EVALUATION OF ACTUAL EVAPOTRANSPIRATION FROM AGRICULTURAL CATCHMENTS, KENYA.

By

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DEDICATION

This thesis is dedicated to my parents Mr. Wilson Lomeri and Mrs. Maria Lomeri for their initiative of taking me to school.

DECLARATION

I hereby declare that this thesis is my original work and has not been submitted for a degree in any other University

10th Nov, 1994

Karongo S. Kpar

Date

This thesis has been submitted for examination with my approval as University Supervisor

Sharma

10/11/1994

Dr. T.C Sharma

Date

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ABBREVIATIONS

A.S.A.E - American Society of Agricultural Engineers

A.S.C.E - American Society of Civil Engineers

C.V - Coefficient of variation

E.A.A.F.R.O - East African Agricultural and Forestry Organization

F.A.O - Food and Agriculture Organization

I.A.H.S - International Association of Hydrological Sciences

I.L.R.I - International institute for Reclamation and Improvement

K.R.E.M.U - Kenya Rangelands Ecological Monitoring Unit

Msc. - Master of Science

U.K - United Kingdom

U.S.A - United States of America

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Symbol

AET - Actual evapotranspiration (mm)
AET_{Ob} - Mean of observed actual evapotranspiration (mm)
AET_{Gb} - Mean of actual evapotranspiration values predicted by using Grindley model (mm)
AET_{Mb} - Mean of actual evapotranspiration values predicted by using Morton model (mm)
AET_{Pi} - Predicted actual evapotranspiration (mm)
AET_{Oi} - Observed actual evapotranspiration (mm)
AW - Available water (mm)
Cu - Consumptive water requirement (mm)
d_1 - Distance from a station to the coast (km)
d - Index of agreement
E_a - Aerodynamic term (mm/day)
d_b - Mean of difference (mm)
E_c - Equilibrium evaporation rate (mm/day)
E_r - Energy balance component of evaporation (mm)
E_o - Estimated annual evaporation (mm/yr)
ET_o - Reference crop evapotranspiration (mm)
E_{TW} - Wet environment areal evapotranspiration (mm)
f - Consumptive use factor
f_o - A conversion factor to convert PET to AET
f_T - Vapour transfer coefficient
k - Consumptive use crop coefficient
K - Storage parameter (days)
kc - Crop coefficient
ks - Soil coefficient
MAE - Mean absolute error (mm)
MW - Maximum storage capacity (mm)
N - Number of samples compared
p - Atmospheric pressure (mbar)
P - Rainfall (mm)
p - Percent of annual total daylight hours
P_A - Mean annual precipitation (mm)
PET - Potential evapotranspiration (mm)
PET_c - A given crop's potential evapotranspiration (mm)
q - Discharge (m^3/s)
R - Runoff (mm)
R_a - Extra- terrestrial radiation (mm)

Rc	- Root constant (mm)
RMSE	- Root mean square error (mm)
R_T	- Net-radiation for soil-plant surface at air temperature (W/m^2)
R_o	- Net outflow water vapour or solid water content from the atmospheric water column (mm)
r^2	- Coefficient of determination
S_a	- Change of total water content in the atmospheric water column (mm)
S	- Storage (m^3)
SMD	- Soil moisture deficit (mm)
s_G	- Standard deviation of AET estimates by Grindley model (mm)
s_M	- Standard deviation of AET estimates by Morton model (mm)
s_O	- Standard deviation of AET estimates by Water balance method (i.e observed values standard deviation) (mm)
t	- Time (days)
T	- Mean air temperature (° C)
TD	- Average daily temperature range (° C)
T_p	- Equilibrium temperature (° C)
T'_p	- Trial value equilibrium temperature (° C)
v_D	- Saturation vapour pressure at dew point temperature (mbar)
v_p	- Saturation vapour pressure at T_p (mbar)
ϵ	- Surface emissivity
▲G_1	- Change in groundwater storage (mm)
σ	- Stephan-Boltzman constant (W/m^2 - K^4)
τ	- Psychometric constant
δT_p	- A correction term (° C)
▲$_p$	- Slope of saturation curve at T_p (mbar)
▲S	- Change in storage (mm or m^3)
▲S_1	- Change in soil moisture (mm)

Abstract

Actual evapotranspiration was evaluated using three models viz water balance, Morton and Grindley. The catchments used in the study were Oruba, Tugenon, Ndarugu and Kimakia each having an area less than 100 sq. km. All the catchments lie in the humid regions of Kenya. The first three catchments are chiefly vegetated with pasture, annual and perennial crops whereas Kimakia is largely under forest.

The water balance method was implemented using daily rainfall data and runoff hydrographs in a manner that allowed the estimation of actual evapotranspiration as the difference between rainfall and runoff over a period of some days. The period in days was determined from the receding limbs of the daily runoff hydrograph assuming the linearity of runoff processes. The Morton model was implemented as documented in the journal of hydrology (Netherlands) by Morton (1983) and all the calculations were done on a monthly basis. Grindley model was implemented as documented in the text "Hydrology in practice" by Shaw (1984). This model in essence is the extension of Penman root constant concept and therefore proceeds with firstly computing the Penman potential evapotranspiration values. The potential values are reduced to actual values by involving soil moisture deficits and root constants for specified vegetations. Computation of the above mentioned quantities in the Grindley model were done on a ten-day time interval as prescribed by Grindley and then converted to monthly values.

The estimates of actual evapotranspiration by the three methods were compared basing the water balance estimates as the standard ones. The annual evapotranspiration by the water balance method ranged from 958.1 mm to 1352.1 mm while the coefficients of variation varied between 0.05 and 0.08 in all the catchments. The results indicated that the Grindley model tended to overestimate the actual evapotranspiration such that the estimates were either equal or close to Penman potential evapotranspiration values in all the catchments. Morton model performed better and actual evapotranspiration estimates by the method, though marginally higher, were closer to the water balance based estimates. The study, therefore, recommends that Morton model may be used in the evaluation of the evapotranspiration component of the water balance. The additional merit of the method lies in its ability to provide the estimates of actual evapotranspiration solely on meteorological data, which are readily available in Kenya.

1.0 INTRODUCTION

1.1 General Background

Evaporation of water from water bodies, bare land surfaces, plant tissues, and leaves of vegetation all summed can be referred to as evapotranspiration from a defined catchment. Loss of water from plant tissues and leaves is commonly known as transpiration and is more or less the dominant factor in the total loss of water from a land surface (Weyman, 1975).

Evapotranspiration may take place at a potential rate as determined by meteorological factors or at a reduced rate depending on the supply of soil moisture. When the supply of moisture is adequate, evapotranspiration occurs at the potential rate usually referred to as potential evapotranspiration (PET) under specified meteorological conditions. When soil moisture is limited the rate of water loss falls below the potential rate commonly referred to as actual evapotranspiration (AET). The actual evapotranspiration occurring over an extended area say a river basin is termed areal evapotranspiration.

1.2 Significance of Study

The water balance of a catchment chiefly involves information on rainfall, runoff and evapotranspiration. Because accurate measurement of runoff from a catchment requires installation of specialised equipment and long periods of data monitoring, indirect means of estimating it becomes very necessary. One such indirect method is through estimation of actual evapotranspiration which can be achieved through the use of meteorological data together with other catchment characteristics. Meteorological data are more readily available than the river flow data which are acquired after considerable expense of resources and time. Therefore from the catchment input (rainfall) and the estimated actual evapotranspiration, it is possible to generate the needed runoff information. Because of the difficulty involved in the measurement of actual evapotranspiration, models for its accurate estimation become a prerequisite; hence the need of establishing the applicability of some of the models under Kenyan conditions.

Two of the models used in the estimation of evapotranspiration are the Morton (1983) and Grindley (1970) models. The Morton model is based on the complementary relationship between areal and potential evapotranspiration. The relationship is based upon the interaction between evaporating surfaces and the air moving over them. The data requirement of this model is mean long-term annual rainfall, mean monthly air and dew-point temperatures, and mean monthly observed sunshine hours. In addition to this, information on altitude and latitude of the meteorological station considered is needed for the model. The Grindley model relates potential evapotranspiration with soil moisture deficit and root constant. The root constant as described by Penman (1949) is a vegetation's characteristic and determines how fast a crop's evapotranspiration reduces below the prevailing potential evapotranspiration. Grindley model requires data on mean monthly air and dew-point temperatures and observed sunshine hours (as in the Morton model), daily rainfall, land-use and windrun. It can be seen that this model attempts to incorporate all the factors influencing evapotranspiration. Ayoade (1988) points out that vegetal cover together with other non-climatic factors play a significant role in determining actual evapotranspiration. Therefore incorporation of such factors in the Grindley model makes it a tool worth trying for the evaluation of actual evapotranspiration. The data requirement of these two models are usually found in most meteorological stations in Kenya and thus they can be used in the estimation of actual evapotranspiration which would facilitate water resources evaluation and planning.

1.3 Research Objectives

The overall research objective was to establish the applicability of Morton and Grindley models for estimating actual evapotranspiration in humid catchments in Kenya. The specific objectives were;

(1) To evaluate the actual monthly and annual evapotranspiration values using water balance, Morton and Grindley models.

(2) To compare the Morton and Grindley models with water balance method and suggest the more favourable model to be used in Kenyan humid catchments.

1.4 Scope of Study

In order to rely on estimates based on the water balance analysis for comparison purposes, the catchment sizes were limited to 100 km^2. This was aimed at improving the estimates of monthly evapotranspiration as small river basins show great fluctuations in seasonal flows from which the short time-interval estimates of actual evapotranspiration can be made. Selection of small catchments was also necessitated by the considerable computation in Grindley model which comes hand in hand with variations in vegetation.

For rigorous testing of the models, long period data of between seven to ten years was used for each of the four catchments selected. The catchments chosen for this study were Oruba, Tugenon, Ndarugu and Kimakia. The meteorological stations from which the data were obtained for the respective catchments were Kibos cotton research, Kericho Timbilil tea research, Jacaranda coffee research and Kimakia forest. The details of the catchments are described in chapter three.

2.0 LITERATURE REVIEW

2.1 Evapotranspiration in the Hydrologic Cycle

Evapotranspiration plays a significant role in the hydrologic cycle as it redistributes heat energy between surfaces and the atmosphere (Wiesner,1970). Evapotranspiration is an important process of the hydrologic cycle such that on a continental basis approximately 75% of the annual precipitation is returned to the atmosphere by this process (Mutreja, 1990). Balek (1983) reports that the most significant component of the water balance of tropical afforested watersheds is evapotranspiration. All the regions from which evaporation occurs may impose restriction on the internal movement of water. However, water movements between the interface of water source and air do not show any fundamental difference in all cases therefore the laws of physics can be applied. Since evaporation and evapotranspiration are affected by the same factors, the processes used to study evaporation can as well be used to analyze evapotranspiration provided the necessary additional concepts are incorporated.

Evaporation from all surfaces including plant transpiration when water is unlimited is referred to as potential evapotranspiration, PET, and was defined by Penman in 1956 as evaporation from an extended surface of short green crop, actively growing, completely shading the ground of uniform height and not short of water. More often the stated conditions are not met in totality. Therefore the rate of water loss drops below the potential rate usually referred to as actual evapotranspiration, AET.

Both potential (PET) and actual evapotranspiration (AET) are governed by energy supply and vapour transport. Solar radiation supplies 80 - 100% of the energy needed for evapotranspiration (Saxton, 1982). Wind speed influences the rate of evapotranspiration as it provides the transport capacity of the air surrounding the evaporating vegetation and land surface. Other climatological factors that affect evapotranspiration include temperature and the relative humidity of the air. The third factor that influences evapotranspiration is the supply of moisture to the evaporating surfaces. It is this concept of supply of moisture that distinguishes the potential and actual evapotranspiration. Both potential and actual evapotranspiration are influenced by vegetation cover, stage of vegetation development and vegetation characteristics (Linsley et al., 1982). Newson (1979) pointed out that PET calculation can at times underestimate actual water loss from vegetation when a substantial proportion of the loss occurs as evaporation of rainfall intercepted on the vegetation canopy. This gives the indication that AET can exceed PET at such times, especially if the vegetal cover is high.

2.2 Measurement of Actual Evapotranspiration (AET)

Measurement of actual evapotranspiration has been achieved only on small field plots called lysimeters. Lysimeters are installed to simulate its immediate environment. Lysimeter-derived values are used as a reference to test the empirical and semi-empirical evapotranspiration formulae (FAO, 1982). Data derived from lysimetry is useful in studying soil-water-plant-atmosphere relationships and for the planning and operation of irrigation schemes and on-farm water management practices. However, the results obtained have often been regarded as unsatisfactory because of the difficulty faced in measuring percolation losses (Linsley et al., 1982). The other difficulty encountered in obtaining accurate evapotranspiration values from lysimeters emanates from the manner in which the soil is filled in the lysimeter (Kijne, 1980). The method of filling the soil affects the soils physical properties which consequently influence the rate of evapotranspiration. Ward and Robinson (1990) report that measured point evapotranspiration suffers from lack of sample representativeness and distorting effects of advection. Advection has been found to be inversely proportional to the size of sample evaporating surface.

In order to obtain actual evapotranspiration rates from lysimeters, a water budget is carried out. The errors in such an approach usually arise from soil moisture measurements over short periods; but seasonal estimates can however be achieved more accurately (Linsley et al., 1982). The errors that may be encountered in soil moisture measurement can be minimized by using hydraulic lysimeters which show the slightest changes in weight. The only drawback with this type of lysimeters is their complexity (Lenselink, 1988).

Lysimeters have only been used in few research stations in Kenya like in East African Agricultural and Forestry Research Organization (EAAFRO) at Muguga between 1960 and 1970 (Edwards and Blackie, 1981). It is well recognised now that more reliable estimates of actual evapotranspiration can be obtained from lysimeters with diameters of 5 m or more (Linsley et al., 1982). However, such accuracy can only be achieved if provision is made at the base of the lysimeter to simulate the suction force similar to that in the natural soil profile.

Suggestions have also been made to integrate point values of actual evapotranspiration just as point rainfall is integrated. Such integration is limited by variations which may be due to changes in radiation, vegetation, slope orientation and elevation of terrain. Additional variation results from differences in soil moisture availability and transpiration characteristics of the vegetation.

The above mentioned constraints entirely limit the use of lysimeters in the measurement of actual evapotranspiration on a catchment basis. But because of the significance of actual evapotranspiration in catchment water balance studies, alternative approaches of obtaining its value have to be sought. The most widely used alternative is through estimation which is discussed in the following sections.

2.3 Estimation of AET Based on PET Estimates

Because of the difficulties faced in the measurement of actual evapotranspiration, estimation techniques have been used. These techniques are based on the factors that affect evapotranspiration. Potential evapotranspiration is first estimated then adjustment made to account for varying vegetation and soil moisture conditions thereby yielding actual evapotranspiration values.

The methods used in estimation of potential evapotranspiration can be classified into three general categories depending on the approach used. The three approaches are the energy balance, the aerodynamic and the combined energy balance and aerodynamic approach. The third approach of combined energy balance and aerodynamic approach was pioneered by Penman in 1948 and is popularly known as the combination method for evaporation.

2.3.1 The combination method for PET

Early methods for estimating evapotranspiration (such as Thornthwaite method) only relied on temperature, but this is only suitable for approximate estimation. For hydrologic estimation, combination of both the energy balance and the aerodynamic approaches is desirable (Newson, 1979). Penman in 1948 in a classical study of natural evaporation, developed a formula for calculating open water evaporation based on fundamental physical principles and incorporating some empirical concepts. The physical principles combine the energy budget and the aerodynamic approach. The basic equations of the two approaches were modified and rearranged to permit the use of meteorological constants and those variables regularly measured at climatological stations (Shaw, 1984).

From later experience, the formula for estimating open water evaporation was modified to allow for the conditions in which both evaporation and transpiration take place from a vegetated surface. The final equation was developed to estimate potential evapotranspiration (PET) directly. Penman presented equations which are widely documented (Mohan, 1991; Michalopoulou and Papaioannuo, 1991; Chiew and McMahon, 1991) to compute both terms in the combination method.

The Penman combination method has received considerable acclaim as a method for estimating both open water evaporation and potential evapotranspiration (Shih and Cheng, 1990). Shaw (1984) reports that practising engineers widely use the Penman method in solving questions on water loss.

Despite the superiority of Penman's combination method, researchers have expressed concern over the bulk of data needed (temperature, vapour pressure, sunshine hours and average wind run); some of it not measured by most meteorological stations. Chiew and McMahon (1991), cite the high data demand as a limitation to the use of Penman's equation in Australia. However, Shih and Cheng (1990) suggested, that any inadequacy of climatological data can be overcome by using the data of a similar area to fill the gaps. The similarity can be assessed in terms of vegetation zones, temperature, rainfall and seasonal characteristics (Critchfield, 1974).

Many procedures for estimating or calculating potential or actual evapotranspiration have been proposed. Priestley and Taylor in 1972 proposed a modification of the Penman equation to ease data requirement. This equation has been found to give similar estimates of PET with the Penman equation in tropical regions lying between latitudes 25 ° N and 25 ° S and rainfall exceeding PET (Gunston and Batchelor, 1983). Most of the formulae are based on one of the three previously outlined methods of studying evaporation while a few others adopt a purely empirical approach while retaining minimal of the actual physical processes involved. But Ward (1967) pointed out that empirical approach is inevitable considering the magnitude and complexity of the problem. Some of the widely acclaimed empirical equations are as follows.

2.3.2 Thornthwaite method for PET

Thornthwaite in 1948 in an attempt to find an expression for PET to serve irrigation engineers' needs, developed a formula based on temperature with an adjustment for the number of daylight hours. The formula only needs data on mean monthly temperature. It is empirical and somewhat complex. It requires nomograms and tables as computing aids. Suitable nomograms are however available and the formula has been widely applied with great success in the related fields of climatology, hydrology and soil studies (Ward, 1967).

Although widely used, it has been found invalid in climates different from that of eastern U.S.A. where it was developed (Shaw, 1984). Lenselink (1988) reports that there is a possibility that the formula underestimates PET in Kenya because of altitude. Similar findings have been reported by Edwards and Blackie (1981). This makes the formula unsuitable for PET estimation in Kenya.

2.3.3 Blaney - Criddle method for PET

Another simplified formula for estimating PET was developed by Blaney and Criddle in 1950 in the arid western regions of U.S.A. The equation involves the use of mean monthly temperature and percent of total annual daylight hours, p', occurring during the period being considered to calculate the consumptive use factor, f' (Doorenbos and Pruitt, 1977). By applying an empirically determined consumptive use crop coefficient, k, Blaney and Criddle established the consumptive water requirements, Cu, by the equation;

$$Cu = kf' = k(p'T/100) \qquad (2.1)$$

Given that T is the mean monthly temperature in ° F

The consumptive water requirement in this case was defined as "the amount of water potentially required to meet the evapotranspiration needs of vegetative areas so that plant production is not limited by lack of water". However, Doorenbos and Pruitt argue that the effect of climate on crop water requirements is insufficiently defined by temperature and daylength; crop water requirements will vary widely between climates with similar values of temperature and percentage of total annual daylight hours. At the same time, the consumptive use crop coefficient will need to vary with both the crop and very much with climatic conditions. Considerable modification on the original Blaney-Criddle equation was undertaken by Doorenbos and Pruitt (1977) to facilitate the evaluation of reference crop evapotranspiration, ET_o. Reference crop evapotranspiration was defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water". Most equations used to estimate PET first begin with the estimation of ET_o. PET can then be obtained from ET_o by undertaking adjustments for crop variations and those other factors affecting crop evapotranspiration under given climatic conditions.

The fact that the original Blaney-Criddle method only used temperature and percentage of total annual daylight hours, suggests that there would be insignificant variation in PET and consequently AET under Kenyan conditions because temperatures show minimum variation. In fact a study carried out in Nigeria a country in the tropics like Kenya supports the above hypothesis (Jackson, 1988). A great deal of literature exists on the original Blaney-Criddle method (Schwab et al.,1981; Mavi,1974)

2.4.4. Woodhead method for PET

Working on open water evaporation at Muguga, Woodhead (1968) established a distinct relationship between annual evaporation totals and altitude. Since temperature is related to altitude, a straightforward relation between annual open water evaporation and temperature was developed. The expression for open water evaporation was given as;

$$E_o = 2422 - 0.358d_l \qquad (2.2)$$

where;

E_o = Estimated annual open water evaporation (mm/yr)

d_l = Distance from the station to the coast (km)

The computed E_o values can then be converted to PET multiplying it by an empirical constant mainly taken to be 0.9. Hence PET = $0.9E_o$. The same ratio was obtained by Pereira and Hosegood (1962) for pine, cypress and bamboo plantations in Kinale area, the lower edge of the Aberdare mountains. The validity of such an approach is still unclear. The empirical constant 0.9 cannot be taken as constant throughout particularly for annual crops whose water demand varies from one stage to the other. This constraint makes it unsuitable in the estimation of AET on agricultural catchments that are mainly under annual crops.

2.3.5 Hargreaves and Samani method for PET

On finding that the data requirement of methods recommended to estimate ET_o was considerable, Hargreaves and Samani in 1985 proposed an equation that only needed values of maximum and minimum temperatures which are measured in most meteorological stations. ET_o is largely influenced by the characteristics of the reference crop, solar radiation, air temperature and advective energy. The interactions of temperature, relative humidity and/or vapour pressures and wind influence advection. These interactions prompted Hargreaves in 1981 and Hargreaves and Samani in 1985 (Hargreaves, 1989) to propose the use of average daily temperature range, TD, for estimating solar radiation. Richardson in 1980 developed a procedure for estimating average minimum monthly relative humidity in percentages from the daily temperature range. Thus from the aforementioned relationships, the equation proposed by Hargreaves and Samani in 1985 was of the form;

$$ET_o = 0.0023Ra(T+17.8)TD^{0.5} \quad \text{(2.3)}$$

where;

ET_o is given in equivalent units of evaporation (mm)

Ra = Extraterrestrial radiation which is obtained from already developed relationships (mm)

T = Mean of maximum and minimum air temperatures

TD = Temperature range = Mean maximum - mean minimum ; all temperature values are expressed in ° C.

This method could be used to evaluate ET_o over a period of five days or a month. The values of ET_o obtained by this method were found to be satisfactory for irrigation scheduling for most of the regions tested (Hargreaves, 1989).

One limitation that has been cited in this approach is its failure to incorporate wind function which has been found to have considerable effect on evapotranspiration. This equation just like the ones already outlined, is empirically derived and consequently requires local calibration. Further the method is relatively new in the field of evaporation and hence its application would always go with considerable scepticism. Hargreaves (1989) pointed out that the method is satisfactory for irrigation scheduling and management but needs to be tested for water resources studies. On the other hand it is important to appreciate the simplicity of this equation and its low data requirement.

2.4. Conversion of PET to AET

As outlined earlier in the Blaney-Criddle method, Doorenbos and Pruitt modified three other formulae to enhance the computation of ET_o. These three others were the Radiation method, Penman method and Pan evaporation method. The Penman method that was modified by Doorenbos and Pruitt (1977) is often referred to as the modified Penman method. The previous equation was found to inadequately simulate the aerodynamic term in arid regions where this component is significant. Therefore the modification that was undertaken by Doorenbos and Pruitt was with the wind function. Kalders (1988) used the modified Penman method to compute ET_o for 90 stations in Kenya using grass as the reference crop.

To obtain AET values for a given crop/vegetation, the corresponding ET_o estimate is first converted to PET by introducing that crop's crop coefficient, kc. Then from the estimated PET, AET is obtained as the product of PET and a soil coefficient, ks. The procedure for obtaining AET estimates from the respective ET_o values is elaborated in the sections that follow.

2.4.1 Conversion of ET_o to PET using crop coefficient, kc

Crop potential evapotranspiration is linked to the reference crop evapotranspiration via the crop coefficient, kc, which gives the effect of crop characteristics on crop water requirements. Values of kc are dependent on the crop, the development stage of the crop, the growing season and the prevailing weather conditions (Doorenbos and Pruitt, 1977). Fig. 2.1 shows the relationship between kc, ET_o and the average recurrence interval of irrigation or significant rain.

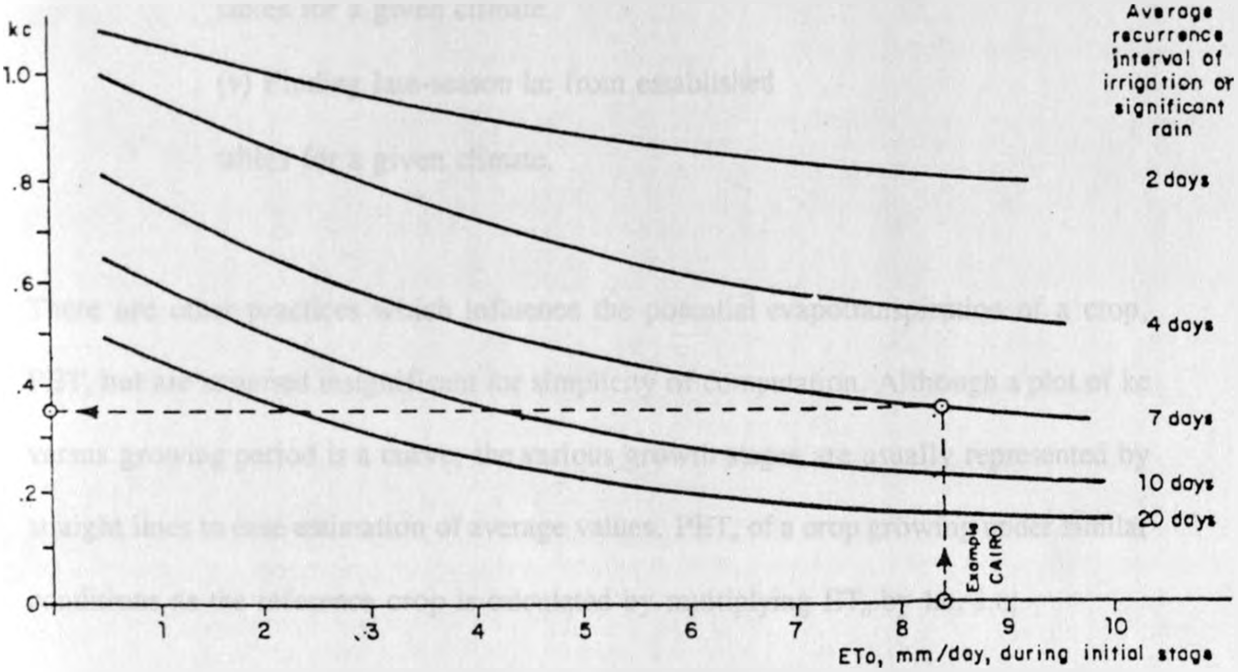

Fig. 2.1 Average kc value for initial crop development stage as related to level of ET_o and frequency of irrigation and/or significant rain.

Source: FAO, 1977

Evaluation of kc values is a five steps procedure namely;

(i) Establishing the planting season from local information or from practices in similar climatic zones.

