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Full Length Research Paper

Evaluation of some empirical methods of estimating potential evapo-transpiration for determination of length of growing season in a tropical wet and dry climate

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A comparison of 4 empirical methods of calculating potential evapo-transpiration (PE) using climatic data for the estimation of length of growing season from rainfall – potential evapo-transpiration model was carried out using 15 years of estimates recorded in Shaki, Southwestern Nigeria. The length of the growing season estimated from the 4 empirical methods of PE were related to the moisture requirements of some selected tropical crops. Data were analyzed by one – way ANOVA taking each yearly mean as the average of the 15 years (1991 - 2005) for the station. Results show that the methods varied greatly in their ability to define the magnitude and variability of the length of growing season. The original Penman and the modified Penman of McCulloch models showed no significant difference in their use for the determination of length of growing season. However, the Thornthwaite, the Priestly and Taylor showed differences in the estimates of length of growing season. Priestly and Taylor gave the least estimate of length of growing season. The relative reliability of each method in terms of accuracy of both measured and extrapolated meteorological data utilized was also discussed.

Key words: Potential evapo-transpiration, length of growing season, moisture requirement, wet and dry climate.

INTRODUCTION

In the wet and dry climate, the length of growing season is mainly controlled by the availability of water. However, depending on rainfall in the determination of the length of growing season of agricultural crops could be of great risk in farming operations. This is because the difference in the soil with regards to the storage capacity and availability of soil moisture strongly influence agricultural potentialities than the volume of rainfall. This may be due to the fact that rainfall might runoff without entering the soil, particularly on hilly terrain. Hence, the balance between water within the root zone of the soil caused by rainfall and the water loss resulting from evapo-transpiration is of fundamental significance in the determination of length of growing season of agricultural crops in the area. Therefore, rainfall (P) and potential evapo-transpiration (PE) are pre-requisite parameters in the determination of growing season. However, the difficulty encountered in using the rainfall and PE model lies mainly in the inability to properly measure or estimate the 2 components. It is observed that while precipitation is measured in numerous places in Nigeria, the accurate field measurement of PE is not only rare but difficult (Bello, 1997). In particular, class A evaporation pan, which has been widely used in Nigeria for estimation of evaporation, is unreliable (Olaniran, 1983).

In view of the difficulties of accurately measuring PE, empirical formulae have been widely adopted to predict PE using climatic data. These have been reported to

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range in complexity depending on the number of climatic parameter involved in that computation. One major problem of the various empirical methods of estimate of PE is that they all have limitation that may be due to either inaccuracies in their methods of determination or the use of questionable assumption (Jackson 1991). Unfortunately, for a specific situation, no guideline can be given for selecting the methods to be used for estimating potential evapo-transpiration for a particular purpose; therefore, it is desirable to develop an understanding of more accurate method. The uncertainties related to estimate methods for any practical application can best be evaluated by comparison of methods (Warnaka et al., 1988).

Research into comparing estimates of evapo-transpiration derived from empirical methods have been carried out extensively in Nigeria but in contrast, research endeavor in relating potential evapo-transpiration in water balance for the purpose of determination of growing season is not common. Notable examples are those by Bello (1997); Duru (1984); Olaniran (1983); Ayoade (1976); Blackie (1965). Hence, attempt have been made in this study to evaluate some of the empirical methods of estimating potential evapo-transpiration for determination of periods of moisture availability as derived from rainfall and potential evapo-transpiration patterns in Shaki. The reliability of methods were also tested by comparing estimated length of growing season from different methods of PE estimate with the moisture requirements for some selected tropical crops during the growing seasons in a given year at the station.

