ASSESSMENT OF THE MAIN METHODS FOR ESTIMATING POTENTIAL EVAPOTRANSPIRATION AT SAMARU IN NORTHERN GUINEA SAVANNA ZONE OF NIGERIA

BY

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DECLARATION

I hereby declare that this thesis has been written by me and that it is a record of my own research work. It has not been presented before in any previous application for a higher degree.

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This thesis "ASSESSMENT OF THE MAIN METHODS FOR ESTIMATING POTENTIAL EVAPOTRANSPORATION IN NORTHERN GUINEA SAVANNA ZONE OF NIGERIA" by ANOSIKE RITA NGOZI meets the regulations governing the degree of DOCTOR OF PHILOSOPHY of Ahmadu Bello University, Zaria and is approved for its contribution to scientific knowledge and literary presentation.

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DEDICATION

This thesis is dedicated to Mary, our mother and Queen of all hearts.

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ABSTRACT

Evapotranspiration is a major component of the water balance in any ecological system. Several methods have been proposed to estimate potential evapotranspiration in different parts of the world. However, the success of most of them has been limited because of uncertainties in the reliability of the methods under subhumid tropical environment.

A study was therefore undertaken at the Institute for Agricultural Research Farm, A.B.U., Zaria (11° ll'N, 07° 38'E, 686m above sea level) to determine the most suitable method for estimating potential evapotranspiration in Samaru within the Northern Guinea Savanna Zone of Nigeria.

To achieve this objective, predictive efficiency of five PET models (BMN, Hamon, Jensen Haise, Penman and Makkink) was examined against measured microlysimetric PET and open pan evaporation. The estimates of the five models were computed from the 30 years (1965-1994) climatic data and compared with pan evaporation. These five equations were also used to compute PET for two years (1996-1997) and compared with measured microlysimetric PET and pan evaporation during this period. It was observed that Hamon, method overestimated PET throughout the entire year. Jensen Haise and Penman methods over estimated slightly above the pan evaporation in some months. BMN method estimated closest to pan evaporation. Makkink method underestimated in some months and slightly below the pan evaporation. Only BMN method predicted

magnitude of performance for the two measured PET was in the order: BMN > Penman > Makkink > Jensen Haise > Hamon. The methods developed by BMN, Penman and Makkink give comparable results which were good approximation of measured PET. The recmmended methods (BMN, Penman and Makkink) are inspite of the observation that they do not exhibit the same degree of oscillation as measured microlysimetric PET and pan evaporation and thus the differences between the maxima and minima are relatively smaller than the other methods.

To further improve on the efficiency of the three equations, adjustment factors were incorporated into them; so that they can estimate as precisely and accurately as the measured PET. Equations relating BMN, Penman and Makkink equations to measured PET were developed. The modified BMN, Penman and Makkink equations are given as follow:

Y = 1.38+0.59 BMN R^2 = 0.99

Y= 2.58 + 0.17 Penman R^2 = 1.00

Y = 0.5 + 0.99 Makkink R^2 = 1.00

Y = -0.08 + 0.99Pan

Y = Microlysimetric PET

For pan evaporation (x)

x = 0.033 + 0.99BMN, R^2 =1.00

x = -0.051 + 1.007Penman, R^2 = 1.00

x = 3.79 + 0.23Makkink, R^2 = 0.95

The BMN method is recommended for application as best satisfying the objective of the study. It is the simplest, most

The BMN method is recommended for application as best satisfying the objective of the study. It is the simplest, most accurate and reliable of the three recommended methods.

It was also observed that the PET is highest in March the warmest month of the year and lowest in August the wettest month in this zone.

Path correlation analysis on the contribution of each of the six important climatic factors (relative humidity, air temperature, wind speed, soil temperature, sunshine hours and solar radiation) indicated that microlysimetric potential evapotranspiration was influenced in the following trends: sunshine hours (18.47%) > soil temperature (13.84%) > relatively humidity (11.49%) > wind speed (11.22%) > air temperature (8.29%) > solar radiation (4.41). Whereas pan evaporation was influenced as follows: soil temperature (39.19%) > sunshine hours (22.28%) > air temperature (7.56%) > wind speed (4.05%) > relative humidity and solar radiation (2.56%).

A comparison of Penman and Monteith equations with measured soil evaporation beneath maize and sorghum crops showed that the Monteith equation is a better estimator of soil evaporation than Penman equation. However, adjustment factors were developed for both equations.

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CHAPTER ONE

INTRODUCTION

World over, conservation of the existing water supplies to meet the requirement of the teaming world population has been the concern of both the soil scientists and agricultural engineers alike. Per capita consumption of water due to rising standards of living and economic activities, especially agriculture is on the rise. Conservation of water is even more critically required in drier areas typical of Savanna Zone of Nigeria, where inadequate water resources have proved to be the major limiting factor in agricultural development.

Conserving the existing water supplies at any particular period entails the monitoring of how much water is available (rainfall, rivers, irrigation) and how much is lost, of which evaporation is the most significant (Kowal and Knabe, 1972). Crop transpiration is another avenue of water loss. The loss of water, by both soil evaporation (E) and crop transpiration (T) is usually referred to as evapotranspiration (ET).

Evapotranspiration represents the second largest component of hydrologic cycle being exceeded only by rainfall. It equals about 70 percent of the average annual precipitation that falls on continental Africa (Blaney et al. 1973). Therefore evapotranspiration, amounting to approximately three thousand billion litres of water daily, returns to the atmosphere between 2½ and 3 times as much water as streams and rivers discharge into

the oceans.

In the humid savanna area about 50 percent of the average annual rainfall is returned to the atmosphere as evapotranspiration, while it amounts to approximately 90 percent of the average annual rainfall in the arid environment of Nigeria. Average annual evapotranspiration for Samaru is about 50 to 60 percent of the average annual rainfall.

Tremendous amount of energy is expended in .the evapotranspiration process. Over four million calories are required to evaporate 9.5 mm of water from an hectare of land. On a warm day over 30,000 kg of water may be removed from an hectare of land by evapotranspiration. These data represent actual evapotranspiration values. Their relative size in comparison to the other components in the hydrologic cycle or in a water balance on a water shed indicates the importance of having accurate measured potential evapotranspiration values for managing water resources.

Evapotranspiration is a serious problem if the crops fail to have adequate moisture from the soils. It is a basic parameter in the design of irrigation projects and, in the analysis of hydrological systems. Evapotranspiration is also a function of the climate, the crop, the soil and the agricultural practice. The combined effect of these factors at a particular time determines the rate of water loss from a crop. This water must be replaced, either by irrigation or rainfall, for continued crop growth.

An estimate of evapotranspiration rate is critical in the design and management of irrigation projects. In countries with advanced agricultural technology, the main concern is to obtain the most efficient use of water delivered to a farm. In less developed areas, the principal need is to estimate evapotranspiration for the purpose of developing new irrigation projects.

There are two types of evapotranspiration namely; actual evapotranspiration (ETa) and potential evapotranspiration (PET). Potential or reference crop evapotranspiration according to Doorenbos and Pruitt (1977) is 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. It is required primarily for estimating the amount of water required by a plant for its maximum growth and hence optimum yield.

There are two broad ways of estimating potential evapotranspiration. These are commonly referred to as the direct and empirical methods.

The specific methods for direct measurement of potential evapotranspiration include lysimetry and pan evapotranspiration.

The more commonly used methods for estimating potential evapotranspiration include those developed by:
Thornthwaite (1948); Penman (1948); Jensen Haise (1963); Blaney - Morin Nigeria (1980); Blaney and Morin (1942) and Blaney - Criddle (1950). Penman was considered most accurate of these methods.

Several attempts have been made in different parts of the world to develop methods to estimate the much desired potential evapotranspiration or water balance from a given area of soil surface. However, the success of most of these methods has been limited because of uncertainties in the reliability of the methods. They often require too complex a set of parameter inputs.

One of the major agricultural problem in savanna zone of Nigeria is the inadequacy of hydrological information for orderly development and management of the water resources. Rainfall, run off and soil moisture storage, which along with evapotranspiration and percolation constitute the components of a water balance, can be determined quite accurately, especially since the development of nuclear techniques for measuring soil moisture content.

Only few studies have been carried out in the savanna ecological zones of Nigeria (Fig.1) to evaluate the reliability of the different methods. Hence need to identify or develop a potential evapotranspiration model that is accurate and can be readily computed with weather data available in the developing economies of tropical Africa.

The overall objective of the present study therefore, is to assess the reliability of the most quoted empirical methods for estimating potential evapotranspiration in the Northern Guinea Savanna Zone of Nigeria.

Specifically, the aim is to

1) estimate potential evapotranspiration by various empirical methods reported to be reliable in the tropical environment
2) measure potential evapotranspiration and evaporation in the

Northern Guinea Savanna environment typified by Samaru (11°11'N, 07°38'E, 686 m above sea level), Nigeria.

3) identify an accurate and simple empirical method for estimating potential evapotranspiration in the Savanna Zone of Nigeria.

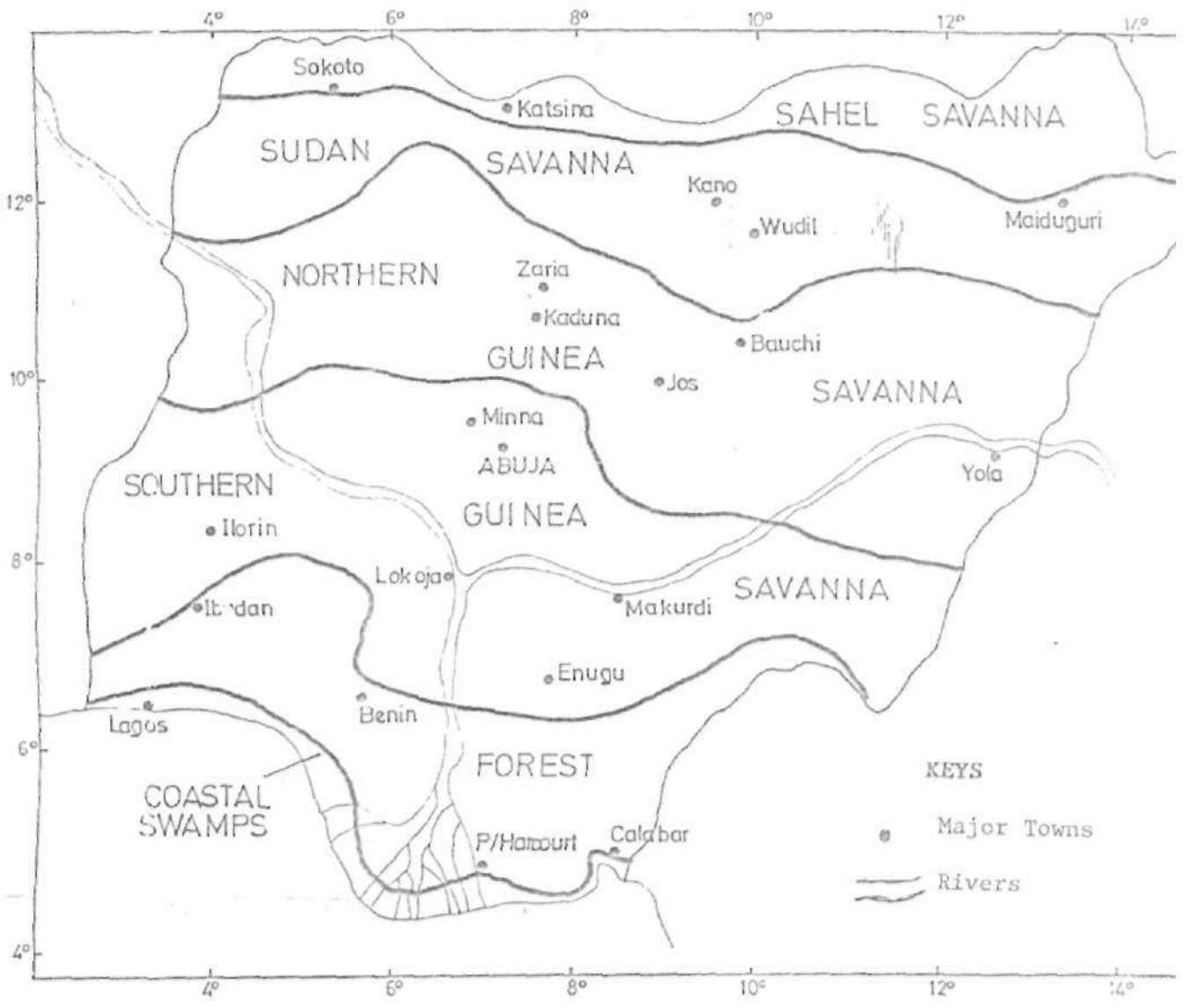


Fig. 1: Ecological zones of Nigeria

CHAPTER TWO

LITERATURE REVIEW

2.1 Evapotranspiration:

Evapotranspiration is a term coined from two physical processes, namely; evaporation and transpiration.

2.1.1 Evaporation

Evaporation according to Penguin dictionary of science is the conversion of a liquid into vapor, without necessarily reaching the boiling point. The fastest moving molecules escape from the surface of a liquid during evaporation, thereby reducing the average kinetic energy of the remaining molecules, and therefore causing cooling. The process of evaporation of water is one of the fundamental components of the hydrological cycle by which water changes into vapor through the absorption of heat energy.

Evaporation from natural surfaces such as open water, bare soil or vegetative cover is a diffusive process, by which water in the form of vapor is transferred from the underlying surface to the atmosphere. The essential requirements in evaporation process include the source of heat to vaporise the water and the concentration gradient of water vapor between the evaporating surface and surrounding air. Evaporation, however, can occur only when the vapor concentration at the evaporating surface exceeds that in the overlying air.

The source of energy for evaporation may be solar energy, the air blowing over the surface or the underlying surface itself. The minimum energy required for evaporation, irrespective of the surface where evaporation is taking place, is 590 calories per

gram of water evaporated at 20°C (Michael, 1978). The fundamental principle of evaporation from a free surface was derived by Dalton in the year 1882. Evaporation, according to Dalton, is a function of the difference in the vapor pressure of the air and the vapor pressure of water. Dalton theorized that evaporation from a surface must be a consequence of the combined influences of wind, atmospheric moisture content, and physical characteristics of the surface.

Keen (1914) studied evaporation from various soil types. He found that vapor pressure within the soil was related to evaporation in terms of gaseous diffusion from a surface.

2.1.2 Transpiration: This is a physiological process by which water vapor leaves the living plant body into the atmosphere. It involves the continuous movement of water from the soil into the roots, through vascular tissue to the leaves or other organs and out through the stomates, lenticels or cuticular surface into the surrounding air.

Basically, transpiration is an evaporation process but to some extent is modified by plant structure and stomatal behaviour. Transpiration is the dominant factor in plant water relations as it produces the energy gradient which causes the movement of water into and through the plants. The rate of transpiration depends on the supply of energy to vaporise water. The water vapor pressure or concentration gradient in the atmosphere which constitutes the driving force, and the resistance to diffusion in the vapor pathway. Transpiration is influenced by climate, soil and such

plant factors as the size of the leaf and height of the plant. Light intensity, atmospheric vapor pressure, temperature and windspeed, are the climatic factors affecting transpiration. Soil and plant factors affecting transpiration are those factors that govern the water supply to the roots, the extent and efficiency of root systems in moisture absorption, the leaf area, leaf arrangement and structure as well as stomatal behaviour.

The rate of evaporation from a free water surface when compared with the transpiration from a crop is of considerable importance. Vegetation ceases to transpire at night as a result of the closure of the stomata, but a water surface like that of a lake or pond continues to evaporate, though at a slower rate even at night.

Briggs and Shantz (1916a,and 1917) in colorado, correlated daily transpiration with weather conditions and later used various types of atmometers and evaporation pans to compare transpiration with evaporation rate from free-water surfaces. Kiesselbach (1916) in Nebraska conducted similar studies with particular emphasis on the corn crop. These workers clearly demonstrated the existence of plant morphological and physiological mechanisms which affect transpiration rates.

Consequently, soil evaporation and plant transpiration are interrelated, and occur simultaneously in nature without any standard means of distinquishing between the two processes. Therefore, evapotranspiration is the total process of water transfer into the atmosphere from vegetated land surfaces. It involves the conveyance of water vapor mass from the earth's surface and the reservoir within the soil into the atmosphere.

Evapotranspiration is considered as an energy transfer phenomenon since the evaporation process which constitutes a crucial component of evapotranspion involves the change of water from liquid to vapor requiring the heat of vaporisation.

For many, evapotranspiration is primarily considered as a component of hydrological balance and the units of measurement are expressed in equivalent of depth of water on the surface. Evapotranspiration is equivalent to consumptive use which includes all the water consumed by plants plus the water evaporated from bare land and water surfaces in the area occupied by the crop. Incoming solar radiation under field - conditions supplies the energy for the evapotranspiration.

Factors that influence both evaporation and transpiration also govern the evapotranspiration process. Wind is important in removing water vapor from the cropped area the prevailing temperature and humidity conditions affect the rate of water vapor loss from the crops. More water is lost when the surrounding fields are bare than when they are cropped and irrigated.

2.1.3 Climate

The climate of Nigeria is characterized by two well-defined seasons: the wet season with cloudy weather and winds from the South West and the dry season with continual sunshine and winds from the North East. The rainfall in Nigeria is controlled by these two air masses. These currents are separated by a boundary, the intertropical front, into the equatorial maritime air mass characterized by rain-bearing south-westerly winds and the tropical continental air mass of dry north easterly winds known as

the harmattan. This front moves northwards across the south of the country in February reaching the northern limits around July and August before retreating to the south again. The movement results in the occurrence of a single rainy season in the northern areas (500-1000mm).(Mosugu, 1989).