(ii) Determining total growing season and length of each growing stage from local information.

(iii) Finding initial stage kc from rainfall frequency and predetermined ET_o.

(iv) Finding mid-season kc from established tables for a given climate.

(v) Finding late-season kc from established tables for a given climate.

There are other practices which influence the potential evapotranspiration of a crop, PET_c but are assumed insignificant for simplicity of computation. Although a plot of kc versus growing period is a curve, the various growth stages are usually represented by straight lines to ease estimation of average values. PET_c of a crop growing under similar conditions as the reference crop is calculated by multiplying ET_o by kc, i.e;

$$PET_c = ET_o * kc \quad \ldots\ldots (2.4)$$

where;

PET_c = A given crop's PET (mm)

kc = Crop coefficient (a ratio, that vary over the range $0.2 \leq kc \leq 1.3$ (Doorenbos and Pruitt, 1977))

2.4.2 Conversion of PET to AET using soil coefficients, ks, and soil moisture deficit (SMD)

Evapotranspiration of a crop is influenced by the amount of moisture available in the soil. Chow et al, (1988) reported that the amount of water in the soil can be represented by the soil coefficient, ks. For a well watered soil (soil at field capacity, soil water tension = 0.1 to 0.3 atm.), a soil coefficient of 1 is allocated while for very dry soils (soil at permanent wilting point, water tension of 15 atm.), the ks is 0. The AET for a given crop is calculated as the product of PET_c and the prevailing ks, i.e.;

$$AET = PET_c * ks \quad \text{......} \quad (2.5)$$

Value of ks varies with soil type, the state of the soil moisture and the meteorological conditions (Ponnambalam and Adams, 1985). This shows that on a catchment basis, ks shows both spatial and temporal variation thereby making its application in AET estimation more complex.

Researchers have also attempted to develop relationships between the soil moisture status and the ratio of AET:PET. Examples of such relationships were those used by Sharma and Irwin (1976) in the analysis of drainage depth from a tile drained watershed (Fig. 2.2).

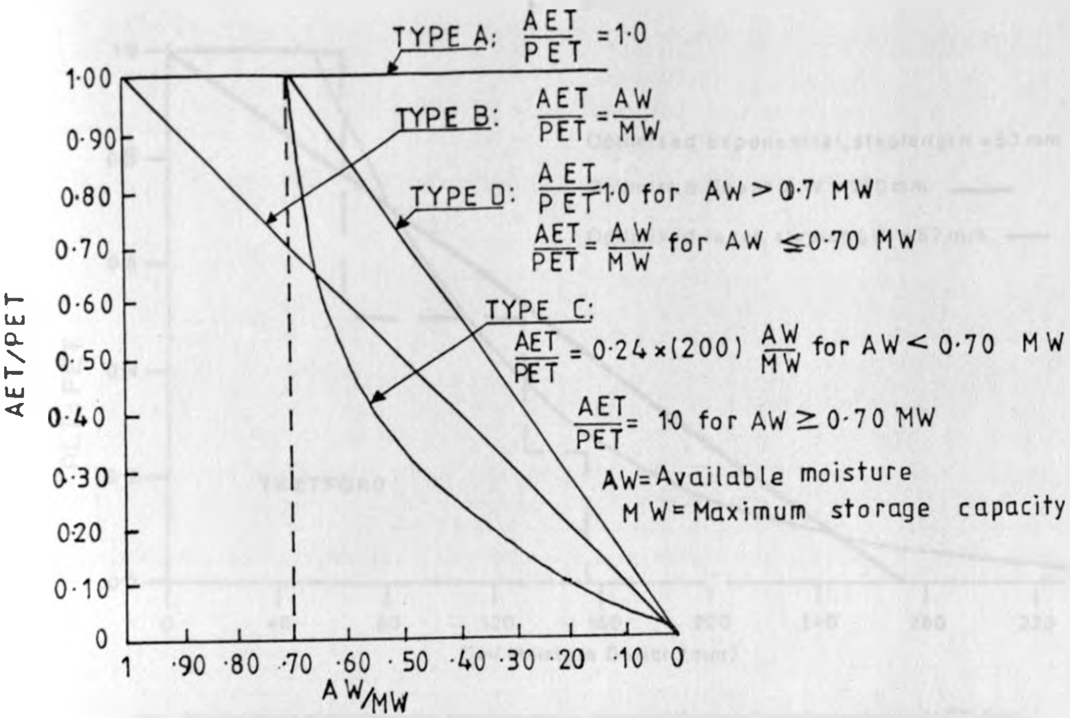

Fig. 2.2 Relationship between AET/PET and available soil moisture

Source: Sharma and Irwin, 1976

In Fig. 2.2, the soil moisture status is expressed as the ratio of available water, AW, to maximum storage capacity, MW. One of the curves of significance among the ones used by Sharma and Irwin is that developed by Thornthwaite and Mather in 1939 which has also been used by Obasi (1970) and Ojo (1974) in station water balance studies. Calder et al, (1983) presented other graphs relating AET:PET with soil moisture, this time expressed as soil moisture deficit, SMD (Fig. 2.3). Another linear relationship between soil moisture status and AET was used in Boughton and HYDROLOG models in calculating actual evapotranspiration (Chiew and McMahon, 1991). The upper constraint on AET in this analysis was the plant-controlled maximum transpiration rate which in most applications was estimated as a fraction of evaporation pan reading.

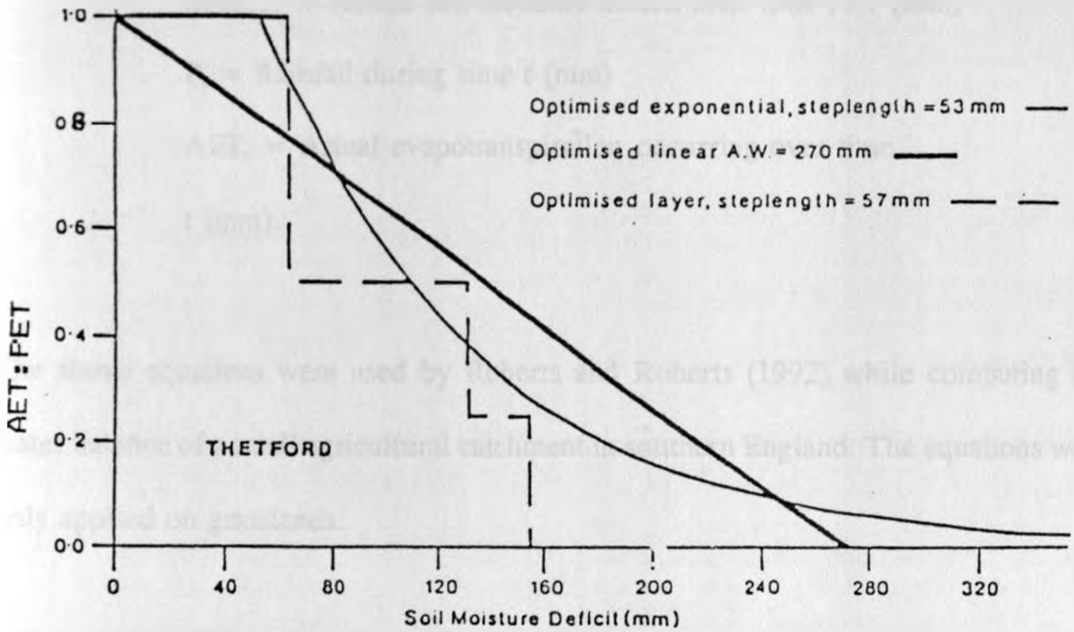

Fig. 2.3 The forms of the regulating functions used to determine the actual evapotranspiration (AET) from potential evapotranspiration (PET) from a sample site

Source: Calder et al., 1983

It is important to note that the two graphs (Fig. 2.2 and Fig. 2.3) can be obtained if measured soil moisture data is accessible but as hinted earlier it is usually difficult to measure soil moisture on a catchment scale. However, Calder et al. (1983) came up with a mathematical formulation of a model to estimate SMD. The formula is;

$SMD_{t+1} = SMD_t + AET_t - P_t$ ....(2.6)

for $SMD_t > 0$ and

$SMD_{t+1} = AET_t - P_t$ ....(2.7)

for $SMD_t < 0$

where;

SMD_t = Actual soil moisture deficit after time t (mm)

SMD_{t+1} = Actual soil moisture deficit after time t+1 (mm)

P_t = Rainfall during time t (mm)

AET_t = Actual evapotranspiration occurring over time t (mm)

The above equations were used by Roberts and Roberts (1992) while computing the water balance of a small agricultural catchment in southern England. The equations were only applied on grasslands.

2.4.3 The Grindley model based on the Penman Root constant concept

Grindley (1970) and Grindley and Singleton (1967) computed SMD using data on rainfall and PET. Soil moisture in this analysis was defined as the amount of water required to restore the soil to field capacity after depletion by the demands of vegetation. As SMD increases, AET becomes increasingly lower than PET. Although SMD and AET have been found to vary with soil type and vegetation, the relative decrease of AET with increasing SMD has been the subject of considerable study by botanists and soil physicists (Shaw, 1984). Evaluation of SMD by the Grindley method is achieved by first evaluating potential soil moisture deficit (PSMD) and then reducing it to actual soil moisture deficit depending on a crop's root constant. Potential soil moisture deficit is given by the equation;

$$PSMD_{(t+1)} = SMD_{(t)} + PET_{(t+1)} - P_{(t+1)} \qquad \text{.....(2.8)}$$

where;

$PSMD_{(t+1)}$ = Potential SMD of period t+1 (mm)

Other terms remains as defined earlier.

Depending on the value of PSMD obtained, the actual soil moisture deficit is calculated to meet the requirements set as outlined in section 3.5. One of the requirements that determined the level of PSMD was the maximum permissible soil moisture deficit which is a crop characteristic. In this context, any value of PSMD greater than the maximum permissible soil moisture deficit was considered equal to this maximum value. Values of this quantity for a number of crops are given in table 2.1

Table 2.1 Maximum permissible soil moisture deficits (mm) for crops/vegetation.

Crop/vegetation	Maximum soil moisture deficit
Maize	200
Beans	100
Potatoes	150
Grass	125
Bananas	100
Tea	250
Sugarcane	150
Pyrethrum	125
Coffee	250
Trees	250

Source: Grindley, 1970

This technique was used by Grindley and Singleton (1967) to prepare SMD maps of the U.K. The estimation of SMD starts at the beginning of a growing season when the soil is at field capacity.

In order to estimate the actual evapotranspiration, the Penman root constant, Rc, concept was used. Penman introduced the concept of a root constant, Rc, which defines the amount of soil moisture (mm depth) that can be extracted from the soil without difficulty by a given vegetation. In this concept, AET is assumed to proceed at the potential rate until SMD reaches a given vegetation's Rc plus a further 25 mm approximately. The 25 mm was added to allow for extraction from the soil immediately below the root zone. Table 2.2 lists some of the typical root constants (Shaw, 1984).

Table 2.2 Root constant values suggested by Penman

Vegetation type	Rc (mm)
Permanent grass	75
Root crops (e.g. potatoes)	100
Cereals (e.g. wheat)	140
Woodland	200

Source: Shaw, 1984

Grindley estimated AET from estimates of SMD and PET by incorporating Penman's root constant concept. The argument here was that as it rains, the soil moisture increases until the soil becomes saturated provided the amount of rainfall is sufficient to cause saturation. Thereafter the soil cannot hold more water. Within the range of field capacity, actual evapotranspiration was assumed equal to the potential evapotranspiration as determined by meteorological conditions. But if no rain replenishes the soil moisture used by vegetation, soil moisture deficit builds up.

The equation proposed by Grindley for estimating actual evapotranspiration over a given period is given by:

$$AET_{t+1} = SMD_{t+1} - SMD_t + P_{t+1} \qquad (2.9)$$

Where;

AET_{t+1} = Actual evapotranspiration over time t+1 (mm)

P_{t+1} = Rainfall during time t+1 (mm).

SMD_{t+1} = Actual soil moisture deficit in time t+1 (mm).

SMD_t = Actual soil moisture deficit at time t (mm)

For the estimation of the actual evapotranspiration of an entire catchment, the AET from each vegetation is multiplied by the proportion of the catchment it occupies then summed. This necessitates a land-use survey and vegetation classification because the rate of transpiration varies from vegetation to vegetation.

The potential evapotranspiration equation used in this approach was that published by Penman in 1963 which is widely documented in evaporation texts (Viessman et al., 1989; Schwab et al., 1981). It is suggested however that computation of SMD and AET over longer periods should be avoided due to anomalies caused by persistent dry spells and the irregular incidence of rainfall (Shaw, 1984).

2.4.4 Kotoda model for AET

Although many researchers have attempted to estimate actual evapotranspiration using the complementary relationship advanced by Morton (1983) and others, little has been done to account for the complicated topography and variable land-use. This was the argument advanced by Kotoda (1989) while developing a model to estimate actual evapotranspiration. In this model PET was first estimated using Penman's combination method and then converted to AET through multiplication by an empirical conversion factor, a constant. The empirical constant, a fraction, was estimated by means of multiple regression which depended on rainfall, temperature and wind speed.

The complicated topography and variable land-use influence the amount of energy available for evapotranspiration. The modification undertaken on the Penman PET estimation method was in the computation of the net solar radiation. Kotoda improved the accuracy of estimation of the net solar radiation by treating the short-wave irradiance to consist of direct, sky-diffuse and ground-reflected diffuse irradiance. The computation of these three components together with other relevant terms are well documented in Kotoda (1989). The model combines Penman relationships developed in 1948 and 1963 thereby having;

$AET = f_o (E_e + E_a)$ ....(2.10)

Given that ;

E_e = Equilibrium evaporation rate (mm/day)

E_a = Aerodynamic term (mm/day)

f_o = Conversion factor to convert PET to AET.

Kotoda model yielded AET values which compared fairly with estimates obtained by water balance analysis.

Other methods which make direct computations of AET are discussed in the sections below.

2.5 Direct Methods of Estimating AET

2.5.1 The Morton - model for AET

Morton (1983) argued that direct measurements of actual evapotranspiration cannot be projected from point to areal values because of unverified assumptions. But after going through most of the literature dealing with actual evapotranspiration estimation, Morton suggested that those techniques based on the complementary relationship could be used. The complementary relationship between AET and PET is given by the equation;

$AET + PET = 2E_{TW}$ ....(2.11)

Where;

AET and PET are as defined before while E_{TW} is the wet environment areal evapotranspiration

(W/m^2).

Therefore actual evapotranspiration can be evaluated as;

$$AET = 2\,E_{TW} - PET \qquad (2.12)$$

Wet environment areal evapotranspiration is the evapotranspiration that would occur if the soil - plant surfaces of the area were saturated. Hence there would be no limitations on availability of water. The areal evapotranspiration (AET) was considered to be evapotranspiration from an area so large that the effects of upwind boundary transitions, such as soil moisture conditions are negligible (Morton, 1983).

The complementary relationship is assumed to hold from the fact that at low moisture content, the potential evapotranspiration is maximum and equals to $2E_{TW}$. But as soil moisture increases, actual evapotranspiration increases and consequently causes the overpassing air to become cooler and more humid. The cooling and increase in humidity produces an equivalent decrease in PET (see Fig. 2.4).

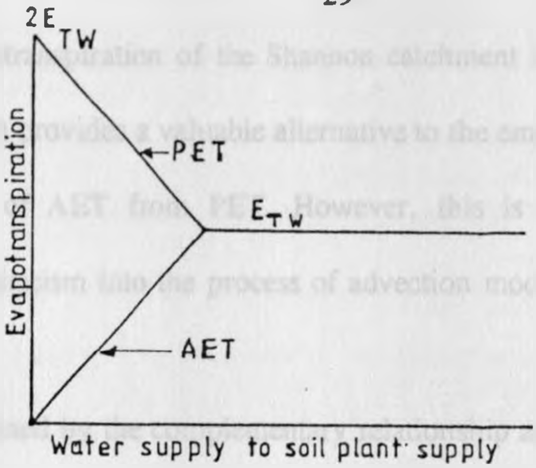

Fig. 2.4 Relationship between evapotranspiration and water supply to the soil plant surface

Source: Morton, 1983

Though it is difficult to verify the complementary relationship, some experimental evidence exist suggesting its validity (Sharma, 1988; Morton, 1983).

One advantage of the complementary relationship is that it avoids the complex processes and interactions of the soil-plant -atmosphere system. The approach only relies on routine climatological observations in computing PET and E_{TW} and avoids the representation of those relationships that are poorly defined.

There are two main components of the complementary relationship namely potential evapotranspiration, PET, and wet-environment areal evapotranspiration, E_{TW}. PET computation is accomplished through estimation of potential evapotranspiration equilibrium temperature, T_P, which is done by an iteration process. T_P is the temperature at which the energy-balance and the vapour transfer for a moist surface give the same result. Net radiation for the soil-plant surface, station atmospheric pressure and other quantities are used to estimate E_{TW}. Doyle (1990) used the Morton model in modelling evapotranspiration of the Shannon catchment in Ireland and found that the Morton approach provides a valuable alternative to the empiricism of the Thornthwaite-style reduction of AET from PET. However, this is achieved at a high cost of introducing empiricism into the process of advection modelling.

The results obtained by the complementary relationship approach were compared with water-budget estimates of areal evapotranspiration for 143 river basins distributed over a wide range of climates by Morton (1983). The mean absolute deviation of AET estimates by the complementary relationship approach from the equality line of the water budget estimates was 3.4%. However, Morton recommended further testing of the complementary relationship models.

2.5.2 Water balance equation for AET

Several water balance equations have been proposed with variations mainly being brought by the dominant elements of the water budget in a given region. Existence of many equations is also brought by the period of analysis and the size of area being dealt with. Because no water is created or destroyed in any segment of the hydrologic cycle, the hydrological balance equation can be taken as a reflection of this situation. The basic hydrological equation is;

Inflow - Outflow = Change in storage

The components of inflow of a river basin would consist of rainfall over the catchment together with any seepage of groundwater across the topographic divide. Outflow on the other hand would consist of evapotranspiration, streamflow and groundwater seepage out of the catchment. Change in storage would largely be reflected by changes in groundwater level and to a lesser extent by variations of soil moisture content, although the later would probably not be very important to the total quantities of water involved (Ward, 1967).

The most widely adopted water balance equation on a catchment basis is expressed as;

$$P = R + AET \pm \blacktriangle S \qquad (2.13)$$

Given that;

P = Precipitation (mm)
R = Runoff (mm)
AET = Actual Evapotranspiration (mm)
$\blacktriangle S$ = Change in storage (mm)

All the above quantities are expressed as depth of water over a given period. In the tropics snowmelt is found only in high mountains otherwise it is only rainfall that is quite significant as an input (Shaw, 1984). From the above equation actual evapotranspiration can be evaluated if the other quantities are known.

In the East African catchment experiments, Edwards and Blackie (1981) described a water balance of a water tight catchment over a given period by the equation;

$$AET = P - R - \Delta S_1 - \Delta G_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.14)$$

Where $\blacktriangle S_1$ refers to change in soil moisture while $\blacktriangle G_1$ represents change in groundwater, all other terms are as defined above. It was however pointed out in this analysis that the calculation of AET by difference becomes more precise when $\blacktriangle S_1$ and $\blacktriangle G_1$ are evaluated in the dry season. This is because the transfer of infiltrated water from soil moisture to groundwater and finally to base flow is slow. During the dry season, $\blacktriangle S_1$ can be measured with great precision and $\blacktriangle G_1$ can be estimated from base-flow recession curves with some confidence (Edwards and Blackie, 1981).

Rainfall and runoff are the only measurable components of the water budget in a catchment. Soil moisture change can also be measured by a number of methods. However, over a long period of analysis say a year or more, the change in storage is usually insignificant. In general the accuracy of the water balance equation depends on the accuracy of the catchment precipitation and streamflow measurements as well as the validity of the assumptions made (Lee, 1980).

Most models developed to estimate actual evapotranspiration have been tested using the water balance estimates (Morton 1983; Kotoda, 1989; Chun, 1989; Sharma, 1988). Hsuen-Chun (1988) used water balance approach to estimate annual AET of a number of catchments in the Southern part of North-East China and later used these estimates to test the accuracy of a mathematical model formulated to evaluate annual evapotranspiration. This shows that the approach is proven although its accuracy depends on the accuracy of measured rainfall and runoff and time scale chosen for the comparison.

2.5.3 Aerological water balance approach for AET

Actual evapotranspiration has also been estimated widely using the aerological approach by meteorologists. It requires data on vertical profile of the wind and specific humidity (Obasi and Kiangi, 1975). Relevant data for the aerological approach is obtained from a good network of radiosonde/rawind station which define the area of interest. Data on vertical profile of the wind and specific humidity helps in determining the net outflow of water and liquid or solid water content from the atmospheric water column, and the change of the total water content in the same portion of the atmosphere. The equation used to estimate actual evapotranspiration by the atmospheric water balance approach can be written as;

$$AET = P - R_o + S_a \qquad \text{.........(2.15)}$$

where;

P = Rainfall (mm)

R_o = Net outflow water vapour and liquid or solid water content from the atmospheric water column (mm)

S_a = Change of total water content in the same portion of the atmosphere (mm)

The aerological water balance approach was used by Kiangi (1972) to estimate large scale actual evapotranspiration over a sector of East Africa using data from Nairobi, Entebbe and Dares-salaam. The aerological approach essentially requires installation of sophisticated equipment for the collection of relevant data as evidenced by the existence of only three stations in the whole of East Africa. It would therefore be an inappropriate method for water resources studies which are mainly situated in rural locations. The method too does not give estimates of AET of a defined catchment.

2.5.4 Turc formula for AET

A formula for estimating actual evapotranspiration of catchments was published by Turc as documented in Shaw (1984). Using data from 254 drainage basins representing different climates in Europe, Africa, America and East Indies together with the water balance equation, Turc evaluated actual evapotranspiration from precipitation and runoff. The annual evapotranspiration from a catchment was thus expressed as;

$$AET = \frac{P_A}{[0.9+(\frac{P_A}{L})^2]^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.16)$$

where;

AET = Annual evapotranspiration (mm)

P_A = Mean annual precipitation (mm)

L = 300 + 25 T + 0.05 T^3 (mm)

T = Mean air temperature (^{0} C)

This equation appears quite simple as it only involves rainfall and temperature. The method can only be used to compute annual AET values therefore is inappropriate for shorter durations say a season. Its application has not been common as it has not been cited much in the recent literature. However, it is hard to conclude the worth of the formula based on its minimal documentation. Hsuen-Chun (1988) has also presented another method of estimating annual evapotranspiration using pan evaporation data, precipitation and average forest cover.

2.6 Estimation of Actual Evapotranspiration in Kenya

As discussed in the literature review, little has been done to estimate areal evapotranspiration from agricultural catchments in Kenya. Obasi and Kiangi (1975) have presented an approach to estimate AET but the approach does not give a picture of the actual loss of water through evapotranspiration from a defined catchment. Although Morton tested the model based on the complementary relationships on some catchments in Kenya, the applicability of the model under specified conditions was not given as it was rather a generalized conclusion of basins throughout the world. Nyenzi (1978) also applied the original Morton model (published in 1971, 1975, 1976 and 1977) to estimate actual evapotranspiration on 106 stations in East Africa. This approach too had a limitation in that it dealt with meteorological stations and not a clearly defined catchment. The work was also not validated so as to appreciate the usefulness of the model for water resources studies. Furthermore Morton improved this model in the 80's which therefore needs testing.

During studies of evapotranspiration in Kenya, Woodhead (1968) estimated open water evaporation from which PET could be estimated. No alternative of AET estimation was proposed. In the East African catchment experiments (Edwards and Blackie, 1981), actual evapotranspiration was obtained by a water balance method simply because it was possible to measure all the components of the water balance except evapotranspiration. However, in most instances measurement of each component of the water balance is laborious and expensive. The East African catchment experiments mainly concentrated on Penman model in evaluating crop coefficients.

The above mentioned limitations prompted seeking of alternative methods of estimating actual evapotranspiration in Kenya to be usable in water resources planning exercises. The use of models was one of the alternatives. The Morton and Grindley models both require meteorological data which are readily available in most stations in Kenya and hence their worth should be established so that either could be used in water resources studies. The findings are expected to help ascertain whether meteorological data which are readily available can be used in evaluating the evapotranspiration component which plays a noteworthy role in water resources planning and management.

3.0 MATERIALS AND METHODS

3.1 Description of Catchments

The studies for evaluating actual evapotranspiration using Morton and Grindley models and water balance method were carried out in four catchments which are shown on a map of Kenya (Fig. 3.1). The details of these catchments are presented in Table 3.1 and Figs. 3.2 through 3.5 respectively.