MATERIALS AND METHODS

Study area

Shaki (8°45'N, 3°25'E) is situated in the derived Savanna Zone of Nigeria (Figure 2a). The derived Savanna Zone of Nigeria lies within the tropical wet and dry region of Africa (Figure 2a). This zone is found in a densely populated east-west band between the main Savanna and the forest zone. The appearance and composition of wet sub-humid, apart from the vestiges of humid forest, are much the same as in the southern areas of Savanna. The impact of man has been so intense in this area that areas left to re-grow tend to grow savanna-type grasses that are susceptible to fire and therefore they limit the lowland species that can regenerate in this area, creating "derived savanna". Remnants of the high forest may be present in upland or rocky areas that are not suitable for agriculture. The study area is characterized by a tropical climate with distinct wet and dry seasons. The wet season is associated relatively with the prevalence of the moist maritime southerly monsoon from Atlantic Ocean and dry season by the continental North Easterly harmattan winds from the Sahara desert. The area is located within a region characterized by bimodal rainfall pattern (commences in March and is plentiful in July and September, with a short dry spell in August). The long dry period extends from November to March. The annual rainfall ranges between 1250 and 1400 mm in Shaki and environs. The region is characterized by relatively high temperature with mean annual air temperature being about 30°C. The greatest variation in temperature is experienced in July (25.7°C) and in February (30.2°C). The humidity is lowest (37 - 54%) at the peak of dry season in February and highest at the peak of the rainy season between June and September (78 - 85%). The geological formation is that of basement complex and it has a well drain soil of tropical ferruginous type.

Empirical methods of estimating PE

There are 4 empirical methods of estimating PE commonly use in the area were followed in this study. They are; the Penman combined equation for potential evapo-transpiration (1948):

$$Eo = 6/(6+y)H + y/(6+y)\, Ea \quad \ldots\ldots (1)$$

$$\text{Where, } H = Rn - G \quad \ldots\ldots (2)$$

H is the available heat, Rn is the net radiation and G is the soil heat flux.

The equation is for open water evaporation and for its application, the value of H, Ea and Δ are required. If net radiation measurement is available, then H which is the available heat may be obtained directly. However, for a developing country like Nigeria, where direct measurement of radiation are rare, H is calculated more often from the incoming and outgoing radiation Ri and Ro respectively which is determined as:

$$H = Ri\,(1 - \alpha) - Ro \quad \ldots.. (3)$$

Where, Ri is the function of Ra which is the theoretical radiation that would be recorded at the ground surface in the absence of an atmosphere and this radiation is fixed by the latitude and season modulated by a function of the ratio n/N of the measured maximum possible sunshine radiation. Since albedo (α) = 0.05 then:

$$Ri\,(1-\alpha) = 0.95 f a\,(n/N) \quad \ldots.. (4)$$

The function $fa(n/N)$ depends on the clarity of atmosphere and the latitude expressed as:

$$Ra\,(0.29\cos Ø + 0.52n/N) \quad \ldots.. (5)$$

$$Ro = \sigma T_K^4\,(0.56 - 0.09\sqrt{e_a})(0.10 + 0.90n/N) \quad \ldots\ldots (6)$$

The H in equation 3 can be obtained by values obtained in equations 5 and 6. Ea is the drying power of air obtained by applying the empirical formula:

$$Ea = 0.26(1-u/100)\,(e_s-e_a) \quad \ldots\ldots (7)$$

Where, Δ = rate of change of temperature of the saturation vapour pressure expressed in millibars per degree °C, γ = the psychrometric coefficient, α = albedo which are factors that express the reduction in the incoming short wave radiation on the evaporating surfaces and corresponding to 0.05 for free water surface and 0.25 for vegetative surface, R_a = short wave radiation received at the limit of the atmosphere expressed in mm of evaporable water, n = sunshine duration for the period considered in hours and tenths, N = sunshine duration astronomically possible for the given period, σT_K^4 = Blackbody radiation expressed in mm of evaporable water for the prevailing air temperature, e_a = saturated vapor pressure expressed in millibars, e_s = vapor pressure for the period under consideration expressed in millibars,

T°C = air temperature measured in the meteorological shelter and expressed in degree Celsius and
U = mean wind speed at an elevation of 2m for the given period and expressed in mile/sec.

The Eo can be converted to potential evapo-transpiration (PE) by multiplying the formal by a seasonal factor whose value are less than unity (obtained from appropriate table):

$$PE = f\,(Eo) \quad \ldots\ldots (8)$$

Where PE = estimate of the potential evapo-transpiration for a given period expressed in mm.