Table 1: Mean monthly Rainfall and potential evapotranspiration rate of the Northern Guinea Savanna zone

Month	Rainfall	P.E
January	0.3	115.5
February	1.5	120.7
March	7.1	146.6
April	36.8	153.2
May	132.1	153.7
June	165.6	125.5
July	221.5	107.7
August	281.4	97.0
September	230.4	106.9
October	36.1	119.6
November	1.3	108.7
December	0.0	106.1
Annual Total	1114.0	1461.5mm

Sources: Atlas of the Federal Republic of Nigeria, 1978.
Smyth and Monotgometry, 1972
Oyediran Ojo, 1977

Table 2: Mean monthly temperature, sunshine hours, and net radiation of the Nothern Guinea Savanna Zone

Month	Temperature °C	Sunshine hours/month	Net radiation Cal cm^{-1} day^{-1}
January	21.8	9.2	156
February	23.4	9.8	166
March	26.9	8.7	352
April	28.3	6.9	580
May	27.3	8.1	636
June	24.8	7.4	647
July	23.6	4.6	591
August	23.2	6.2	551
September	23.8	7.4	635
October	24.4	8.2	566
November	23.2	8.6	281
December	22.0	9.0	151
Annual Mean	24.4	7.8	442.7

Source: Mosugu, 1989, The National Atlas of Nigeria (1978).

2.1.4 Climatic Factors

Evapotranspiration depends on net radiation, temperature, length of day, humidity, wind-velocity, and soil moisture.

2.1.4.1 Radiation

Is one of the most important meteorological parameter. Radiant energy from the sun is the ultimate source of energy for driving the atmosphere and producing our weather. It provides the energy for the production of all our fossil fuels and is the source of energy for photosynthesis and evapotranspiration.

The net radiation is the difference between total upward and downward radiation fluxes and is a measure of the energy available at the ground surface. The importance of this parameter is that it is the fundamental quantity of energy available at the earth's surface to drive the processes of evaporation, air and soil heat fluxes as well as other smaller energy - consuming processes such as photosynthesis.

Growing competition for available water among industry, recreation and agriculture has made the efficient use of water an important national and as well as a global problem. The efficient use of irrigation water in crop production, to a large degree, is dependent on a satisfactory means of measuring water losses. The forecasting of water use, drying conditions, minimum air temperature, soil temperature, dew formation and duration, harvest dates and crop quality all depend to a greater or lesser extent on a knowledge of the incident solar energy.

The difference between the shortwave radiation absorbed by the earth and atmosphere and the long wave radiation re-radiated to space is the energy available for those meteorological

processes going on at the earth's surface or in the atmosphere. For short periods in time and at different sites on the earth, there is imbalance of the incoming and outgoing fluxes of radiation. This imbalance accounts for circulation in the atmosphere and oceans (wind and currents) evaporation or condensation of water vapor, change in temperature of air, earth's surface including vegetation and clouds.

A large part of the solar radiation reaching the atmosphere is absorbed in the atmosphere by dust, clouds, water vapor and the air, so that the maximum received at the ground is between 200 or 220 Kcal/cm^2 per annum in the desert regions. Tropical forest receives about 120 to 160 Kcal/cm^2. On reaching the vegetation and soil, part is reflected. Vegetation reflects 10, 15 or even 30 percent depending on type. Consequently only about half the solar energy entering the atmosphere is ultimately available at the ground and only a quarter of this is of the correct wavelength for photosynthesis. Briggs and Shantz (1916a), in their classical work on water use by plants, recognized the importance of solar radiation in transpiration. A high correlation of evapotranspiration and radiation has been reported by a number of workers. Examples of earlier work on evaporation using energy balance concepts are those of Bowen (1926). Cummings and Richardson (1927), McEwen (1930), Cummings (1936), Kennedy and Kennedy (1936), Cummings (1940) and Richardson (1966). The application of theoretical concepts to cropped surfaces received major attention in the 1950's after the work of Penman (1948). Generally, the relationship (between theoretical concepts and cropped surfaces) has been established for daily or longer data

periods; however, in some cases a close relationship between evapotranspiration and net radiation has been observed for hourly or shorter periods.

Pruitt (1964) reported studies which demonstrated that net radiation is more closely related to evapotranspiration than variables such as air temperature and humidity. Problems affecting measurement of radiation includes:

1) Varying inclinations of the solar beam associated with diurnal and seasonal effects.
2) Lack of spatial homogeneity of flux due to synoptic situations.
3) Influence of local topography.

Solar radiation measurements are taken at a weather Bureau by a network of instruments of several types. The most widely used instrument is the Eppley 180-deg pyranometer.

2.1.4.2 Air temperature: Factors influencing air temperature include latitude, nearness to water body, relative humidity and relative amount of dust in the air. The amount of heat received annually is greatest between 15°N and 15°S. At higher latitudes the high intensity of solar radiation is combined with a long day and temperatures in summer may exceed those nearer the equator. Winters will be cooler.

There is a fall of approximately 6.0°C for every 1000m rise in altitude. Location near water have much reduced diurnal and lower maximum temperatures. At such locations humidity will behigh and solar radiation reduced.

Within the tropics the temperature at sea level rarely falls below 16°C. Where humidity is high the maximum shade temperature rarely exceeds 38°C, but where the humidity is low 55°C may exceptionally be reached. Low temperature, which is often a limiting factor to plant growth in temperate agriculture, is only limiting in high altitude areas of the tropics.

Tropical crops have a higher optimum growth temperature than temperate crops but the temperature range over which crops are successfully grown varies not only between crops but between varieties of a crop. Bananas, cocoa, kolanut, oil palms, rubber, sisal and sugar cane are true tropical perennial crops requiring a high minimum temperature for growth, whereas citrus, gum arabic, coffee, tea and avocado will grow over a wider range of temperature conditions provided that frost does not occur.

2.1.4.3 Relative Humidity: Relative humidity is the ratio of actual to saturation vapor pressure at the same temperature. Water vapor is furnished to the air only from the evaporating surfaces of land and water. Water vapor transport into and through the layer of air adjacent to the ground is analogous to heat transport. Heat and water vapor are transferred to the upper air primarily by convection or "eddy diffusion". The net transport of heat is usually upward during the day and downward at night. The net vapor transport usually follows this pattern with evaporation occurring by day and dew deposition by night. However, there exist many climatic situations where evaporation continues throughout much or all of the night. At day, vapor pressure reaches its peak near midday and is greatest within the canopy. At night, relative humidity reaches this peak as

temperatures fall. There is usually less vapor in the air at night than during the daytime, but since temperatures also decrease at night, the capacity of the air to hold vapor drops sharply and relative humidity rises. Synchronization may result, at least in part, from the strong evaporative stress on plants in the early afternoon that occurs in the Great Plains and other semi-arid and arid regions. The stress is frequently sufficient to cause stomates of the leaves to close. The rate of transpiration then decreases as the vapor pressure decreases, due to turbulent transport of vapor away from the crop. As transpiration decreases, the quantity of energy consumed in sensible heat generation increases. This effect may contribute to the mid-afternoon temperature peak. With peak temperature and reduced vapor pressure, relative humidity falls to its lowest diurnal value in mid-afternoon. Water vapor content/humidity is measured with hydrometers.

2.1.4.4 Vapor pressure: Vapor pressure decreases with elevation except when condensation is occurring. At dawn, there may be no change in vapor pressure with elevation. As the day progresses with increasing evaporation or transpiration the vapor concentration near the surface increases. The effectiveness of vapor removal, from the surface increases with increasing windiness and turbulence. By late afternoon or early evening, evaporation flux decreases as does turbulence.

2.1.5 Rainfall: A trend is observed which shows a north to south variation in rainfall characteristics such as amount, intensity and seasonality. The Northern Guinea Savanna zone has an annual mean of about 1114mm (Fig. 2).

Rainfall in Nigeria is highly seasonal in character with well-marked wet and dry seasons such as are characterstic of monsoonal types of climate. Like the total, amount of rainfall, the length of the raindays is 100 days in the Northern Guinea savanna zone (Fig. 3) The wet season extends for four to five months in the Northern Guinea savanna (Mosugu, 1989). A year to year variation in the rainfall characteristic is experienced in this zone which is sometimes caused by local variations in other climatic factors such as temperature.

2.1.6 Evapotranspiration

In the Northern Guinea savanna zone, an estimated total annual potential evapotranspiration rate of 1461.5mm is recorded (Table 1).

Northern Guinea savanna zone has 3 to 6 months in which rainfall exceeds evapotranspiration (Davies, 1973). There is much lower evapotranspiration during the rainy season than during the dry season.

Temperature, Net Radiation and Sunshine hours vary widely from the north to the south of Nigeria. In the Northern Guinea Savanna zone (Table 2) mean daily temperature of 22°C in December and 28.3°C in April are observed with annual mean of about 24.4°C.

In this zone, temperatures are highest between April and May,

and lowest in December corresponding to the beginning of the rainy season and middle of the harmattan period respectively, (Atlas of the Federal Republic of Nigeria, 1978; Kowal and Knabe, 1972).

The Northern Guinea Savanna zone experiences a mean annual net radiation of 442.7 cal/cm/day (Table 2).

Mean annual sunshine hours of 7.8 hours per months is recorded for this zone (Kowal and Knabe, 1972; Smyth and Montgometry, 1962).

2.1.7 Seasonal Evapotranspiration

This is the amount of water used in evapotranspiration by a cropped area during the entire growing season. It is expressed as the depth of water in cm or volume of water per hectare. It's values are required to evaluate and determine the seasonal irrigation water requirement.

2.1.8 Peak Evapotranspiration (period consumptive use)

This is the average daily water use rate during the few days of the highest consumptive use of the season. Peak period consumptive use is the design rate used in planning an irrigation. In irrigation project design, the peak period of consumptive use is the period during which the weighted average daily rate of consumptive use of the various crops grown in the project area is at a maximum.

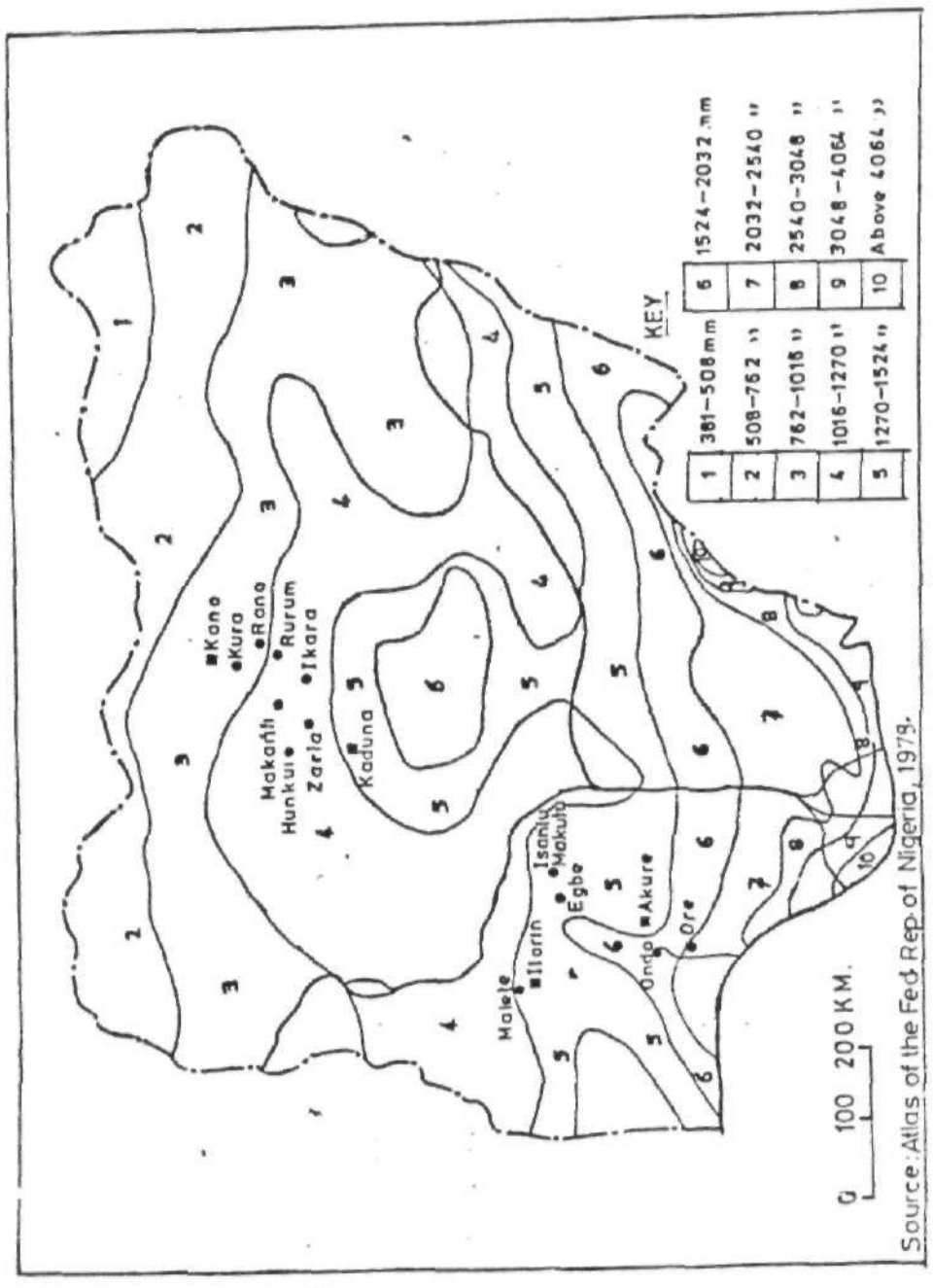


Fig. 2. Mean annual rainfall.

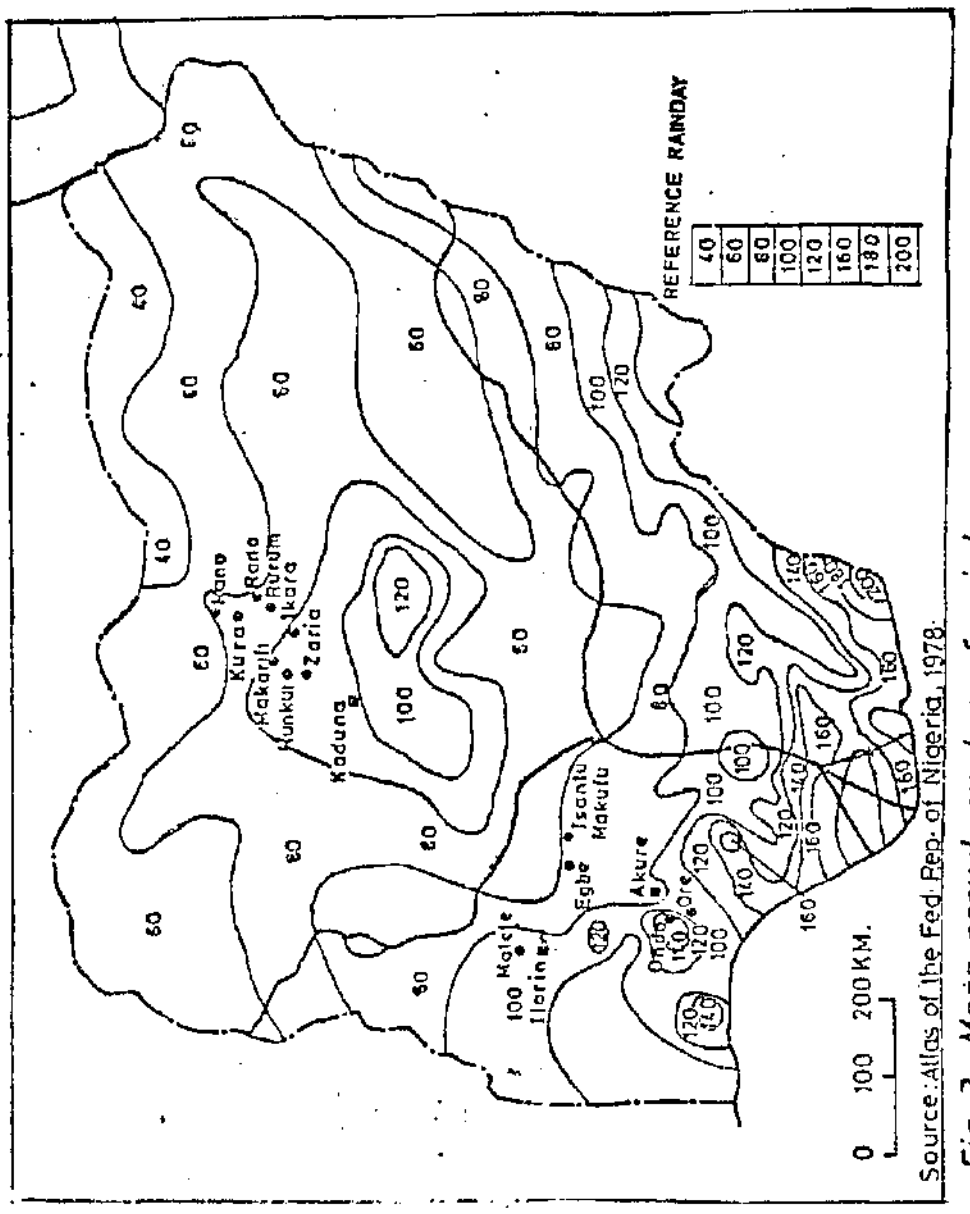


Fig. 3. Mean annual number of raindays.

2.1.9 Annual Evapotranspiration

Annual Evapotranspiration includes seasonal and off-season evapotranspiration. The off-season period is from harvest of one crop to the planting of the next crop where only one crop is grown each year. This is very important in optimizing the use of a limited supply of water for irrigation since stored soil water following a shallow-rooted crop may be used by a deep-rooted crop, and excess water applied to a shallow-rooted crop may replace deep soil water.

2.2 Types of evapotranspiration.

There are two types of evapotranspiration, namely; actual evapotranspiration (ETa) and potential evapotranspiration (PET).

2.2.1 Actual evapotranspiration

The actual evapotranspiration from a crop (ETa) is obtained by multiplying potential evapotranspiration by an appropriate experimentally - determined crop factor (Kc):

$$ETa = Kc\ PET$$

2.2.2 Potential evapotranspiration

This is defined as the amount of water which evaporates from soil air interface and from plants when the soil is at field capacity (W.M.O, 1958). Potential evapotranspiration is the amount of water that will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of the vegetation. It offers an approach towards the understanding of the role of moisture in climate.

Potential evapotranspiration is required primarily for estimating the amount of water required by a plant for its maximum growth and yield. It is an essential component for determining the water balance in respect of the rate of water loss from a reservoir and/or plant canopy.

The comparison of potential evapotranspiration with rainfall permits the classification of a particular climate into humid and dry seasons which is a crucial set of information for the planning of farming systems. The knowledge of the potential evapotranspiration is needed to determine irrigation requirements. Potential evapotranspiration is affected by the type of soil and vegetative cover.