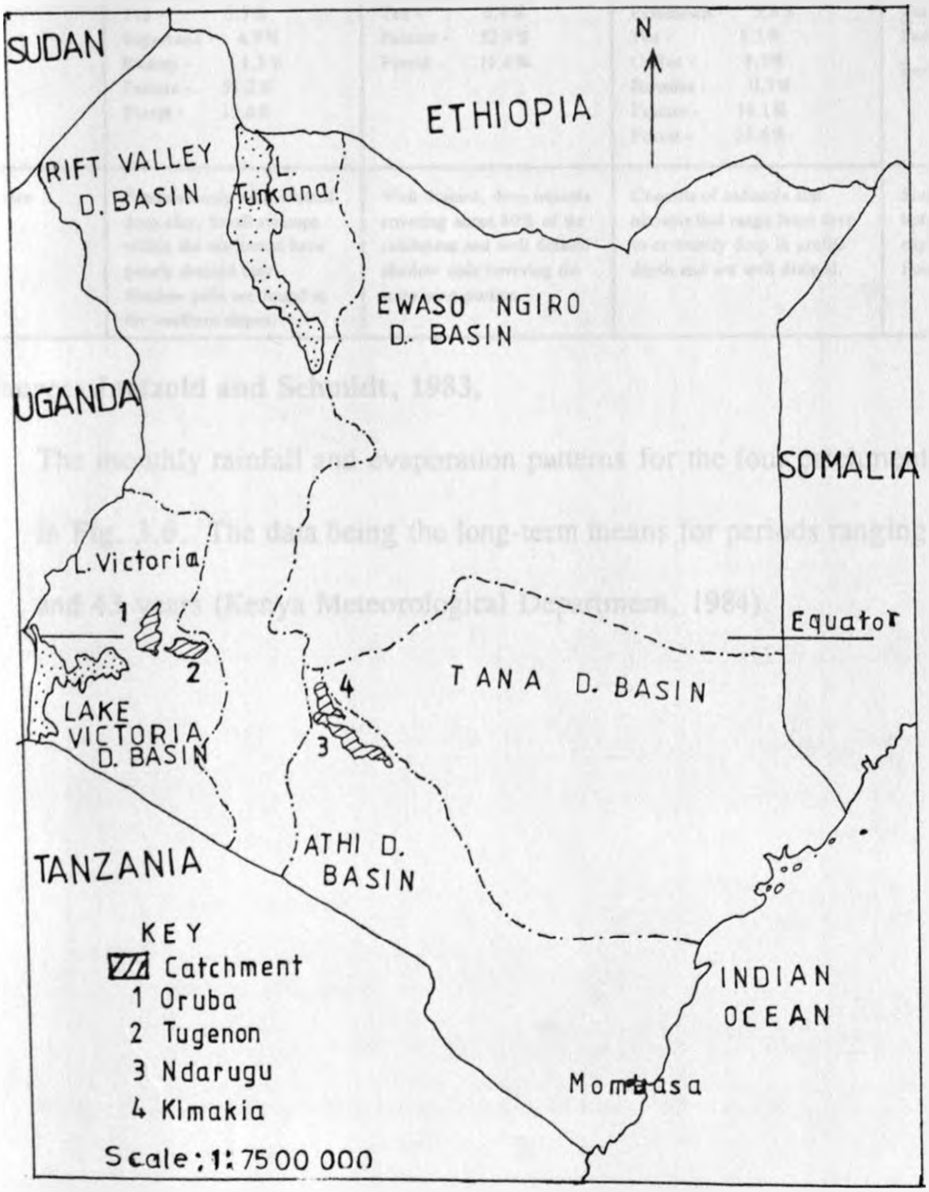

Fig. 3.1 Location of catchments in Kenya

Table 3.1: Catchments characteristics

Catchment	**Oruba**	**Tugenon**	**Ndarugu**	**Kimakia**
Area (km^2)	62.2	46.6	97.0	51.5
Boundary Latitudes	0° 05' N and 0° 01'S	0° 14'S and 0° 18'S	0° 51'S and 1° 00'S	0° 43'S and 0° 50'S
Boundary Longitudes	34° 58'E and 35° 02'E	35° 25'E and 35° 31'E	36° 37'E and 36° 55'E	36° 42'E and 36° 48'E
Agro-ecological zones	-Lower highland -Upper midland -Lower Midland Rainfall is bimodal and falls between February-May and July-October Mean annual rainfall is 2168.2 mm	Upper highland and Lower highland. Mean annual rainfall and pan evaporation are 1783.7 mm and 1355 mm respectively. Rainfall comes during the months of March-November	-Upper highland -Lower Midland -Upper Midland. Long-term annual rainfall is about 1500 mm. Long rains fall from March-May short rains come in October and November.	The catchment is entirely under the upper highland zone and receives high rainfall (mean of 2178.8 mm/yr) and falls in two seasons, first; March-June, second; October-December.
Major Land-use	Maize - 20.1% Beans - 2.1% Potatoes - 0.9% Tea - 3.7% Sugarcane - 4.9% Swamp - 1.5% Pasture - 51.2% Forest - 15.6%	Maize - 20.2% Beans - 5.9% Pyrethrum - 3.3% Tea - 6.8% Pasture - 52.4% Forest - 11.4%	Maize - 18.8% Beans - 5.2% Potatoes - 3.4% Pyrethrum - 3.8% Tea - 8.5% Coffee - 8.3% Bananas - 0.3% Pasture - 16.1% Forest - 35.6%	Maize - 1.1% Beans - 0.2% Potatoes - 0.3% Tea - 0.9% Pasture - 0.8% Forest - 96.7%
Major Soil types	Predominantly well drained deep clay. Small swamps within the catchment have poorly drained clay. Shallow soils are found in the southern slopes.	Well drained, deep nitosols covering about 80% of the catchment and well drained shallow soils covering the remaining portion.	Consists of andosols and nitosols that range from deep to extremely deep in profile depth and are well drained.	Similar to that of Ndarugu but generally deep. This explains why the forest has flourished.

Source: Jaetzold and Schmidt, 1983.

The monthly rainfall and evaporation patterns for the four catchments are shown in Fig. 3.6. The data being the long-term means for periods ranging between 14 and 43 years (Kenya Meteorological Department, 1984).

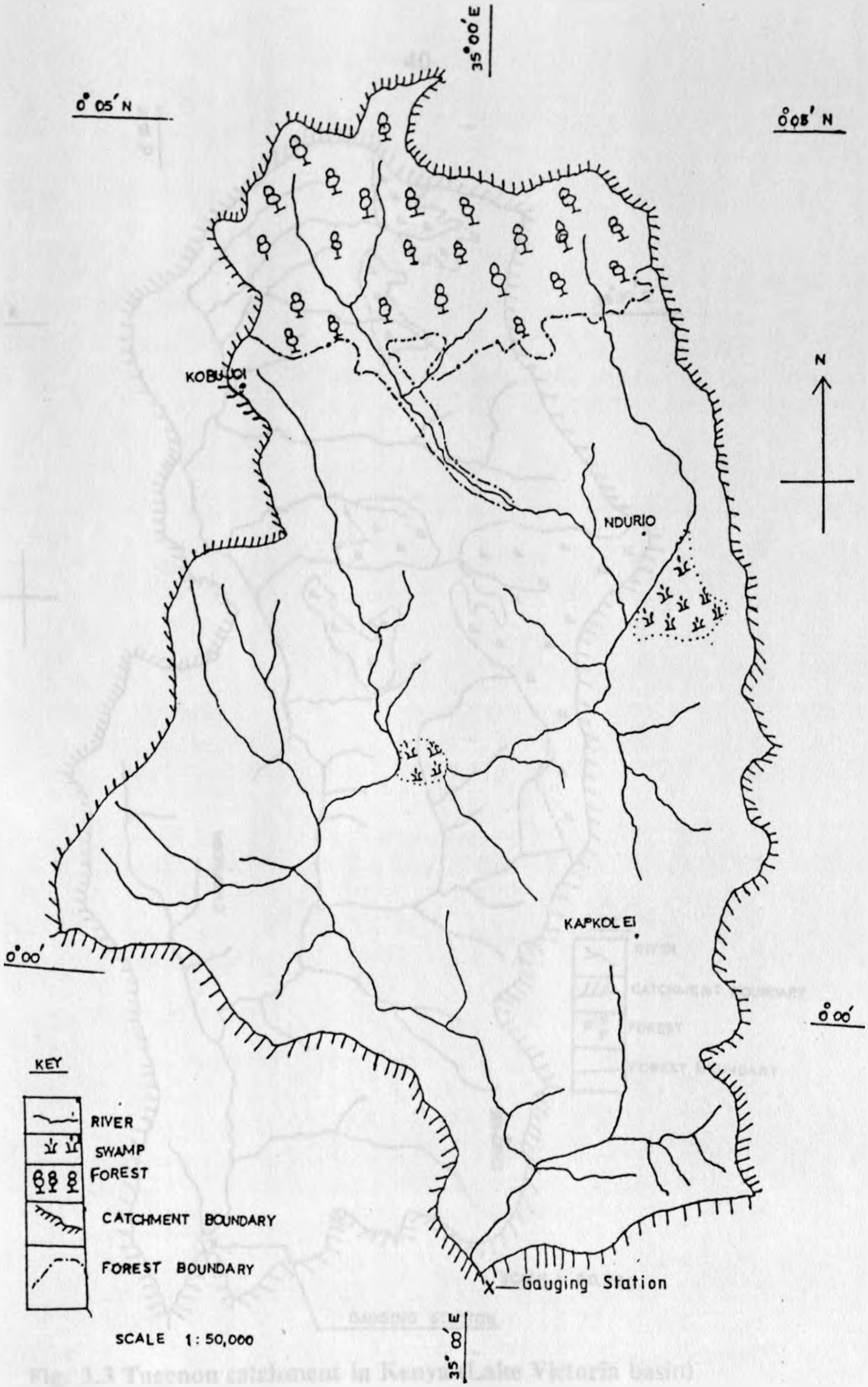

Fig. 3.2 Oruba catchment in Kenya (Lake Victoria Basin)

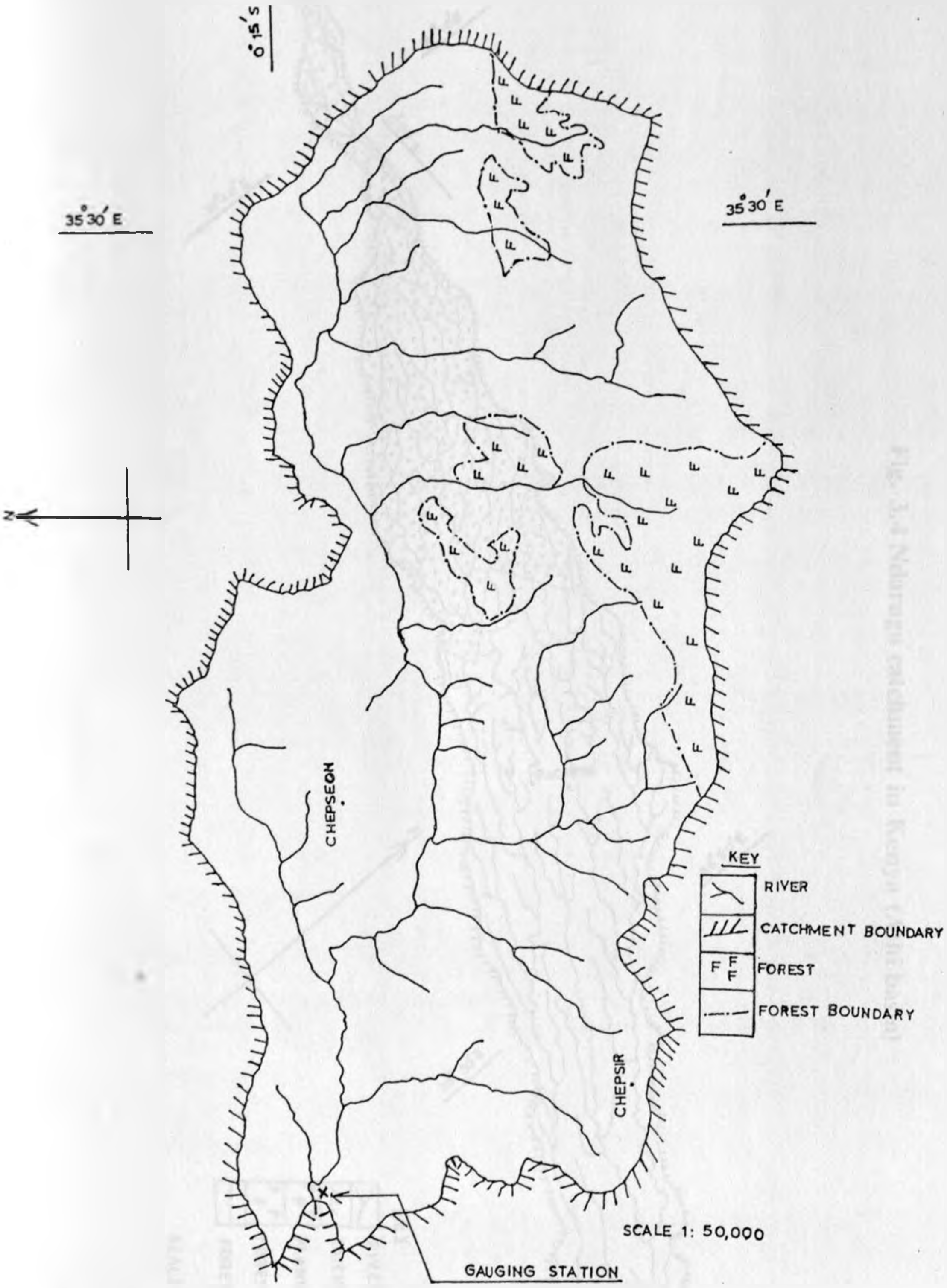

Fig. 3.3 Tugenon catchment in Kenya (Lake Victoria basin)

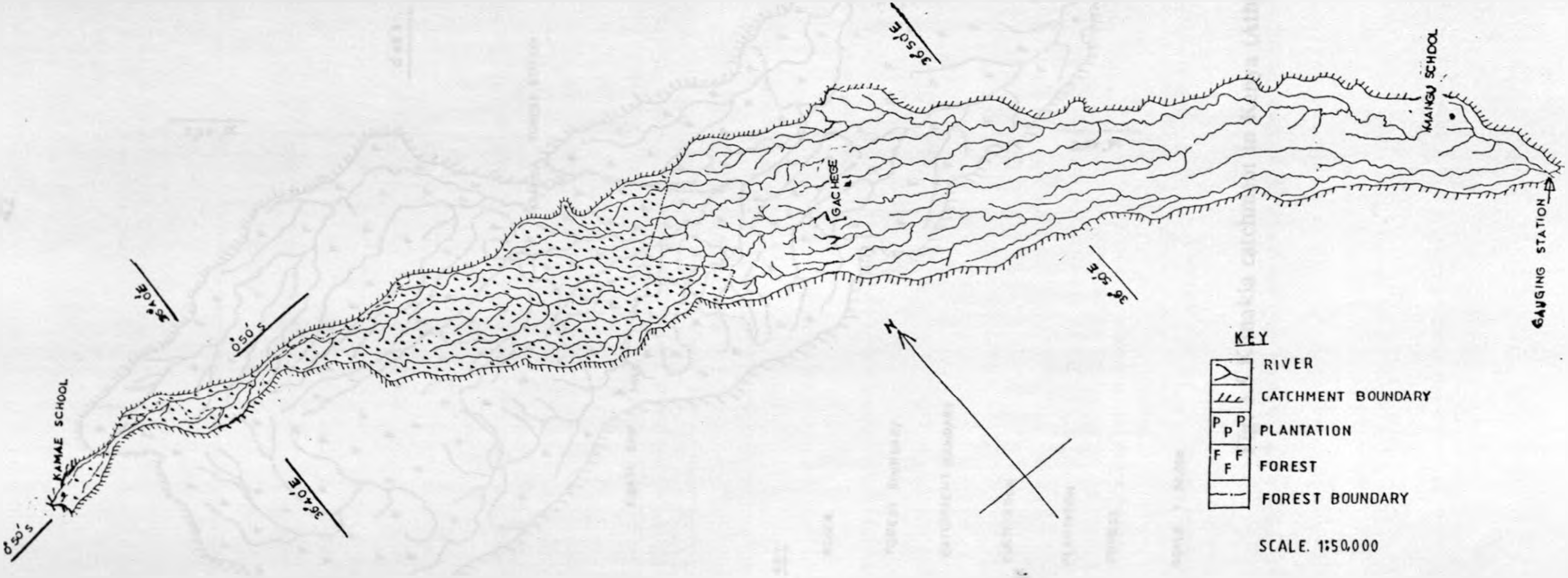

Fig. 3.4 Ndarugu catchment in Kenya (Athi basin)

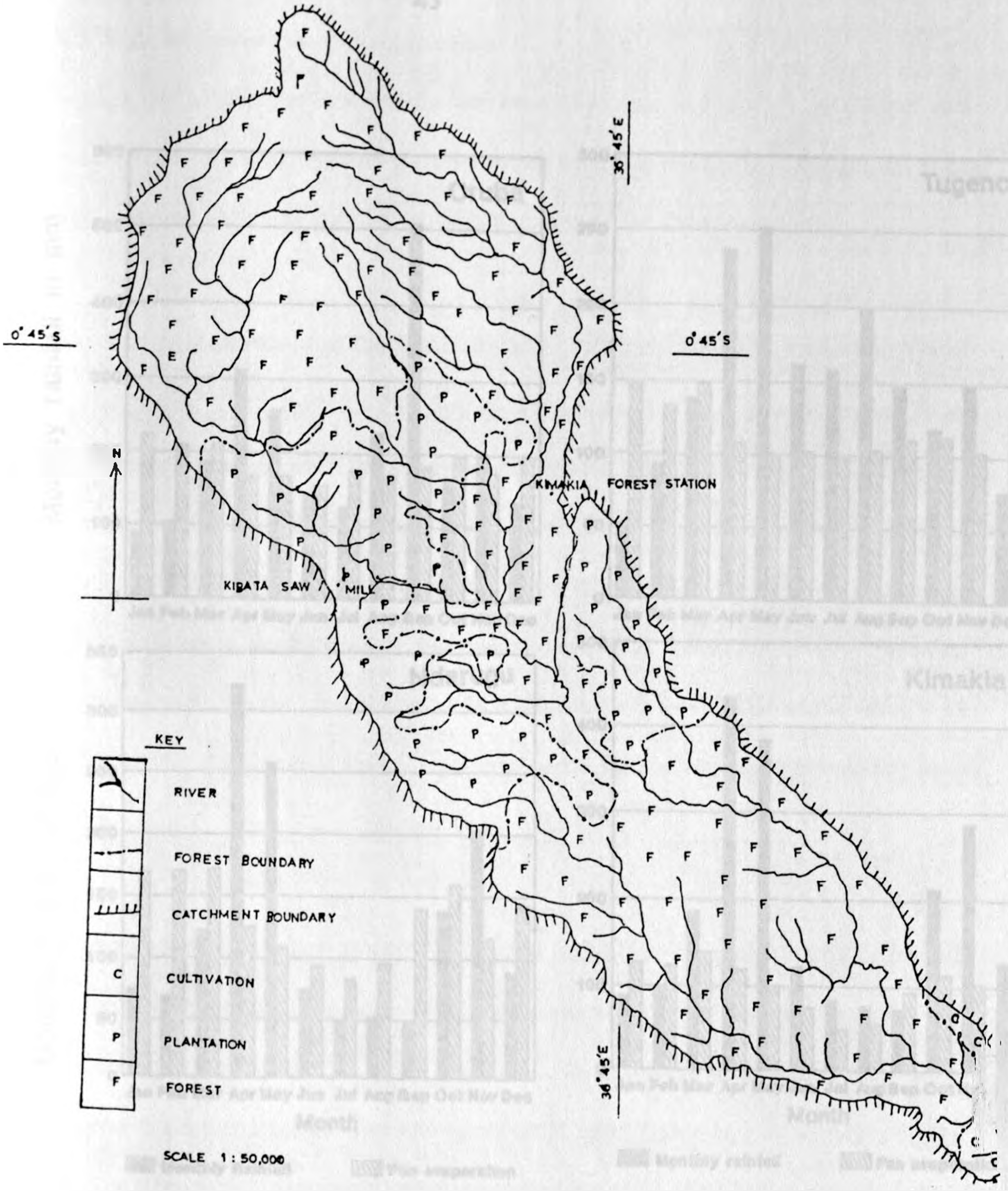

Fig. 3.5 Kimakia catchment in Kenya (Athi basin)

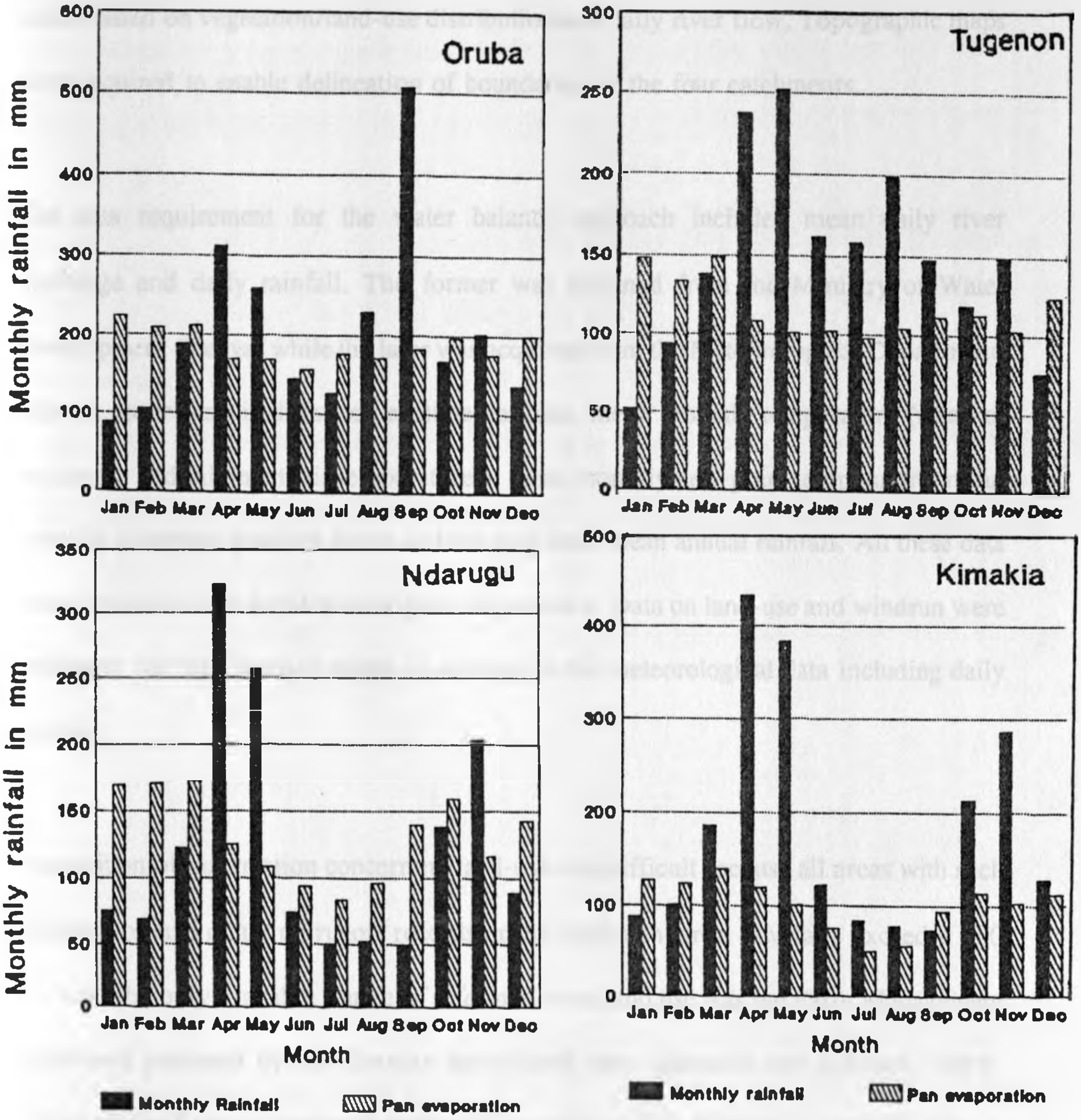

Fig. 3.6 Rainfall and evaporation pattern in study catchments

3.2 Data Requirement and Acquisition

Meteorological data was essential for the two models used in this study. Additional data were needed on vegetation/land-use distribution and daily river flow. Topographic maps were required to enable delineation of boundaries of the four catchments.

The data requirement for the water balance approach included mean daily river discharge and daily rainfall. The former was obtained from the Ministry of Water Development (Kenya) while the later was acquired from the Meteorological Department. Morton model required data on altitude, latitude, mean monthly temperature (mean of maximum and minimum air temperatures), mean monthly dew-point temperature, mean monthly observed sunshine hours and the long-term mean annual rainfall. All these data were acquired from the Meteorological Department. Data on land-use and windrun were necessary for the Grindley model in addition to the meteorological data including daily rainfall.

Acquisition of information concerning land-use was difficult because all areas with such information had either no runoff records or the catchment areal coverage exceeded 100 sq. km. The only available source of information on land use was the Farm Management Handbook prepared by the German agricultural team (Jaetzold and Schmidt, 1983). Although the Kenya rangelands ecological monitoring unit (KREMU) prepares data on land use, their work started only recently and thus does not correspond with the period when the other data sets were available. The data prepared by Jaetzold and Schmidt has a much smaller scale compared to the scale of the topographic maps used to delineate the catchment boundaries. Topographic maps were acquired from the Survey of Kenya.

The data sets were not simultaneously available for consecutive years, therefore some years had to be skipped but the total number of years of analysis was not less than seven for each catchment.

3.3 Implementation of the Water Balance Method

For the water balance equation to be used to estimate AET, streamflow data were organized (see appendix 10) and daily hydrographs were drawn (Fig. 3.7).

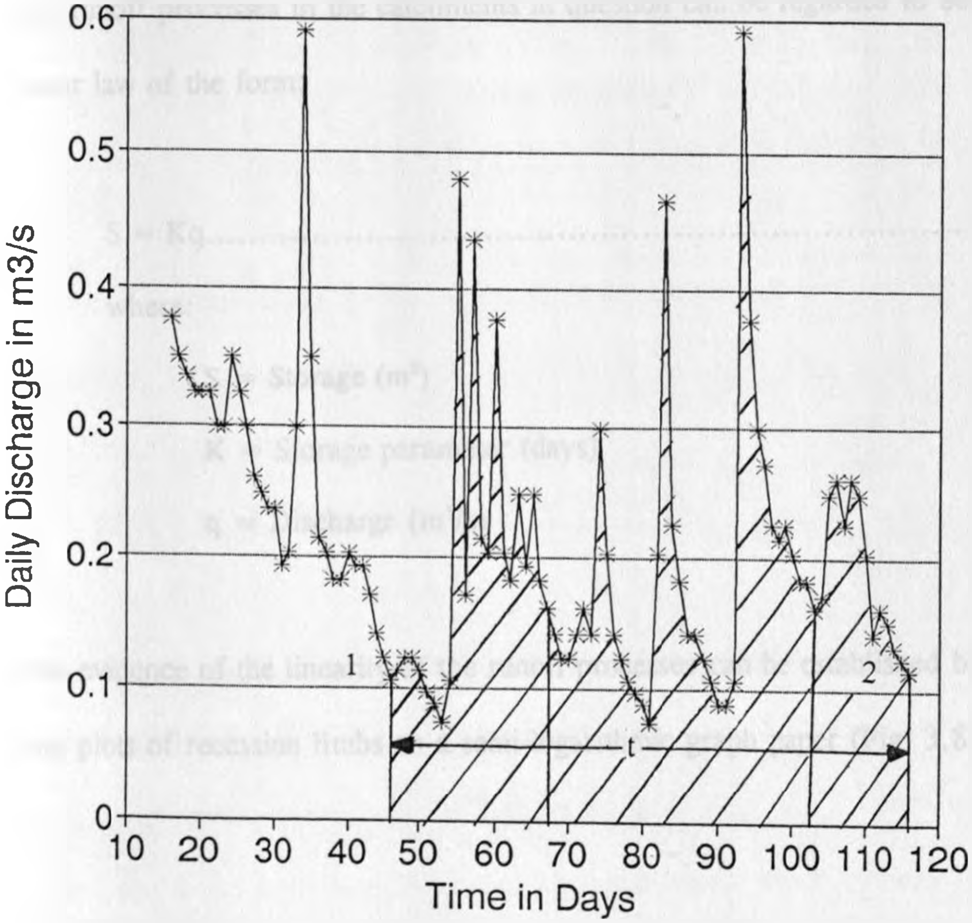

Fig. 3.7 Mean daily discharge hydrograph for Kimakia catchment

The daily hydrographs were plotted for the duration of the record in chronological order. The hydrographs obtained displayed a number of troughs and crests (Fig. 3.7) from which identical recession limbs were used to discern the time interval over which a water balance equation was applied in a simple form.

Once the daily hydrograph for a given time interval was drawn, two points with equal discharges (say 1 and 2 as shown in Fig 3.7) were chosen each on a recession limb. The water balance between points 1 and 2 is given by Eq. 2.13.