The modified Penman's approach of McCulloch (1965)

This method was developed in East Africa to modify the original equation of Penman by assuming that the available energy for evaporation is equal to the net radiation. McCulloch also modified the equation by adding an altitude correction term (h) which represents the altitude of site or location above the sea level. The aerodynamic term in the Penman equation above was modified as follow:

$$Ea = 0.26(1 + h/20{,}000)\ (1 - u/100)\ (e_s - e_a) \quad \ldots\ldots (9)$$

Where, h is the altitude of measured site above the sea level in meters.

The advection-aridity model of Priestly and Taylor (1972)

$$PE = \alpha 6/6+6\ \gamma\ (Rn-G) \quad \ldots\ldots (10)$$

The approach of Priestly and Taylor concluded that α is a constant between 1 and (Δ + γ)/ Δ, indicating that PE from large saturated areas is bounded by the equilibrium evaporation and (Rn - G), respectively. Therefore, the formation of the Priestly and Taylor model of wet surface evaporation always assumes a positive or zero sensible heat flux. The constant value of α was found experimentally to be 1.26 for conditions of minimal advection (Priestly and Taylor, 1972; Davies and Allen, 1973; Steward and Rouse, 1976; Steward and Rouse, 1977; Jury and Tanner, 1975; Parlange and Katul, 1991). The energy difference (Rn - G) was identical to that used in the calculation of PE using Penman approach.

The temperature method of Thornthwaite (1948)

The procedure of Thornthwaite followed was according to the expression of the form:

$$PE = 16.2b\ [10T/I]^a \text{ in millimeter} \quad \ldots\ldots (11)$$

Where, T = the mean monthly temperature in °C, b = the adjustment factor account for the fact that sunshine is not 12 h a day and the months are not 30 days in duration. The values of b were obtained from standard table as a function of month (Shaw, 1994).

$$I = \text{annual heat index} = \sum_{n=1}^{12} (T/5)^{1.51}$$

$$a = 67.5 \times 10^{-8} I^3 - 77.1 \times 10^{-6} I^2 + 0.0179 I + 0.0492$$

The meteorological data used for the estimation of PE values according to selected methods were temperature (°C), relative humidity (%), wind speed (Km/h) and sunshine (h); measured values of climatic parameter were obtained for Shaki for 15 years (1991 - 2005). Shaki was selected for this study because of the consistency in the availability of meteorological records for considerable length in the station. Other required variables, of which measured values were not available but were estimated using meteorological table (Shaw, 1994) were radiation received at the top of the atmosphere (Ra) in mm/day, daily maximum possible sunshine duration (N), mean saturated vapour pressure (e_d), Blackbody radiation (σT_K^4) in mm of water weighting factor for effect of temperature and altitude (w). Furthermore, rainfall data was obtained for the location. Climatic records of temperature, vapour pressure or relative air humidity, sunshine and wind speed allowed calculation of PE on monthly bases. Hence, values of each dekad (10 days) of year were deduced graphically. Also, rainfall data were estimated from monthly data by graphical interpolation to get the decadal value. This was because monthly intervals were too long as they may hide dry spells of 1 or 2 weeks which may be highly critical for the development and yield of some crops.

The reliability of the methods considered in this study was assessed by comparing the relationship between rainfall (P) and PE estimates derived by each method in a water balance diagram of Cocheme and Franquin (1967). This was to give an idea of the extent to which each of the estimates described moisture regime and water availability in the study area. The reliability of methods were also tested by comparing estimated length of growing season from different methods of PE estimate with the moisture requirements for some widely cultivated selected crops during the growing seasons in a given year at the station. The growing period of several varieties of tropical crops has been given (Gordon, 1981; Bello, 1987; Jackson, 1991). From the authors, the growing periods of the selected crops were extracted (Table 1).

The length of growing season from Cocheme and Franquin (1967) model combine the time designated humid - HP (p > PE), intermediate - IP (intervals before and after the wet season when p > 0.5 PE < PE) and residual moisture depletion - PRM (0.1PE < p <0.5PE) as shown in Figure 1.

