*	*0.06*
Trans-Nzoia (Humid)	*P**	1014.2	1460.3	1068.2	1335.7	1042.0	1025.5	1282.0	1460.0	1169.9	1138.6	*1200.0*	*174.0*
	ET_0	1612.8	1515.1	1612.8	1664.1	1681.7	1721.1	1681.7	1638.8	1661.5	1713.6	*1650.3*	*60.1*
	ET	1005.6	1229.4	1056.1	1212.1	972.0	1123.7	1045.9	1452.7	1126.4	988.0	*1121.2*	*146.5*
	ET_{Kc}	1088.7	1273.1	1077.6	1325.4	957.6	1135.0	1008.5	1560.3	1145.8	994.6	*1156.7*	*183.9*
	ET/ET_0	0.62	0.81	0.65	0.72	0.57	0.65	0.62	0.89	0.68	0.57	*0.68*	*0.11*
	ET_{Kc}/ET_0	0.67	0.84	0.66	0.80	0.57	0.66	0.60	0.95	0.69	0.58	*0.70*	*0.12*

*mm/year

similarity of the monthly mean precipitation was regardless of the season since it did not follow the seasonal pattern of Kenya.

Conclusions

In this study, we estimated long-term (2000–2009) reference and real evapotranspiration using a one-dimensional Palmer-type soil model for two synoptic stations found in two different climatic regions of Kenya. It was established that:

1. Annual ET_0 estimates were high in Taita-Taveta County with values ranging from 1,838 mm/year to 2,119 mm/year compared to Trans-Nzoia County where its estimates ranged from 1,515 mm/year to 1,721 mm/year.

2. Annual evapotranspiration without (*ET*) and with maize coefficient (ET_{Kc}) varied in the two climatic regions under study. The estimates ranged from 447 mm/year to 737 mm/year and 461.6 mm/year to 748.8 mm/year in Taita-Taveta County respectively, whilst in Trans-Nzoia the range was from 972 mm/year to 1,453 mm/year and 958 mm/year to 1,560 mm/year respectively.

3. The evaporative stress indices were low in Taita-Taveta County with and without the maize coefficient. It ranged from 0.22 to 0.38 and from 0.21 to 0.38 with and without maize coefficient respectively. This was because of the low amount of annual precipitation and high temperatures. However, in Trans-Nzoia County, evaporative stress indices were high with a range of 0.60 to 0.95 and 0.57 to 0.89 with and without maize coefficient due to varying annual precipitation amounts among the years.

4. The highest evaporative stress index was experienced in Trans-Nzoia County when the annual precipitation was high. For instance, in 2001 and 2007 the annual rainfall amount was 1,460.3 mm and 1,460 mm respectively, and the evaporative stress indices were 0.84 and 0.81 with and without maize coefficient in 2001 and 0.95 and 0.89 with and without crop coefficient in 2007 respectively.

The study concludes that these results are important to different climatic conditions in Kenya which are endowed with various agricultural necessities in terms of topography, amount of precipitation received, and different soil characteristics such as moisture, drainage, and depth among others. The variation in estimated real evapotranspiration in various climatic regions should be applied in farmers' decision-making in their choice of crops to be planted, variety of farming systems, choice of planting seasons, and duration of crops to maturity. Therefore, it is fundamentally important to estimate ET_0, ET and ET_{Kc} with and without specific crop coefficients considering their daily, monthly and annual variability, more so in agriculturally potential regions of Kenya. Further, the study is important for the shifting planting seasons of various crops which differ in terms of soil moisture requirements.

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