The runoff processes in the catchments in question can be regarded to be obeying the linear law of the form;

$$S = Kq \quad \ldots\ldots (3.1)$$

where:

S = Storage (m^3)

K = Storage parameter (days)

q = Discharge (m^3/s)

The evidence of the linearity of the runoff processes can be established by the straight line plots of recession limbs on a semi-logarithmic graph paper (Fig. 3.8).

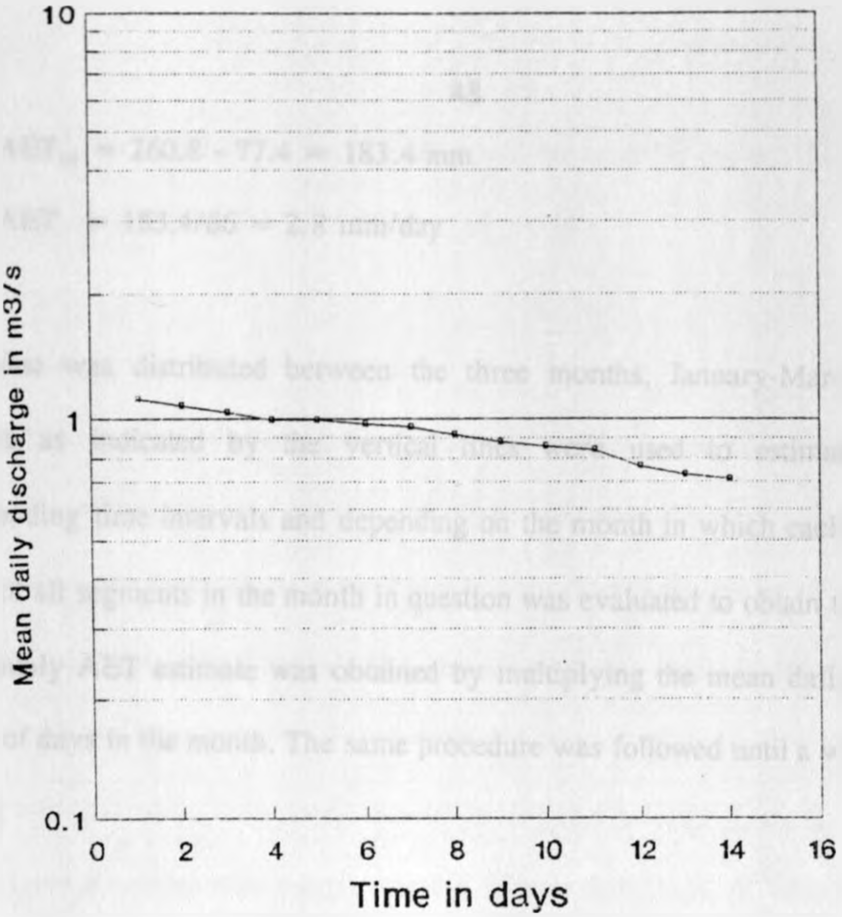

Fig. 3.8 River flow versus time on a semi-log scale depicting the linear law

Therefore for points 1 and 2 showing the same discharge, $\Delta S_t = 0$ and hence Eq. 2.13 reduces to;

$$AET_t = P_t - R_t \quad \text{......(3.2)}$$

The value of runoff was obtained as the area of the shaded region, whereas P_t was obtained as the sum of daily rainfall between points 1 and 2. Taking the hydrograph of Kimakia catchment in the year 1972 as an example (Fig. 3.7), the rainfall between points 1 and 2 (66 days) was 260.8 mm while the runoff was 77.4 mm. Therefore;

$AET_{66} = 260.8 - 77.4 = 183.4$ mm

$AET = 183.4/66 = 2.8$ mm/day

This value was distributed between the three months, January-March. The other segments as indicated by the vertical lines were used to estimate AET over corresponding time intervals and depending on the month in which each segment fall, a mean of all segments in the month in question was evaluated to obtain the daily AET. The monthly AET estimate was obtained by multiplying the mean daily AET by the number of days in the month. The same procedure was followed until a whole year was covered.

It is important to mention that certain periods of the year could not yield similar recession limbs. This was common particularly when the daily rainfall was 30 mm or more and fell for three or more consecutive days. When this happened the AET estimates of the adjacent month(s) was/were regarded applicable depending on their similarity in terms of rainfall. Taking Kimakia as an example, the daily AET for the month of November in 1969 could not be estimated by the outlined approach so the mean of October and December was taken as applicable for this month as they all fall on the same rainy season (see Fig. 3.6). The similarity in terms of rainfall was assumed to be a better indicator as the water for AET is mainly supplied by rainfall. Those months which fall within the same rainy season were assumed to have the same AET. For instance, if the hydrographs of the month of May did not give AET estimates then either that of April or June or their mean could be taken as the satisfactory estimate. The same procedure was followed for the dry months.

3.4 Implementation of Morton Model

The complementary relationship is usually arrived at after a series of computations. This necessitated compounding of all the component relationships into a single program. However, the use of a single program brought some complications so it was broken into two sections. One section of the program, which calculated the extra-atmospheric global radiation (referred to as program 1, appendix 11), calculated some intermediate values. The intermediate values were later entered as in-put data in program 2, appendix 12. The computer program was written for the relationships used in estimating AET as documented in the journal of hydrology by Morton (1983).

As outlined earlier, PET was computed by first estimating the potential evapotranspiration equilibrium temperature, T_P. The two equations used to estimate T_P are;

$$PET = R_T - (\gamma p f_T + 4\epsilon\sigma(T_P+273)^3)(T_P - T) = R_T - \lambda_T f_T (T_P - T) \ldots\ldots (3.3)$$

and

$$PET - f_T(v_P - v_D) \qquad (3.4)$$

where;

T_P = Equilibrium temperature (° C)

T = Air temperature (° C)

R_T = The net-radiation for soil-plant surfaces at air temperature (W/m^2)

f_T = Vapour transfer coefficient (Dimensionless)

σ = Stephan-Boltzmann constant ($W/m^2/K^4$)

ϵ = Surface emissivity (Dimensionless)

v_D = Saturation vapour pressure at the dew point temperature (mbar)

v_P = Saturation vapour pressure at T_P (mbar)

Υ = psychometric constant (Dimensionless)

p = Atmospheric pressure (mbar)

All other terms remain as defined earlier.

In the iteration process, T_P was obtained as the sum of a trial value T'_P, which was initially set equal to the mean air temperature, T, and a correction δT_P. The iteration process was performed on δT_P until its absolute value was less than 0.01. This is set to ensure that the number of trials is limited to four even in arid climates where the difference between air and equilibrium temperatures may exceed 10 ° C. Using the estimated value of T_P, PET was evaluated using Eq. 3.3.

In the quest of developing a useful method of evaluating AET, Morton considered those relationships based on the laws of physics and derived an equation to estimate E_{TW}. The equation which was also used in this analysis can be expressed as;

$$E_{TW} = b_1 + b_2[1+\gamma \frac{p}{\Delta_p}]^{-1} R_{TP} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

Where;

E_{TW} = Wet environment areal evapotranspiration (W/m^2)

b_1, b_2 = Constants

R_{TP} = Net radiation for soil-plant surfaces at the potential evapotranspiration equilibrium temperature (W/m^2)

$\blacktriangle_P$ = Slope of saturation vapour pressure curve at T_P (mbar/°C)

The other terms remain as defined earlier.

Upon estimation of PET and E_{TW}, the value of AET is then explicitly determined using

Eq. 2.12. The above outlined equations for estimating PET and E_{rw} gave daily values expressed in power units (W/m^2). To obtain monthly AET values in units of evaporation (mm depth), the estimates were divided by the latent heat of vaporization of water and then multiplied by the number of days in that month. Annual AET estimates were obtained as the sum of the monthly values.

3.5 Implementation of the Grindley Model

Grindley model was implemented by using Eq 2.9. Potential evapotranspiration, PET, was first computed by the modified Penman formula using monthly climatological data.

$$PET = (\Delta/(\Delta + \gamma))E_r + (\gamma/(\Delta + \gamma))E_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

where;

Δ = slope of the saturated vapour pressure curve at air temperature T (Pa/ ° C)

E_r = Energy balance component of evaporation (mm)

E_a = Aerodynamic component of evaporation (mm) while γ remains as defined previously.

Rainfall, P, was computed on ten day interval. The monthly PET estimates were divided by three to achieve the ten-day value which was used in Eq. 2.8 to evaluate PSMD and consequently SMD over this time interval. Values of SMD were evaluated from those of PSMD depending on by how much PSMD exceeds Rc + 25 for a given vegetation.

From data tabulated in Shaw (1984), it was found that PSMD showed an almost linear relationship with Rc and SMD for values of PSMD exceeding Rc + 25. These data were used to establish the equations that reduce PSMD to SMD via the root constant and the equations are given as follows:

$$SMD_{t+1} = PSMD_{t+1} * 0.4 + 0.7 * Rc \quad \text{...(3.7)}$$

for $Rc + 25 \leq PSMD \leq Rc + 75$

$$SMD_{t+1} = PSMD_{t+1} * 0.08 + Rc + 25 \quad \text{...(3.8)}$$

for $PSMD \geq Rc + 75$

For all values of PSMD less than RC + 25 mm, SMD values were equated to the corresponding PSMD. The estimated SMD and rainfall were then used in Eq. 2.9 to evaluate the ten-day AET for a given crop/vegetation. Soil moisture deficits were computed on 10-day intervals to minimize anomalies caused by recurrent dry spells as suggested by Grindley (1970).

To enhance computation over a period of ten years, a program was written in basic (program 3 in appendix 13) to estimate PET, SMD and AET consecutively. The catchments considered were under variable land uses as indicated in Table 3.1. The proportion of land surface covered by the various crops varied from catchment to catchment and hence the agro-ecological zone map for each catchment was used in conjunction with the small farm survey data to establish the proportional coverage of each crop in each catchment.

The beginning of the rainy season was established from the rainfall data so that estimation of soil moisture deficits could commence from the period when rainfall exceeds PET and hence the initial SMD could safely be assumed to be zero. Soil moisture deficit was assumed to build when PET exceeded rainfall. This approach was based on the assumption that all rainfall received was first used to replenish any soil moisture deficits and the surplus lost as runoff. Successive days' moisture deficits were taken as the cumulative soil moisture deficits.

The proportion established to be covered by a given crop was multiplied by its AET estimate obtained above to achieve the AET contributed by that crop in that particular catchment. For example, in Kimakia catchment in the year 1966, the PET for December was 126.0 mm and hence PET for the last 10 days (i.e. PET_{t+1}) would be 126/3 = 42.0 mm. The soil moisture deficit (SMD_t) for the previous 10 days was 118.7, 87.4, 118.7, 100.0 and 118.7 mm for maize, beans, potatoes, pasture and forest/tea respectively. Rainfall that fell in the last 10 days of 1966 (P_{t+1}) was 0 mm. Therefore, by Eq. 2.8, $PSMD_{t+1}$ for the respective crops in the same order as above (Rc's = 140, 57, 97, 75, and 200 mm) would be 160.7, 129.4, 160.7,142.0 and 160.7 mm respectively. Since some of these prevailing PSMD values exceeded Rc + 25 (i.e. that of beans), they were reduced accordingly as stipulated in conditions of Eqs. 3.7 and 3.8. For forest/tea $PSMD_{t+1}$ is less than Rc + 25 mm, hence this equals to SMD_{t+1}. SMD_{t+1} values for maize, beans, potatoes and pasture thus become 160.7, 91.7, 132.2 and 109.3 mm respectively. By Eq. 2.9, AET_{t+1} for forest/tea becomes:

$$AET_{t+1\ (forest/tea)} = 160.7 - 118.7 + 0 = 42.0 \text{ mm}$$

From Table 3.1, forest/tea covers 97.6% of the catchment and hence its AET contribution for the last 10 days of December 1966 equals: 42 * 0.976 = 40.99 mm. In the same way the AET contribution of the other crops were 0.46, 0.01, 0.04 and 0.07 mm. The total AET for this period for all crops/vegetation present in the catchment thus becomes 41.57 mm (i.e. 41.6 mm) by summing all the aforementioned values.

An assumption which was made in this analysis was that land use remained constant over the study period. This was prompted by lack of recurrent land use data. However, this assumption could be justified because data from the agricultural census statistics of medium-large farms indicate that the proportion under temporary and permanent crops in Kericho District (where Tugenon catchment is located) varied between 13-14% and 58-61% respectively (Jaetzold and Schmidt, 1983). Forested land only reduced from 11% to 9% over the same period of four years (1975-1978). Findings by Peden et al., (1984) in Kericho District showed that land under pasture was 46% which was within the coverage of 1977.

4.0 RESULTS AND DISCUSSION

4.1 Monthly and annual AET Estimates by various models

4.1.1 Standardization of water balance method

Before commenting on the AET estimates by the various methods, it is desirable to emphasize that the water balance is being regarded as the standard method for comparison as it has been found to yield correct AET estimates (Linsley et al., 1982; Sharma, 1988; Kotoda, 1989; Chun, 1989).

Nonetheless, before using the water balance method in evaluating the models used in this study, an exercise was carried out to see how this method fared with the approach in which all the components of the water balance were measured. The only data for validation of the water balance method were annual AET estimates of a neighbouring catchment to Kimakia and the data was available for seven years. These estimates were regarded good as they were derived from the water balance equation which incorporated all the components in the measured form (Eq. 2.14) and the catchment instrumentation was of high quality (Edwards and Blackie, 1981; EAAFRO, 1979). This adjacent catchment was under the same agro-ecological zone as Kimakia and hence expected to behave similarly.

The summary of the annual estimates by the two water balance methods are presented in Table 4.1 along with their percentage differences.

Table 4.1 Comparison of annual AET estimates of a neighbouring catchment with those of Kimakia

Year	Annual AET by Eq. 2.14 (mm)	Annual AET by Eq. 3.2 (mm)	Diff. btn 1 and 2 (%)
1964	1134.0	1141.0	0.60
1965	1114.5	1245.0	11.70
1966	1099.0	1176.8	7.10
1969	1300.5	1137.5	-12.50
1970	1091.0	1165.0	6.80
1972	1334.2	1225.8	-8.10
1973	1077.5	1125.5	4.50
Mean	1164.4	1173.8	5.10

The results show that the estimates by the two water balance equations i.e. column 2 and 3 do not differ significantly and the mean difference is about 5%. A discrepancy of 5% can be regarded negligible in view of the errors associated with the graphical procedure of estimation involved in the water balance analysis and existence of carried-over moisture. Analysis of variance test also suggested that these sets are indistinguishable from each other (calculated and tabulated values of the F-statistic were 0.05 and 4.65 respectively).

Therefore the water balance approach adopted for estimation of monthly AET values in this study can be regarded satisfactory. The monthly and annual AET estimates based on water balance approach can be used as the standard values against which estimates by Morton and Grindley methods can be compared (i.e. as done by Kotoda, 1989;

Morton, 1983; Hsuen-Chun, 1988).

4.1.2 Behaviour of mean AET estimates by various methods

The monthly and annual AET estimates by the three methods were calculated and are presented in Tables 4.2 to 4.13 for the four catchments studied and over the years considered. The means and coefficients of variation (C.V.) are also included in the aforementioned tables. The striking feature of the annual estimates is that the mean of the annual AET's by combining all catchments can be computed as 1488, 1252, and 1148 mm by Grindley, Morton and water balance methods. In other words Morton appears to be closer to water balance method in relation to Grindley, which is being explored in the forthcoming section.

Table 4.2 Monthly and annual AET Estimates by Water Balance Method for Oruba Catchment in mm.

M\Yr	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	Mean	C.V.
Jan	102.3	83.7	89.9	71.3	89.9	71.3	89.9	89.9	99.2	108.5	89.6	0.13
Feb	84.0	87.0	58.8	92.4	50.4	81.2	84.0	137.2	56.0	87.0	81.8	0.30
Mar	86.8	105.4	89.9	120.9	62.0	124.0	105.4	151.9	105.4	96.1	104.8	0.23
Apr	87.0	102.0	84.0	117.0	102.0	120.0	102.0	102.0	102.0	105.0	102.3	0.11
May	99.2	127.1	108.5	124.0	130.2	74.4	111.6	108.5	105.4	120.9	111.0	0.15
Jun	99.0	96.0	96.0	108.0	126.0	75.0	111.0	129.0	114.0	105.0	105.9	0.15
Jul	83.7	86.8	86.8	102.3	124.0	62.0	114.7	83.7	105.4	124.0	97.3	0.21
Aug	102.3	127.1	99.2	124.0	102.3	71.3	102.3	99.2	80.6	105.4	101.4	0.17
Sep	105.0	102.0	99.0	81.0	102.0	123.0	99.0	102.0	123.0	96.0	103.2	0.12
Oct	117.8	99.2	96.1	83.7	148.8	142.6	120.9	124.0	117.8	136.4	118.7	0.18
Nov	111.0	132.0	84.0	87.0	144.0	111.0	96.0	117.0	111.0	126.0	111.9	0.17
Dec	99.2	130.2	80.6	65.1	99.2	99.2	99.2	108.5	80.6	120.9	98.3	0.20
Annual	1177.3	1278.5	1072.8	1176.7	1280.8	1155.0	1236.0	1352.9	1200.4	1331.2	1226.1	0.07

Table 4.3 Monthly and annual AET Estimates by Water Balance Method for Tugenon Catchment in mm.

M\Yr	1964	1965	1966	1968	1975	1977	1978	1979	1980	Mean	C.V.
Jan	96.1	71.3	114.7	89.9	96.1	93.0	114.7	96.1	74.4	94.0	0.16
Feb	95.2	78.4	72.8	84.1	78.4	81.2	89.6	72.8	66.7	79.9	0.11
Mar	105.4	86.8	80.6	99.2	114.7	89.9	108.5	99.2	83.7	96.4	0.12
Apr	99.0	84.0	99.0	126.0	117.0	87.0	111.0	93.0	81.0	99.7	0.16
May	114.7	114.7	105.4	127.1	102.3	83.7	96.1	99.2	86.8	103.3	0.14
Jun	111.0	105.0	93.0	90.0	105.0	69.0	72.0	93.0	87.0	91.7	0.16
Jul	120.9	114.7	108.5	105.4	124.0	86.8	96.1	93.0	89.9	105.4	0.13
Aug	111.6	127.1	105.4	99.2	99.2	83.7	96.1	99.2	74.4	99.2	0.15
Sep	105.0	102.0	93.0	90.0	111.0	66.0	87.0	81.0	72.0	90.0	0.17
Oct	96.1	99.2	99.2	96.1	102.3	80.6	105.4	80.6	96.1	95.1	0.09
Nov	81.0	93.0	96.0	81.0	69.0	72.0	81.0	81.0	81.0	81.7	0.11
Dec	68.2	83.7	62.0	74.4	65.1	68.2	62.0	65.1	65.1	68.2	0.10
Annual	1204.2	1159.9	1129.6	1162.4	1184.1	961.1	1119.5	1053.2	958.1	1105.6	0.08

Table 4.4 Monthly and annual AET Estimates by Water Balance Method for Ndarugu Catchment in mm.

M\Yr	1963	1964	1965	1972	1973	1974	1975	1977	1978	Mean	C.V.
Jan	111.6	105.4	130.2	111.6	120.9	86.8	120.9	124.0	114.7	114.0	0.11
Feb	106.4	98.6	117.6	101.5	100.8	78.4	103.6	100.8	113.1	102.3	0.11
Mar	108.5	102.3	127.1	102.3	105.4	89.9	114.7	117.8	120.9	109.9	0.10
Apr	111.0	108.0	123.0	105.0	108.0	111.0	117.0	102.0	120.0	111.7	0.06
May	93.0	102.3	102.3	80.6	89.9	102.3	120.9	102.3	124.0	102.0	0.14
Jun	87.0	63.0	90.0	69.0	96.0	90.0	93.0	87.0	108.0	87.0	0.16
Jul	74.4	71.3	89.9	71.3	86.8	74.4	62.0	71.3	74.4	75.1	0.11
Aug	71.3	71.3	65.1	68.2	71.3	68.2	62.0	68.2	74.4	68.9	0.05
Sep	75.0	60.0	72.0	66.0	96.0	96.0	60.0	60.0	63.0	72.0	0.20
Oct	77.5	89.9	74.4	74.4	108.5	99.2	111.6	62.0	65.1	84.7	0.22
Nov	75.0	63.0	75.0	72.0	114.0	96.0	102.0	105.0	69.0	85.7	0.22
Dec	71.3	77.5	71.3	74.4	117.8	105.4	105.4	108.5	71.3	89.2	0.22
Annual	1062.0	1012.6	1137.9	996.3	1215.5	1097.6	1173.1	1108.9	1117.9	1102.5	0.06

Table 4.5 Monthly and annual AET Estimates by Water Balance Method for Kimakia Catchment in mm.

M\Yr	1964	1965	1966	1969	1970	1972	1973	1974	1975	1976	Mean	C.V.
Jan	93.0	111.6	83.7	86.8	74.4	102.3	80.6	127.1	93.0	71.3	92.4	0.19
Feb	84.1	86.8	81.2	81.2	81.2	95.7	72.8	81.2	81.2	69.6	81.5	0.09
Mar	93.0	108.5	93.0	102.3	93.0	102.3	80.6	93.0	93.0	77.5	93.6	0.10
Apr	105.0	117.0	123.0	102.0	105.0	105.0	105.0	105.0	105.0	81.0	105.3	0.10
May	111.6	127.1	127.1	111.6	111.6	105.4	80.6	111.6	114.7	111.6	111.3	0.12
Jun	99.0	99.0	120.0	99.0	99.0	102.0	72.0	99.0	111.0	96.0	99.6	0.12
Jul	77.5	77.5	74.4	77.5	77.5	77.5	80.6	77.5	77.5	80.6	77.8	0.02
Aug	99.2	111.6	86.8	99.2	99.2	99.2	111.6	99.2	99.2	80.6	98.6	0.10
Sep	96.0	90.0	84.0	96.0	96.0	96.0	111.0	96.0	105.0	96.0	96.6	0.08
Oct	108.5	108.5	108.5	108.5	124.0	114.7	117.8	80.6	111.6	108.5	109.1	0.10
Nov	78.0	102.0	99.0	99.0	108.0	111.0	123.0	78.0	99.0	99.0	99.6	0.14
Dec	96.1	105.4	96.1	74.4	96.1	114.7	89.9	65.1	117.8	96.1	95.2	0.17
Annual	1141.0	1245.0	1176.8	1137.5	1165.0	1225.8	1125.5	1113.3	1208.0	1067.8	1160.6	0.05

Table 4.6 Monthly and annual AET Estimates by Morton Model for Oruba Catchment in mm.

M\Yr	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	Mean	C.V.
Jan	107.3	96.3	85.2	90.4	64.0	64.6	83.4	80.1	76.2	86.0	83.1	0.15
Feb	119.5	115.3	82.0	107.4	68.3	69.3	98.1	105.0	75.3	78.5	91.9	0.20
Mar	134.8	109.7	100.4	130.5	112.1	91.3	121.0	108.3	92.2	106.9	110.7	0.13
Apr	94.4	89.9	97.9	104.6	113.3	82.2	127.4	111.6	97.0	87.4	100.6	0.13
May	97.2	86.7	95.4	100.6	97.5	113.0	98.4	108.8	87.7	103.4	98.9	0.08
Jun	84.3	78.9	81.5	90.8	96.0	95.3	88.3	85.8	83.7	73.9	85.8	0.08
Jul	82.6	65.3	63.7	76.9	78.7	83.6	62.0	62.4	88.2	72.1	73.6	0.13
Aug	81.0	69.9	68.5	102.1	45.6	78.1	79.3	67.4	88.3	82.7	76.3	0.19
Sep	73.1	75.4	92.5	94.7	63.1	81.7	73.4	72.6	89.8	98.3	81.5	0.14
Oct	72.7	75.9	75.4	103.8	88.4	77.7	90.9	79.0	77.6	97.4	83.9	0.12
Nov	77.1	72.8	79.7	90.1	81.8	69.4	90.7	75.1	73.2	109.8	82.0	0.14
Dec	76.5	66.2	98.2	67.7	94.9	89.8	70.9	81.8	69.4	112.3	82.8	0.18
Annual	1100.5	1002.3	1020.4	1159.6	1003.7	996.1	1083.9	1037.9	998.6	1108.7	1051.2	0.05

Table 4.7 Monthly and annual AET Estimates by Morton Model for Tugenon Catchment in mm.

M\Yr	1964	1965	1966	1967	1975	1976	1977	1978	1979	1980	Mean	C.V.
Jan	127.8	116.6	129.7	96.5	102.0	135.4	110.7	127.3	88.5	97.8	113.2	0.14
Feb	115.6	114.4	119.1	89.8	107.0	102.4	104.2	95.6	114.1	110.6	107.3	0.08
Mar	136.9	129.6	142.6	120.1	138.7	143.8	122.4	111.3	129.6	128.5	130.3	0.08
Apr	108.0	120.0	108.9	110.7	93.5	104.0	83.2	115.9	103.8	118.5	106.6	0.10
May	120.8	131.1	126.8	107.4	110.7	104.9	104.5	124.7	114.2	101.0	114.6	0.09
Jun	106.3	127.1	112.8	106.9	96.5	108.1	95.2	98.4	97.5	96.6	104.6	0.09
Jul	98.4	113.5	104.0	95.7	99.0	99.8	100.8	95.6	108.3	119.1	104.3	0.07
Aug	105.6	115.3	114.7	94.3	105.4	101.9	105.1	102.7	110.7	122.2	107.8	0.07
Sep	103.9	133.5	102.9	125.9	102.9	116.3	117.7	108.6	129.6	132.0	117.3	0.10
Oct	109.3	104.2	125.3	108.5	99.4	109.6	119.3	109.3	121.1	121.4	112.7	0.07
Nov	99.3	97.5	99.4	101.6	111.4	116.2	98.8	110.6	88.7	94.8	101.8	0.08
Dec	113.5	125.7	108.9	125.2	122.9	100.3	103.9	107.5	122.9	118.0	114.9	0.08
Annual	1345.5	1428.5	1395.1	1282.6	1289.5	1342.7	1265.8	1307.6	1329.1	1360.5	1334.7	.04

Table 4.8 Monthly and annual AET Estimates by Morton Model for Ndarugu Catchment in mm.