Length of growing season determined from rainfall – Potential evapo-transpiration model in Shaki with different methods of estimation of PE

Furthermore, data were analyzed by one – way ANOVA using the Genstat statistical package (Release 4.24 Discovery Edition) to determine the yearly mean and standard error of length of growing season computed from the selected estimates for the 15 years records for the station. Results were compared to check if there were differences at a 0.05 level of significance. Mean standard error of length of growing season determined from rainfall – potential evapo-transpiration model in Shaki with different methods of estimation of PE were also presented graphically.

RESULTS AND DISCUSSION

A comparison of 4 equations which estimates PE using climatological data for the estimation of length of growing season show that the equation varied greatly in their ability to define the magnitude and variation of length of growing season (Table 2). The growing season length varied with the method of estimation of PE used in the precipitation – evapo-transpiration model values for Shaki. However, the Penman and McCulloch method

Table 1. Growing periods of some selected crops.

Crops	Growing periods (days)
Sorghum (Guinea corn)	100 - 140
Maize	100 - 140
Millet	90 - 120
Rice	90 - 150
Groundnut	90 - 140
Sugarcane	270 - 365
Yams	240 - 300
Cocoyams	180 - 270
Cassava	270 - 730
Sweet potatoes	90 - 180

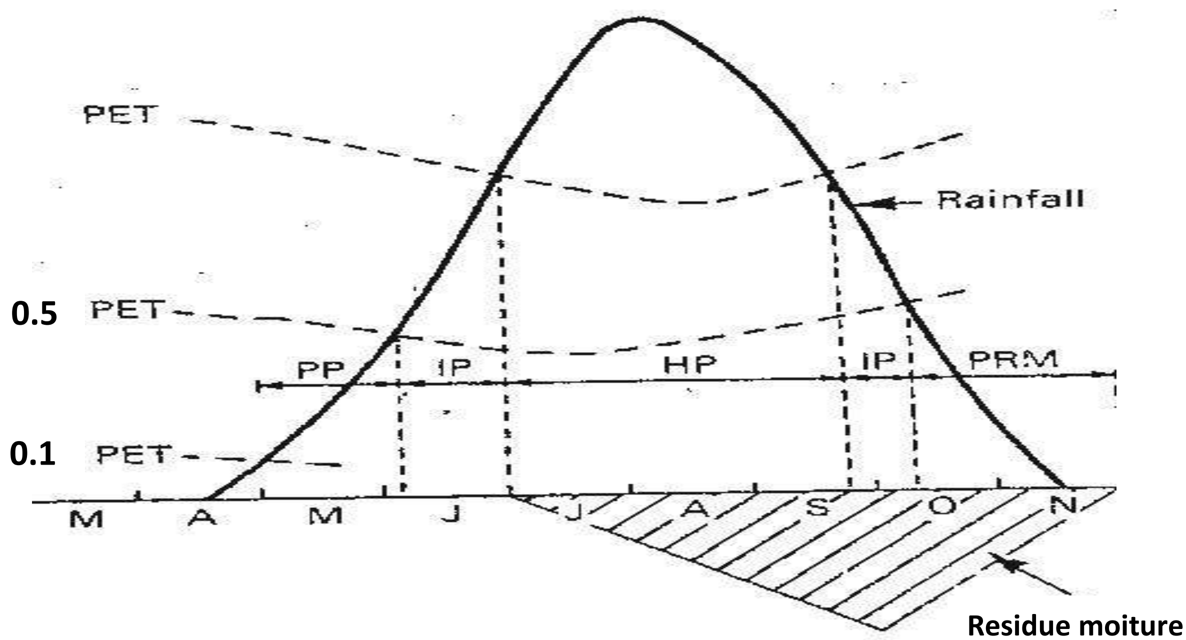

Figure 1. Period of moisture availability for cropping as derived from rainfall and potential evapotranspiration patterns of Cocheme and Franquin adopted from “Yayouk et al. (1988)”.

agreed closely in their relation to rainfall value given the mean length of growing season estimated at 239.7 and 237 days, respectively. This may be due to the fact that the attitude correction term included in the McCulloch equation has little or no effect on Penman’s original equation.