2.2.3 The Concept of Sensible Heat Advection

The concept of potential evapotranspiration as discussed above may be unreal for a number of reasons. One of the most serious errors lies in the assumption of infinite upwind fetch. All fields are influenced by their surroundings to some degree, and the influence is likely to be greatest in sub-humid and arid regions where the differences in moisture availability due to irrigation and crop roughness differences are greatest from field to field.

Advection is defined by the meteorologist as "the process of transport of an atmospheric property solely by the mass motion of the atmosphere". In recent evapotranspiration research, advection has come to mean transfer of energy in the horizontal plane in the down wind direction. The advection of sensible heat from one field to another or from one region to another is our main

concern.

Tanner (1957) suggests a terminology to describe advection effects. When advected energy is drawn from the air, an oasis effect prevails. In areas where sensible heat has been generated through crops, a "clothesline" effect exists.

Large scale or local and global advection terms have also been used in attempts to identify sources of preconditioned air. In this regard Slatyer and Mcllroy (1961) suggested that even in moist homogeneous areas large scale or upper level advection due to movement of weather systems may lead to latent heat consumption which exceeds average net radiation received, often for long periods of time. This may arise over surface of relatively warm dry air masses, generated over large relatively hot dry surfaces else where. Certain regions, though well provided with incoming radiant energy, act as long-term sinks of sensible heat, due to the general pattern of circulation over them, provided that sufficient moisture is available for the amount of evaporation involved.

It should be understood that in nature, advection is the normal rather than the abnormal situation; only when the surface under consideration is identical in its characteristics of colour, roughness and moisture availability with an infinite surface upwind will non- advective condition prevail. Dyer and Pruitt (1962) and others have attempted to define fetch requirements needed in micro-meteorological research. Only locally generated advective effects will be eliminated when upwind fetch is finite. Air masses conditioned in very distant regions and climates continue to move over surfaces of different characteristics and

their effects on local micrometeorological processes remain observable.

The concern with advection evidenced by irrigationist, is due to the fact that this supplemented energy supply is utilized, when water is available largely in evapotranspiration. The climate of the windswept Great Plains suggest that advection of large quantities of sensible heat into the region as well as the generation and transport of small quantities of sensible heat from dry land into irrigated fields contribute materially to the amount of energy which is utilized in evapotranspiration.

The origin of sensible heat for advection to other localities depends on surface conditions. Generally, the availability of water on land surfaces determines the partition of energy between sensible, latent and soil heat fluxes. This is well illustrated in work by Fritschen and Van Bavel (1962) at Phoenix, Arizona. They measured water use with precision lysimeter, solar and net radiation and soil heat flux with appropriate sensors.
When soil was wet, evapotranspiration (latent heat flux) consumed slightly more than energy supplied by the net radiation. Some quantities of energy were distributed to the soil and sensible heat flux at first. When the soil had dried, the consumption of net radiation as latent heat was greatly reduced and sensible heat was generated. This would then be available for consumption in the evapotranspiration process.

De Vries (1959) and Philip (1959) evaluated the nature and extent of changes caused by passage of warm dry air over irrigated fields by use of the equation of motion. Both concluded that the rapidly with decreasing distance downwind of the leading edge of

discontinuity but that the effect should persist nevertheless for great distances downwind.

2.2.4 Methods for Measuring Advection

Two techniques offer the best means of estimating the contribution of advected energy of evapotranspiration. These are:

a) Energy balance calculations, where the net radiation, the soil heat flux and the evaporation are precisely measured and advective heat contributions are computed by difference; and

b) Measurements of the vertical transfer of horizontal momentum and turbulent transfer of heat and vapor at increasing distances downwind of a field's leading edge. These measurements may be effectively employed in aerodynamic or Bowen ratio estimates of evapotranspiration, particularly if the estimates are tested against a precise lysimeter.

2.2.5 The Concept of Potential Evapotranspiration

In 1948 both Thornthwaite and Penman put forth the concept of "potential evapotranspiration". The concept has had major influence on geographical studies of world climate and on attempts to predict water needs in irrigated agriculture, pedology and hydrology.

The concept of potential evapotranspiration has been so widely accepted that a detailed discussion of its meaning is needed. The following synthesis of definition may apply.

Potential evapotranspiration is the water evapotranspired by a dense vegetation that does not suffer water shortages. It is the evaporation from an extended surface of short green crop which

fully shades ground, exerts little or negligible resistance to the flow of water and is always well supplied with water. Potential evapotranspiration cannot exceed free water evaporation under the same weather conditions. In general this is the water irrigated crops require.

Real evapotranspiration differs from the potential under most circumstances. The reasons for these differences are best explained by *reference to the conditions imposed by the definition* of potential evapotranspiration and an analysis of the reality of these conditions.

i) The Influence of Soil Water Availability.

Plants are not always well supplied with water, in the case of range land and dry land agriculture. This can be the case in irrigation agriculture as well, by intention, for when the supply becomes limited it may allow the farmer to get the greatest yield per unit of water expended. Strategic irrigation at certain stages of crop growth may lead to great increases in yield with little irrigation. Marlatt *et al*, (1961) and others have shown that with decreasing soil moisture availability the rate of evapotranspiration is reduced below the potential.

Van Bavel (1967) suggested that the transpiration rate in alfafa begins to diminish after a soil water potential of about 4 bar is reached and cited other works in which this breaking point has ranged from - 0.2 to - 1.0 - bar for corn and cotton, respectively. The point is that the potential rate of evapotranspiration cannot prevail if the soil is not kept well

supplied with water and depending on the crop involved, this condition may not exist for any signifcant length of the growing season.

Ritchie and Co-workers (1972a, 1972b) have shown that evaporative flux by sorghum and cotton is conditioned by soil moisture status after a critical level of water extraction has occurred. In the Houston Black clay soils studied, this critical level or lower limit for potential evaporation occurred after 18.2 cm of water had been extracted from a soil which, when initially wet holds about 48% water by volume. The ratio of the latent heat flux to net radiation (LE/Rn) was about 1, before the critical moisture level was reached. Thereafter the ratio dropped rapidly, so that when a further 6 cm of water had been with-drawn evapotranspiration virtually ceased.

Bouchet and Roberlin (1969) attempted to deal with certain difficulties cited above, particularly those stemming from the plant and soil factors. They considered that potential evapotranspiration is entirely controlled by climate and varies as a function of season. The real maximum evapotranspiration (ETM) is defined in a given climate by the development of the plant and its physiology when it is well supplied with water. Potential evapotranspiration minus real maximum evapotranspiration, in essence is a measure of the canopy resistance. Real evapotranspiration (ETR) results when poor soil water supply causes a reduction of the exchange surfaces for the transfer of water and may combine both the plant and soil resistance to evapotranspiration.

Eagleman and Decker (1965) suggested that the ratio ETR/ETP

may be defined as a function of soil water potential for any given soil. They further considered that this relationship depends upon the unsaturated conductivity of the soil, which decreases as soil water is depleted. Stern (1967) also showed a marked drop in real evapotranspiration for cotton in an advective environment in Western Australia when soil moisture is depleted to less than 60% of the available water.

ii) The Influence of Crop Cover.

Row crops do not normally shade the ground fully excepts in some cases at advanced stages in their development. Broadcast crops like alfalfa do not shade the ground for sometime after periodic cuttings. Water use as we know may continue to increase with increasing leaf area even when leaf area dense enough to fully shade the ground has been achieved. Brun, Kanemasu, and Powers (1972), had shown that in soybean fields the proportion of water lost as transpiration is closely corrected to leaf area index with transpiration being approximately 50 percent of the total evapotranspiration at a leaf area index of 2. This proportion increases to 95 percent of the total evapotranspiration at a leaf area index of 4.

iii) The Influence of Crop Height

Many of the important crops grown worldwide are not short; examples are corn, sorghum, winter and spring grains, cotton, and trees in river valleys. The taller the crop, the more effective its exchange of energy with the ambient air. Alfafa is a short

crop. Stanhill (1965) and El Nadi and Hudson (1965) had shown that the quantities of water evaporated by this crop increases with increasing crop height. The type of leaf also influences the evapotranspiration rate and broad-leafed plants transpire more than the grasses (Fritschen, 1965; Blad and Rosenberg, 1974).

iv) The Influence of Extended Surfaces or "Fetch".

An extended surface means, great fetch. Stanhill (1965) suggested that fields be at least 20 m from the centres in any direction from which the wind blows. Dyer and Crawford (1965) found temperature profiles up to 5m not fully adjusted to the new surface at 200m from the edge of a field. Any visible difference in plant growth along the border of a field or the existence of non logarithmic profiles of temperature and humidity is evidence of inadequate field size for measuring potential evapotranspiration within the meaning of the phrase "extended surface".

v) The Relation of Free Water Evaporation and Plant Water Use

The condition that potential evapotranspiration cannot exceed free water evaporation under the same weather conditions probably applies well in humid regions in which the net daily and net seasonal energy balance involve some sensible heat generation and transport to the ambient air. Pruitt and Lawrence (1968) reported that the amount of water used by fescue and rye grass at Davis, California is about 80% of that evaporated from open water in evaporation pans except when winds are strong and the air is hot

and dry. Then the ratio drops still further apparently because these conditions cause an increase in the stomatal resistance.

In the Great Plains and arid regions well-watered crops that exert little canopy resistance and are tall can, conceivably, consume more energy and transpire more water than is evaporated from free water surfaces. The differences may be very pronounced, if the free water surfaces are very extensive and crop areas are not (Fritschen, *et al*, 1965).

Rosenberg and Powers (1970) compared soybean evapotranspiration in the experimental field at Mead to pan evaporation measured immediately adjacent and to north of the field. During the period June 26 - July 26, 1969 the height of AMSOY soybeans increased from about 30 to 102 cm. On the twenty days uninterrupted by rain or irrigation the average daily lysimeter, evapotranspiration (the mean of two lysimeters) was 8.33 mm day^{-1}. It was observed that free water evaporation need not always indicate the upper limit or the potential evapotranspiration in subhumid and arid regions as it does, apparently, in humid regions.

vi) The Internal Plant Resistance to Water Flow

This condition presupposes that plants behave passively as wicks for the transport of water from the soil to air. Penman recognized that this assumption did not hold in all circumstances and with Schofield (1951) attempted to adjust for stomatal influence on transpiration. Van Bavel (1967), Van Bavel *et al*, (1962) and Van Bavel and Ehrler (1968) have shown, that alfafa, sudan grass and sorghum exert very little canopy resistance to

evapotranspiration.

Rosenberg (1969b) supports this view with respect to alfafa for most of the growing season. Cold weather, however, had a significant effect on the resistance of an alfafa crop. A major increase in canopy resistance was indicated as evapotranspiration was greater than net radiation on April 21, but after a cold night evapotranspiration was greatly reduced on April 22.

There is some evidence of significant stomatal influence on evapotranspiration rates in sugar beets (Brown and Rosenberg, 1970) *and dry and snap beans (Rosenberg, 1966; Rosenberg et al,* 1967). Van Bavel *et al,* (1967) also suggested a considerable canopy resistance for an orange orchard. Lee (1967) stimulated a spirited argument by suggesting a major role for stomatal regulation of evapotranspiration and thus, a major role in the hydrologic cycle of the earth.

2.3 Potential Evapotranspiration

There are four main methods for direct measurement of potential evapotranspiration, namely;

(i) lysimeter experiments

(ii) soil moisture depletion studies

(iii) water balance method

(iv) field experimental plots

2.3.1 Lysimeter Experiments:

Lysimeter is an instrument for measuring the change of water content change in soil. Lysimeter experimental studies involve

growing of crops in large containers and measuring their daily water loss or gain. The soil and crop conditions in the lysimeter must be near to the natural conditions. The measurements (floating lysimeters) involve weighing by floating the lysimeter tank in water in which the change in liquid displaced is computed against water loss from the tank. (Michael, 1978). The tank is buried permanently in the ground and surrounded by a large area of the crop of the same height if the readings are to bear good relation to losses from the crop in the field. The water table is maintained at a specific depth in the tank by connecting it to a supply tank provided with a floating mechanism which has an arrangement for receiving excess water that tends to build up in the tank. Water is applied in measured amounts to the lysimeter as irrigation is applied to the surrounding cropped area. The over flow and deep percolation are measured. The water received either from the reservoir or precipitation without outflow constitutes the water used by the crop.

Lysimeters, although providing the means of precise and direct measurement of the amount of water supplied to and lost by crops, have a lot of problems. The major limitations are the maintenance of the physical condition such as water table, temperature, soil texture and density within the lysimeter comparable to those outside in the field. The bottom of an isolated soil column often requires artificial application of a moisture suction similar to that present at the same depth in the natural soil, to ensure proper drainage. The soil temperature in the lysimeter is raised in some cases to such an extent that air conditioning of the whole system becomes a necessity.

2.3.2 Soil Moisture Depletion Studies

This method is usually used to determine the consumptive use of irrigated field crops grown on fairly uniform soils when the depth to the ground water does not influence the soil moisture fluctuation within the root zone: Soil moisture depletion studies involve measurement of soil moisture from various depths at a number of times through out the growth period. Consumptive use (CU) is calculated from the change in soil water content in successive samples from the equation below:

$$U = \sum_{i=1}^{n} \frac{M_1 i - M_2 i}{} \cdot Ai \cdot Di \qquad \text{--------} \quad (1)$$

where;

U = Water use from the rootzone from successive sampling periods or within one irrigation cycle, mm.

n = No of soil layers sampled in root-zone depth, D.

$M_1 i$ = Soil moisture percentage at the time of the first sampling in the ith layer.

$M_2 i$ = Soil moisture percentage at the time of the second sampling in the ith layer.

Ai = apparent specific gravity of the ith layer of the soil.

Di = depth of the ith layer of the soil, mm.

Seasonal consumptive use is calculated by summing the consumptive use values of each sampling interval ($CU = \Sigma U$). A correction is made by adding potential evapotranspiration values for accelerated water loss for the intervals just after irrigation and before soil moisture sampling.

Water balance in a soil can be described hydrologically by:

Precipitation = Evapotranspiration + surface runoff + sub-surface drainage + change in soil water contents --- (2)

This method is also called inflow-outflow method. It is suitable for large areas (water sheds) over long periods. The accuracy of this method depends upon the accuracy with which precipitation, runoff and change in soil moisture content are measured. Recent soil physics research (Van Bavel, Brust et al. 1968) has shown that measurements of the change in soil moisture content may not truly reflect the quantities of water that either percolate of evaporate from the soil because of large quantities of vapor and liquid flow in both directions due to thermal and hydraulic gradients. An improved method for estimating ET in hydrological studies is proposed by Davidson and Barad, (1969), who measured soil water flux at various depths with and without surface evaporation so as to develop better estimates of the seepage term.

2.3.4 Field Experimental Plots

Measurements of water supplies to the field and changes in soil moisture contents of field plots which depend on computing seasonal water requirement of crops are better than the measurements with small tanks or lysimeter (which has limitations). The seasonal water are determined by adding the effective rainfall received during the season, the contribution of moisture from the soil and measured quantities of irrigation water. This may be expressed in the equation below:

$$WR = ER + IR + \sum_{i=1}^{n} \frac{Mbi - Mci}{} \cdot Ai \cdot Di \quad \text{------} \quad (3)$$

in which,

WR = seasonal water requirement, mm

ER = seasonal effective rainfall, mm

IR = total irrigation water applied, mm

Mbi = moisture percentage at the beginning of the season in the ith layer of the soil.

Ai = Apparent specific gravity of the ith layer of the soil.

Di = depth of the ith layer of the soil within the root zone, mm.

Mci = moisture percentage at the end of the season in the ith layer of the soil.

n = number of soil layers in the root zone D.

This method requires that the amount of water applied to a field is measured accurately. The method, even though satisfactory for determining seasonal water requirements does not provide information on intermediate soil moisture conditions, profile use, short term use, deep percolation losses and peak use rate of the crop.

2.3.5 Other methods of measuring Potential Evapotranspiration

Other methods which have been used to determine potential evapotranspiration include the measuring of soil moisture through gravimetry, neutron scatter, conductivity blocks, tensiometers and tube sampling. Each method, however, has its limitations. Most are laborious, time consuming, expensive, cumbersome and requiring intensive and/or destructive sampling.

2.4.0 Estimation of Evapotranspiration From Evaporation Data

There is a close relationship that exists between the rate of pan evaporation and the rate of consumptive use by crops. The standard US Weather Bureau Class A open pan evaporimeter or the sunken screen open pan evaporimeter (Sharma and Dastane, 1968) can be used for the measurement of pan evaporation. The relationship between evapotranspiration and pan evaporation is given by the crop factor: viz

Evapotranspiration = pan evaporation x crop factor. Thus this approach has much to recommend it, in view of the availability of the data, the simplicity of measurement and the cheapness of the equipment. Yet in arid or semiarid regions, it is important to remember that the ratio of pan to crop evaporation will vary depending on the down wind distance from the boundary between the crop and its dry surrounding (De Vries 1959).

The value of the factor for any crop depends on foliage characteristics, stage of growth, environment and geographical location. During the early stages of crop growth consumptive use values are low and increases as the plant approaches maturity. There is a general decline after the stage of maturity. At each location the values ofthe factor for a particular crop should be determined experimentally.

2.5.0 Micrometeorological Methods for Estimating Evapotranspiration

2.5.1 The Mass Transport Method

This method has a general formula which predicts evaporation as a function of vapor pressure:

$$E = C\,(eo - ea) \quad \ldots\ldots\ldots\

despite its vulenerability, offers the advantage of simplicity in calculation once the empirical constants have been developed.

Brutsaert and Yu (1968) have attempted to improve available empirical coefficients used in mass transfer equations with data on evaporation from free water surfaces in pans of various sizes and shapes.

Pruitt (1963) has proposed still another modification of the Dalton expression in which:

$$E = f(u)\ (e_o - e_{100}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ (8)$$

where eo is calculated as saturation vapor pressure at the temperature of the surface, eloo is vapor pressure at 100 cm above the surface and f (u) is obtained graphically from a plot of windspeed at 100 cm versus ET /(eo - eloo).
ET is measured by a lysimeter (Pruitt and Aston, 1963).