Mon\Yr	1963	1964	1965	1972	1973	1974	1975	1976	1977	1978	Mean	C.V.
Jan	128.3	148.9	162.5	140.0	147.6	127.0	119.5	134.3	132.9	134.5	137.5	0.08
Feb	119.4	134.0	126.7	123.1	137.3	107.4	120.4	107.2	119.4	137.7	123.3	0.08
Mar	137.6	140.4	115.6	126.5	136.5	100.3	119.5	121.8	129.2	129.6	125.7	0.09
Apr	93.4	120.6	108.4	105.5	105.0	104.1	127.5	112.1	105.4	118.7	110.1	0.09
May	107.0	106.8	108.7	87.0	93.1	115.0	107.7	90.3	123.0	117.7	105.6	0.11
Jun	84.4	78.1	99.3	69.2	57.7	66.3	80.2	50.0	73.0	52.6	71.1	0.20
Jul	83.8	51.5	50.5	76.8	50.1	85.1	69.9	68.5	65.7	75.6	67.7	0.19
Aug	84.5	106.2	56.8	66.5	58.7	94.2	82.6	80.8	114.7	91.2	83.6	0.22
Sep	101.7	93.8	91.7	95.2	105.0	80.8	83.7	108.5	114.6	102.5	97.8	0.10
Oct	112.0	108.6	97.7	108.6	121.4	108.1	95.8	120.1	148.6	127.6	114.7	0.13
Nov	108.0	119.8	120.6	121.0	119.2	117.9	130.8	96.0	112.0	128.3	117.4	0.08
Dec	107.1	122.5	133.6	129.3	126.0	131.5	135.8	125.3	122.8	111.6	124.5	0.07
Annual	1267.3	1331.2	1272.2	1248.7	1257.7	1237.7	1273.2	1214.9	1361.3	1327.6	1279.2	0.03

Table 4.9 Monthly and annual AET Estimates by Morton Model for Kimakia Catchment in mm.

M\Yr	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	Mean	C.V.
Jan	143.1	132.7	158.8	146.9	159.4	149.2	104.7	142.7	151.6	120.1	140.9	0.12
Feb	131.9	147.4	140.9	143.0	121.6	106.0	134.6	130.3	119.1	136.0	131.1	0.09
Mar	144.6	157.5	134.9	154.1	110.7	129.6	144.1	150.5	131.8	164.6	142.2	0.11
Apr	104.6	126.0	108.2	125.4	103.5	143.4	120.4	125.4	155.4	137.4	125.0	0.13
May	98.9	102.8	109.9	96.8	97.0	97.0	99.8	87.2	101.3	102.9	99.4	0.06
Jun	89.9	99.6	88.8	77.2	76.7	63.8	90.3	73.6	91.5	76.9	82.8	0.12
Jul	42.1	57.0	63.4	64.9	41.4	60.4	93.5	54.0	77.5	78.6	63.3	0.25
Aug	75.5	83.5	97.5	95.4	30.1	95.0	47.2	56.3	89.9	48.7	71.9	0.32
Sep	98.0	124.0	115.7	102.2	132.2	114.1	108.7	122.6	108.3	99.5	112.6	0.10
Oct	102.7	114.9	131.5	112.2	130.3	163.1	138.9	145.4	117.4	145.9	130.2	0.14
Nov	130.5	100.8	113.4	114.5	91.1	119.4	110.2	128.9	119.6	105.7	113.4	0.10
Dec	106.7	128.4	149.2	131.1	144.4	148.7	140.1	122.8	129.3	121.5	132.2	0.10
Annual	1268.6	1375.6	1412.2	1363.8	1238.1	1389.7	1332.4	1339.8	1392.4	1337.5	1345.0	0.04

Table 4.10 Monthly and annual AET estimates by Grindley model in mm for Oruba catchment

Mon\Yr	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	Mean	C.V
Jan	145.9	188.5	185.6	197.5	220.2	206.5	174.1	164.8	174.0	191.2	184.8	0.12
Feb	143.7	162.3	186.7	159.7	205.9	154.2	153.2	169.7	176.9	154.1	166.6	0.11
Mar	159.2	173.5	203.5	169.0	218.6	146.3	175.8	170.9	202.9	196.4	181.6	0.13
Apr	124.1	144.2	160.2	145.9	152.1	129.3	178.5	146.9	146.9	182.2	151.0	0.12
May	127.7	148.4	155.9	155.1	133.4	136.5	144.2	144.2	132.6	145.1	142.3	0.07
Jun	135.2	139.2	153.2	145.1	125.3	129.3	149.6	136.5	123.8	131.3	136.9	0.07
Jul	145.2	135.3	146.2	149.0	139.2	140.4	142.6	146.3	132.6	141.8	141.9	0.04
Aug	152.3	138.1	164.9	159.1	157.6	154.5	169.7	141.2	135.7	152.5	152.6	0.07
Sep	159.8	138.5	178.8	152.7	178.6	171.8	171.9	156.6	146.3	171.9	162.7	0.09
Oct	177.3	166.3	169.2	174.0	165.2	178.5	177.6	172.8	158.2	168.3	170.7	0.04
Nov	146.3	164.8	154.2	153.5	154.8	152.9	174.0	176.3	153.5	148.0	157.8	0.07
Dec	135.7	167.1	174.1	201.6	172.0	171.4	193.0	182.2	148.7	172.8	171.9	0.11
Annual	1752.4	1866.2	2032.5	1962.2	2022.9	1871.6	2004.2	1908.4	1832.1	1955.6	1920.8	0.05

Table 4.11 Monthly and annual AET estimates by Grindley model in mm for Tugenon catchment

Mon\Yr	1964	1965	1966	1975	1977	1978	1979	1980	Mean	C.V.
Jan	147.8	147.3	147.5	163.3	116.1	135.2	131.9	147.7	142.1	0.10
Feb	124.9	144.5	105.9	163.6	115.2	123.0	107.5	129.8	126.8	0.15
Mar	131.9	150.1	122.7	147.9	137.0	113.0	152.9	155.3	138.9	0.11
Apr	97.6	105.6	104.2	120.5	82.9	58.8	121.5	123.8	101.9	0.22
May	106.7	111.0	124.0	105.6	95.7	113.2	104.5	99.3	107.5	0.08
Jun	94.4	106.0	109.3	90.2	92.5	95.2	91.2	92.5	96.4	0.07
Jul	89.0	100.7	101.8	93.4	90.8	102.3	103.9	110.4	99.0	0.07
Aug	95.8	104.9	106.9	93.2	99.9	100.7	109.9	122.7	104.3	0.09
Sep	95.0	114.6	117.0	97.8	115.8	111.7	119.3	123.3	111.8	0.09
Oct	103.9	97.4	124.1	107	112.3	117	150.6	132.3	118.1	0.15
Nov	123.0	91.9	122.6	131.6	86.7	116.6	123.1	108.4	113.0	0.14
Dec	116.6	111.4	151.7	132.3	117.1	121.1	133.5	125.6	126.2	0.10
Annual	1326.6	1385.4	1437.7	1446.5	1262	1307.8	1449.8	1471.1	1385.9	0.06

Table 4.12 Monthly and annual AET estimates by Grindley model in mm for Ndarugu catchment

Mon\Yr	1963	1964	1965	1972	1973	1974	1975	1977	1978	Mean	C.V.
Jan	126.4	143.4	143.2	137.4	135.1	165.0	159.4	140.8	123.7	141.7	0.10
Feb	131.0	131.5	160.2	133.2	137.8	168.6	161.3	147.2	123.9	143.9	0.11
Mar	144.8	132.2	153.0	159.2	175.0	158.0	173.1	154.7	120.9	152.3	0.12
Apr	119.3	106.9	119.3	135.2	148.0	124.1	132.4	112.2	110.3	123.1	0.10
May	91.3	100.9	122.1	106.1	116.3	114.1	119.9	118.1	108.9	110.9	0.09
Jun	86.1	86.7	106.1	89.1	86.2	74.3	96.2	80.2	74.3	86.6	0.12
Jul	98.7	77.2	101.3	94.0	96.1	78.2	88.3	71.0	77.1	86.9	0.13
Aug	88.3	88.5	110.9	96.3	94.1	87.2	95.3	104.0	85.5	94.5	0.10
Sep	118.7	98.0	147.9	123.5	111.3	110.2	110.9	107.7	111.9	115.6	0.12
Oct	121.6	110.8	130.4	116.2	136.4	149	125.8	133.8	121.8	127.3	0.09
Nov	114.9	123.9	113.2	121.3	125.9	118.6	125.7	96.7	115.4	117.3	0.08
Dec	99.5	115.2	147.6	120.4	148.9	145.0	127.9	115.9	107.9	125.4	0.14
Annual	1340.6	1315.2	1555.2	1431.9	1511.1	1492.3	1516.2	1382.3	1281.6	1425.2	0.10

Table 4.13 Monthly and annual AET estimates by Grindley model in mm for Kimakia catchment

Mon\Yr	1964	1965	1966	1969	1970	1972	1973	Mean	C.V.
Jan	126.5	114.0	136.4	124.3	97.0	124.0	108.1	118.6	0.11
Feb	114.7	123.7	120.8	97.8	120.2	105.1	115.0	113.9	0.08
Mar	127.1	140.0	120.2	115.9	128.7	159.4	155.8	135.3	0.13
Apr	100.6	113.6	101.0	120.8	105.7	127.5	127.0	113.7	0.10
May	87.9	95.5	99.2	87.3	89.2	92.1	94.2	92.2	0.05
Jun	75.9	88.9	75.8	96.3	74.7	78.3	68.9	79.8	0.12
Jul	56.9	67.3	65.4	68.7	78.6	71.3	70.5	68.4	0.10
Aug	72.4	76.1	83.1	82.4	60.2	78.2	64.6	73.9	0.12
Sep	83.4	109.4	101.2	99.0	94.2	97.8	90.0	96.4	0.09
Oct	98.6	106.3	114.8	131.3	103.1	106.9	122.6	111.9	0.10
Nov	117.9	98.7	104.1	105.2	98.7	105.9	98.7	104.2	0.07
Dec	101.7	114.2	126.0	123.5	116.5	114.7	108.8	115.1	0.07
Annual	1163.6	1247.7	1248.0	1252.5	1166.8	1261.2	1224.2	1223.4	0.03

It is shown in Tables 4.2 through 4.13 that the mean monthly AET estimates by either method varied from month to month as well as from one catchment to another. The Grindley model gave AET estimates which were either close or equal to PET values as estimated by the modified Penman equation in all the catchments. However, these estimates were exceptionally high for Oruba catchment (Fig. 4.1) and could be attributed to the difference in meteorology between the catchment and the meteorological station used for the data. The station i.e. Kibos, located in the lowland where temperatures and windruns were higher than those of the catchment and hence the high estimates of AET by Grindley model. It also indicates that soil moisture deficits were less than Rc plus 25 mm for most of the study period. Hence Eq. 2.9 would give estimates equivalent to PET values. Though there were few dry months in the other catchments whereby SMD exceeded Rc plus 25 mm, the reduction on PET was not significant to affect the mean AET over the study period. In short, Grindley model tended to overestimate AET values almost in all the catchments and throughout the year in relation to the water balance method (Figs. 4.1 through 4.4).

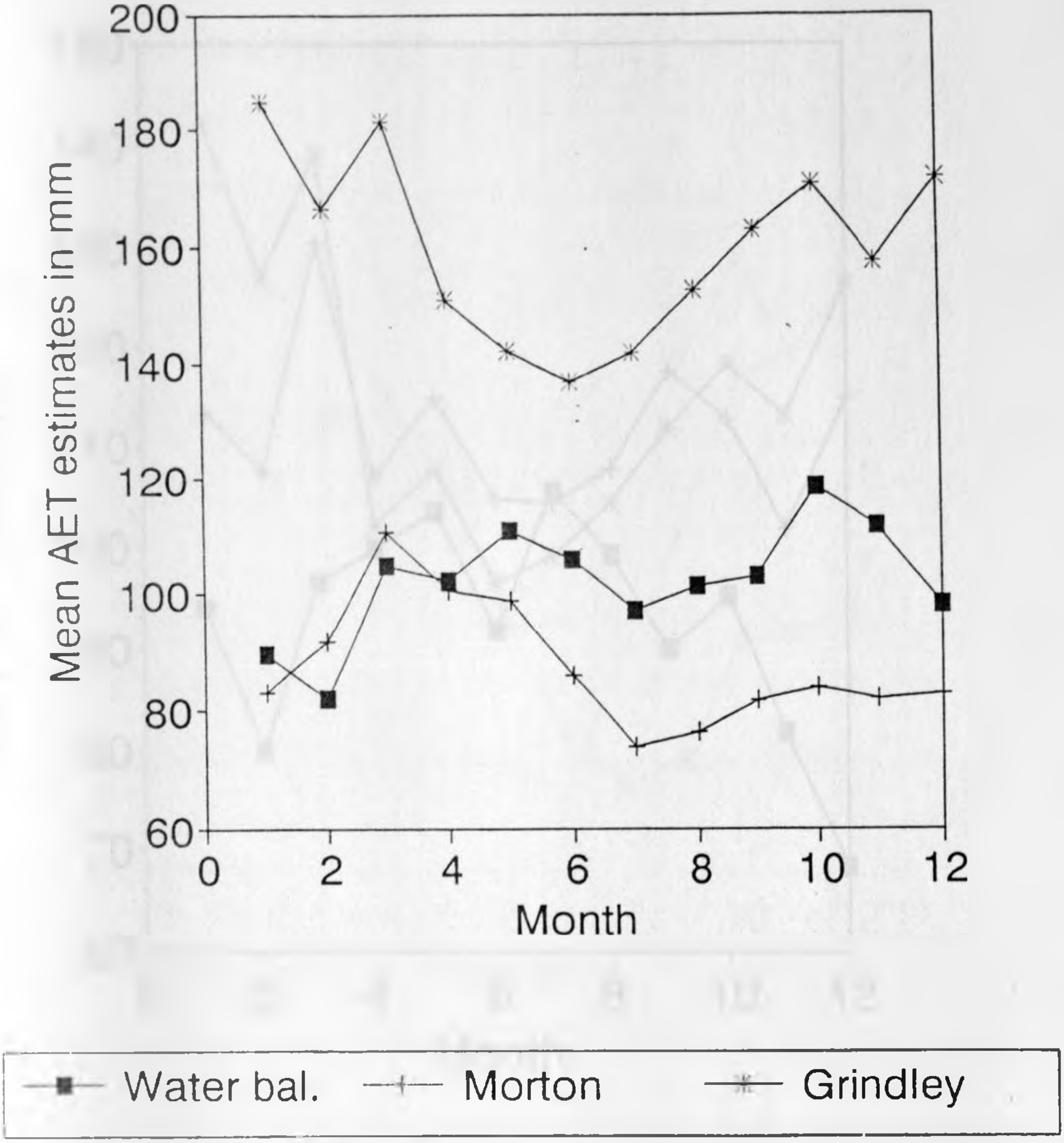

Fig. 4.1 Comparison of mean monthly AET estimates in Oruba catchment

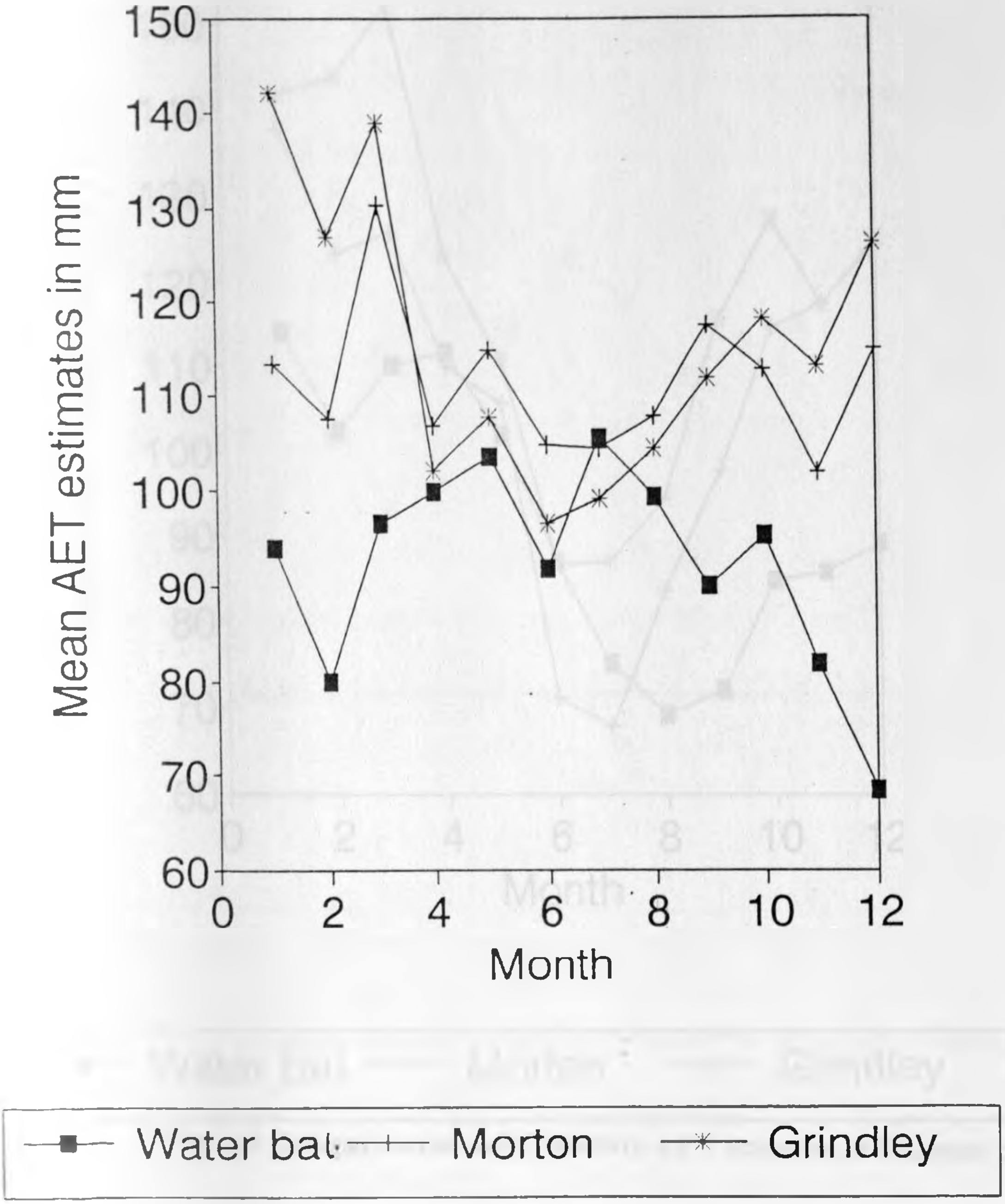

Fig. 4.2 Comparison of mean monthly AET estimates in Tugenon catchment

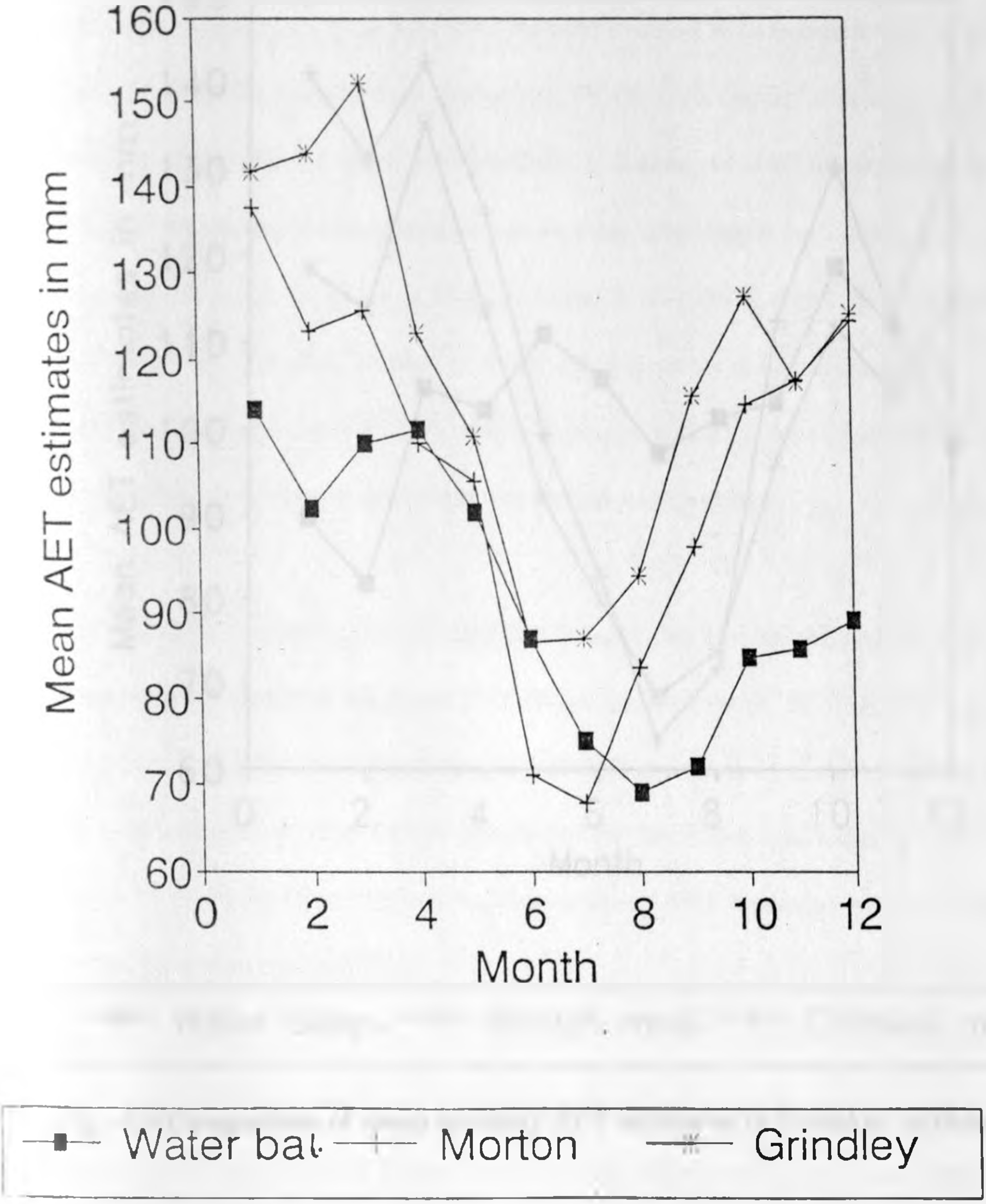

Fig. 4.3 Comparison of mean monthly AET estimates in Ndarugu catchment

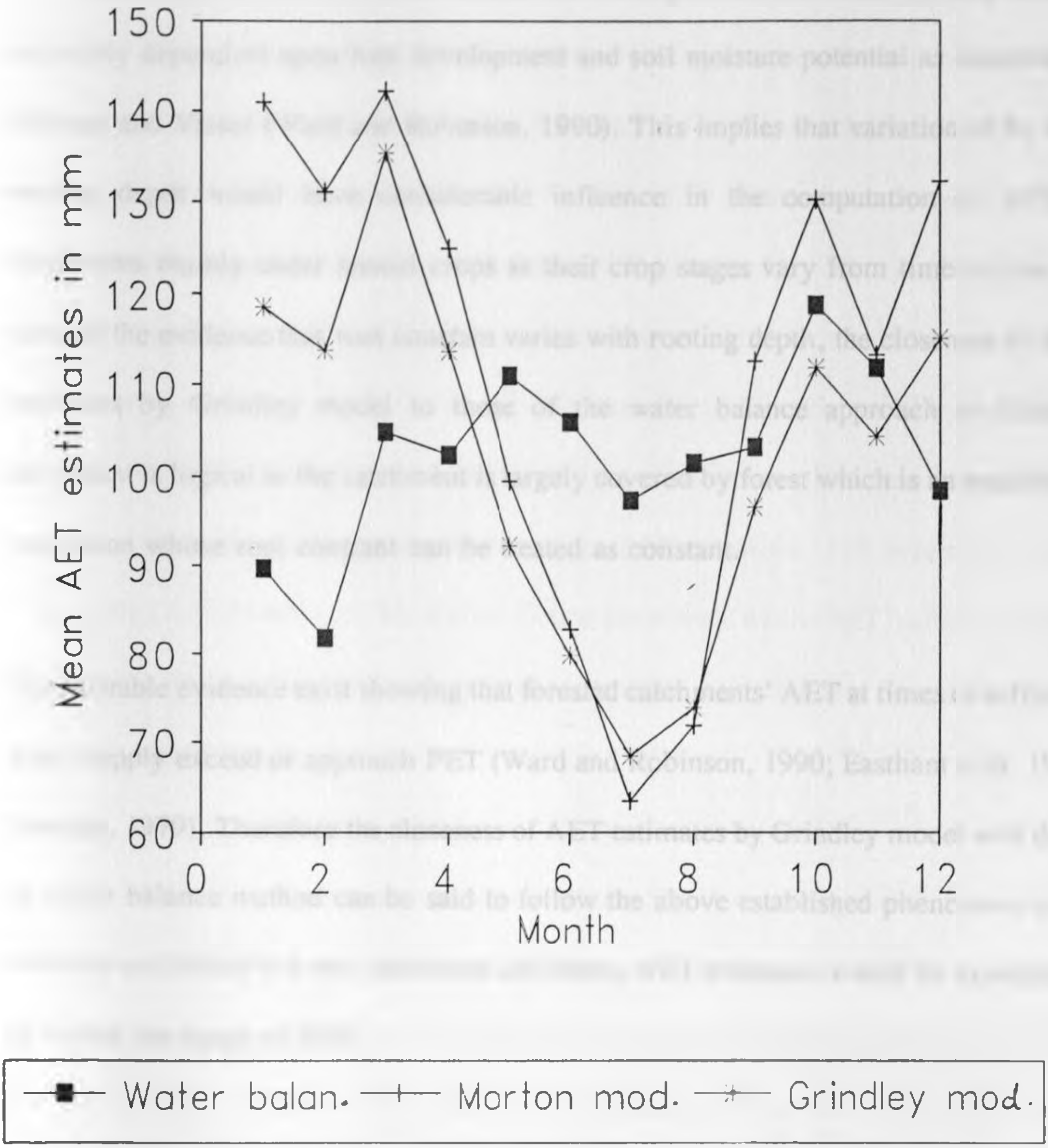

Fig. 4.4 Comparison of mean monthly AET estimates in Kimakia catchment

One other aspect that could have led to the poor performance of the Grindley model in all catchments other than Kimakia could be its assumption on invariability of a crop's root constant with varying rooting depth and soil type. This actually is an oversight as root constant is a measure of available moisture which depends on rooting depth and soil type.

Field experiments have even shown that the capture of soil water by crop roots is not solely dependent upon root development and soil moisture potential as assumed by Penman and Visser (Ward and Robinson, 1990). This implies that variation of Rc with rooting depth would have considerable influence in the computation of AET in catchments mainly under annual crops as their crop stages vary from time to time. In view of the evidence that root constant varies with rooting depth, the closeness of AET estimates by Grindley model to those of the water balance approach in Kimakia catchment is logical as the catchment is largely covered by forest which is an established vegetation whose root constant can be treated as constant.

Considerable evidence exist showing that forested catchments' AET at times of sufficient water supply exceed or approach PET (Ward and Robinson, 1990; Eastham et al, 1988; Newson, 1979). Therefore the closeness of AET estimates by Grindley model with those by water balance method can be said to follow the above established phenomena since Kimakia catchment is a wet catchment and hence AET estimates would be expected to be within the range of PET.