The Thornthwaite method also gave a close length of growing season to those of Penman and McCulloch with 227.2 days. However, the radiation based approach of Priestley and Taylor consistently gave the highest estimate of monthly PE as compared to the other 3 equations and consequently gave a low value of length of growing season at 214.6 days. Figure 3 clearly shows this relationship for several years of length of growing season estimates for the PE methods at the location as discussed earlier. Figure 4 shows that the cultivation of cereals and some roots crops such as groundnut and sweet potatoes can be recommended as appropriate in Shaki; this is in agreement with length of growing season from all estimates. It is pertinent to stress that whereas the use of Penman and McCulloch method in estimating PE for the determination of growing season gave the cultivation of cocoyam as appropriate, the Thornthwaite and Preistly and Taylor gave a marginal or insufficient period for the growth of cocoyam in most of the years considered.

Furthermore, Figure 4 indicates that the growing period of cassava was much longer than the duration of the

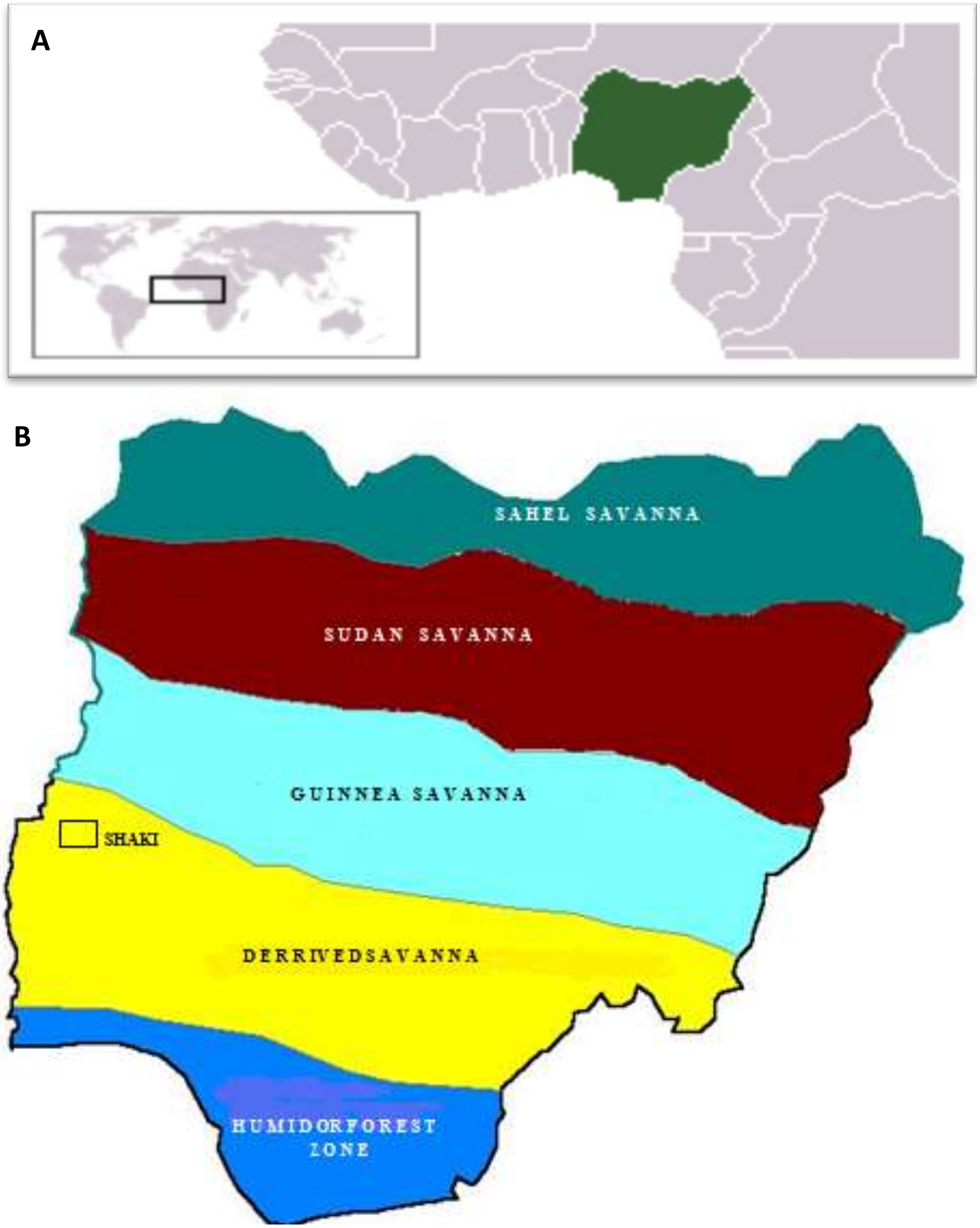

Figure 2. a: Location of Nigeria b: Map of Nigeria showing different vegetation zones and the study area.

moist period using all method through the years. Nevertheless, this is not to say that cassava cannot be grown. It can be recalled that Porter (1976), showed that cassava is drought resistant particularly after it has fully established itself and therefore, it has low consumptive use of water during the growing periods. Generally, the Penman and McCulloch approach showed more reliable and effective period of water availability for the cultivation of cereals and some roots crops than the other 2 methods in the estimation of PE; a useful tool in the determination of growing season for agricultural crops in Shaki. The mean and standard error of the yearly values are given in Table 2. The result shows that all except Thornthwaite and Priestly and Taylor indicate a