2.5.2 Aerodynamic Methods

Three vertical fluxes resulting from turbulent diffusion in the surface boundary layer are given by:

$T = Pa\ k_m \frac{\delta u}{\delta z}$, the flux of momentum,

$A = -Pa\ C_p K_H \frac{\delta T}{\delta z}$, the flux of sensible heat

$E = -P\ k_v \frac{\delta q}{\delta z}$, the flux of water vapor

C_p is the specific heat of air at constant pressure and q is the specific humidity, if it is assumed that:

$K_m = K_H = K_v$.

Thus E may be calculated from the water vapor gradient if the

gradient of T or U is measured simultaneously and the flux of sensible heat or momentum is known. Independent measurements of sensible heat or momentum flux are, however, difficult to achieve and are rarely made.

Thornthwaite and Holzman (1942), assuming that km = kv, proposed that evaporation could be estimated from a relationship involving the gradients of specific humidity qf and the logarithmic wind profile. Their equation is given by:

$$E = Pa\ K^2\ \frac{(q^2 - q^1 \times U_2 - U_1)}{\ln (Z_2/Z_1)^2} \quad \ldots\ldots\ldots\ldots\ldots (9)$$

Following Thornthwaite and Holzman's work, many others (e.g Pasquill, 1950; Rider 1954a; Munn, 1961; Pruitt, 1963 and Webb, 1965) have proposed stability-corrected aerodynamic methods for estimating the flux of vapor. These are complex methods demanding stringently accurate observations of wind speed and specific humidity or vapor pressure at a number of heights above the surface, as well as temperature measurement to permit stability-corrections.

Other notable contributions to aerodynamic theory are to be found in Sutton (1936, 1948 and 1953), Sverdrup (1936, 1939,1946), Thornthwaite and Halstead (1942), Priestly and Swinbank (1947), Sheppard (1946), Calder (1949), Panofsky (1952), Cramer and Record (1953), Batchelor(1953), Monin and Obukhov (1954).

Aerodynamic methods have been popular with scientists because of its origins in classical fluid dynamics theory. The methods, however, have not reached a degree of development that makes them applicable for routine use.

2.5.3 Eddy Correction Methods

Swinbank (1951) proposed an eddy correlation method to estimate the vertical flux of heat or vapor. The equation is given below:

$$H = Cp\ eTw \quad \text{---------- (10).}$$

Where H is the upward heat transport/unit area. W is the vertical component of windspeed and T is the air temperature.

Sheppard (1958) following Swinbank's (1951) development showed that in fully turbulent flow, the mean upward vertical flux (F) of entity (S) per unit mass of fluid is given by

$$F = pSw \quad \text{---------- (11)}$$

where p is the fluid density, W the vertical component of velocity and the bar indicates a space - time mean for the height Z at which measurements are made.

Instrumentation for direct measurement of the eddy and its properties has been under development for a number of years (Taylor and Dyer, 1958; Dyer and Pruitt; 1962; Dyer and Maher; 1965; Dyer, Hicks et.al.1967). These instruments use hotwire anemometers to sense vertical windspeed W and fine wire wet and dry thermocouples or thermistors to sense rapid changes in temperature and humidity.

The art of eddy correlation instrumentation resolves into two problems. First, to be able to detect simultaneous changes in temperature, vapor pressure and windspeed due to the rapid passage of different eddies. The frequency of the eddy changes that are reflected in temperature and humidity fluctuations increases as the surface is approached and the eddy size diminishes.

Second, if the properties of each eddy are to be separately

measured, tremendous quantities of data will be accumulated rapidly.

2.5.4 Bowen Ratio-Energy Balance Method

The energy balance at the earth's surface was written as:

$$Rn = S + A + LE + P + n \quad \text{----------} \quad (12)$$

Where Rn is the net radiation, S the soil heat flux, A is the sensible heat to the air and LE the energy consumed in evaporation, (L is the latent heat of evaporation and E the quantity of water evaporated). The terms P and M represent photosynthesis and miscellaneous exchanges respectively. The miscellaneous term includes energy exchange which are due to metabolic activity and the storage of heat in plant tissue or volume of the canopy. The sum of P and M terms is usually smaller than the experimental error in measurement of the major components, they are generally ignored, so that:

$$Rn = S + A + LE \quad \text{----------} \quad (13).$$

This equation adequately describes the energy budget of the earth's surface.

Bowen (1926) recognized that soil heat flux S constitutes only a small fraction of net radiation when soil moisture is not limiting. He thus partioned net radiation between sensible and latent heat.

Evaporation (LE) and sensible heat (A) were expressed as functions of the eddy diffusivities as follows:

$$LE = -\frac{PLE}{P}\,\frac{Kv\ \delta e}{\delta z} \quad \text{----------} \quad (14)$$

$$A = Cp\ K_H \frac{\delta T}{\delta z} \quad \text{---------- (15)}$$

Bowen devehowever the relationship:

$$\beta = \frac{A}{LE} = \frac{Cp\ K_H \frac{\delta T}{\delta z}}{LE\ Kv \frac{\delta e}{\delta z}} = \frac{PCp}{LE} \frac{T}{e} \quad \text{---------- (16)}$$

A simplifying assumption required to compute Bowen's ratio is $K_H = K_v$. The validity of this assumption has been the subject of considerable disagreement among proponents of both aerodynamic and energy budget methods of ET estimation.

Despite this apparent difficulty the Bowen ratio has been shown to be accurate for practical applications and is widely used.

Suomi and Tanner (1958) made instrumental arrangement for the determination of Bowen ratio. Fritschen (1965), too, developed instrumentation for direct determination of the Bowen ratio over crop surfaces. Fritschen (1966) used the device he developed to calculate ET over alfafa; barley, cotton, sorghum, oats and wheat in Arizona. Alfafa was the greatest water consumer before cuttings but cotton reached the same peak-water use when fully developed. The rough broad leafed plants used more water than did the grasses, likely because the aerodynamic roughness of these leaves caused greater heat extraction from the air.

Hanks, Bowers and Bark (1961) demonstrated that detectable differences in net radiation are observed over mulches of different types. Net radiation was greatest over black gravel of the mulches used, which included clear plastic, aluminum, straw and uncovered soil. Differences in albedo and surface radiating

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temperatures determined the total black radiation from the earth's surface and, therefore, the value of the net radiation over each surface.

Waggoner and Reifsnyder (1961) observed that paper, foil, hay and black film mulches influenced outgoing radiation but increasing transpiration from plants which partially shaded the ground by illuminating or increasing radiant energy incident on their lower leaves.

Yao and Shaw (1964a) had shown that differential corn spacing resulted in net radiation differences which were in part reflected in water use from plots. Higher planting rates resulted in greater uptake of net radiation (Yao and Shaw,1964b). Denmead et. al.(1962) has earlier conducted studies which showed that plant spacing might be regulated to minimize the quantity of net radiation available at the soil surface where its only effect could be direct evaporation of soil water, thereby increasing the energy available to the crop for photosynthesis.

Bowers, Hanks and Stickler (1963) in Kansas found, on the other hand, that the portion of the net radiation absorbed under cropped conditions is only slightly influenced by row spacing but that the distribution between evapotranspiration and soil heating was much affected by row spacing.

Aubertin and Peters (1961) found that spacing of corn plants and row widths affect relative amounts of energy absorbed by plants and by the soil. The authors suggested that knowledge of total net radiation and area in crop should enable estimation of the total water requirement of the crop.

Tanner (1957) and Tanner (1958) had shown that lysimeter

determine ET was highly correlated with net radiation over an alfafa brome hay field and over corn Wisconsin. It was suggested that for humid regions where there is little vertical transfer of sensible heat, net radiation will closely predict potential evapotranspiration. Good agreement between evapotranspiration and net radiation was observed for period shorter than one hour (Tanner and Pelton, 1960).

Tanner and Lemon (1962) suggested that most of the energy of net radiation is transformed into sensible and latent heat and that the division between the two depends upon the amount of water available for evaporation. Data presented by the authors indicate that when soil moisture is available and a substantial crop cover shades the ground, most of the net radiation energy is used in the evapotranspiration process.

Sharp (1958) disagreed with Tanner's suggestion that evapotranspiration is best estimated by net radiation. He cited Kiesselbach's (1916) studies in Nebraska which showed that transpiration by corn plants growing in potometers was better estimated by air temperature than by percent possible sunshine which was the only measure of radiation in these studies.

In a more recent report, however, Decker (1964) found total reliance on the energy balance approach to be unsatisfactory. Evapotranspiration estimated by energy balance did not agree closely with measurements of the hydrologic balance and neutron probe soil moisture measurements.

Janes (1960b) had indicated that potential evapotranspiration can be estimated as a linear function of the difference in evaporation between black and white atmometer which is taken to be

a measure of, or proportional to the net radiation.

Pruitt (1960) had shown that net radiation and evaporative flux are generally closely related but evapotranspiration consistently exceeds net radiation during late afternoon, apparently due to convective heat transfer from air to evaporating surfaces. In a later study (Pruitt and Aston, 1963) it was found that especially on calm days diurnal evapotranspiration from rye grass was not in phase with latent heat flux. Convective heat flux away from the soil reached a peak value by mid-morning, dropped to zero by mid-afternoon with considerable heat transfer from air to surface thereafter. Evapotranspiration exceeded net radiation each of 24 hours of a single day at Davis because of advection.

Dyer and Pruitt (1962) compared evaporation from the weighing lysimeter at Davis to results of estimations based on an eddy flux evapotron and to net radiation. Results were good when the surroundings were moist. When only the sample field remained moist agreement was poor. They concluded that a fetch of 30 - 50 times the observation height is not adequate to eliminate horizontal gradients in temperature and humidity, a condition necessary for proper application of eddy correlation and aerodynamic techniques.

Van Bavel and Fritschen (1965) investigating the energy balance of bare surfaces in arid climates found that on a daily basis, evaporation from wet soils was closely related to net radiation. It was also noted that periods of low evaporative flux were coincident with low windspeeds and higher evaporation rates with higher windspeeds. The contribution of advected energy to

total evaporation was considered to be of minor significance. The authors showed that as a surface dries its albedo increases resulting in a decrease in the net radiation term and proportionately larger amounts of energy are consumed in heating the soil and air. They showed that evaporation from well-watered grass growing in the lysimeters exceed evaporation from both free water and wet soil. Latent heat used in potential evapotranspiration also exceeded net radiation available at the surface indicating the influence of advective heat. It was found that lysimetrically measured evapotranspiration by grass could be closely approximated with simpler devices such as water tanks, radiometers, or with suitable formula combining standard meteorological quantities.

Van Wijk and de Vries (1954) in a critical evaluation of Thornthwaite's technique emphasized that radiation rather than temperature controls evapotranspiration. The authors suggested that transpiration may be represented by a function of evaporation from a wet surface of shape similar to the transpiring parts of the leaf and a reduction factor determined by physiology of the plant, that is, diffusion resistance of stomata.

2.5.5 Resistance approach

It was shown earlier that the transport of sensible heat from surface to air proceeds at a rate directly proportional to the temperature gradient and inversely proportional to the aerial resistance to thermal conductivity ra:

$$A = Pa\ Cp\ \frac{(Ts - Ta)}{ra} \qquad (17)$$

It can be shown that the transport of vapor is directly proportional to gradient in vapor pressure from the evaporating surface to the air and inversely proportional to the aerial resistance to the diffusion of water molecules.

The source of water vapor in the transpiration process is the substomatal cavity of the leaf, unlike sensible heat, which originates at the surface. In that cavity, air is saturated or nearly so unless the plant is under severe water stress or is desiccated. The vapor must diffuse through the stomatal openings controlled by the guard cells. A second resistance must therefore be considered in transpiration from a leaf - the stomatal resistance rs.

Monteith (1963) proposed that evaporation could be predicted if the resistance ra and rs were known. The equation analogous to that for A above would be

$$LE = Pa \frac{LE}{P} \frac{(s - a)}{ra + rs} \quad \text{---------- (18)}$$

rs is usually in order of 1 - 10 or 20 sec cm^{-1},

ra is generally 0 .1 - 1 or 2 sec cm^{-1}.

Tanner (1963) suggested that the sources and sinks for sensible and latent heat in a crop canopy are unlikely to be identical and, therefore, the same resistance values cannot be used.

Brown and Rosenberg (1973) had proposed a resistance model that can be used to predict the influence of weather condition or imposed treatments on latent heat flux by crops. The model is too complex and requires iteractive solutions, although the only weather inputs required are net radiation, soil heat flux, air

temperature, vapor pressure, and air and stomatal resistance.

$$LE = [f\ (\underline{Rn - S - LE})\ \underline{ra + Ta}) - ea)\ \underline{M_w/Ma}(Pa] \text{ --- (19)}$$
$$ra + rs \qquad P$$

Air resistance can be related effectively to windspeed. Stomatal resistance can be measured with diffusion parameters of various kinds.

Blad and Rosenberg (1974) proposed a simplification of this approach so that evaporation from large areas can be measured. It requires the measurement of the surface temperature with air-borne or satellite - borne thermometer.

The crop temperature could be represented by :

$$Tc = \underline{(Rn - S - LE)\ ra + Ta} \text{ ---------- (20a)}$$
$$Cp \quad Pa$$

Bartholic, Namken and Wiegand (1972) had shown that available instrumentation for the remote sensing of thermal regimes is capable of detecting temperature differences due to moisture stress in cotton. Latent heat flux could be estimated from a reduced number of direct environmental measurements and aerial resistance need be inferred from windspeed information.

2.6.0 EMPIRICAL METHODS

Empirical methods are the methods which relate evaporation or evapotranspiration to one or more meteorological parameters. However, any formula containing empirical constant might properly fit into this classification. Several general methods for estimating evaporation or evapotranspiration have been developed which require only minor modification to be applicable to local situations where an appropriate weather record exists. These are

the ones most often applied to agricultural surveys.

2.6.1 Thornthwaite Method

Thorntwaite (1948) describes the biological and physical importance of evapotranspiration in climatic determination. As a consequence of his efforts in studies of climatic classification systems, he developed an equation for estimating potential evapotranspiration (PET). From the initial formula:

$e = ct^a$ .....(21) 1 where e is monthly evapotranspiration; T is monthly mean temperature and c and a are constants, he developed the general formual:

$e = 1.6(\frac{10T}{I})^a$ .....(22) 2

Calculation of e is very laborious because of the complexity of the exponent (a) which is defined as:

$a = 6.75 \times 10^{-7} I^3 - 7.71 \times 10^{-5} I^2 + 1.79 \times 10^{-2} I + 0.49$ -- (23)

I is a heat index derived from the sum of 12 monthly index values (i) and (i) is in turn a function of the monthly normal temperature.

$i = (t/5)^{1.514}$ ---------- (24)

The factor (e) represents monthly potential evapotranspiration (in cm) and T is the monthly mean temperature (°C).

The Thornthwaite method gives a reasonable estimate of potential evapotranspiration in the temperate, continental climate of North America where the formula was originally derived because there the temperatures and radiation are strongly correlated. In

other parts of the world this approach has been less successful. The shortcomings of the method as enumerated by Chang (1968) are as follows:

(i) temperature alone is not a good indication for the energy available for evapotranspiration, (ii) air temperature of a place lags behind radiation (iii) according to this method evapotranpiration will cease when mean temperature is below 0°C which by no means is true, although the amount of evaporation will be very small; (iv) The method does not take into account the wind effect which might be an important factor in some areas. (v) It also does not consider the effect of warm and cool air on the temperature of a place

Sanderson (1950) measured the daily potential evapotranspiration at Toronto over a vegetated soil surface and found that potential evapotranspiration predicted by the Thornthwaite formula compared favorably with measured values. Under natural conditions, however, it was found that as the surface soil dried sub-surface water losses diminished and potential evapotranspiration diverged from actual evapotranspiration.

Leeper (1950) obtained anomalous results with Thornthwaite method applied to various Australian locations where mean temperatures were similar but where the actual climate differed greatly with consequent differences in known evapotranspiration as well. He suggested incorporation of atmospheric moisture and wind parameters to make results of potential evapotranspiration more meaningful.

In another evaluation of the Thornthwaite method, Pelton *et*

al , (1960) found that potential evapotranspiration measurements based on short-term mean temperatures are unreliable.

They concluded that methods based on mean temperature can be used to some degree for estimates during the growing season for annual estimates of potential evapotranspiration, however, energy balance methods are preferable if radiation data are available. The failure of the Thornthwaite method over short time periods is attributed to the fact that short term mean temperature is not a suitable measure of incoming radiation. Success on a long-term basis is explained as due to the fact that both evapotranspiration and mean temperature are similarly functions of net radiation and are, therefore, autocorrelated over relatively long periods of time.

Marlatt *et al*, (1961) found that the Thornthwaite method, applied to snap beans on sandy loam, gave good estimates of evapotranspiration proceeded asymptotically to a linear decrease in water loss. This was due to the increasing soil matric suction which continued until the permanent wilting percentage level was reached.

Palmer and Havens (1958) developed a graphic solution for the Thornthwaite equation which utilizes a series of nomogram to avoid the laborious task of calculating potential evapotranspiration arithmetically.

Sanderson (1950), working at Norman wells, NWT, Canada (64°N), made the first known comparisons of empirically derived and measured evapotranspiration in the sub-arctic. The study was in good agreement between potential evapotranspiration derived by Thornthwaite's method (Thornthwaite, 1948) and the amount of water

evapotranspired from a soil with sparse grass cover. The Thornthwaite method has been used as delinear climatic region in sub-arctic. (Sanderson, 1950; Patric 1966). Patric (1966) found that Thornthwaite potential evapotranspiration estimates agreed with pan evaporation measurements for several locations in Alaska. Based on nearly 50 years of climatic data at Fairbanks, Alaska, Patric (1966) estimated an annual potential evapotranspiration of 0.46 m and a water deficit of 0.15 m.

Garnier (1956) tested the validity of Thornthwaite's formula in Nigeria under West African conditions. In his investigation, University College, Ibadan and Northern Research Station of the Nigerian Department of Agriculture, Samaru were used as his study areas. It was observed that at Ibadan there was a close relationship between measured and computed potential evapotranspiration, while at Samaru a similarly close relationship exists only in the months of the wet season from May or June to the end of October. During the rest of the year measured values were a good deal higher than those computed. In the dry seasons, the daily rate of measured potential evapotranspiration at Samaru was very much higher than at Ibadan.

2.6.2 Penman Method

Penman (1948) proposed an equation for evaporation from open water surface in mm/day, based on a combination of energy balance and sink strength, which is given below:

$$E_o = \frac{mH + 0.27\,E_a}{m + 0.27} \qquad \text{.....(25)}$$

where;

M = slope of the saturation vapor pressure curve for water at mean

T_a (mm/Hg/°F) 0.27 = constant in standard hygrometer

equation mm/Hg/°F.