The Morton model gave higher AET estimates in Tugenon and Ndarugu catchments than the water balance method for much of the time of the year. In Oruba, AET estimates by this model were lower than water balance based estimates. The same happened for the period between May and August in Kimakia catchment. The Morton model resulted in high discrepancies in relation to the water balance in other months (Fig. 4.4). A possibility of poor accounting of advection in the Morton model could have led to the aforesaid discrepancies in AET estimates observed in Kimakia which is predominantly forested. This is because calibration of constants relating to advection in this model was done using data of arid catchments which are expected to respond differently from wet catchments of which Kimakia is one. At the same time, the argument of the complementary relationship between PET and AET advanced by Morton (1983) can be a basis of the high and low AET estimates obtained in Kimakia and Oruba catchments respectively. Another explanation for the discrepancies in Kimakia could be associated with the low PET values experienced in such wet catchments which as a consequence of the complementary relationship leads to high AET estimates. The opposite of what is happening in Kimakia can be said of Oruba catchment where PET values are very high thereby reducing the AET values to an extent that they are lower than those by the water balance approach.

The high AET estimates by water balance method (Fig. 4.4) during the four months in Kimakia catchment could be associated with errors caused by assuming AET estimates of adjoining months to be equal as hydrographs for these months often did not allow the application of Eq.3.2 strictly. The meteorological stations for the other three catchments were either within the catchment (i.e. Kimakia) or close by and hence such data could be taken as representative of the catchment in question. Although Morton model in general tended to yield AET estimates lower than the Grindley model and thus closer to the water balance, the general trend for the three methods showed considerable similarity in all the catchments (Figs. 4.1 -4.4).

4.1.3 Behaviour of coefficients of variation of AET by various methods

In terms of the coefficients of variation, no definite trend was observed in relation to months, model for AET estimation and the nature of the catchment (Figs. 4.5 to 4.8). Nonetheless, it can be seen that coefficients of variation based on Grindley model showed least temporal variation as compared to water balance and Morton method in all catchments studied. This could be attributed to the low temperature variation usually evident in tropical regions. The low temperature variation is reflected in the near uniform estimates of PET and in turn in AET estimates by Grindley model. Similar trend is expected from the Morton based estimates as a number of constants used in the empirical equations are temperature dependent. One should expect coefficients of variation by the water balance method towards the higher side as these estimates are graphically derived and involve some element of intuition and subjectivity. The mean values of coefficients of variation for all months and catchments combined together were found as 0.14, 0.12 and 0.11 by water balance, Morton, and Grindley methods. As expected, the coefficients of variation of annual estimates were much lower and the mean values were 0.07, 0.04 and 0.06 respectively for the aforementioned methods.

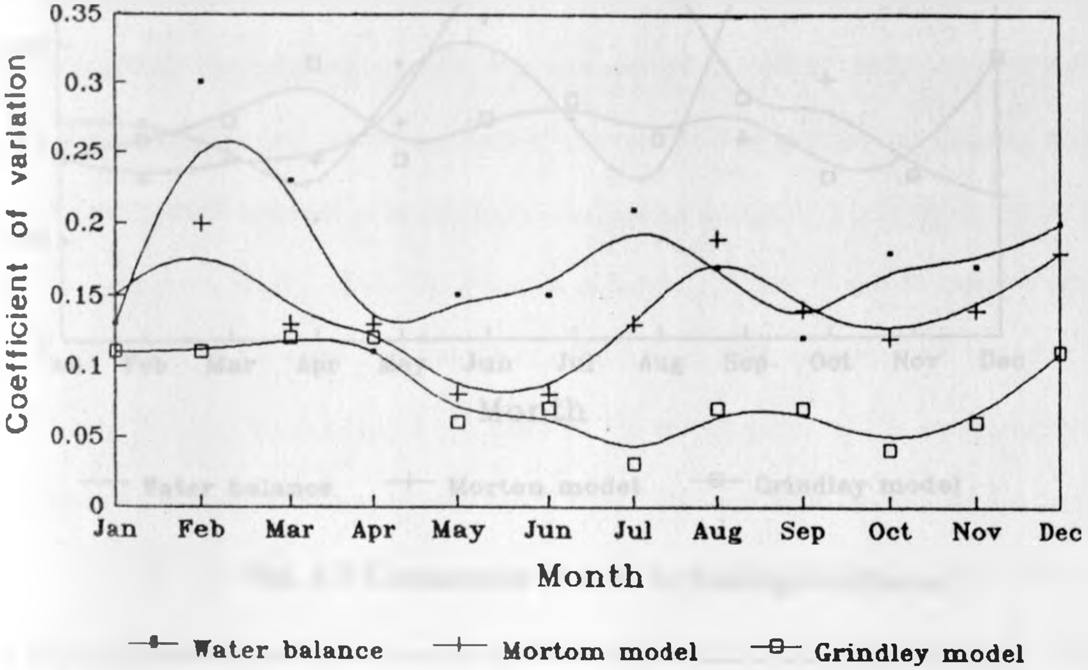

Fig. 4.5 Comparison of C.V. in Oruba catchment

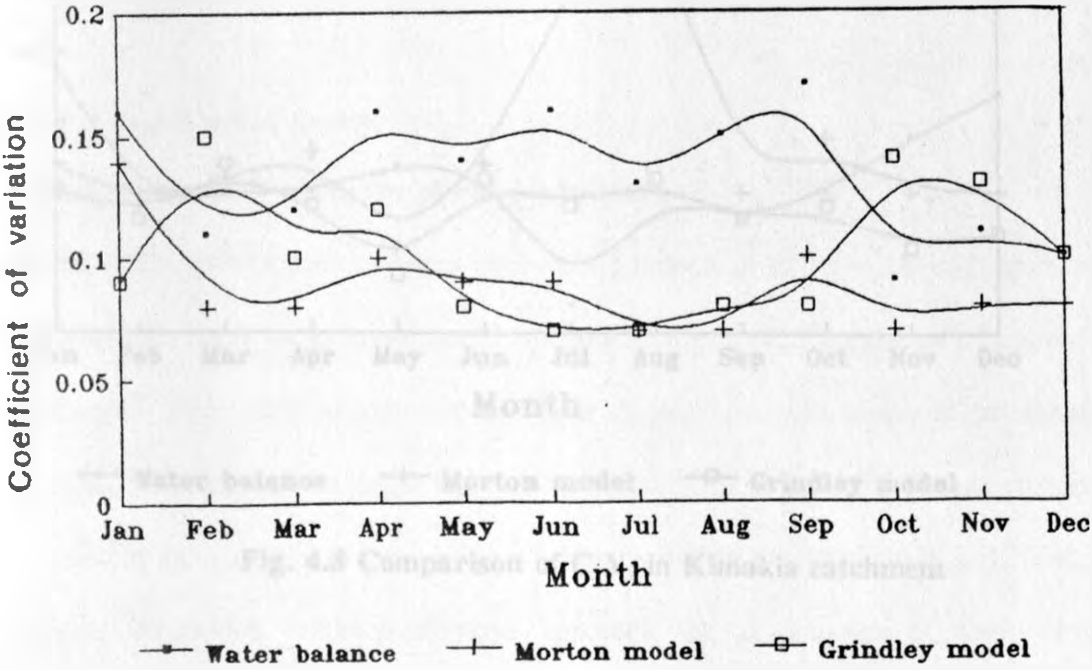

Fig. 4.6 Comparison of C.V. in Tugenon catchment

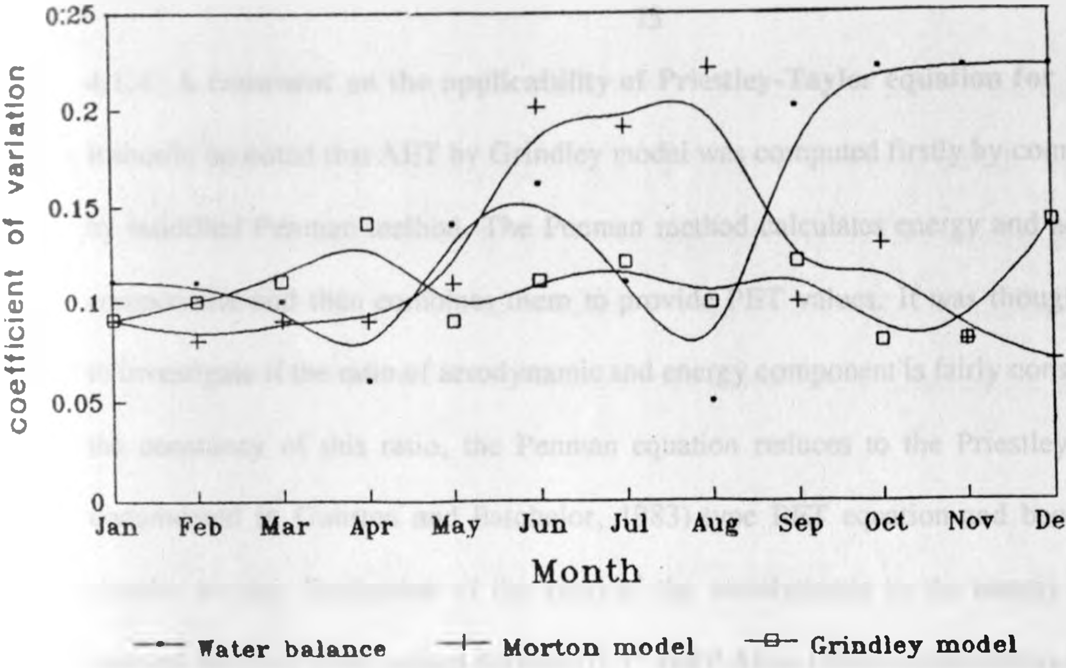

Fig. 4.7 Comparison of C.V. in Ndarugu catchment

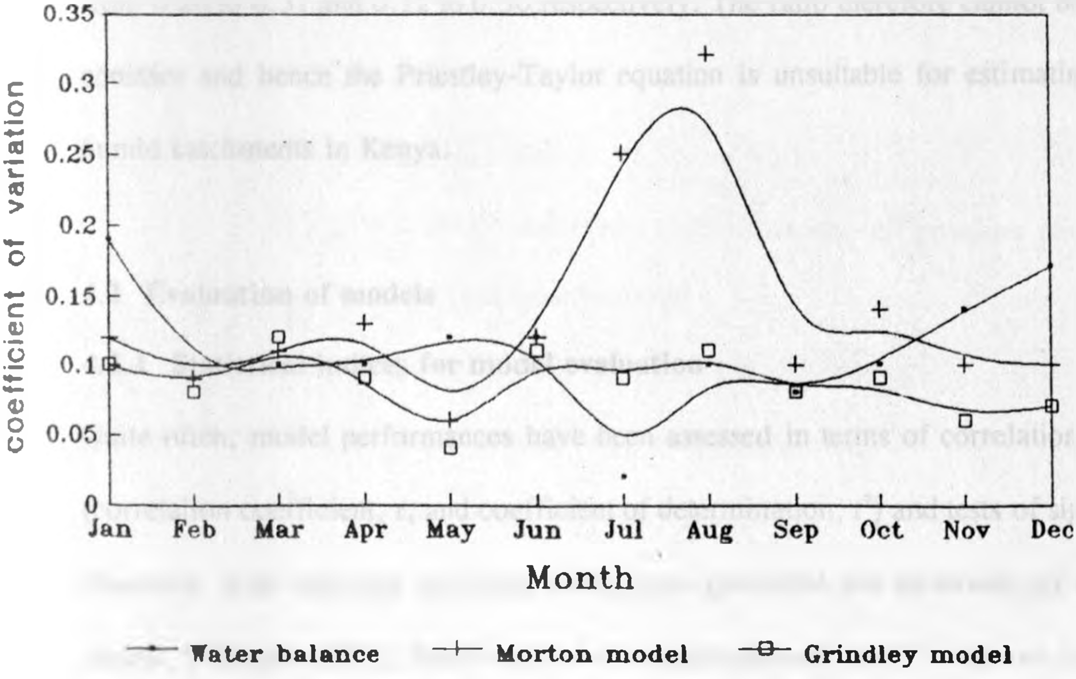

Fig. 4.8 Comparison of C.V. in Kimakia catchment

4.1.4 A comment on the applicability of Priestley-Taylor equation for PET

It should be noted that AET by Grindley model was computed firstly by computing PET by modified Penman method. The Penman method calculates energy and aerodynamic components and then combines them to provide PET values. It was thought desirable to investigate if the ratio of aerodynamic and energy component is fairly constant. Under the constancy of this ratio, the Penman equation reduces to the Priestley-Taylor (as documented in Gunston and Batchelor, 1983) type PET equation and becomes much simpler to use. Evaluation of the ratio of the aerodynamic to the energy component showed that this value ranged between 0.37 and 0.58 in Oruba catchment and from 0.24 to 0.45 in Tugenon catchment. In Ndarugu and Kimakia catchments, the ratio varied from 0.20 to 0.31 and 0.12 to 0.30 respectively. The ratio therefore cannot be regarded constant and hence the Priestley-Taylor equation is unsuitable for estimating PET in humid catchments in Kenya.

4.2 Evaluation of models

4.2.1 Statistical indices for model evaluation

Quite often, model performances have been assessed in terms of correlation measures (correlation coefficient, r, and coefficient of determination, r^2) and tests of significance. However, after carrying out some analysis on predicted and observed (or measured) values, Willmott (1982), found out that the magnitudes of r and r^2 were not consistently related to the accuracy of prediction; where accuracy of prediction here is defined as the degree to which model-predictions approach the magnitudes of their observed counterparts. Therefore these quantities are sometimes misleading indicators of model performance. Having illustrated that r and r^2 are not sufficient to deduce a given model's accuracy, Willmot proposed a descriptive measure called the index of agreement, d, in addition to the difference and summary indices initially proposed by Fox (1981) to facilitate cross-comparisons between models. The equations to evaluate the index of agreement and the other difference measures are given by the equations as follows;

$$d - 1 - [\sum_{1}^{N} (AET_{P_i} - AET_{O_i})^2 / \sum_{1}^{N} (|ANT_{P_i}| + |ANT_{Oi}|)^2] \ldots\ldots (4.1)$$

$$0 \leq d \leq 1$$

where;

$ANT_{Pi} = AET_{Pi} - AET_{Ob}$

$ANT_{Oi} = AET_{Oi} - AET_{Ob}$

AET_{Ob} = mean of observed values i.e. mean of the values obtained by water balance (mm/mon) method

AET_{Pi} = predicted AET of month i (mm/mon)

AET_{Oi} = observed AET of month i (mm/mon)

d = index of agreement (a ratio)

N = Number of pairs compared

$$d_b - 1/N \sum_{1}^{N} (AET_{P_i} - AET_{Oi}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

where:

d_b = mean of difference between predicted and observed values (mm/mon)

$$RMSE = [1/N \sum_{1}^{N} (AET_{P_i} - AET_{Oi})^2]^{0.5} \quad \text{.....................} (4.3)$$

where:

RMSE = root mean square error (mm/mon)

$$MAE = 1/N \sum_{1}^{N} |AET_{P_i} - AET_{Oi}| \quad \text{..........................} (4.4)$$

where:

MAE = mean absolute error (mm/mon)

The means and standard deviations of the observed and predicted values are also computed along with the above indices. Evaluation of the above parameters can be done for all months and catchments combined or for the mean monthly values and catchments combined. Likewise, the analysis can be undertaken on individual catchment basis i.e. handling each catchment independently. In the case of this study, the analysis was undertaken for three cases:

(i) monthly values for each catchment independently

(ii) combining all months and catchments

(iii) combining mean monthly values and catchments.

Since the water balance method was considered as the basis for comparison in this study, its AET estimates were regarded as the observed values.

The means and standard deviations of the observed and predicted values in this analysis were represented by AET_{Ob}, AET_{Mb}, and AET_{Gb}, s_O, s_M, and s_G with the subscripts representing water balance, Morton and Grindley models respectively.

4.2.2 Evaluation of models by considering monthly values for each catchment independently

The measures outlined above were used in demonstrating the superiority of one model to the other taking the water balance estimates as the observed values. The quantitative measures of the monthly AET estimates on individual catchment basis are summarized in Table 4.14 for all the catchments.

Table 4.14 Quantitative measures of monthly AET model performance on individual catchment basis

Catchment	Model	Quantitative measures									
		d_r	AET_{Ob}	AET_{Pb}	s_O	s_P	N	MAE	RMSE	d	r^2
Oruba	Morton	-14.6	102.2	87.6	19.83	16.21	120	23.9	28.6	0.422	0.005
	Grindley	57.9	102.2	160.1	19.83	20.82	120	31.7	47.0	0.276	0.051
Tugenon	Morton	20.3	91.4	111.7	15.72	12.39	96	23.1	28.2	0.419	0.001
	Grindley	24.1	91.4	115.5	15.72	19.75	96	29.5	37.1	0.271	0.071
Ndarugu	Morton	15.3	91.9	107.2	19.87	24.74	108	22.3	27.9	0.637	0.217
	Grindley	26.9	91.9	118.8	19.87	24.22	108	28.9	35.3	0.549	0.224
Kimakia	Morton	15.4	97.8	113.2	14.19	28.19	84	27.2	34.0	0.367	0.006
	Grindley	4.1	97.8	102.2	14.19	21.61	84	20.3	25.3	0.412	0.004

The results show that the Grindley model consistently overestimates AET in all catchments in relation to the water balance method as compared to the Morton model which underestimates in Oruba catchment. The same behaviour was revealed by the graphical plot in Fig. 4.1. The RMSE and MAE depict that Morton model performs better than Grindley in three of the four catchments. The Grindley model performed marginally better (Table 4.14) than the Morton model in Kimakia catchment as shown by all the quantitative measures. Although in three out of four catchments, Morton model appeared to be performing better yet, it was considered appropriate to lump all the monthly estimates of AET in order to assess the overall performance of the models as described in section 4.2.1.

4.2.3 Evaluation of models by combining monthly values for all catchments

The results for the combined monthly estimates are presented in Tables 4.15.

Table 4.15 Quantitative measures of combined monthly AET model performances

	d_r	AET_{Ob}	AET_{Pb}	s_O	s_P	N	MAE	RMSE	d	r^2
Morton	7.7	96.0	103.7	18.41	23.43	408	24.0	29.5	0.432	0.007
Grindley	30.7	96.0	126.7	18.41	31.11	408	35.8	45.4	0.381	0.025

It can be observed from AET_{Mb}, AET_{Gb}, s_M and s_G that both models overestimate the corresponding water balance parameters, AET_{Ob} and s_O. AET_{Mb} and AET_{Gb} are both in error by 8.0% and 32.0% with AET_{Ob} respectively, thereby showing Morton model as the better model between the two. Simultaneously, Morton model does better than the Grindley model at predicting variability contained in the water balance estimates. It should be noted that the aforementioned values of 8% and 32% are based on percentages calculated from column 2 and 3 in Table 4.15.

With respect to MAE and RMSE, the results suggest that the Morton model is closer to the water balance estimates by as much as 11.8 (differences in column 7) and 15.9 mm/mon (differences in column 8) than Grindley model. In terms of index of agreement, Morton model is more accurate than the Grindley model by as much as 5.1% (based on values in column 9).

4.2.4 Evaluation of models by combining mean monthly values for all catchments

Analysis of the mean monthly AET estimates portrayed a similar trend to that of all the months combined. The RMSE and MAE values indicate that the Morton model estimates are closer to those of the water balance by 15.0 and 11.1 mm/mon (Table 4.16) respectively.

Table 4.16 Quantitative measures of mean monthly AET model performances

	d_r	AET_{Ob}	AET_{Pr}	s_o	s_p	N	MAE	RMSE	d	r^2
Morton	8.7	95.7	104.4	12.23	20.73	48	20.6	24.1	0.415	0.016
Grindley	28.4	95.7	124.1	12.23	28.24	48	31.7	39.1	0.353	0.091

As regards the degree of agreement in this case, Morton model is 6.2% more accurate than the Grindley model. The above procedure of model evaluation was also adopted by Michalopoulou and Papaiaonnuo (1991) while comparing monthly evapotranspiration estimates of several stations in Greece. These estimates were obtained by three methods with one being taken as the standard. The evidence of the above measures are supported by the graphical plots of the mean AET estimates presented in Figs. 4.9 and 4.10.

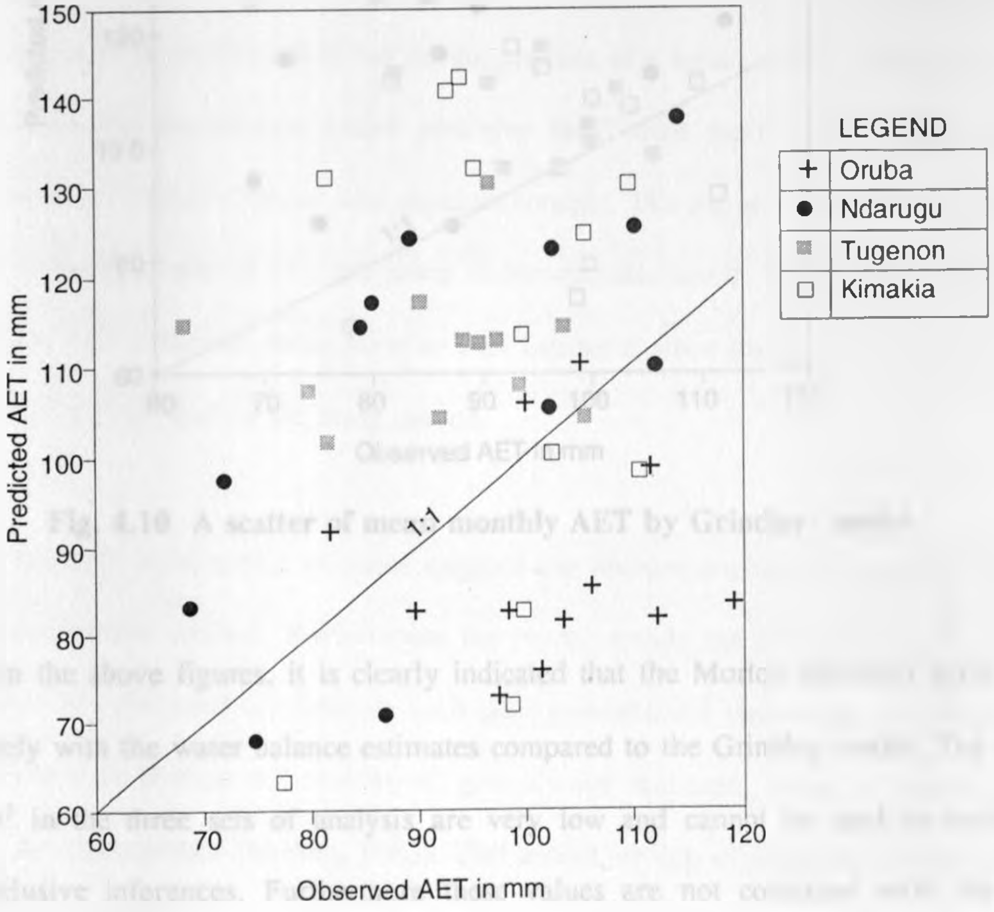

Fig. 4.9 A scatter of mean monthly AET by Morton model

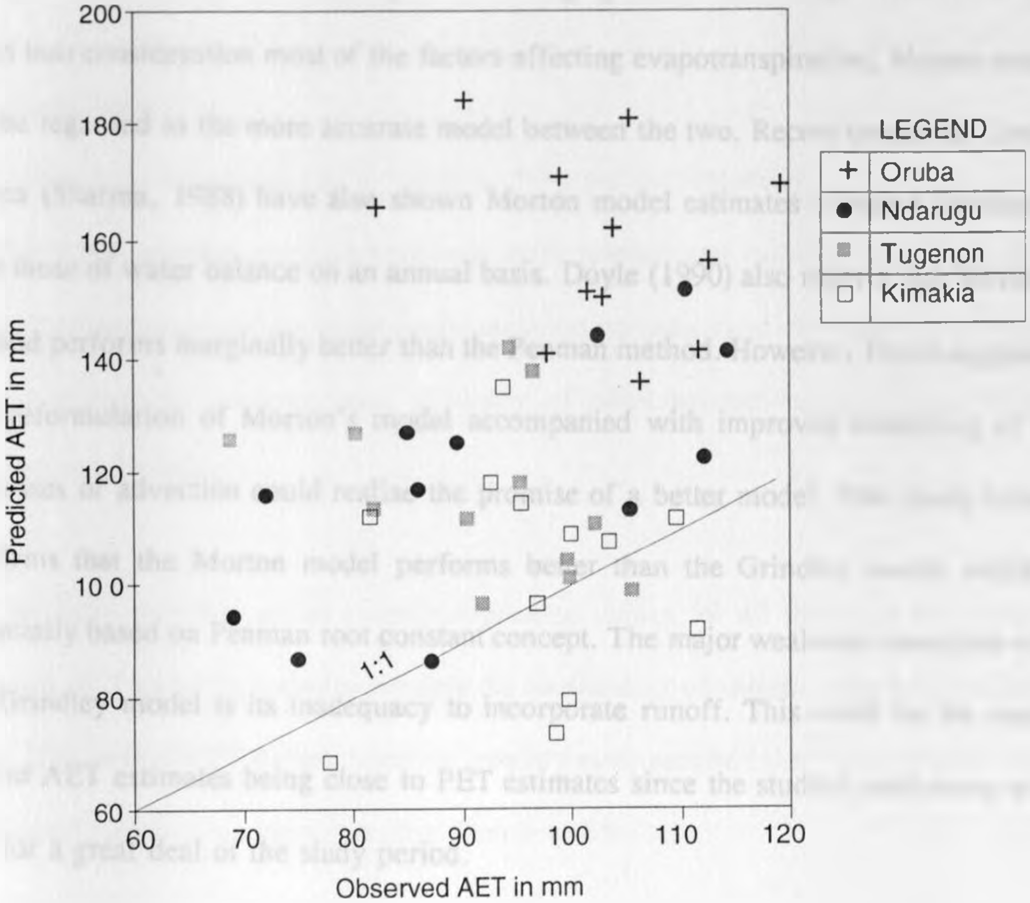

Fig. 4.10 A scatter of mean monthly AET by Grindley model

From the above figures, it is clearly indicated that the Morton estimates agree more closely with the water balance estimates compared to the Grindley model. The values of r^2 in the three sets of analysis are very low and cannot be used to derive the conclusive inferences. Furthermore these values are not consistent with the other statistical measures shown in the aforementioned tables.

Though Willmott (1982) and Fox (1981) have proposed the above indices as appropriate for model performance evaluation, it has been recommended that a model's choice should be based on its scientific grounds and graphical outlook. By virtue of having taken into consideration most of the factors affecting evapotranspiration, Morton model can be regarded as the more accurate model between the two. Recent studies in Central Africa (Sharma, 1988) have also shown Morton model estimates compare favourably with those of water balance on an annual basis. Doyle (1990) also reports that Morton's method performs marginally better than the Penman method. However, Doyle suggested that reformulation of Morton's model accompanied with improved modelling of the processes of advection could realise the promise of a better model. This study further confirms that the Morton model performs better than the Grindley model which is essentially based on Penman root constant concept. The major weakness associated with the Grindley model is its inadequacy to incorporate runoff. This could be the reason behind AET estimates being close to PET estimates since the studied catchments were wet for a great deal of the study period.