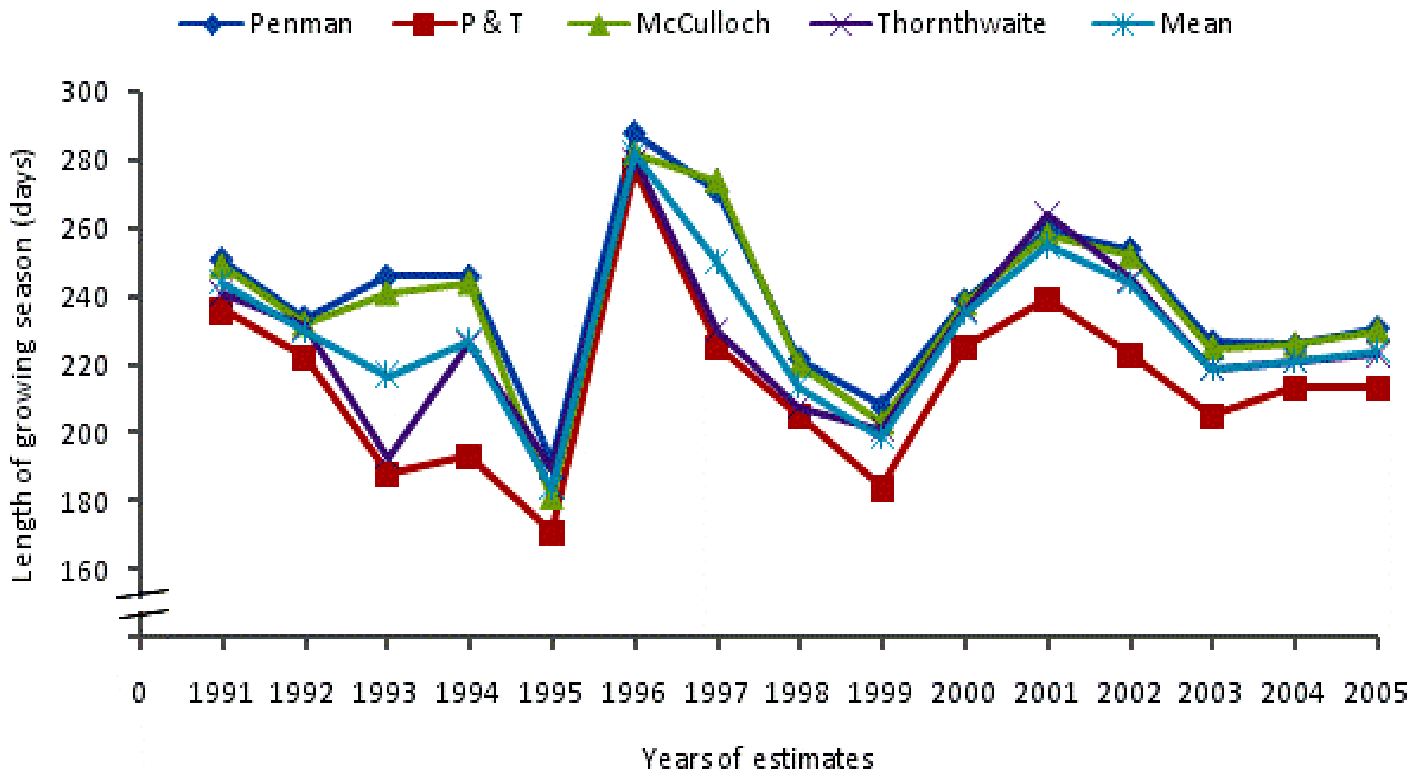

Figure 3. Length of growing season determined from rainfall – potential evapo-transpiration model in Shaki with different methods of estimation of PE.

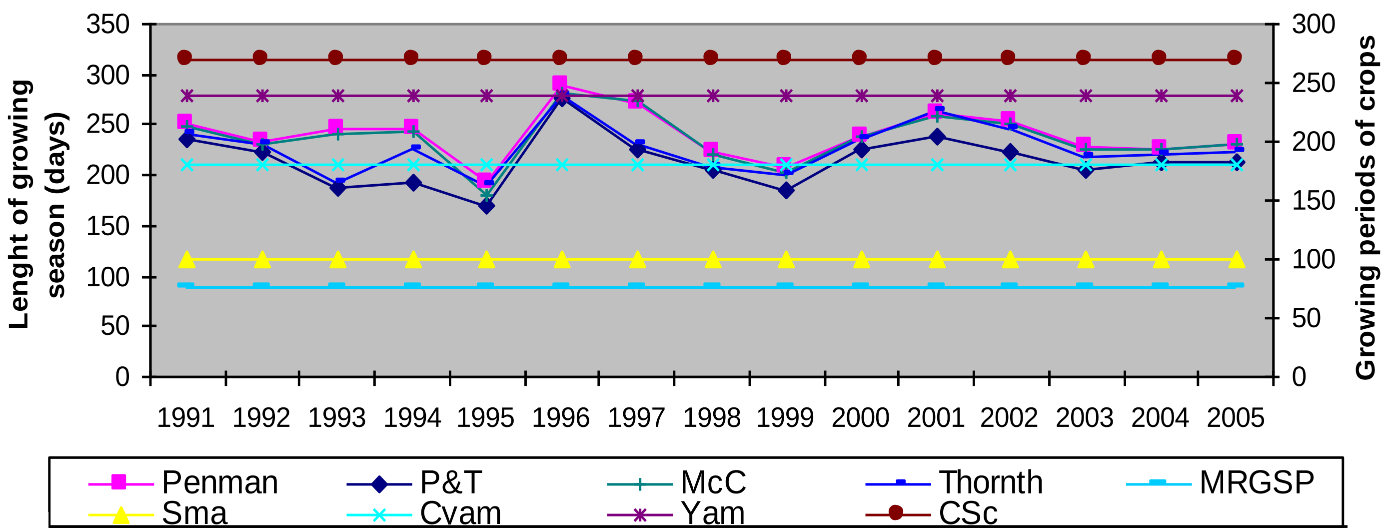

Figure 4. Relationship between the length of growing season and the growing periods of some selected crops in Shaki. LMP = length of moist periods; MRGSP = millet, rice, groundnut and sweet potatoes; Sma = sorghum and maize; Cyam = cocoyams; Yam = yams; and Csu = cassava and Sugarcane.

significant difference at the 0.05 level, which may be as a result of scale shift in the estimate. Figure 5 compares the mean SE of the yearly values. Priestly and Taylor gave the least estimate of length of growing season p <