H = an estimate of net radiation in evaporation equivalents of mm/day.

$E_a = 0.35 (e_a - e_d)(I + u_2 \times 10^{-2})$ mm/day.

ed = saturation vapor pressure at dew point

ea = saturation vapor pressure at mean Ta.

U_2 = mean windspeed in miles/day at 2m.

Penman's equation has a more sound physical basis than that of Thornthwaite but it requires knowledge of vapor pressures, sunshine duration, net radiation, windspeed and mean temperature. Few of these parameters are measured regularly at any but special observatories and therefore must be estimated. Another problem arises in converting E_o to ET over vegetated surfaces.

The problem of estimating evapotranspiration in situation where optimum water supply is not maintained led Penman (1949a) to a modification of his original method. He assumed roots occupy a depth of soil which will yield a definite amount of water at a maximum rate. He found that after this amount of water is lost the subsequent rate of loss is limited by the ability of sub-surface soil layers to transmit water. It is necessary to determine subsequent rate of loss for each specific soil type. The method was tested against drain-flow records and it was found that available water in the root zone yields satisfactory estimates of evapotranpsiration from turf. The available water, inturn, is a function of spring rainfall and hence varies

considerably from year to year.

Penman (1950) tested his equation at 100 stations in the British Isles against precipitation runoff records for 40 water sheds. Good results were obtained.

De Vries and Van Duin (1953) applied Penman's method to data taken by Briggs and Shantz (1917) in an alfafa stand. They found that the ratio of transpiration to calculated evapotranspiration was almost constant in most cases and was better than comparison between measured transpiration and evaporimeter readings.

Purvis (1961) developed a graphic solution for the Penman equation to be used in the vicinity of Columbia South Carolina. With minor modifications and adjustments this technique should be adaptable to any location in which the Penman method is found to be acceptable. More contributions to Penman's equation are to be found in Penman (1949b, 1952, 1956) Van Bavel and Wilson (1952), Businger (1956), Gerber and Decker (1961), Wang and Wang (1961) and Van der Bijl and Bark (1960).

2.6.3 Blaney - Criddle method

Blaney and Morin (1942) correlated pan evaporation with monthly mean temperature, relative humidity, percentage of total yearly day-light hours for each individual month and derived an empirical consumptive use index:

$$EL = 0.0167T\ (114 - RH) \qquad (26)$$

where EL is lake evaporation in inches, T is annual mean temperature, and RH is the annual mean relative humidity. A factor of evaporative force (heat energy available) was computed from the product of monthly mean of total annual day - light

hours.

$$e = K(t_p)\ (114 - rh) = K_f\ (114 - rh) \text{ ---------- (27)}$$

where e is monthly evaporation (in inches), K is monthly coefficient which varies with the type of evaporimeter or water surface used; t is mean monthly temperature; p is the monthly mean percent of annual day light hours; tp is the evaporative heat factor; and rh is the monthly mean relative humidity.

Blaney and Criddle (1950) with the above formula as a starting point, developed a consumptive use technique which correlated existing data on crop consumptive use of water with monthly temperature, monthly percentage of annual day light hours, precipitation and length of the growing or irrigation season. The equation:

$$U = KsF = \sum Kmf \text{ ---------- (28)a}$$

where U is the consumptive use in inches during the period of interest. Ks = seasonal or growing period consumptive use coefficient. K_m is the monthly consumptive use coefficient.

$f = \frac{t.P}{100}$ = monthly consumptive used factor

t = monthly mean temperature (°F)

P = monthly percent of total annual day light hours.

F = $\sum f$ for the total period

U = kmf = monthly consumptive use (inches)

This method has been used extensively, particularly in the Western United States and Nigeria.

The following assumptions underlay the Blaney - Criddle method. Seasonal consumptive use (U) varies directly with the

consumptive use factor (F); water supply to the growing crops and fertility and producing powers of the soil do not differ significantly among areas to be compared.

The method is easy to use. Necessary data are readily obtainable from weather Bureau records and results have been sufficiently accurate from many practical applications. Nomograms for calculation of consumptive use and a list of consumptive use coefficient are given by Criddle (1953).

Schleusener, *et al*, (1961), Williams (1954) and Sommer halder (1962) adapted the Blaney - Criddle approach to planning irrigation of corn and pasture in Nebraska. Evaluations of potential evapotranspiration using this method have been prepared by Tomlinson (1951, 1953) for Wyoming and by Davis, *et al*, (1952) for North Dakota.

Damagnez, Riou et. al. (1963) compared the Thornthwaite, Turc, Penman and Blaney - Criddle methods of estimating potential evapotranspiration from climatological data with evapotranspiration measured by non weighing lysimeters. Their study used data from five sites in Tunisia. It was observed that only the Penman and Turc methods gave acceptable estimates of potential evapotranspiration.

Nixon et.al.(1963) presented comparisons of the Thornthwaite and Blaney-criddle methods of estimating evapotranspiration from alfafa with measured soil moisture depletion. They used three California sites of differing climate coastal, fogbelt, coastal valley and interior valley locations. The study showed that neither method gave close estimates in these areas but that the Blaney - Criddle method gave slightly closer estimates than the

Thornthwaite method.

2.6.4 Lowry - Johnson Method

Lowry and Johnson (1942) noted a high correlation between annual consumptive use (Cu) and effective heat accumulated (degree days of daily maximum temperature above 32°F). The linear relation they developed is expressed by the following equation:

$$Cu = 0.00185HE + 10.4 \quad \text{---------- (29)b}$$

where;

HE = effective heat in degree days above 32°F.

Monthly estimates of consumptive use are determined by using a ratio of the monthly degree-days to the annual degree days multiplied by the annual consumptive use. The relation expressed in equation 29 was determined from basin-wide studies of the hydrologic budget using inflow, outflow precipitation and change in the quantity of ground water in storage.

2.6.5 Hamon Method

Hamon (1961) formulated a simplified expression for estimating potential evapotranspiration. The expression is represented by the equation:

$$E_T = CD^2Pt \quad \text{---------- (30)}$$

where

E_T = average potential evapotranspiration in inches per day;

D = possible hours of sunlight, in units of 30 days of 12 hours each;

P_t = saturated water - vapor density at the daily mean

temperature, in Cg/m^3 and

C = coefficient chosen to give appropriate yearly values of potential evapotranspiration.

Hamon empirically determined the value of C to be 0.55 from comparisons with the results of the Thornthwaite method and the Lowry - Johnson study.

The Hamon method is based on the relation between potential evapotranspiration, maximum possible incoming radiant energy and the moisture-holding capacity of the air at the prevailing air temperature. In using this method, values of mean monthly temperature and the latitude of the site are required. The absolute humidity at saturation, Pt, is determined directly from mean air temperature. The possible hours of sunlight, D, are determined from the latitude of the site.

2.6.6 Weather Bureau Method

The weather bureau method was developed by Kohler et.al (1955). It is a modification of the Penman's method (1948) and was derived by applying the Penman approach to a composite record of a number of weather stations in the United States and to the Lake Hefner studies by Kohler (1954). Estimation of lake evaporation, which is assumed to approximate potential evapotranspiration is determined from the equation.

$$EL = 0.70\ [(Qn\delta + EaY)]\ [\delta + Y] \quad \text{----------} \quad (31)$$

where,

EL = average daily lake evaporation in inches

Qn = net radiant energy, in inches per day.

δ = slope of the curve relating saturation vapor pressure to temperature at the observed air temperature;

Ea = evaporation given by the aerodynamic equation in which water temperatures are assumed equal to air temperature;

Y = factor defined by the equation for Bowen's (1926) dimension less ratio.

Kohler et.al.(1955), in order to simplify the computation have presented nomograph for estimating mean daily lake evaporation from mean daily or monthly values of air temperature, dew point temperature, wind movement, and solar radiation.

2.6.7 Lane Method

Lane (1964), using 551 sets of monthly data for pan evaporation, solar radiation and air temperatures at various sites in the United States, developed the equation below to express the relation between lake evaporation, solar radiation and temperature.

$$10^4 \frac{EL}{Qs} = 2.67T - 51.46 \quad \text{---------- (32)}$$

where;

EL = average monthly lake evaporation, in inches.

Qs = average monthly incoming solar radiation, in Langleys per day;

T = average monthly air temperature, (in $^{\circ}F$).

Lane used a coefficient of 0.70 to adjust observed pan

evaporation to the values he used for lake evaporation. A comparison of results obtained by equation 32 with published lake evaporation at various sites in the United States indicated to him that a coefficient of 0.92 should be applied to his results. This reduced equation 32 to another form for estimating lake evaporation:

$$EL = 0.92 \times 10^{-4} Qs (2.67T - 51.46) \text{ ---------- (33)}$$

Values of mean monthly solar radiation and mean monthly air temperature are required for use in this method.

Stephen and Stewart (1963) used data for Southern Florida. In their work, a comparison of correlation coefficients for measured pan evaporation versus computed monthly pan evaporation and for evapotranspiration measured by a lysimeter against computed potential evapotranspiration was examined. The method of estimating potential evapotranspiration from climatological data used in their study were obtained from Thornthwaite, Penman, Blaney - Criddle, Hamon fractional evaporation equivalent and U.S weather Bureau. Modifications of the Penman, Blaney-Criddle, and fractional evaporation equivalent methods were also used in their comparison study that was based on a 6 - year period of record. Of the methods compared, the weather Bureau method had the highest correlation and the Thornthwaite method had the lowest.

Cruff and Thompson (1967) compared the six common methods of estimating potential evapotranspiration from climatological data in Arid and subhumid environments. The methods used in the study were Thornthwaite, U.S weather Bureau, Lowry-Johnson, Blaney-Criddle, Lane and Hamon methods. The results of the study showed that the Blaney-Criddle method was best for estimating potential

evapotranspiration.

2.6.8 Van Bavel's Method

Building on Penman's earlier work, Van Bavel (1966) has developed a combination method for estimating potential evaporation.

Potential evaporation is given by:

$$LEO = - \frac{m/YH + LBvda}{m/Y + 1} \text{ cal cm}^{-2} \text{ min}^{-1} \quad \text{---------- (34)}$$

where H is the sum of energy inputs excluding A and LE (cal cm^{-2} min^{-1}); da is vapor pressure deficit in mb at elevation Za.
Bv is a transfer coefficient for water vapor in cal cm^{-2} min^{-1} mb^{-1} and is defined by:

$$Bv = \frac{PEk^2}{P} \quad \frac{Ua}{(\ln {}^{za}/zo)^2} \text{ gcm}^{-2}\text{min}^{-1}\text{mb}^{-1} \quad \text{---------- (35)}$$

where, Ua = windspeed at height za in km day^{-1} zo = Zero plane displacement

The model was tested against lysimetrically measured evaporation from open water, wet bare soil and well-watered alfafa and showed good agreement between calculated and measured values on an hourly basis. A wide range of climatic conditions were encompassed in the tests including, typical, advection of sensible heat to the evaporating surface.

Van Bavel's method requires no empirical constants and is not restricted to grass or any other specific set of surface condition other than water supply be unrestricted.

An application of this method to estimate water use by an orange orchard was made by Van Bavel et.al.(1967). Potential

evapotranspiration calculated on a daily basis with available meteorological data exceeded actual water use by the orange orchard. The difference between potential and actual use was calculated as being due to stomatal transpiration resistance. Stomatal resistance thus calculated was in good agreement with measured stomatal resistance of sweet orange leaves.

For use on a daily basis the Van Bavel equation is:

$$EO = \frac{\frac{M}{Y} Rn/L + BVda}{\frac{m}{Y} H+1} \quad \text{---------- (36)}$$

with Bv 1.222×10^{-2} $\frac{Ua}{In(\frac{za}{zo})^2}$

where Ua = windspeed at height za in Rm/day

zo = Zero plane displacement.

da = saturation vapor deficit (mbar)

2.6.9 Christiansen Method

Christiansen (1968) proposed a revised empirical method, originally developed by him in 1966, to estimate pan evaporation from climatic data when reliable measured pan evaporation data are not available for estimation of evapotranspiration. Available pan evaporation data may not sometimes be reliable to make estimates of evapotranspiration, because of variations in size and shape of pans, their exposure, the presence or absence of algae in water, the specific methods of measuring the loss of water from the pan and protection against use of water by birds and animals. The

following is the Christiansen's revised equation developed at logan (Utah), U.S.A., for estimating pan evaporation:

$$Ev = kev \cdot R \cdot Ct \cdot Cw.Ch.Cs.Ce.Cm \text{ ---------- (37)}$$

where EV =computed Pan evaporation equivalent to class A pan evaporation,

Kev =a dimensionless empirically developed constant, the value of which is given by Christianson as 0.473;

R = extra-terrestrial radiation in the same evaporation units as Ev.

Ct, Cw, Ch, Cs and Ce are coefficients for temperature, wind velocity, relative humidity, percent of possible sunshine and elevation, respectively and Cm is a monthly coefficient or factor by which all the basic formula would have to be multiplied to obtain the measured evaporation and averaged to obtain the mean monthly values of Cm. The value of Cm mostly range between 0-90 to 1.10 and vary from latitude to latitude. The simplified and non-dimensionless equations for different coefficient are given below:

$Ct = 0.393 + 0.027bTc + 0.0001189Tc^2$

where, Tc = mean monthly temperature (^oC)

$Cw = 0.708 + 0.00339w - 0.0000039w^2$

where, W = the wind velocity in km/day at 0.6m height.

$Chm = 1.25-0.87Hn + 0.75Hn^2-0.85Hn^4$

where Hn is the mean monthly relative humidity at noon, expressed decimally or $Chm = 1.25-3.37Hm-0.65Hm^5$.

Where Hm is the mean relative humidity for the month expressed decimally.

$Cs = 0.542 + 0.805-0.78S^2+0.62S^3$

S = Mean sunshine percentage expressed decimally

Ce = 0.970 + 0.0000984E

S = elevation in meters.

The equations for the coefficients given by Christiansen may not yield desirable results when the mean values of the climatic factors of a place differ much from the standard values used by him. Therefore, the standard values of the climatic factors, for reliable estimates, must be worked out for the local data and the same may be used to derive equation for coefficients of those factors.

2.6.10 Jensen - Haise Methods

Jensen and Haise (1963) developed a method for predicting potential evapotranspiration from knowledge of the mean air temperature and the solar radiation. The regression equation developed was

PET = (0.014T-0.37) Rs ---------- (38)

where PET is calculated in inches day^{-1} and Rs in the evaporation equivalent of the solar radiation, also in inches day^{-1}. This equation was developed from the study of about 1000 reported measurements for various sampling periods with various crops in the Western United States.

A "modified Jensen - Haise method" was proposed by Jensen, Robb and Franzoy (1970):.

PET = CT (T-Tx)Rs ---------- (39)

where CT is an air temperature coeffivent which is constant for a given area and is derived from the long-term mean maximum and minimum temperatures for the month of highest mean air temperature

and T is mean daily air temperature and Tx is a constant for a given area (linear intercept, CT, the air temperature coefficient, is derived from

$$CT = \frac{1}{38 + 7.3\ CH}$$

$$\text{and } CH = \frac{50mbar}{e_2 - e_1} \qquad \text{---------- (40)}$$

where e_2 and e_1 are saturation vapor pressure at the mean maximum and mean minimum temperatures for the warmest month.

The Jensen and Haise (1963) method was tested against lysimetric measurements of daily water use by alfafa and soyabeans at Mead, Nebraska. The results of June and July (high advection in the eastern Great Plains) indicate serious under estimation. During August, when the advection is minor the Jensen-Haise method gave good results. The modified Jensen-Haise method (1970) was also tested against the same lysimetric measurements and tended to underestimate even more seriously.

Dylla, *et al*, (1980) estimated water used by irrigated corn in west central Minnesota using four years of comparison made of measured evapotranspiration to amounts calculated with the standard and refined Jensen-Haise potential evapotranspiration equations and corn crop coefficients from south-eastern North Dakota data. Measured evapotranspiration was also compared with evapotranspiration estimates determined by Lundstrom-stegman "check book method" and by crop coefficients with pan evaporation. Crop coefficients with pan evaporation provided the better evapotranspiration estimates, however, the check book method was the simplest and was about as accurate for estimating

evapotranspiration as the Jensen-Haise potential evapotranspiration equation with south eastern North Dakota crop coefficients.

Brun, *et al*, (1985) tested eight models, using pan evaporation, soil water content, or both to predict evapotranspiration. The two simple variables did a good job of predicting evapotranspiration and describing the relationship of soil water content and potential evapotranspiration to actual plant water use.

Hatfield (1996) compared different forms of the evapotranspiration (ET) equations that include Priestley-Taylor and Penman-Monteith for reference ET. To estimate actual ET, the Priestley-Taylor with an adjusted coefficient for available soil water and the Penman Monteith with a variable surface resistance were compared to water use for grain sorghum, cotton and grass forage at three locations. Davis- Calif; Lubbock-Tex; and Logan-Utah. Both models provided acceptable results, however, the Penman-Monteith model with daily meteorological data input provided more consistent results over the growing season. The Priestley-Taylor over estimated actual ET when crops were limited in soil water because the adjustment for available soil water was not sensitive to soil-water depletion.

2.6.11 Makkink Method

Makkink (1957) proposed the equation below for estimating potential evapotranspiration from grass.

$$E^{+} = 0.61 \frac{\Delta}{\Delta + Y} \frac{Si}{L} - 0.12 \text{ mm/day} \qquad (41)$$

where Δ is the slope of the curve of the saturation vapor pressure versus temperature. I is the psychrometrics constant, Si is the global radiation and l is the latent heat of vaporization of water.

Hansen and Aslyng (1982) modified Makkink equation to:

$$E^{+} = 0.7 \frac{\Delta}{\Delta + Y} \frac{Si}{Y} \quad \text{----------} \quad (42)$$

The results obtained by this modified Makkink equation have been compared with the results of the Penman equation, which was found to be reliable for grass at Tastrup (Hansen et.al. 1981).