In a nutshell, all scientific evidence suggests that Morton is a better model than Grindley for catchments studied. Furthermore the model avoids the complexities of soil-plant system and the need to represent such poorly-understood phenomena like infiltration, soil-moisture storage and movement, groundwater recharge, uptake of water by roots and stomatal control (Morton, 1983). This model, on top of performing better than the Grindley model, still enjoys the advantage of low data requirement contrary to the Grindley model which requires daily rainfall and windrun data which are not readily available in most rural stations in Kenya.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be deduced from the present study;

1. The water balance equation involving daily rainfall and runoff hydrographs gives satisfactory estimates of the actual evapotranspiration values and can be used as the basis for evaluating the adequacy and reliability of other estimation procedures such as Morton and Grindley.

2. The mean monthly actual evapotranspiration values for all the catchments ranged between 68.2 and 118.7 mm/mon while the coefficients of variation varied from 2% to 30%. The annual AET values based on monthly sums ranged from 958.1 to 1352.1 mm with coefficients of variation varying from 5 to 8%.

3. In general, Grindley model tended to overestimate actual evapotranspiration in catchments where pasture and crops were predominant, whereas its performance in a catchment with forest vegetation appeared to be satisfactory. In overall, the overestimation on monthly basis in relation to the water balance method was of the order of 32%.

4. Generally, Morton method agreed closely with the water balance method, though tending to overestimate marginally by 8%. This model performed better in catchments predominantly covered by pasture, annual and perennial crops.

5. Computation of the ratio of the aerodynamic to the energy component in the Penman combination equation for potential evapotranspiration was not constant but varied from 0.12 to 0.58. Hence the Priestley-Taylor equation offers limited applicability in study catchments.

6. It is recommended that one should use Morton method for evaluating the evapotranspiration component in the water balance calculations on a monthly and annual basis. The annual values should be computed by summing the monthly values.

5.2 Recommendations

1. Although the two models were applied on humid catchments which are located on nearly the same latitude, they should be tried on arid and semi-arid catchments whose evaporative demands are relatively higher and water supply is critical to an extent that its conservation is a necessity.

2. The two models should be applied on catchments with recurrent land-use data to facilitate deduction of the link between land use change and evapotranspiration which has been expressed in certain instances. This will also help attain a better understanding on the variation of root constant with crop stage and evapotranspiration; a phenomena that has been found to require further research.

3. As the amount of rainfall that falls over a catchment is the input into the hydrological system, areal rainfall should be used in the Grindley model instead of the point rainfall

as prompted by data insufficiency in the present study.

4. Since the area of the catchments studied was limited to 100 sq. km, it would be advisable to test the two models on larger catchments. This is prompted by the possibility of having a water supply site downstream of a catchment with area exceeding 100 sq. km.; a common feature in rural ungauged catchments, where need may arise to assess the water resources.

5. Kimakia catchment behaved differently from the other catchments possibly because it is largely under forest. There is need to test the Morton model exhaustively by considering other forested catchments in view of its less satisfactory performance in Kimakia.

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7.0 APPENDICES

APPENDIX 1

Monthly and annual rainfall (mm) for Oruba catchment.

Mon\Yr	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972
Jan	126.1	30.5	85.5	89.9	0.0	36.0	249.0	292.2	73.9	80.9
Feb	160.5	182.9	0.0	238.9	51.2	130.3	201.0	124.8	37.8	121.4
Mar	185.1	189.0	123.7	464.4	142.3	224.8	199.8	226.3	13.4	49.2
Apr	371.6	268.1	250.3	838.8	255.3	467.4	179.4	289.2	379.0	311.7
May	257.4	257.3	215.4	148.7	276.7	131.8	340.6	288.9	261.1	193.6
Jun	132.7	88.5	91.6	213.2	177.0	144.4	161.9	124.5	141.1	184.8
Jul	93.7	199.8	97.6	261.8	91.3	95.2	124.0	69.8	191.6	243.8
Aug	137.0	185.4	141.5	663.2	193.5	252.5	20.9	185.7	285.4	135.9
Sep	149.4	110.2	181.7	133.6	246.2	414.6	96.5	99.2	200.0	163.3
Oct	127.5	118.7	184.4	122.9	160.1	153.8	314.1	181.3	176.6	176.5
Nov	255.2	130.8	215.3	138.6	364.6	319.5	132.0	114.8	38.7	213.4
Dec	166.1	151.3	122.5	10.4	166.1	145.9	13.2	69.8	103.4	93.5
Total	2162.3	1912.5	1709.5	3324.9	2124.3	2516.2	2032.2	2066.5	1902.0	1967.8

APPENDIX 2

Monthly and annual rainfall (mm) for Tugenon catchment.

Mon\Yr	1964	1965	1966	1968	1975	1977	1978	1979	1980
Jan	12.4	44.9	79.5	32.3	47.0	112.6	114.4	111.7	54.7
Feb	63.2	5.8	127.3	211.7	52.0	70.1	199.0	217.1	4.1
Mar	136.1	95.6	68.8	257.2	145.6	67.3	222.7	78.8	88.4
Apr	291.6	172.9	234.7	397.8	148.0	180.7	174.0	118.4	123.6
May	214.9	154.0	86.8	203.7	257.7	223.6	171.5	200.7	249.2
Jun	111.8	38.0	68.6	171.7	188.1	158.9	200.3	194.0	104.3
Jul	171.5	198.5	124.7	251.6	172.3	170.8	145.6	115.6	102.8
Aug	223.2	140.9	120.7		368.1	179.1	176.1	135.8	74.8
Sep	214.6	85.5	106.6	37.9	221.5	74.2	100.1	70.0	57.6
Oct	87.1	145.8	72.5		171.2	137.0	135.0	27.9	49.2
Nov	12.7	61.1	37.6		19.6	172.6	31.7	69.7	74.7
Dec	54.8	59.2	46.5		83.7	62.8	54.8	13.2	
Total	1593.1	1201.9	1174.3		1874.8	1609.7	1725.0	1352.9	

APPENDIX 3

Monthly and annual rainfall (mm) for Ndarugu catchment.

Mon\Yr	1963	1964	1965	1972	1973	1974	1975	1977	1978
Jan	115.1	41.9	70.1	119.5	124.8	6.5	19.0	165.2	105.6
Feb	90.5	199.4	69.0	170.6	106.8	27.6	6.1	97.8	89.8
Mar	160.9	165.1	62.5	39.3	4.2	163.5	164.2	196.2	258.6
Apr	633.6	461.3	310.2	137.1	323.2	567.5	341.2	590.2	570.7
May	325.4	208.7	281.8	200.2	147.7	142.8	252.9	311.1	201.7
Jun	48.3	43.4	57.1	122.9	80.9	123.0	46.5	46.5	92.9
Jul	14.0	45.5	46.0	21.1	26.8	201.8	99.6	71.9	28.0
Aug	42.7	50.1	22.0	21.8	56.4	80.8	50.1	96.1	16.5
Sep	14.7	76.3	36.4	75.8	89.1	40.3	105.1	27.2	67.5
Oct	42.7	120.1	134.6	400.7	123.9	98.8	173.6	145.1	143.8
Nov	189.8	98.7	280.5	232.6	209.3	229.4	85.6	385.5	94.0
Dec	239.9	81.3	50.1	26.5	39.3	48.0	76.1	136.4	137.0
Total	1917.6	1591.8	1420.3	1568.1	1332.4	1730.0	1420.0	2268.5	1806.1

APPENDIX 4

Monthly and annual rainfall (mm) for Kimakia catchment.

Mon\Yr	1964	1965	1966	1969	1970	1972	1973	1974	1975	1976
Jan	121.9	131.5	56.5	191.5	237.0	144.7	117.1	40.8	12.0	56.5
Feb	118.4	69.6	64.0	40.6	253.1	193.9	144.1		14.0	72.5
Mar	218.6	84.4	279.6	116.4	234.6	88.8	37.4	14.7	64.2	83.0
Apr	295.6	214.8	592.3	66.0	437.2	233.4	412.8	206.9	343.1	192.4
May	430.3	311.4	382.0	604.5	590.0	643.8	567.4	204.7	322.1	770.8
Jun	140.8	90.1	249.2	97.8	221.2	136.3	128.9	139.9	158.0	125.5
Jul	106.9	137.6	125.4	268.9	124.3	201.0	111.5	412.6	345.0	96.0
Aug	214.6	171.2	95.4	323.8	220.0	106.8	114.5	134.1	288.0	135.2
Sep	87.4	93.6	92.6	101.5	89.8	317.8	142.6	89.6	80.3	195.3
Oct	250.4	208.2	409.0	172.8	238.4	558.2	201.6	50.3	235.4	132.9
Nov	125.0	369.3	256.4	183.7	153.6	323.4	221.0	88.7	117.4	299.6
Dec	106.0	220.7	0.0	48.4	54.7	109.3	100.7	27.5	110.9	120.5
Total	2215.9	2102.4	2602.4	2215.9	2853.9	3057.5	2299.6		2090.4	2279.2

APPENDIX 5

Monthly and annual runoff (million m^3) for Oruba catchment

Mon\Yr	1963	1965	1966	1967	1968	1969	1971	1972
Jan	1.646	1.214	0.667	0.273	1.501	1.780	0.746	0.761
Feb	1.453	0.687	0.892	0.175	1.847	2.674	0.309	0.799
Mar	1.292	0.754	1.753	0.193	1.737	1.967	0.223	0.517
Apr	2.386	1.376	2.459	0.943	2.791	1.492	1.218	0.586
May	6.879	2.388	2.057	2.023	3.651	2.344	2.418	1.347
Jun	4.305	0.933	1.917	1.413	3.071	1.740	1.705	1.471
Jul	2.754	0.961	1.586	1.449	2.719	1.612	1.643	1.484
Aug	2.086	0.915	1.506	1.196	2.858	2.119	2.350	1.975
Sep	1.760	.885	1.536	1.238	2.582	1.919	2.968	1.564
Oct	1.266	.844	1.320	1.120	2.668	1.483	2.261	1.773
Nov	1.784	1.866	1.098	2.411	2.649	1.242	1.488	3.543
Dec	4.441	1.391	0.680	0.976	2.827	0.744	0.993	2.341
Total	32.508	14.218	17.537	13.418	30.906	21.122	18.326	18.257

APPENDIX 6

Monthly and annual runoff (million m^3) for Tugenon catchment

Mon\Yr	1964	1965	1966	1968	1977	1978	1979	1980
Jan	0.087	0.020	0.005	0.014	0.031	0.854	0.323	0.116
Feb	0.028	0.010	0.009	0.015	0.023	0.610	3.132	0.106
Mar	0.032	0.010	0.006	1.080	0.009	2.664	0.876	0.125
Apr	1.386	0.016	0.267	8.850	0.171	2.102	1.183	0.658
May	0.924	0.028	0.021	5.219	3.468	2.261	1.187	2.734
Jun	0.408	0.011	0.019	0.889	3.780	1.613	2.172	1.007
Jul	1.332	0.021	0.021	1.741	2.662	2.547	1.451	1.426
Aug	2.967	0.020	0.358	3.348	3.343	2.252	1.896	0.796
Sep	3.367	0.014	1.062	0.120	2.001	2.076	1.186	0.373
Oct	1.021	0.025	0.011	0.056	0.705	1.591	0.521	0.205
Nov	0.045	0.044	0.008	0.041	4.753	1.079	0.198	0.088
Dec	0.027	0.012	0.002	0.030	0.842	0.764	0.134	0.072
Total	11.631	0.236	1.795	21.410	21.883	20.419	14.264	7.713

APPENDIX 7

Monthly and annual runoff (million m^3) for Ndarugu catchment

Mon\Yr	1963	1964	1965	1972	1973	1974	1975	1978
Jan	3.715	5.827	4.254	1.464	3.925	1.000	1.839	6.034
Feb	2.522	3.024	2.351	1.681	2.429	0.717	1.086	3.243
Mar	2.240	3.381	1.603	1.377	1.563	1.072	1.041	7.827
Apr	11.368	11.720	2.173	1.301	3.082	9.330	2.009	32.655
May	23.179	16.065	5.747	2.167	6.154	10.946	2.817	21.321
Jun	10.693	6.975	4.849	4.085	3.697	6.219	2.424	6.746
Jul	4.982	4.021	2.670	3.164	2.586	18.037	2.029	3.894
Aug	2.980	3.454	1.919	2.111	2.038	8.007	1.812	2.730
Sep	1.906	2.341	1.320	1.632	1.670	3.969	1.575	2.145
Oct	1.534	2.312	1.338	4.967	1.429	3.092	1.705	2.314
Nov	2.094	2.314	4.812	20.001	1.640	3.739	2.211	3.036
Dec	6.375	3.586	3.876	7.616	1.491	2.957	1.855	3.760
Total	73.953	65.025	36.917	51.572	31.709	69.090	22.411	95.711

APPENDIX 8

Monthly and annual runoff (million m^3) for Kimakia catchment

Mon\Yr	1964	1965	1966	1969	1970	1972	1973	1975	1976
Jan	2.661	1.548	0.950	1.148	0.271	0.919	1.911	0.280	0.417
Feb	1.038	0.605	0.402	0.492	0.205	2.185	1.242	0.033	0.195
Mar	1.141	0.307	1.579	0.470	0.474	1.073	0.853	0.046	0.176
Apr	11.289	2.178	13.067	0.517	9.345	1.398	2.536	1.941	0.539
May	19.414	9.458	12.540	6.382	12.123	2.635	2.434	5.751	3.151
Jun	10.656	3.303	3.832	1.689	6.653	5.312	3.271	2.419	2.106
Jul	1.807	1.360	1.486	0.685	1.567	1.837	1.153	0.564	2.065
Aug	0.895	0.580	1.036	0.380	0.817	0.745	0.818	0.686	1.221
Sep	1.015	0.411	0.563	0.197	0.358	1.107	0.464	0.965	0.810
Oct	0.918	0.719	0.295	0.137	0.262	4.525	0.670	1.070	0.393
Nov	1.0816	11.052	2.189	0.268	0.518	14.507	2.265	1.985	0.756
Dec	3.597	2.598	0.653	0.071	0.293	5.371	1.818	1.044	0.984
Total	56.253	34.124	38.777	12.441	32.873	41.620	19.440	16.790	12.821

APPENDIX 9

A SAMPLE YEAR'S MEAN DAILY DISCHARGES

DAY GAPS OR LESS WERE BRIDGED BY LINEAR INTERPOLATION

THE DISCHARGES ARE IN CUBIC METRES PER SECOND RIVER KIMAKIA R G S NUMBER 4CA16

BASED ON OBSERVATIONS OF RIVER STAGES. CATCHMENT AREA IS 52 SQUARE KILOMETRES YEAR 1965

DATE	JAN	FEB	MARCH	APRIL	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
01	0.801	0.364	0.106	0.203	2.127	2.991	0.558	0.261	0.193	0.106	0.974	1.789
02	0.857	0.392	0.193	0.203	2.101	2.459	0.607	0.249	0.182	0.097	1.640	1.640
03	0.877	0.364	0.193	0.193	2.047	2.047	0.675	0.237	0.193	0.089	6.084	1.427
04	0.896	0.378	0.161	0.203	1.917	1.995	0.710	0.203	0.182	0.097	6.907	1.313
05	0.877	0.406	0.193	0.226	1.917	1.942	0.801	0.226	0.193	0.081	6.698	1.203
06	0.801	0.378	0.182	0.261	1.891	1.917	0.857	0.203	0.171	0.089	6.532	1.203
07	0.765	0.450	0.182	0.249	5.112	1.917	0.710	0.203	0.193	0.097	6.286	1.160
08	0.693	0.350	0.171	0.237	4.741	1.917	0.591	0.193	0.203	0.089	6.084	1.118
09	0.675	0.324	0.161	0.203	4.559	1.891	0.526	0.171	0.203	0.097	6.004	1.055
10	0.693	0.311	0.151	0.214	4.381	1.865	0.510	0.182	0.193	0.114	6.246	0.994
11	0.624	0.286	0.106	0.249	4.205	1.291	0.465	0.161	0.182	0.106	5.492	0.954
12	0.675	0.261	0.106	0.261	4.031	1.203	0.591	0.161	0.193	0.106	4.381	0.915
13	0.641	0.249	0.097	0.298	4.031	1.160	0.746	0.151	0.171	0.106	5.492	0.839
14	0.624	0.226	0.089	0.450	4.136	1.118	0.710	0.182	0.171	0.114	5.300	0.877
15	0.542	0.226	0.089	0.435	4.066	1.055	0.624	0.193	0.161	0.123	5.112	0.915
16	0.480	0.203	0.081	0.465	3.929	0.994	0.591	0.203	0.171	0.142	5.037	0.877
17	0.465	0.182	0.066	0.465	3.895	0.954	0.495	0.203	0.161	0.151	4.924	0.954
18	0.465	0.171	0.081	0.558	3.794	0.915	0.465	0.237	0.171	0.161	4.559	0.896
19	0.450	0.171	0.089	0.542	3.693	0.896	0.435	0.249	0.171	0.182	4.381	0.857
20	0.480	0.171	0.081	0.510	3.862	0.857	0.406	0.261	0.151	0.193	4.205	0.839
21	0.465	0.161	0.074	0.465	4.031	0.820	0.378	0.273	0.142	0.203	3.862	0.857
22	0.465	0.161	0.074	0.435	3.929	0.801	0.350	0.298	0.142	0.237	3.693	0.820
23	0.450	0.151	0.066	0.421	3.862	0.801	0.392	0.286	0.132	0.261	3.178	0.801
24	0.435	0.151	0.059	3.998	3.693	0.765	0.364	0.261	0.106	0.226	2.750	0.839
25	0.421	0.142	0.066	2.960	3.627	0.710	0.350	0.237	0.114	0.203	2.181	0.801
26	0.392	0.132	0.066	2.181	3.432	0.641	0.350	0.203	0.106	0.203	2.127	0.765
27	0.406	0.132	0.059	1.917	3.368	0.624	0.337	0.203	0.106	0.801	2.047	0.729
28	0.392	0.114	0.052	2.047	3.464	0.591	0.324	0.226	0.097	0.896	1.969	0.710
29	0.378	*****	0.106	2.181	3.368	0.558	0.286	0.203	0.097	1.015	1.917	0.675
30	0.364	*****	0.151	2.181	3.208	0.542	0.286	0.203	0.106	0.994	1.865	0.624
31	0.378	*****	0.203	*****	3.053	*****	0.261	0.193	*****	0.954	*****	0.624

MONTHLY SUMMARY

MILLION CUBIC M	1.548	0.605	0.307	2.178	9.458	3.303	1.360	0.580	0.411	0.719	11.052	2.598
MAX CUMEC	0.896	0.450	0.203	3.998	5.112	2.991	0.857	0.298	0.203	1.015	6.907	1.789
MIN CUMEC	0.364	0.114	0.052	0.193	1.891	0.542	0.261	0.151	0.097	0.081	0.974	0.624
MEAN CUMEC	0.578	0.250	0.114	0.840	3.531	1.274	0.508	0.216	0.158	0.268	4.264	0.970

ANNUAL SUMMARY

MILLION CUBIC METRES 34.124 CUMEC MAX. 6.907 CUMEC MIN. 0.052 CUMEC MEAN 1.082

APPENDIX 10

MEAN DAILY DISCHARGES (m3/S) REARRANGED ACCORDING TO MONTHS IN KIMAKIA CATCHMENT

Date	Kim'63	Kim'64	Kim'65	Kim'66	Kim'69	Kim'70	Kim'72	Kim'73	Kim'74	Kim'75	Kim'76
1	1.225	1.203	0.801	0.591	0.801	0.203	0.286	0.675	0.226	0.182	0.203
2	1.247	1.160	0.857	0.574	0.765	0.029	0.350	0.641	0.214	0.182	0.203
3	1.269	1.182	0.877	0.542	0.765	0.024	0.350	0.591	0.203	0.171	0.193
4	1.203	1.160	0.896	0.526	0.693	0.024	0.311	0.558	0.203	0.161	0.237
5	1.139	1.139	0.877	0.526	0.624	0.029	0.286	0.526	0.193	0.161	0.237
6	1.160	1.118	0.801	0.510	0.607	0.024	0.286	0.820	0.182	0.151	0.226
7	1.097	1.097	0.765	0.465	0.591	0.203	0.311	0.765	0.171	0.142	0.226
8	0.994	1.118	0.693	0.465	0.558	0.171	0.273	0.658	0.161	0.142	0.214
9	1.015	1.097	0.675	0.480	0.526	0.089	0.249	0.591	0.161	0.171	0.203
10	0.915	1.139	0.693	0.465	0.495	0.081	0.273	0.542	0.151	0.182	0.203
11	0.935	1.097	0.624	0.435	0.450	0.074	0.350	0.510	0.142	0.151	0.193
12	0.896	1.118	0.675	0.392	0.435	0.081	0.337	0.465	0.132	0.142	0.182
13	0.877	1.139	0.641	0.406	0.406	0.203	0.311	0.421	0.132	0.114	0.171
14	0.877	1.203	0.624	0.378	0.406	0.106	0.273	0.378	0.214	0.106	0.171
15	0.857	1.182	0.542	0.364	0.392	0.074	0.226	0.675	0.182	0.097	0.161
16	0.820	1.160	0.480	0.324	0.378	0.046	0.203	2.074	0.161	0.089	0.161
17	0.839	1.097	0.465	0.324	0.350	0.034	0.203	1.995	0.151	0.089	0.151
18	0.801	1.035	0.465	0.298	0.337	0.024	0.182	1.891	0.142	0.081	0.142
19	0.710	0.954	0.450	0.286	0.324	0.081	0.161	1.592	0.132	0.081	0.132
20	0.693	0.896	0.480	0.311	0.324	0.046	0.151	1.225	0.123	0.081	0.123
21	0.658	0.877	0.465	0.261	0.324	0.040	0.214	0.857	0.114	0.074	0.114
22	0.641	0.857	0.465	0.249	0.298	0.465	0.624	0.641	0.114	0.074	0.114
23	0.624	0.820	0.450	0.237	0.298	0.203	0.641	0.495	0.106	0.066	0.106
24	0.591	0.801	0.435	0.203	0.350	0.089	0.839	0.435	0.097	0.059	0.097
25	0.607	0.801	0.421	0.203	0.324	0.046	0.729	0.392	0.089	0.052	0.097
26	0.591	0.765	0.392	0.214	0.298	0.089	0.675	0.350	0.089	0.052	0.114
27	0.607	0.729	0.406	0.193	0.261	0.034	0.591	0.311	0.081	0.046	0.106
28	0.591	0.710	0.392	0.182	0.249	0.029	0.337	0.311	0.074	0.040	0.106
29	0.574	0.729	0.378	0.193	0.237	0.024	0.226	0.273	0.066	0.040	0.089
30	0.558	0.710	0.364	0.203	0.237	0.015	0.203	0.249	0.066	0.034	0.081
31	0.542	0.710	0.378	0.203	0.193	0.465	0.193	0.214	0.059	0.034	0.074
32	0.526	0.710	0.364	0.203	0.203	0.052	0.171	0.203	0.059	0.029	0.074
33	0.510	0.693	0.392	0.214	0.298	0.106	0.624	0.203	0.059	0.029	0.074
34	0.465	0.675	0.364	0.182	0.591	0.097	0.783	0.193	0.052	0.029	0.066
35	0.495	0.624	0.378	0.161	0.350	0.089	0.675	0.182	0.046	0.024	0.089
36	0.526	0.591	0.406	0.171	0.214	0.081	0.675	0.171	0.046	0.019	0.097
37	0.510	0.801	0.378	0.161	0.203	0.106	1.203	0.161	0.074	0.019	0.106
38	0.542	0.480	0.450	0.171	0.182	0.106	1.160	0.298	0.074	0.019	0.106
39	0.542	0.465	0.350	0.182	0.182	0.237	0.658	0.273	0.066	0.019	0.097
40	0.526	0.465	0.324	0.171	0.203	0.203	1.269	0.261	0.059	0.015	0.089
41	0.465	0.435	0.311	0.171	0.193	0.106	1.336	0.237	0.059	0.015	0.089
42	0.480	0.421	0.286	0.161	0.193	0.106	1.381	0.214	0.052	0.015	0.081
43	1.015	0.406	0.261	0.151	0.171	0.123	1.225	0.337	0.052	0.015	0.081
44	1.139	0.364	0.249	0.161	0.142	0.203	1.118	0.526	0.046	0.015	0.074
45	0.935	0.337	0.226	0.171	0.123	0.132	0.915	0.624	0.046	0.011	0.066
46	0.877	0.350	0.226	0.181	0.106	0.089	0.641	0.558	0.052	0.011	0.074
47	0.801	0.337	0.203	0.191	0.114	0.059	0.658	0.839	0.052	0.011	0.074
48	0.801	0.324	0.182	0.201	0.123	0.046	0.783	0.954	0.046	0.011	0.074

APPENDIX 11

Program 1

```
Program calulate (input, output);
uses  crt;
var phi,a,z,z1,n,ge,w,theta,d4,z2: real;
    i: integer;
    flag:boolean;
    lst: text;
    begin
clrscr;
assign (lst,'prn');
rewrite (lst);
writeln('please enter value of phi in degrees');
readln(phi);
for i:= 1 to 12 do
begin
theta:=23.2*sin((29.5*i-94)*3.142/180);
z:=(phi-theta)*3.142/180;
if (cos(z)<0.001) then z1:=0.001 else z1:=cos(z);
a:=1-(z1/(cos(phi*3.142/180)*cos(theta*3.142/180)));
if (a<-1) then a:=-1 else a:=
1-(z1/(cos(phi*3.142/180)*cos(theta*3.142/180)));
w:=0;
writeln('cos(phi) = ',cos(phi*3.142/180 ):8:4);
writeln('cos(theta) = ',cos(theta*3.142/180));
writeln('cos(89.9) = ',sin(90.1*22/(180*7)));
writeln('cos(45) = ',cos(45*22/(180*7)));
writeln('cos(180) = ',cos(3.142));
flag:=true;
while (w<180) and (flag) do
begin
IF (trunc(COS(w * 3.142 / 180) * 1000) / 1000) =
(trunc(1000 * a) / 1000) THEN flag:=false;

w:=w+0.05;
d4:=(z1+((180/(3.142*w)*sin(w*3.142/180))-1)*cos(phi*3.142/180)*
cos(theta*3.142/180));

end;
n:=1+(1/60*(sin((29.5*i-106)*3.142/180)));
ge:=1354/(sqr(n)*180)*w*(z1+((180/(3.142*w)*sin(w*3.142/180))-1)*
cos(phi*3.142/180)*cos(theta*3.142/180));
writeln('for i= ',i,' : ge=',ge :8:2);
writeln('for i= ',i,' : z=',z :8:4);
writeln('for i= ',i,' : d4=',d4 :8:4);

        writeln(lst,'for i= ',i,' : ge=',ge :8:2);
        writeln(lst,'for i= ',i,' : z=',z :8:4);
        writeln(lst,'for i= ',i,' : d4=',d4 :8:4);


end;
writeln(cos(3.142/180*(-20.941)));
writeln(1/sqrt(2));
end.
```