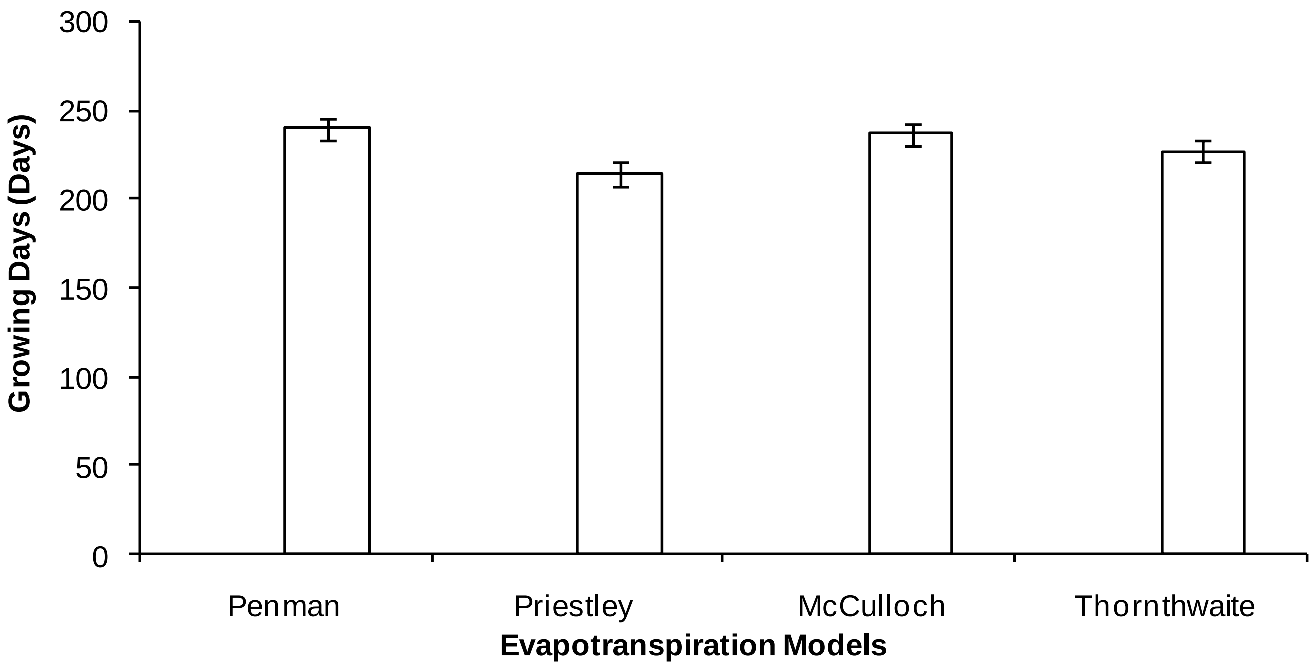

Figure 5. Mean SE of length of growing season determined from rainfall – potential evapo-transpiration model in Shaki with different methods of estimation of PE.

0.05, followed by Thornthwaite. However, there was no significant difference between the Penman approach and the modified Penman approach of McCulloch.

Conclusion

It has been shown that water supply from rainfall can reasonably support the growth of cereals and some roots crops such as groundnut and sweet potatoes in the study area using all the selected estimate methods whereas Penman and McCulloch methods gave a clear difference with the roots crops particularly yam. Thus, in the study area which is characterized by an irregular sequence of wet and dry spell and having seasonal and variable distribution of rainfall coupled with high temperature that does not vary much during growing season (Bello, 1997: 270), the Penman approach and the modified Penman approach of McCulloch gave comparatively more desirable results than the other 2 methods in the estimation of potential evapo-transpiration used in the computation of length of growing season. The temperature approach of Thornthwaite, which also gave a closer value of growing season length, can be adopted where climatological data for the Penman method is not available since the area is characterized by little temperature variation. Lastly, the modified radiation method of Priestly and Taylor is not as reliable as the others. This may be because the method is based on local estimates of radiation, which has to be extrapolated because of non availability of direct measurement of radiation in the study area. However, the availability of accurately measured climatic data is a major consideration in selecting a model for calculating reliable result for PE. Where the bulk of data are obtained by extrapolation from nearby station and general description of climate, a less reliable result can be expected. Hence, a well-equipped weather station is necessary to derive accurate meteorological data required for the estimation of PE, which are pertinent for a reliable prediction of the length of growing season – a useful tool in agricultural planning.

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