2.6.12 Priestley-Taylor Model

Priestley and Taylor (1972) proposed that in humid climates where advection is not a major factor in determining ET, a more simplified model would be practical. They proposed that

$$Pet = \alpha \frac{\Delta}{\Delta x Y} (RN-G) \quad \text{----------} \quad (43)$$

where α = Priestley-Taylor coefficient. Pet = potential evapotranspiration ($mmday^{-1}$); Δ = slope of the saturation vapor pressure temperature curve ($Kpac^{-1}$), Y = psychometric constant ($Kpac^{-1}$); RN = net radiation expressed in water depth equivalents of energy (mmd^{-1}); G = soil heat flux in water depth equivalents (mmd^{-1}). The values for α, have been found to range from 1-08 to 1.34 depending on the crop and the location. Priestley and Taylor (1972) originally proposed a value of 1.26. Hatfield (1996) reported a value of 1.28 but also suggested that advection would greatly affect α. They proposed that α be modified for advection

as follows:

$$\alpha = 1 + (\alpha - 1)\ (es - ea)\ (es-ea) \quad \text{----------} \quad (44)$$

where es-ea = mean vapor pressure deficit for crop growing season.

Jagtap and Alabi (1995) made an evaluation of evaporation by adjusted Penman formula with US class 'A' pan at humid and subhumid regions of Nigeria and Republic of Benin using long-term daily data. Although there were insignificant changes in the accuracy during dry seasons, however, the application of the adjustment factors reduced the percentage of over estimation during the crop growing seasons from 30% to 5% at Ibadan and Onne. Annual over estimations of 15% was reduced to 4% for both Ibadan and Onne. At Cotonou the effect of adjustment factors could not be verified with 5 years available data.

Rosenberg, *et al*, (1967) found in eastern Nebraska that the ratio of evaporation from bare soil measured lysimetrically and estimated by Van Bavel's method ranged from 0.80 to 1.54 during the fall season. Actual evaporation, however, was low-ranging from 1.4 to 3.0 mm day^{-1}. In tests of the method under low potential evapotranspiration conditions error in locally observed meteorological measurements applied to the site may tend to bias results more seriously than would be true during period of greater evaporative demand.

The ratio of measured evaporation to potential evaporation computed by Penman's method for the same days gave results comparable to those with Van Bavel's method.

Halkias, *et al*, (1955) tested the Thornthwaite, Penman and

Blaney-Criddle methods against atmometer evaporation and gravimetric soil moisture measurement techniques and suggested that only soil moisture samples give reliable data or extraction. Burman and Partridge (1962) summarised results of evapotranspiration measurements over small grain, corn and beans in north western Wyoming. Comparisons were made between the Thornthwaite and Blaney-Criddle methods but no interpretation of the results was given.

Calembert (1954) compared the Thornthwaite and Penman methods at seven stations in Belgium and Luxembourg over a 5 year period. Penman's method was a better estimator of March-May evaporation. while Thornthwaite's method was better for September-November. No results were given for the summer months. Van Bavel and Wilson (1952) tested the Thorntwaite, Penman and Blaney-Criddle methods against evaporation pans and found fair agreement.

2.6.13 Book Keeping Methods

Van Bavel (1956) developed nomograms using incident radiation and temperature which he considered to be the two most important parameters in the Penman method, to calculate potential evapotranspiration in the eastern United States.

His procedure requires data on solar and sky radiation, percentage possible sunshine and air temperature. A daily balance sheet is kept on which date, weather condition, rainfall or irrigation amounts and evapotranspiration are recorded. The method is found to be of sufficient accuracy for production planning, but it is applicable only to large uniform areas where the surface is covered with vegetation and soil moisture does not

become limiting.

Due to its simplicity, book keeping techniques have considerable appeal for agriculturalists. According to Van Bavel "The method is most applicable in the eastern United States because:

(a) soil moisture holding capacities are, generally, limited:
(b) frequent rains occur during the growing season; and
(c) each year during the winter months the root zone is fully replenished with moisture".

The principal limitation to the Van Bavel method (1956) and to most other book keeping methods is that no allowance is made for either type or density of ground cover.

Holmes and Robertson (1959) developed a modulated soil moisture budget which considers soil moisture stress, plant rooting characteristics, stage of growth and soil physical factors while making use of the usual meteorological parameters.

Baier and Robertson (1965) proposed a versatile soil moisture budget in which soil moisture was estimated from standard meteorological data. Simultaneous moisture withdrawal from different depths of soil was considered in this method. Adjustments were made for runoff, drainage and different drying characteristics of the various soil types. The effect of atmospheric demand rate on the ratio of actual to potential evapotranspiration is also considered.

Numerous assumptions are made which in turn enhance the possibility of error. These include: (a) moisture near the surface is evapotranspired at the potential rate; (b) potential evapotranspiration is modulated so that sub-surface moisture is

with drawn at a decreasing rate; (c) available moisture is withdrawn from the surface layers of the soil before extraction occurs from lower layer; (d) rainfall occurring after a dry spell is evapotranspirated at the potential evapotranspiration rate until it has been depleted, unless rainfall percolates into a transitional zone, then potential evapotranspiration is modulated and withdrawal is at a slower rate; (e) percolation is regarded as complete if the soil is saturated, rainfall is regarded as runoff and (f) soil moisture amounts between saturation and field capacity are assumed to percolate. The method involves a fairly simple book-keeping technique if representative soil moisture depletion curves are established and accurate estimates of the atmosphere's drying ability is available.

More discussions of book keeping approaches to the evapotranspiration problem and irrigation scheduling can be found in Allred and Chen (1965), Staple and Lehane (1944), McQuigg (1954), and Pruitt 1964).

A report issued by Jensen et.al.(1973) indicated that seasonal rainfall was adequate nearly every year for agronomic crops to attain maximum yields in interior Alaska. Their findings were based on 10 years of seasonal precipitation and potential evapotranspiration data, but did not account for the soil as a potential source of water.

Sharratt (1993) studied crop water use taken into account morphological traits of the crop (example, green leaf area, root distribution) weather (example, vapor pressure, wind) and soil properties-water storage capacity, depth.

In recent years, evidence has shown that the inadequacy and

inaccuracy of potential evapotranspiration estimation is due solely to the under estimation and or over estimation of the above parameters (climatic factors) that influence potential evapotranspiration.

Only few studies have been carried out in the sub-humid environment of Nigeria. Water - use studies employing a hydraulic weighing lysimeter (Kowal and Stockinger, 1973) have, however, been conducted by the Institute for Agricultural Research at Samaru - Zaria in canopies of groundnut (Kassam *et al*, 1975) millet (Kassam and Kowal, 1976), Sorghum (Kowal and Andrews, 1973), maize (Kowal and Kassam, 1973) and cowpea (Owonubi, 1981). Duru and Yusuf (1980) examined effects of temperature, radiation and humidity on potential evapotranpsiration in Zaria, under Northern Guinea Savanna conditions.

Duru (1984) further modified his earlier work by designing a chart for easy determination of potential evapotranspiration. He took into consideration the effects of temperature in the range of 15°C to 45°C, humidity from 10% - 100% (mm Hg) and radiation on potential evapotranspiration.

Duru and Yusuf (1980) equation is given below:

$$PET = rf\ (0.45T + 8)(520 - R^{1.31})/100$$

where rf = radiation ratio, T = Temp. (°C),

R = Relative humidity (%)

Balogun (1974) examined the relative importance and the influence of some climatological factors on the amount of evaporation and evapotranspiration at Ibadan. The climatic parameters include windspeed, soil temperature, mean air temperature, solar radiation, relative humidity and sunshine

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hours. Of all the climatic parameters, only windspeed was very weakly correlated with evaporation and evapotranspiration, possibly because either the evaporating surface area was small or the wind which blew over the surfaces were weak.

Ramalan and Owonubi (1995) estimated potential evapotranspiration and compared it with lysimeter measurements from earlier studies to obtain seasonal crop coefficients, KC, for maize, sorghum, millet, cowpea, groundnut and cotton. A graphical presentation of KC on a phenology axis was provided for ease of computation of evapotranspiration irrespective of planting date. The results showed that the daily estimates of Pet ranged between 1.4 mm day^{-1} for a cloudy day (sunshine hour = 0) and 10 mm day^{-1} on cloudless day (sunshine hours > 26.4°C) for the six seasons (1970 - 75). Maize, sorghum, millet, cowpea, groundnut and cotton have KC values at effective cover of 0.80, 0.74, 0.86, 1.07, 0.81 and 0.92 respectively.

Daamen, *et al*, (1992) studied the impact of sparse millet crops on evaporation from soil in semi-arid Niger. In the study evaporaion from soil was measured using microlysimeters under two different cropping intensities during the 1991 and 1993 seasons. Two models for estimating ES were compared with field data and some components of an improved model were developed. The new modelling approach offers an explanation of the apparent contradiction in the results of previous studies regarding the effectiveness of management practices in modifying crop water use efficiency.

An Agriculturist or hydrologist interested in the potential evapotranspiration for an area generally must estimate values from

climatological data by an empirically, derived method. Many methods are available but a researcher must determine the one most suitable for his investigation.

2.7.0 Instrumentation for Measurement of Evaporation

2.7.1 Lysimeters

The lysimeter is an instrument for the measurement of water, content change in soil. A lysimeter consists of an isolated block of soil, as nearly identical as possible in its physical and chemical properties with the surrounding soil, which can be weighed to determine the amount of water added to it by precipitation or irrigation and removed by ET. There are a number of types of lysimeters. These are all somewhat expensive devices but, since lysimeters provide the only absolute measure of mass transfer from a nearly natural part of the earth's surface, their use is very important in micrometeorology.

In a review, Pelton (1961) discussed lysimetric practice and the design of weighing and floating lysimeters and potential evapotranspirometers. He also discussed the requirements for the proper use of lysimeters in evapotrnaspiration research and considered the following factors to be of major importance in the proper design and installation of lysimeters.

i) Uniformity of soil mass to surroundings

ii) Forced drainage or very deep construction

iii) A large area/rim ratio

iv) Similarity to the surface surroundings.

Van Bavel (1961) discussed the importance of forced drainage in lysimeters in simulating the natural distribution of water with

depth that occurs in adjoining soils. The provision of facilities for forced drainage is essential for maintaining normal water distribution with depth except where the lysimeter is to function as a potential evapotranspirometer. Forced drainage is achieved in lysimeters by application of negative-pressure (suction) to soil in the lower portions of the lysimeters.

2.7.2Potential Evapotranspiromters

Thornthwaite (Wilm, 1946) was responsible for the development of the first potential evapotranspirometer, a device in which the water table is held constant in a mass of soil and ET proceeds at the potential rate. This device was particularly useful for calibrating empirical expressions used in estimating potential evapotranspiration.

Gilbert and Van Bavel (1954) reported a simple installation for measuring potential ET. A soil column is suspended over a gravel layer separated from water in the bottom of the lysimeter by an air space. By continued observation of the quantity of percolated water and the amounts added to the soil, a measure of the ET may be derived. Values of potential evapotranspiration over a 4 to 5 day period were obtainable.

A more recent use of potential evapotranspirometers is reported by Willhite et.al.(1965). Their lysimeter permits precise regulation of the water table to evaluate water table interaction with soil depth and the effect of nitrogen, fertilization on the production and persistence of a timothy stand under mountainous conditions.

EL Nadi and Hudison (1965) in the Sudan, reported the design

of drainage lysimeter in which through frequent applications of water and measurement of drainage effluent, virtual potential evapotranspiration conditions are maintained.

2.7.3 Weighing Lysimeters

Colman and Hamilton (1947) described the complex of hydrology research devices used in the San Dimas experimental forest of California. These include four types of lysimeters, one of which is intended for measurement of evapotranspiration. Cylindrical galvanized iron tubs holding either 720 or 145 kg of soil rest on pedestals in concrete lined trenches and are weighed by a crane. The results obtained with lysimeters of this type have apparently not been very satisfactory.

The coshocton lysimeters of which have been written by Harrold and Dreibelbis (1958) constitute an installation of major importance in hydrology research. They are large concrete walled lysimeters in which a monolithic volume of soil is encased. The entire structure of about 60 metric tons is weighable on mechanical scales, installed below ground, to an accuracy of about 2.3 kg or 0.25 mm water equivalent. Drainage water can be collected easily from the monolithic blocks of soil. Additional suction to improve drainage is not needed. In a relatively humid region, monthly mean evapotranspiration values up to about 6.5 mm day^{-1} have been reported from these lysimeters.

Pruitt and Angus (1960) give details of the large weighing lysimeter at Davis, California. the lysimeter has a soil pan of 6-m diameter and about 1-m depth. Drainage is forced by means of suction devices dispensed throughout the lower layers of the soil. Weight changes are measured on a large truck scale. Weight changes of about 90 kg has water loss of approximately 0-03 mm.

Morris (1959) reported an instrument for detecting the changes in weight in wet soil masses caused by evaporation and transpiration. His device was a large square box mounted on a sensitive balance. Border effects were minimised by growing plants around the system. Weight changes equivalent to 0.75 mm of water were detectable with this device.

Van Bavel and Myers (1962) described the workings of precision automatic weighing lysimeters used at the soil and water

conservation Laboratory, Phoenix, Arizona. These consist of containers 1 x 1 x 1 m that weigh about 3 tons with soil of field capacity. Weight changes due to evaporation or condensation are detected by a strain gauge load cell to an accuracy or 0.01 mm of water. Observations may be made hourly or even more frequently with this type of lysimeter. Rosenberg and Browen (1970) report an improved version of this lysimeter.

Ritchie and Burnett (1968) have designed a precise weighing lysimeter that is popular, primarily because the load cell is more easily accessible in the event repairs are needed than is true in other available lysimeter. Mcllory and Angus (1963) described a multiple installation of weighing lysimeters. These consist of an inner soil-filled concrete cylinder placed within a large outer cylinder. Units are derrick weighed periodically. Particular care has been taken in this installation to ensure uniformity of surface cover and of water application by sprinkling.

Garnier (1957) designed a simple evapotranspirometer which works on the principles of a lysimeter. It consists of an evapotranspirometer tank made of an oil drum cut to about two-thirds of its original depth. The inside is painted for water-proofing. The tank has a layer of gravel and stones at the bottom, about four to six inches deep. The rest of the tank is filled with draining soil, of about the texture of a sandy loam and grass is grown in the tank. There is also an overflow chamber in which is collecting can. The tank and overflow chamber are

connected by 3/4 in pipe. The outlet from the bottom of tank must be covered by a copper mesh, to avoid blockages.

2.7.4Floating Lysimeters

Floating lysimeters are usually simpler and less expensive than weighing lysimeters. King, Tanner and Suomi (1956) developed one of the First floating lysimeters. This is a type of lysimeter that floats on water. Large air spaces were required to maintain the soil-filled bin in a buoyant condition. Suomi and Tanner (1958) used lysimeter of this type of test the energy balance - Bowen ratio method of evapotranspiration estimation.

Mcmillan and Paul (1961) described a simpler lysimeter of the floating type. It consisted of large soil container, which floats in a solution of zinc chloride (sp.gravity about 1.90). The use of a heavy liquid eliminates the air spaces such as were needed in the King *et al*, (1956) lysimeter. Changes of weight were observed manometrically. Temperature influences on the manometer liquids introduce errors in reading and procedures to compensate for this error are given.

Konstantinov (1963) described a large floating lysimeter at the Valdai Hydrological Research Laboratory in the U.S.S.R. A soil monolith of 5 m^2 cross sectional area and 2 m depth is encased in a steel container from which radiates a number of massive floats. These rest in a water-filled annular basin. Weight changes in the monolith are equal to the vertical

displacement of the floats, which can be measured automatically - The lysimeter makes provision for the measurement of runoff water but not apparently for drainage. Displacement of the system can be measured with an accuracy of 0.01 mm.

Glover and Forsgate (1962) constructed a lysimeter that bears on water-filled bags. Pressure on the bags changes as a function of the total lysimeter weight. They consider that in the climate of Kenga errors due to changing temperature of the water in the bags are not consequential. They do, however, use an above ground thermostat manometer to observe pressure changes in the hydraulic portion of the system.

Hanks and Shawcroft (1965) have described a similar device. In this case the inner (or soil containing) tank exerts pressure on two rubber bags filled with an antifreeze solution. Pressure changes are read on a manometer above ground. Temperature effects on the manometric liquid may introduce errors of as much as 100% in evapotranspiration estimation. Corrections for temperature effects are made by reference to a dummy tube filled with the same liquid and exposed in the same way. The lysimeter is suitable only for measuring daily values of evapotranspiration.

Kowal and Stockinger (1973) designed and constructed a hydraulic weighing lysimeter (366 x 366 cm x 122 cm deep) that had been used successfully at Samaru since 1968. The lysimeter is the filled in hydraulic type, operating on the principle that changes in the total weight of the tank containing the soil are

transmitted by means of flexible, water filled bolsters on which the tank rests to a manometer and are read off as changes in the manometer level.

Abdulmimin (1987) designed and constructed another hydraulic weighing lysimeter 122 cm x 122 cm in area and 122 cm deep at Kadawa in the Kano River Project; Nigeria. The weighing system consists of water filled bolster, on which the tank rests, connected to pressure measuring system, which may consist of fluid manometer; or pressure transducers. This is an improvement over the design of a similar lysimeter at Samaru (Kowal *et al*, 1973) that requires several weeks to service. This can be serviced within two days - The test results showed that the lysimeter is performing with acceptable accuracy.

2.7.5 Microlysimeters

The microlysimeter is undisturbed soil core typically (1-3 kg) taken in the field and sealed at the base. The core (10 cm deep) is then mounted in a liner tube set into the soil so that the top of the core is level with the soil surface. It is weighed daily (or more frequently) to determine water loss. The weight loss of the microlysimeter cores is used to determine soil evaporation. These isolated volumes of soil can be extracted from and the mounted in the soil beneath a crop canopy allowing soil evaporation fluxes from transpiration fluxes.

The diameters of the microlysimeters vary from 5 cm to 22 cm

and depth of 10 cm to 20 cm. According to Boast (1986), the microlysimeter method is arguably the most simple, direct and independent measurement of soil evapotranspiration.

2.7.5.1 Microlysimeter Construction

The microlysimeter cores and liners are always both constructed from unplastic polyvinyl chloride (PVC) pipe. Unplasticised PVC has a heat capacity of 0.95 Jg^{-1} K^{-1} at 25°C (Koleske and Wartman, 1969) and a Thermal conductivity of 0.16 - 0.17 $wm^{-1}K^{-1}$ between 20°C and 90°C (Sheldon and Lane, 1965).