APPENDIX 12

PROGRAM 2

```
10 REM This program is based on Morton's 1983 paper
12 REM It estimates Monthly and Annual AET
22 REM Nday stands for number of days in a given month
24 REM LA is the latitude in degrees (being -ve for Southern Hemisphere)
26 REM AL is the altitude in metres
28 REM AR is the average annual rainfall in mm
30 REM P is the atmospheric pressure of a place in mbars
32 REM Ps  is the sea level pressure in mbars
34 REM Pr is the ratio of P to Ps
36 REM A,AD,AZ,AZZ,AZD, stand for albedos
38 REM B stands for the net long wave radiation
40 REM AET represent areal evapotranspiration in mm
42 REM AET is a table
44 REM PET represents potential evapotranspiration
46 REM ETW stands for wet-environment areal evapotranspiration
48 REM FT is the vapour transfer coefficient between surface &
     REM instrument level
50 REM G is the incident global radiation (W/m^2/K^4)
52 REM GE is the extra-atmosp. global radiation
54 REM GO is clear sky radiation
58 REM RT is the net radiation for soil-plant surface at air temp.
60 REM RTP is net radiation for soil-plant surface at Pot.evapot.
62 REM RTC is equilibrium temp.
64 REM RTC is RT with RTC >=0
66 REM S is the ratio of observed (SN) to max. sunshine hours(SNM)
68 REM TA is the average air temp. (oC)
70 REM TD is the average dew point temp.(oC)
72 REM VD and V represent vapour pressure in mbars at temp. TD and TA
74 REM PWV is precipitable water vapour
80 REM DEL is the slope of saturation vapour pressure
82 REM ZEI is the inverse of stability factor
84 REM NETA is the radius vector of the sun
86 REM THETA is the declination of the sun
88 REM RO is the proportional increase in atm. radiation due to clouds.
90 REM TU, TUA, are related to transmittancy and absorption
92 REM Z is the noon distance of the sun
94 REM ZZ is the average angular distance of the sun
96 REM GE is the extra-atmospheric global radiation

 100 DIM Etw(10, 13), PET(10, 13), ART(10, 13), AET(10, 13)
 105 DIM iy(10), medu(13), stdu(13), var(13), cvdu(13)
P$ = "con": F$ = "A:\motkim.dat"
  OPEN F$ FOR INPUT AS £1
  OPEN P$ FOR OUTPUT AS £2
PRINT "Program, Morton, printing to"; P$
WHILE NOT EOF(1)
 200 INPUT £1, stan, Name$, LA, AL, AR, ny
 205 IF stan = 0 THEN 1590
 220 Pr = ((288 - .0065 * AL) / 288) ^ 5.256
 225 AZD1 = 1 + ABS(LA / 42) + (LA / 42) ^ 2
 230 AZD = .26 - (.00012 * AR) * (Pr) ^ .5 * AZD1
 235 IF AZD <= .11 THEN AZD = .11
 240 IF AZD >= .17 THEN AZD = .17
 250 i = 1
 300 INPUT £1, iyear, monn, Nday, TA, TD, Ge, Z, ZZ, SN, snm
 301 IF iyear = 0 THEN END

 305 VD = 6.11 * EXP(17.27 * TD / (TD + 237.3))
 310 V = 6.11 * EXP(17.27 * TA / (TA + 237.3))
 315 DEL = 4098.17 * V / ((TA + 237.3) ^ 2)
 320 LET azz = AZD
 330 IF azz >= .5 * (.91 - VD / V) THEN azz = .5 * (.91 - VD / V)
```

```
333 IF azz <= .11 THEN azz = .11
335 CO = V - VD
340 IF CO <= 0 THEN CO = 0
345 IF CO >= 1 THEN CO = 1
350 AZ = azz + (1 - CO ^ 2) * (.34 - azz)
355 AO = EXP(.012 * 57.3 * Z) * (SIN(Z) + (2.16 * COS(Z) / 3.14))
360 AO = AZ * (EXP(1.08) - AO) / (1.473 * (1 - SIN(Z)))
365 PWV = VD / (.49 + (TA / 129))
370 C1 = 21 - TA
375 IF C1 <= 0 THEN C1 = 0
380 IF C1 >= 5 THEN C1 = 5
385 TC = (.5 + 2.5 * (COS(ZZ)) ^ 2) * EXP(C1 * (Pr - 1))
390 TU = (-.089 * (Pr / COS(ZZ)) ^ .75) - .083 * (TC / COS(ZZ)) ^ .9
392 TU = TU - .029 * (PWV / COS(ZZ)) ^ .6
395 TU = EXP(TU)
400 TUA = (-.0415 * (TC / COS(ZZ)) ^ .9) - (.054 * (PWV / COS(ZZ)) ^ .3)
402 TUA = EXP(TUA)
403 TUA1 = (-.0415 * (TC / COS(ZZ)) ^ .9) - .029 * (PWV / COS(ZZ)) ^ .6
404 TUA1 = EXP(TUA1)
405 IF TUA <= TUA1 THEN TUA = TUA1
410 GO = 1 + ((1 - (TU / TUA)) * (1 + AO * TU))
415 GO = GO * Ge * TU
420 s = SN / snm
425 G = s * GO + Ge * ((.08 + .3 * s) * (1 - s))
430 A = AO * (s + (1 - s) * (1 - (Z * 57.3 / 330)))
435 C2 = 10 * ((VD / V) - s - .42)
440 IF C2 <= 0 THEN C2 = 0
445 IF C2 >= 1 THEN C2 = 1
450 RO = (1 - C2) * (1 - s) ^ 2 + C2 * (1 - s) ^ .5
455 RO = (.18 * RO) / Pr
460 B = 5.22 * 10 ^ -8 * (TA + 273) ^ 4
465 B = B * (1 - (.71 + .007 * VD * Pr) * (1 + RO))
470 IF B <= .05 * 5.22 * 10 ^ -8 * (TA + 273) ^ 4 THEN
     REM B = .05 * 5.22 * 10 ^ -8 * (TA + 273) ^ 4
475 RT = G * (1 - A) - B
480 LET RTC = RT
485 IF RT <= 0 THEN RTC = 0
487 GAM = .66 * Pr
490 ZEI = (DEL * RTC) / ((GAM * Pr ^ -.5) * 28 * (V - VD))
495 ZEI = ZEI + .28 * (1 + (VD / V))
497 IF ZEI >= 1 THEN ZEI = 1
500 FT = ZEI * (Pr ^ -.5) * 28
505 LEM = GAM + ((20.88 * 10 ^ -8) * (TA + 273) ^ 3) / FT

510 REM ITERATION FOR COMPUTING EQUILIBRIUM TEMPERATURE
515 LET TP = TA
520 VP = 6.11 * EXP((17.27 * TP) / (237.3 + TP))
525 DELP = (4098.17 * VP) / ((237.3 + TP) ^ 2)
530 DET = ((RT / FT) + VD - VP + LEM * (TA - TP)) / (DELP + LEM)
535 IF ABS(DET) > .01 THEN 545
540 IF ABS(DET) <= .01 THEN 555
545 TP = TP + DET
550 GOTO 520
555 PET = RT - (LEM * FT * (TP - TA))
560 RTP = PET + (GAM * FT * (TP - TA))
565 Etw = 14 + (1.2 * RTP) / (1 + (GAM / DELP))
570 IF Etw <= .5 * PET THEN Etw = .5 * PET
575 IF Etw >= PET THEN Etw = PET
580 AET = 2 * Etw - PET
585 AET = (AET * Nday) / 28.5
600 iy(i) = iyear
605 Etw(i, monn) = Etw
610 PET(i, monn) = PET
615 AET(i, monn) = AET
620 IF monn < 12 THEN 300
```

```
625 s1 = 0
630 s2 = 0
635 s3 = 0
640 FOR j = 1 TO 12
645 s3 = s3 + AET(i, j)
646 NEXT j
647 AET(i, j) = s3
648 i = i + 1
649 IF i <= ny THEN 300
650 PRINT £2, "AET estimation using Morton model"
651 PRINT £2,
655 PRINT £2, "Station No is"; stan; "station name is "; Name$;
660 PRINT £2,
665 PRINT £2, "Estimates of AET"
670 FOR i = 1 TO ny: FOR j = 1 TO 13
675 ART(i, j) = AET(i, j)
680 NEXT j: NEXT i
685 GOSUB 1500
690 PRINT £2,
695 FOR i = 1 TO ny: PRINT £2, USING "££££"; iy(i)
700 FOR j = 1 TO 13
   PRINT £2, USING "  ££££.£"; AET(i, j);
    NEXT j
   PRINT £2,
    NEXT i
705 PRINT £2, "Mean";
710 FOR j = 1 TO 13
715 PRINT £2, USING " ££££.£"; medu(j);
720 NEXT j
725 PRINT £2,
730 PRINT "Std. dev";
735 FOR j = 1 TO 13
740 PRINT £2, USING " £££.£"; stdu(j);
745 NEXT j
750 PRINT £2,
755 PRINT £2, "Cov";
760 FOR j = 1 TO 13
765 PRINT £2, USING "££.££"; cvdu(j);
NEXT j
770 GOTO 200

1500 REM "Estimation of AET statistics"
1505 sum = 0
1510 FOR j = 1 TO 13: FOR i = 1 TO ny
1515 sum = sum + ART(i, j)
1520 NEXT i
1525 medu(j) = sum / ny
1530 sum = 0
1535 NEXT j
1538 sum = 0
1540 FOR j = 1 TO 13: FOR i = 1 TO ny
1545 sum = sum + (ART(i, j) - medu(j)) ^ 2
1550 NEXT i
1565 var(j) = sum / ny
1570 stdu(j) = var(j) ^ .5
      cvdu(j) = stdu(j) / medu(j)
1575 sum = 0
1580 NEXT j
     sum = 0
1585 RETURN
1590 STOP
1600 WEND
```

APPENDIX 13

PROGRAM 3

```
1 REM This Program Calculates PET By PENMAN Equation
15 DIM En(10, 13), AE(10, 13), ETP(10, 13), iy(10)
20 DIM DUM(10, 13), meau(13), stdu(13), cvdu(13), Var(13), Ro(10, 13)
22 DIM PE(10, 36), PET(480), AET(480), AEG(10, 13), P(480), R1(10, 36),
SMD(480), PSMD(480)
P$ = "prn": F$ = "b:\metkima.dat"
OPEN F$ FOR INPUT AS £1
OPEN P$ FOR OUTPUT AS £2
REM PRINT "PROGRAM PENMAN, PRINTING TO "; P$
WHILE NOT EOF(1)
24 IF EOF(1) THEN END
25 INPUT £1, STAN, NAME$, ELEV, ny
26 IF STAN = 0 THEN 1590
35 ALB = .25
40 sigm = 11.71 * 10 ^ -8
45 Gam = .584
46 Rc = 200
47 Pc = .878
50 I = 1
55 INPUT £1, iyear, monn, Nday, Ta, Td, Ra, U, S, SM
56 IF iyear = 0 THEN END
60 rs = (.25 + .5 * (S / SM)) * Ra
65 rns = (1 - ALB) * rs
70 ea = 6.11 * EXP((17.27 * Ta) / (237.3 + Ta))
80 ed = 6.11 * EXP((17.27 * Td) / (237.3 + Td))
90 rnl1 = sigm * (Ta + 273) ^ 4
95 rnl2 = rnl1 * (.34 - .044 * ed ^ .5)
100 rnl = rnl2 * (.1 + .9 * (S / SM))
105 rn = rns - rnl
110 rn = rn / 58.89
115 Del = (.00815 * Ta + .8917) ^ 7
120 w = Del / (Del + Gam)
125 wf = .27 * (1 + U / 100)
130 Enc = w * rn * Nday
135 Aec = ((1 - w) * wf * (ea - ed)) * Nday
140 Et = Enc + Aec
145 Ratio = Aec / Enc
150 iy(I) = iyear
155 En(I, monn) = Enc
160 AE(I, monn) = Aec
165 ETP(I, monn) = Et
170 Ro(I, monn) = Ratio
175 IF monn < 12 THEN 55

180 S1 = 0
185 S2 = 0
190 S3 = 0
195 FOR j = 1 TO 12
200 S1 = S1 + En(I, j)
205 S2 = S2 + AE(I, j)
210 S3 = S3 + ETP(I, j)
215 NEXT j
220 En(I, 13) = S1
225 AE(I, 13) = S2
230 ETP(I, 13) = S3
232 Ro(I, j) = AE(I, 13) / En(I, 13)
235 I = I + 1

242 IF I <= ny THEN 55
245 REM PRINT £2, "Evapotranspiration using Penman Formula"
250 REM PRINT £2,
255  PRINT £2, "Station No"; STAN; "Stan "; NAME$
```

```
260 REM PRINT £2, "Elevation is"; ELEV; "M"
265 REM PRINT £2, "Estimates of Pot. Evapotranspiration"
300 FOR I = 1 TO ny: FOR j = 1 TO 13
305 DUM(I, j) = ETP(I, j)
310 NEXT j: NEXT I
315 GOSUB 1500
325 REM PRINT £2,
    FOR I = 1 TO ny:  REM PRINT £2, USING "££££"; iy(I)
    FOR j = 1 TO 13
    REM PRINT £2, USING " ££££.£"; ETP(I, j);
     NEXT j
    REM PRINT £2,
     NEXT I
340  REM PRINT £2, "Mean";
  REM PRINT £2,
345 FOR j = 1 TO 13
350 REM PRINT £2, USING " ££££.£"; medu(j);
355 NEXT j
360 REM PRINT £2,
365 REM PRINT £2, "Std";
  REM PRINT £2,
370 FOR j = 1 TO 13
375 REM PRINT £2, USING " £££.£"; stdu(j);
380 NEXT j
385 REM PRINT £2,
390  REM PRINT £2, "Cov";
  REM PRINT £2,
395 FOR j = 1 TO 13
396  REM PRINT £2, USING "££.££"; cvdu(j);
397 NEXT j
REM PRINT £2,
 REM PRINT £2, "Printing ratios"
400 FOR I = 1 TO ny: FOR j = 1 TO 13
    DUM(I, j) = Ro(I, j)
     NEXT j: NEXT I
410 GOSUB 1500
REM PRINT £2,
FOR I = 1 TO ny
 REM PRINT £2, USING "££££"; iy(I)
 FOR j = 1 TO 13
 REM PRINT £2, USING "£.££ "; Ro(I, j);
  NEXT j
 REM PRINT £2,
  NEXT I
 REM PRINT £2, "Mean";
 REM PRINT £2,
 FOR j = 1 TO 13
REM  PRINT £2, USING "£.££ "; medu(j);
 NEXT j
 REM PRINT £2,
 REM PRINT £2, "Std";
 REM PRINT £2,
 FOR j = 1 TO 13
REM PRINT £2, USING "£.££ "; stdu(j);
 NEXT j
 REM PRINT £2,
 REM PRINT £2, "cov";
 REM PRINT £2,
 FOR j = 1 TO 13
REM PRINT £2, USING "£.££ "; cvdu(j);
 NEXT j

440 I = 1
450 monn = 1
    j1 = 1
```

```
    j2 = 3
500 FOR j = j1 TO j2
   PE(I, j) = ETP(I, monn) / 3
   NEXT j
   monn = monn + 1
   j1 = j1 + 3
   j2 = j2 + 3

   IF j2 > 36 THEN 550
   GOTO 500

550 I = I + 1
   IF I > ny THEN 555
   GOTO 450
REM making a table of (10*36) values of rain
555 FOR I = 1 TO ny
   INPUT £1, iy(I)
FOR j = 1 TO 36
 INPUT £1, R1(I, j)
 NEXT j
 NEXT I
REM Starting calculation of SMD
REM The caclulations start at beginning of the calendar year
ii = 1

FOR I = 1 TO ny: FOR j = 1 TO 36
   PET(ii) = PE(I, j)
   P(ii) = R1(I, j)
   ii = ii + 1
   NEXT j
   NEXT I

570 REM Calculate SMD
571 jj = ny * 36
572 SMD(1) = 66.5
    SMD(108) = 66.5
    SMD(180) = 66.5
573 AET(1) = PET(1) * Pc
REM PRINT £2,
 REM PRINT £2, "Soil moisture deficits"
REM PRINT £2,

574 FOR I = 1 TO jj

575 PSMD(I + 1) = SMD(I) + PET(I + 1) - P(I + 1)
578 IF PSMD(I + 1) <= 0 THEN 600
579 IF PSMD(I + 1) <= Rc - 25 THEN 605
580 IF PSMD(I + 1) >= Rc + 25 AND PSMD(I + 1) <= (Rc + 75) THEN 610
582 IF PSMD(I + 1) >= Rc + 75 THEN 615
585 IF PSMD(I + 1) > 400 THEN 620
600 SMD(I + 1) = 0: GOTO 660
605 SMD(I + 1) = PSMD(I + 1): GOTO 660
610 SMD(I + 1) = PSMD(I + 1) * .4 + (.7 * Rc): GOTO 660
615 SMD(I + 1) = PSMD(1 + 1) * .08 + (Rc + 25): GOTO 660
620 SMD(I + 1) = 250: GOTO 660

660 AET(I + 1) = (SMD(I + 1) - SMD(I) + P(I + 1)) * Pc
662 IF AET(I + 1) >= PET(I + 1) * Pc THEN 665
663 IF AET(I + 1) < 0 THEN 667
665 AET(I + 1) = PET(I + 1) * Pc: GOTO 670
667 AET(I + 1) = 0: GOTO 670
670 REM PRINT £2, USING "£££.£ "; SMD(I);
    NEXT I

    REM PRINT £2,
```

```
    REM PRINT £2, "Decade AET estimates"
    REM PRINT £2,
    FOR I = 1 TO jj
REM PRINT £2, USING "££££.£ "; AEG(I);
   NEXT I
REM REARRANGE THE TABLE OF AEG(I,MONN)
705 I = 1
    j1 = 1
    j2 = 3
720    sum = 0
    monn = 1
750 FOR j = j1 TO j2
755 sum = sum + AET(j)
760 NEXT j
765 AEG(I, monn) = sum
770 sum = 0
775 j1 = j1 + 3
780 j2 = j2 + 3
785 monn = monn + 1
786 IF monn > 12 THEN 800
    GOTO 750
800 I = I + 1
     IF I > ny THEN 900
     GOTO 720
900 sum = 0
     FOR I = 1 TO ny: FOR j = 1 TO 12
     sum = sum + AEG(I, j)
     NEXT j
     AEG(I, 13) = sum
     sum = 0
     NEXT I
    REM PRINT £2,
       PRINT £2, "These are the AET estimates by Grindley2 model for"
       "Forest/Tea in Kimakia"
      PRINT £2,
     FOR I = 1 TO ny:  PRINT £2, iy(I)
     FOR j = 1 TO 13
      PRINT £2, USING "££££.£ "; AEG(I, j);
     NEXT j
   PRINT £2,
     NEXT I

  FOR I = 1 TO ny: FOR j = 1 TO 13
  DUM(I, j) = AEG(I, j)
  NEXT j
  NEXT I
  GOSUB 1500
 REM PRINT £2,
REM PRINT £2, "Mean estimates of AET"
 REM PRINT £2, "mean"
FOR j = 1 TO 13
 REM PRINT £2, USING "££££.£ "; medu(j);
NEXT j
 REM PRINT £2,
 REM PRINT £2, "Std.dev"
FOR j = 1 TO 13
 REM  PRINT £2, USING "££££.££ "; stdu(j);
NEXT j
 REM PRINT £2,
 REM PRINT £2, "Cov"
FOR j = 1 TO 13
 REM PRINT £2, USING "££££.££ "; cvdu(j);
NEXT j

 1589 STOP
```

```
1590 WEND

1500 REM "Estimation of Evapotranspiration Statistics"
1505 sum = 0
1510 FOR j = 1 TO 13: FOR I = 1 TO ny
1515 sum = sum + DUM(I, j)
1520 NEXT I
1525 medu(j) = sum / ny
1530 sum = 0
1535 NEXT j
     sum = 0
1540 FOR j = 1 TO 13: FOR I = 1 TO ny
1545 sum = sum + (DUM(I, j) - medu(j)) ^ 2
1550 NEXT I
1565 Var(j) = sum / ny
1570 stdu(j) = Var(j) ^ .5
     cvdu(j) = stdu(j) / medu(j)
1575 sum = 0
1580 NEXT j
     sum = 0
1585 RETURN
```

APPENDIX 14

Monthly and annual PET (mm) for Orubu catchment

Mon\Yr	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	Mean	C.V
Jan	145.9	188.5	185.5	197.4	220.0	206.4	174.2	164.8	173.9	191.3	184.8	0.11
Feb	143.7	162.7	186.7	159.7	205.9	154.3	153.2	169.5	176.8	154.1	166.7	0.11
Mar	159.2	173.5	203.5	169.0	218.7	146.4	175.8	170.8	202.9	196.4	181.6	0.12
Apr	124.1	144.2	160.1	145.9	152.2	129.4	178.4	147.0	146.9	182.2	151.0	0.12
May	127.7	148.3	155.9	155.1	133.3	136.3	144.1	144.1	132.6	145.1	142.3	0.06
Jun	135.1	139.2	153.2	145.1	125.2	129.4	149.5	136.5	123.9	131.3	136.8	0.07
Jul	145.3	135.4	146.2	148.9	139.2	140.6	142.6	146.4	132.6	141.7	141.9	0.03
Aug	152.3	138.1	164.9	159.1	157.6	154.6	169.6	141.2	135.8	152.6	152.6	0.07
Sep	159.8	154.3	178.8	152.8	178.6	171.8	172.0	156.6	146.3	171.9	164.3	0.07
Oct	177.3	166.3	169.2	173.9	165.1	178.4	177.7	172.8	158.2	168.5	170.7	0.04
Nov	146.3	164.8	154.4	153.5	154.7	152.8	173.9	176.2	153.5	147.8	157.8	0.06
Dec	135.8	167.2	174.1	202.6	172.0	171.3	193.0	182.1	148.7	172.8	172.0	0.11
Total	1752.5	1882.4	2032.6	1963.0	2022.6	1871.6	2003.8	1908.0	1832.1	1955.8	1922.5	0.04

APPENDIX 15

Monthly and annual PET (mm) for Tugenon catchment

Mon\Yr	1964	1965	1966	1975	1977	1978	1979	1980	Mean	C.V
Jan	148.0	147.3	147.5	163.3	116.1	135.1	131.9	147.8	142.1	0.09
Feb	125.0	144.4	105.8	163.5	115.1	122.9	107.5	145.7	128.7	0.15
Mar	133.5	150.2	122.7	147.9	137.0	113.0	152.9	155.2	139.0	0.10
Apr	99.0	105.6	104.2	121.5	82.9	106.9	121.5	123.9	108.2	0.12
May	106.7	111.0	123.9	105.5	95.6	113.2	104.5	99.2	104.7	0.08
Jun	94.4	105.9	109.3	90.2	92.5	95.3	91.3	92.5	96.4	0.07
Jul	89.0	100.8	101.8	93.4	90.7	102.4	103.9	110.4	99.1	0.07
Aug	95.8	104.8	114.2	93.2	99.8	100.7	110.0	122.7	105.2	0.09
Sep	94.9	114.5	116.9	97.8	115.7	111.8	119.4	123.4	111.8	0.08
Oct	103.9	97.4	124.1	106.9	112.3	117.0	150.5	132.4	118.1	0.14
Nov	122.9	91.8	122.7	131.5	86.7	116.7	123.2	108.5	113.0	0.13
Dec	116.6	111.4	151.6	132.4	117.1	121.1	133.4	132.9	127.1	0.10
Total	1329.6	1385.1	1444.6	1447.1	1261.5	1356.0	1450.1	1494.5	1396.1	0.05

APPENDIX 16

Monthly and annual PET (mm) for Ndarugu catchment

Mon\Yr	1963	1964	1965	1972	1973	1974	1975	1977	1978	Mean	C.V
Jan	126.1	143.4	143.0	146.8	134.9	164.6	159.0	140.5	123.4	142.4	0.09
Feb	130.6	131.2	159.8	135.1	137.5	168.3	160.8	146.9	123.7	143.8	0.10
Mar	144.5	131.9	153.4	171.9	174.7	157.7	172.7	154.3	120.6	153.5	0.11
Apr	109.2	106.9	119.0	158.0	147.7	123.8	132.2	112.0	110.2	124.3	0.14
May	91.0	100.8	121.9	119.1	116.0	113.9	119.6	117.7	108.6	112.1	0.09
Jun	85.8	86.4	105.8	91.8	86.0	74.2	95.9	80.1	74.2	86.7	0.11
Jul	98.5	77.1	101.2	89.5	95.9	78.0	88.2	70.8	77.0	86.2	0.12
Aug	88.1	88.3	110.9	109.0	93.9	86.9	95.0	104.0	85.3	95.7	0.10
Sep	118.4	97.9	147.7	131.4	111.2	109.9	110.9	107.5	111.6	116.3	0.12
Oct	143.9	110.6	130.3	134.4	136.4	148.8	125.5	133.5	121.5	131.6	0.08
Nov	114.6	123.7	113.1	126.7	125.6	118.2	125.4	96.5	115.3	117.7	0.08
Dec	99.2	115.0	147.3	139.1	148.7	144.7	127.6	115.7	107.6	127.2	0.14
Total	1350.1	1313.1	1553.1	1552.8	1508.3	1489.1	1512.9	1379.4	1279.1	1437.6	0.07

APPENDIX 17

Monthly and annual PET (mm) for Kimakia catchment

Mon\Yr	1964	1965	1966	1969	1970	1972	1973	Mean	C.V
Jan	126.4	114.1	136.3	124.4	97.0	124.0	108.0	118.6	0.10
Feb	114.8	123.6	121.0	97.8	120.3	105.2	115.1	114.0	0.08
Mar	127.0	140.0	120.4	116.0	128.5	159.4	155.7	135.3	0.12
Apr	100.6	113.6	100.9	120.8	105.6	127.4	126.8	113.7	0.09
May	87.8	95.4	99.2	90.3	89.2	92.1	94.2	92.6	0.04
Jun	75.8	88.8	75.6	96.3	74.8	78.3	68.9	79.8	0.11
Jul	56.8	67.3	65.4	68.7	78.5	71.4	70.5	68.4	0.09
Aug	72.5	76.1	83.1	82.4	60.2	78.2	64.6	73.9	0.11
Sep	83.4	109.4	101.3	99.0	94.2	97.8	89.9	96.4	0.08
Oct	98.6	106.3	114.9	131.3	114.6	107.0	122.5	113.6	0.09
Nov	117.9	98.6	104.2	105.2	98.7	105.9	98.6	104.2	0.06
Dec	101.8	114.4	126.0	123.5	116.5	114.8	108.8	115.1	0.07
Total	1163.4	1247.7	1248.3	1255.7	1178.3	1261.6	1223.8	1225.5	0.03