Daamen et al, (1992) recorded evaporation from microlysimeters of diameters 214mm, 152mm and51mm which was not significantly different. A comparison of 100mm and 200 mm deep microlysimeters showed that depth had no significant influence during the first two days after extraction from the soil profiles and for periods beginning more than two days after rain; significant differences may not occur for up to seven days. Microlysimeters extracted at different times showed significant differences in evaporation immediately following a rain event and no significant differences thereafter.

2.7.6 Comparison of the Different Types of Lysimeters

Of the modern types of lysimeters in use and in development today, precision weighing units appear most able to meet the requirements of micrometeorological research in

evapotranspiration. Evapotranspiration can be determined with accuracies in order of hundredths of a millimeter over periods shorter than one hour with such units as those of Pruitt and Augus (1960). Van Bavel and Myers (1962) and Ritche and Burnett (1968).

Less expensive are the floating types that is those that actually float in water or some other liquid or that rest on resilient cushions. The temperature sensitivity of the liquid or gas on which the soil mass rests limits the convenience and accuracy of such systems. With proper correlations for temperature sensitivity, however, the floating units can be made accurate enough for determining daily values of evapotranspitation.

2.7.7 Atmometer

Atmometer are porous ceramic or porous paper evaporating surfaces connected to some type of water reservoir. The evaporating surfaces are usually coloured black or white. Since black absorbs and white reflects incident radiation, the difference in water evaporated between black and white units can be used as an indication of the intensity of radiation. However, atmometers are generally more sensitive to changes in windiness than to changes in radiation. For this reason the choice of the elevation for their placement and the standardization of the elevation are very important.

Atmometers, like evaporation pans, are passive devices that

lose water in some way related to their absorption of radiant energy and to the windiness and dryness of the ambient air. Pans and atmometer cannot effectively indicate evapotranspiration for crops that exert some degree of resistance to the passage of water vapor into the air; Nor should they be expected to do more than indicate the evaporating potential of the atmosphere.

Jane (1960) used an atmometer in the relatively moderate climate of connecticut to indicate potential evapotranspiration. The difference in the amount of water evaporated by black and white atmometer was considered an indication of the net radiation. Net radiation in a non advective climate should approximate the maximum energy available for evapotranspiration.

2.7.8 Pan Evaporometers

Pans of various sizes, shapes and depths of placement have been used throughout the world to measure free water evaporation. These measurements are interpreted to estimate evapotranspiration rates. In regions where advection of sensible heat is unimportant free water evaporation from pans may indeed give realistic estimates of the potential evapotranspiration. Usually, the crop water use can be taken as some 60 - 90% of pan evaporation in such climates.

In more arid localities and where advection is considerable, the pan may give unrealistically low values. This is probably due to the very small roughness of the water surface compared to that

of growing crops. The inadequancy of evaporation pans in regions of sensible heat advection was discussed earlier. Pans have some positive virtues. They are inexpensive and easily maintained. The measurement of the quantity of water evaporated is easily accomplished with calibrated gauges of various kinds.

2.7.9 Transport of Water Vapor from Evaporating Surfaces to Air

The laminar sublayer of air surrounding a leaf in an air stream or over a surface of wet soil or free water partly control the rate of evaporation of water into air. Through this still air layer, vapor passes by diffusion into the zone of transition and turbulence.

Heat passes through this zone largely by molecular conduction, but vapor moves through diffusion. In both cases the process rate is determined by the thickness of the sub layer and by the gradient of temperature or vapor pressure. In the case of free water bodies or moist soils, it may be assumed that the vapor pressure at the evaporating surface is essentially the same as the saturation vapor pressure at the temperature of the surface. The assumption at the leaf surface is often made, since the vapor in the sub stomatal cavities of plant leaves is at or near saturation.

In order for heat to move through the laminar sublayer, the air resistance must be overcome. Vapor transport requires forces

great enough to overcome air resistance. In the case of plant transpiration, vapor must also pass through an additional resistance imposed by the stomates of plant leaves. In some species a significant amount of vapor is transpired through the cuticle of the leaves as well.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of Study Site

Direct measurements of potential evapotranspiration were made using microlysimeters during the wet season at the Institute for Agricultural Research's experimental farm at Samaru (11°11'N, 07°38'E, 686m above sea level); Nigeria, in 1996 and 1997.

Samaru lies in the Northern Guinea Savanna ecological zone of Nigeria with a mean annual rainfall of 980mm, occurring almost entirely in the period of May to October.

Climatological data show that the total annual potential evapotranspiration of 1455 mm is in excess of the total annual rainfall of 1268mm. A monthly record of temperature taken over 5 years shows a range of 23.2 to 28.0°C with an annual mean of 25.0°C (Kowal and Knabe, 1972).

Samaru soils are fairly representative of the loess plain soil unit of Northern Nigeria covering some 45,000 square kilometers of the most agriculturally important lands of the region. The surfaces of these soils are largely covered by a deposit of loess containing a high proportion of fine sand and have a texture varying from loamy sand to sandy loam (Lawes, 1962). The soils are classified as oxic to ultic Haplustalfs according to the USDA soil Taxonomy (Awujoola, 1979).

3.2 The Empirical Equations (Models)

The best known and more widely used evapotranspiration models were evaluated in this study. They are Penman (1948), Blaney Morin Nigeria (1984), Hamon (1961), Jensen Haise (1963) and Makkink (1982) each of the five methods for estimating PET from climatological data is briefly described below.

3.2.1 Blaney Morin Nigeria ET Model (BMN)

The BMN Model (1980) has the form:

$$PET = rf\ (0.45T + 8)(520-R^{1.31})\ /100 \quad \text{----------} \quad (1)$$

where, PET = pot. evapotranspiration (mm/day)

rf = ratio of maximum possible incident radiation outside the atmosphere to the annual maximum, T = temperature (°C); R = relative humidity- in percent.

3.2.2 Hamon Method

The Hamon (1961) method is represented by the equation:

$$ET = CD_2Pt \quad \text{----------} \quad (2)$$

where,

E_T = average potential evapotranspiration, (mm/day);

D = possible hours of sunlight; in units of 30 days of 12 hours each;

Pt = saturated water-vapor density (absolute humidity at saturation) at the daily mean temperature; in centigrams per

cubic meter;

C = coefficient chosen to give appropriate yearly values of potential evapotranspiration.

3.2.3 Jensen Haise

The equation is given by linear relationship

$$PET = 10.C_T\ (T - Tx)\ Rs/L \quad \text{----------} \quad (3)$$

where;

PET = potential evapotranspiration (mm/day)

C_T = an air temperature coefficient

T = temperature in degree celsius

Tx = the intercept on a temperature axis when PET and T are plotted;

Rs = incident solar radiation in $calcm^{-2}\ day^{-1}$

L = latent heat of water in $calgm^{-1}$.

The temperature coefficient, C_T is given as;

$$C_T = \frac{I}{C_1 + C_2\ CH} \quad \text{----------} \quad (i)$$

where;

$C_1 = 38 - (^{\circ}C \times EL\ 305)$ ---------- (ii)

$CH = 50\ mbar\ /(e_2 - e_1)$ ---------- (iii)

$C_2 = 7.6\ ^{\circ}C.$

The intercept, Tx is estimated thus:

$Tx = 2.5 - 0.14\ (e_2 - e_1)\ ^{\circ}C/mbar - EL/550$ -------- (iv)

where; e_2 and e_1 = saturation vapor pressure of water at the mean

maximum and mean minimum temperatures, respectively for the warmest month of the year in a location.

EL = elevation of the location above sea level in meter. The latent of water, L, which varies directly with ambient temperature is estimated by

$$L = 595.9 - 0.55\ T \quad \text{---------- (v)}$$

where; T is the mean daily temperature (°C)
Incident solar radiation, Rs is estimated by

$$Rs = R_A\ (0.18 + 0.55n/N) \quad \text{---------- (vi)}$$

RA = incident radiation at upper atmosphere in $calcm^{-2}\ day^{-1}$.

n = observed number of hours of bright sunshine

$$N = 7.7 + 0.367\ (x - 10.3) \quad \text{---------- (vii)}$$

X = latitude in degrees north or south of equator.

3.2.4 Penman method : In its simplified form, the Penman equation may be written in the form:

$$PET = \frac{\Delta Ra/\lambda + YEa}{\Delta + Y}$$

or

$$E_T = \frac{\frac{Po}{P}.\frac{\Delta}{Y}[0.75RA(0.18 + \frac{0.55^n}{N}) - \sigma TK^4(0.56 - 0.079\sqrt{ed}\,]}{\frac{Po}{P}.\frac{\Delta}{Y} + 1.00}$$

or

$$\frac{(0.10 + 0.90^{n}/N) + 0.26(ea - ed)(1.00 + 0.54\mu)}{\frac{Po}{P}\,\Lambda\,Y} \quad \ldots\ldots\ldots\ldots (4)$$

and provides an estimate of evaporative loss from an open water surface (mm/day).

Po = mean atmospheric pressure (mbar) at sea level.

P = mean atmospheric pressure (mbar) as a function of altitude

A = rate of change with temperature of the saturation vapor pressure mbar °C

Y = the psychrometric coefficient = 0.66

0.75 = factors expressing the reflection of short wave radiation by the evaporating surfaces

R_A = short wave radiation in mm of evaporable water

n = sunshine duration (in hours)

N = sunshine duration astronomically possible for the given period.

σTk^4 = Blackbody radiation in mm of evaporable water for prevailing air temperature;

ea = saturation (air) vapor pressure (mbars)

ed = vapor pressure at dew point temperature (Td), Td = Tm

T°C = air temperature measured meteorological shelter (°C).

$T_k°$ = Average air temperature, °k (T°C + 273)

u_2 = windspeed at a height of 2 meters (m/sec).

_ = latent heat of vaporisation of water cal/cm^2/mm.

3.2.5 Makkink Method

Modified Makkink (1982) equation:

$$PET = 0.7 \frac{\Delta}{\Delta + Y} \frac{RS}{58.5} \quad \ldots\ldots\ldots (5)$$

where, Δ is the slope of the curve of the saturation vapor pressure versus the temperature, Y is the psychrometric constant, Rs is the global radiation and 58.5 is the latent heat of vaporisation of water.

The monthly mean pan evaporation is used through out the analysis. Potential evapotranspiration measurements, obtained from microlysimeter are also included in the statistical comparison.

3.3 CLIMATIC DATA SOURCES

All climatological data used in the computation of the five equations were obtained from meteorological unit of the Soil Science Department of the Institute for Agricultural Research (I.A.R.); A.B.U., Zaria, for the period of 1965 - 1994 (30 years). Type of data available in this unit include rainfall, solar radiation, Pan evaporation, air temperature (maximum and minimum), relative humidity (maximum and minimum) windspeed, vapor pressure, sunshine hours and soil temperature. Data collection were done by trained meteorological staff and weather instruments installation conform to WMO standard.

3.3.1 Analysis of the Climatic Factors

Simple correlation coefficients between PET (y) and pan evaporation (Y) and the climatic factors (x) and within the climatic factors themselves were worked out using the following formula given by Steel and Torrie (1948).

$$rxy = \frac{SPxy}{\sqrt{SSx.SSy}}$$

r = coefficient of correlation of x and y.

Sp = sum of product of x and y; $\Sigma(x - \bar{x})\ (y - \bar{y})$

SSx = sum squares of x, $\Sigma(x - \bar{x})^2$

SSy = sum of squares of y, $\Sigma(y - \bar{y})^2$.

The climatic factors influencing potential evapotranspiration and pan evaporation indicated in the literature are air temperature, windspeed, relative humidity, sunshine hours, soil temperature and solar radiation. Correlation of these parameters with the PET and pan evaporation and within the above parameters themselves were calculated using the same formula. These correlations were further used to develop simultaneous equations to work out path coefficients as described by Wright (1960) and given as follows:

$r_{17} = P_1 + r_{12} P_2 + r_{13}P_3 + r_{14}P_4 + r_{15}P_5 + r_{16}P_6$ ---------- (1)

$R_{27} = R_{12}p_1 + P_2 + r_{23}P_3 + r_{24}P_4 + r_{25}P_5 + r_{26}P_6$ ---------- (2)

$r_{37} = r_{13}P_1 + r_{23}P_2 + P_3 + r_{34}P_4 + r_{35}P_5 + r_{36}P_6$ ---------- (3)

$r_{47} = r_{14}P_1 + r_{24}P_2 + r_{34}P_3 + P_4 + r_{45}P_5 + r_{46}P_6$ ---------- (4)

$r_{57} = r_{15}P_1 + r_{25}P_2 + r_{35}P_3 + r_{45}P_4 + P_5 + r_{56}P_6$ ---------- (5)

$r_{67} = r_{16}P_1 + r_{26}P_2 + r_{36}P_3 + r_{46}P_4 + r_{56}P_5 + P_6$ ---------- (6)

The unknown (P_i), P_1, P_2, P_3, P_4, P_5 and P_6 values were worked out using the above equations. They represent the path coefficient and measure the direct contributions of an individual factor on PET and pan evaporation. r_{12} -------r_{56} are the coefficients of correlation which measure a mutual association between the two factors. The combined contributions of the two factors is estimated with the formula:

Cij = 2PiPjrij where C - combined effect of i and j

rij = coefficient of correlation between i and j.i and j depict direct and indirect contributions respectively.

The residual factor Rx which is unaccounted for by the direct and combined contributions is estimated by the following formula:

Rx = 1-(P1r17+P2r27 +P3r37 +P4r37 _ P5r57 + P6r67) or 100 - total contributions of the climatic factors, rij = total contribution of factors i and j represented by the coefficient of correlation in the above simultaneous equations. The three components of direct effect, combined contribution and residual effect should add to unity. Dewey and Lu (1959) suggested Fig. 4 (a - d) diagrams to estimate the direct (P_i) and indirect contributions (rijPj).

3.4.0 Measurement of PET

3.4.1. Design and Construction of Microlysimeter

3.4.1.1 Design Considerations

In designing a lysimeter, several factors are usually considered. These are cost, strength of material, accuracy, ease

of operation and maintenance. The accuracy level attained by a lysimeter depends very much on how closely it simulates the natural crop environment. Unplasticised polyvinyl chloride (PVC) pipe or metal sheets are normally used for the construction of a microlysimeter. For the present investigation, unplasticised polyvinyl chloride pipe would be used as to prevent heat effect of the surrounding soil. Generally, there are various sources of design error, which include microlysimeter size, the field site, crop arrangement and soil disturbance (Pruitt and Angus, 1960). Critical measures are to be (according to Daamen *et al*, (1992) taken to reduce as much as possible the sources of errors. These will include:-

1) extraction of microlysimeters from the soil profile immediately after rain and replacement of these microlysimeters within 12 hours.

2) daily replacement until root extraction of water from the soil ceases.

3.4.1.2 Microlysimeter Description and Dimensions

3.4.1.3 Microlysimeters: Microlysimeter consists of diameter of 105 mm and 170 mm depth which provides a representative canopy cover, minimise wall effects, as well as provides good root growth. The area of the microlysimeter is 86.59 cm^2 (8659 mm^2). Microlysimeters are used as the sampling tubes (cores).

3.4.1.4 Liners: This is the pipelining holes (dia of 152 mm

and height 330 mm) in which the microlysimeters are mounted. The microlysimeters and liners are made up of PVC.

3.4.1.5 Drainage Basin

This is made of plastic container of size 162 mm height and 100 mm in diameter with base cover which is perforated with a small hole. Cloth is used to tie the base of the microlysimeter which fits tightly into a positioned liner tube. The drainage basin sits directly on the soil at the bottom of the liner (Plate 1) .

Plate 1. Liner, microlysimeters and drainage container.



3.4.1.6 Weighing Balance

A portable weighing balance that weighs up to 2kg was used in determining the weight loss which is equivalent to the water loss through evapotranspiration. The weighing balance was kept in a shelter in the meteorological station to protect it against wind during the measurement.

3.4.1.7 Detailed Calculation

The weight (mass) of the microlysimeter filled with soil, = $\pi d^2 hp$

where; d = diameter of the microlysimeter = 10.5 cm

h = depth of the " = 17.0 cm

P = bulk density of the soil = 1.4g/cm^3

$$\text{Mass} = \frac{\pi(10.5)^2}{4} \times 17 \times 1.4 \text{ cm}^2 \times \text{cm} \times \text{g} \times \text{cm}^{-3}$$

$$= 2060.85\text{g} = 2.06 \text{ kg}$$

$$\approx 2.0 \text{ kg}$$

The microlysimeter holds about 2 kg of soil.

3.4.2 Microlysimeters construction

The microlysimeters (twenty-five in number) were constructed to the various diameters and depths. Twelve of them were constructed to the dimensions of 105 mm diameter and 170 mm depth. The other thirteen microlysimeters were constructed to the

dimensions of 100 mm and 50 mm diameters and 100 mm depth. The area is 19.63 cm^2.

3.4.3Installation and Routine Measurement with Microlysimeters

Field measurements were concentrated in a selected sample area located close to the meteorological field. The sample area covers a total area of 0.75 ha. In the study, two representative plots (Fig.4), each of size 6 m x 6 m were selected. Six holes (dia = 250 mm and ht = 330 were dug in each of the plot for the installation of liners as shown in experimental layout (Fig 5). Field data were taken during 1996 and 1997 rainy season. These trials lasted from:

i) 20th August to October 31st 1996 and

ii) 7th July to 31st October 1997.

Each microlysimeter (105 mm and 170 mm) was installed inside a liner tube in the bare soil. The liner tubes were left slightly higher than the soil surface to minimise runoff entering the liners and soil was banked up to the outside edge with its surface flush with or slightly above the soil surface (Plate 2). The liners were used for a whole season and the area surrounding them was left undisturbed following insertion.

3.4.4 Measurement in the Open and under Canopy

The twelve microlysimeters were back-filled with soil and 1 - 3 grasses manually by alternately inserting the pipe length 5 - 10 cm and then excavating a slightly over sized pillar of soil to a depth 2 - 3 cm below the base of the core. This procedure was adopted to minimise disturbance of the soil within the core and

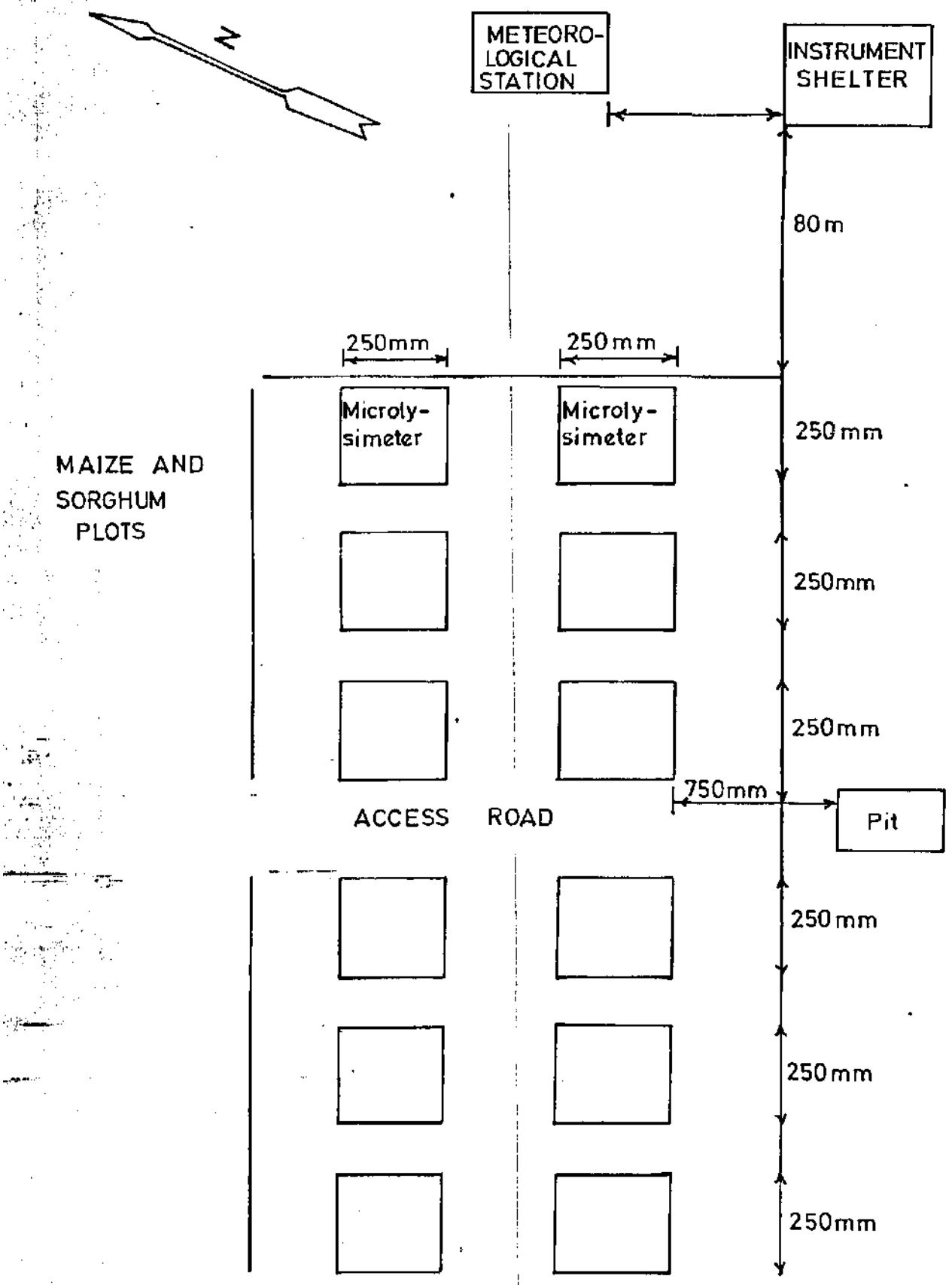


FIG. 4 : Experimental layout

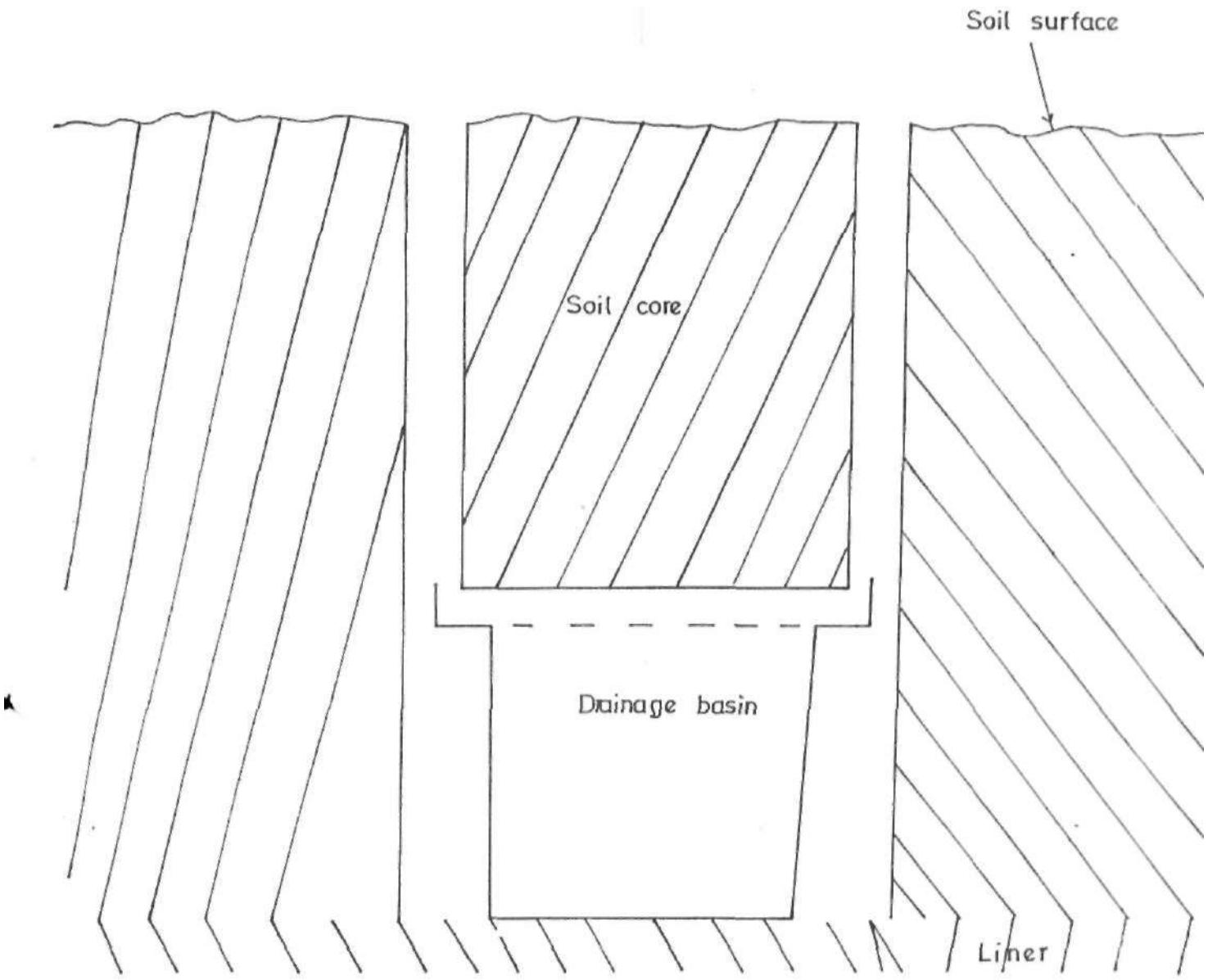


FIG. 5: 3 Schematic diagram of the position of microlysimeter in the soil



Plate 2: Microlysimeter installed into the liner.



Plate3: Microlysimeter under sorghum canopies.



Plate4: Microlysimeter under maize canopies.

little or no compaction was noted. After the cores were trimmed flush at the base, the bases were tied with cloth using rubber bands. The microlysimeters were then placed on the drainage basins.

Drainage systems at the bottom of each microlysimeter allowed the removal of excess water, if necessary. The weight of each microlysimeter, corresponding to a gain or loss of water, was recorded every day at 10 am with 2 kg electrical weighing balance. They are sensitive to weight change equivalent to 0.12 mm depth of water. The soil has a uniform texture.

3.4.5 Evaporation Under Crop Canopy

In both years (1996 and 1997) evaporation from the microlysimeter was measured in a sorghum/maize intercrop system. Maize was planted on 15th June 1996 and 20th June 1997 at 25 cm apart within rows for the sole crop and at 2 m apart for the intercrops. Sorghum was planted on 22nd June 1996 and 16th June 1997 on alternate maize ridges. The plot size for the intercrops and the sole plots were 6 m x 6 m. The crops were harvested on 10th October 1996 and 11th October 1997 for maize, 20th November 1996 and 22nd November 1997 for sorghum.

A leaf area meter (Li - COR, lincoln, NE) was used to determine the leaf area. Leaf area index in the field was calculated by dividing the leaf area with land area.

Two soil cores were extracted from the soil profile and

mounted within each plot between maize and sorghum, sorghum only and maize (Plate 3-4) only giving a total of 12 microlysimeters for each day of measurements. The pairs of soil cores were randomly located in the plot. Soil cores were also extracted from within the experimental plots containing the crops.

3.4.6 Prediction of Evaporation from Soil

Penman (1963) Monteith (1965) and Ritchie (1972) equations were used to estimate soil evaporation below the growing sorghum and maize Crops.

Potential evaporation (Eo) is calculated using Penman equation (1963).

$$Eo = \left[\frac{\Delta}{Y} Rno + 0.262\ (1 + 0.0061u)(e_o - e_a)\right]\left(\frac{\Delta}{Y} + 1\right)^{-1} \quad \ldots\ldots (6)$$

where;

Δ = slope of the saturation vapor pressure curve at mean air temperature;

$\Delta(I) = 33.8639\ [0.05904\ (0.00738T + 0.8072)^{7} - 0.000342]$

Y = constant of the wet and dry bulb psychrometer equation;

= 0.66 mb/°C

U = windspeed at a height of 2m;

eo = saturation vapor pressure at mean air temperature; (millibar)

ea = mean vapor pressure of the atmosphere calculated from Tw and Td as measured during a day, millibar

Tw = wet bulb temperature, °C

Td = dry bulb temperature, °C

Eo = potential evaporation rate above the plant canopy, mm/day

Rno = daily net radiation above the canopy.

The main components of evaporation are:

i evaporation directly from the soil surface (Es)

ii evaporation of water intercepted by the canopy (Ei) = E-Ep-Es

iii transpiration through plants, per unit field are Ep

iv total actual evaporation from all sources (E)

Potential evaporation beneath crop canopy at the soil surface, Eso is calculated using leaf area index as below:

$$Eso = \left(\frac{\Delta}{\Delta + Y}\right) Rno \exp^{-kl} \quad \text{---------- (7)}$$

where;

K = crop coefficient, K for maize and sorghum = 0.58 and 0.54 respectively, L = leaf area index.

Evaporation from soil surface Es was calculated as Es = 0.19 Eso. 0.19 - fraction of the incoming solar radiation reaching the soil through the crop (albedo) for Samaru;

Evaporation from plant leaves, transpiration was determined by

$Ep = Eo\ (-\ 0.21 + 0.7L^{\frac{1}{2}})\ 0.1 < L > 2.7$ ---------- (8)

Ep = 0 when LAI < 0.1, Ep becomes almost dependent on Eo until the soil water available to plant roots becomes limited, when LAI > 2.7.

Total evaporation from all sources (E) = Es + Ep. E can be at least 0.5 Eo. The results are presented on Appendix D.

3.4.7 Prediction of Water use Efficiency and Grain Yield

Water used by the crops throughout the growing period termed water use efficiency of the crops was calculated as follows

$$WUE = \frac{\text{Yield per unit area}}{\text{Total water used}}$$

Maize yield = Grain yield + stover yield

2. Grain yield prediction

Relationship between grain yield and seasonal water use was determined by the equation

G = 178 + 85.8 wet ---------- (9), where wet = 151.68

Linear relationship between grain yield and measured seasonal evapotranspiration in the field was estimated as described by Pruitt et al (1975):

$$Y = YP\ (1 - ß)\left(1 - \frac{ET}{PET}\right) \quad \text{---------- (10)}$$

where; Y = yield associated with a given value of ET.

Yp = potential yield associated with PET and ß is the slope of relative yield (Y/Yp) vs relative Et relation (ET/PET)

ß = 1.11. The results are presented on Table 25a.

Monteith Equation: To estimate actual ET from a surface, Monteith (1965) equation was used as below:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho C_p(e_s - e_a)/ra}{\Delta + Y(r_a + r_s)/r_a} \quad \text{.....(17)}$$

where e_a = actual vapor pressure (kpa); r_a = aerodynamic resistance (Sm^{-1}), r_s = surface resistance (Sm^{-1}), R_N = net

Vapor pressure - temperature curve ($kpaC^{-1}$), G = soil heat flux in water depth equivalents (mmd^{ay-1}) Y = Psychometric constant ($KpaC^{-1}$). The result is included in Table 24.0

3.5.0 Observed Difficulties in the Field

1. Light problem (power failure), most of the time after heavy rainfall, electric light was interrupted by lightening/wind which damaged the electric cables. This resulted in the use of mechanical balance which has only one decimal point.

2. Deposit of finer soil particles on the drainage basin which affects the weight of the microlysimeter.

3.6.0 Pan Evaporation Measurement

A U.S. Weather Bureau class A evaporation pan about 80m North of the microlysimeter area was read daily at 10.00 am and 4.00 pm. The pan was surrounded by mown grass in all directions.

3.7.0 Other Climatic Measurements

Rainfall at the site was measured with a standard rain gauge. The cumulative rainfall that occurred during the two wet seasons are presented in Appendix C and in Figure 6. Air and earth temperatures were measured with thermometers. Wind vane and a cup anemometer were used to measure windspeed. Relative humidity data were measured and recorded with a hair element hygrothermograph. Sunshine hours was recorded using sunshine recorder. Solar

radiation, windspeed, relative humidity, vapor pressure, temperature and sunshine duration were also recorded with an 16.99 Automatic weather station (Eijkelcamp Agrisearch Equipment, the Netherland).

3.8.0 Soil Analysis

A — Field sampling and sample preparation.

For general soil characterization of the experimental site, soil samples were collected from a soil profile pit sunk beside the site. The samples were air_ dried and passed through a 2mm sieve. All samples were stored for analysis.

B Soil physical characterization.

Particle size distribution was determined by the hydrometer method according to Bouyoucos (1951). Soil moisture content: The procedure was according to the method described by Walter Gardner (1990). The saturated hydraulic conductivity was determined from fresh soil core samples in the laboratory with the aid of a constant head permeameter described by Youngs (1991). Soil bulk density : This was determined by oven-drying the soil core samples at 105_0 C for three days, and expressed as mass of dry soil per unit volume of moist soil (Campbell and Henshall, 1991). The bulk density was used to calculate porosity and macroporosity of the soil.

c. Soil Chemical Characterization.

Soil chemical analyses were carried out on the air-dried sieved soil using procedures described as follows:

Soil pH: soil pH was determined in water and in 0.01m CaCl2 with a pH glass electrode using a soil:solution ratio of 1:2.5.

Organic Carbon: The soil organic Carbon was determined by the **Walkley-Black wet combustion method** (Walkley and Black, (1965).

Exchangeable bases (Ca, Mg, K and Na).

The analysis was done by 1N NH4OAc extraction method. Cation exchange capacity (CEC) was determined by the 1N NH4OAc (pH 7.0) method (Chapman,1965). Exchangeable acidity was determined by the 1N KCL extraction method (Peech, 1965). Base saturation percentage (%BS) was calculated by dividing the total exchange capacity (ECEC) and expressed in percentage. Soil available P was determined by the method of (Bray and Kurtz, 1945).

3.8.1 Total Porosity

This was calculated from the result of bulk density and an assumed particle density of 2.65 gcm^{-3} from the following relationship:

$$P = 100\ (1-\frac{Db}{Pd}) \text{ and } n = (P - \frac{Db\Theta w}{Dw})$$

P = Total porosity

n = Air - filled pores

Dd= Particle density

Dw= Density of water

Θw= Moisture constant (dry) wt)

Macro-porosity was calculated as the difference between total porosity and field capacity (0.1 bar) values. Available H_2O was

calculated as the difference between the field capacity and the 15 atm.

3.8.2 Exchangeable Acidity

KCl - extractable acidity (hydrogen) was determined by leaching soil sample with 1N Kcl solution. 10 gm of soil were weighed into a funnel fitted with whitman filter paper N0 2, connected to a 250- ml volumetric flask. The soil was leached with 1N Kcl adding a small portion at a time.

Hydrogen and Aluminum were determined by titrating 50 mls of the lacked with 0.1N NaOH to a pink end point. The extractable aluminum was determined by adding one drop of 0.1N Hcl and 10 mls of NaF solution to the resulting solution which was subsequently titrated with 0.1N Hcl to a colourless solution, (McLean, 1965).

3.8.3 Cation Exchange Capacity (CEC)

This was determined by the summation of exchangeable metallic cations plus exchange acidity.

3.8.4 Base Saturation

Base saturation was calculated from the sum of the exchangeable cations (Ca, Mg, K and Na) divide by the CEC values obtained by the simulation of exchangeable cations plus exchange acidity.

3.8.5 Total and Available Phosphate

Total phosphate was determined by yellow method. The Bray No 1 method was used for extraction of phosphate and ammonium Molybdate-blue method was used for determining the available phosphate (Bray and Kurtz, 1945).

3.9.0 STATISTICAL PROCESSING OF DATA

3.9.1 Climatological Information

Monthly average values of all climatic data are presented in Appendix A. The Appendix contains information on:

i) Temperature

ii) Relative humidity

iii) Windspeed

iv) Sunshine hours

v) Solar radiation

vi) Maximum and Minimum temperature

vii) Pan evaporation and

viii) Microlysimetric data

Data processing was carried out on IBM compatible PC. A Basic Computer program was written to compute monthly and daily PET by Blaney Morin Nigeria, Hamon, Jensen Haise, Penman and Makkink equation. The average monthly PET computed using input data values of the 30 years for each model were compared with PET obtained by applying a factor of 0.7 (Doorenbos and Pruitt, 1977) to open pan evaporation measured with standard class A pan of the United States weather Bureau.

The comparison of daily yearly and monthly PET from the five

equations, U.S. class A pan and also PET measured from microlysimetric data during 1996 - 1997 period was done using analysis f variance (ANOVA), regression, correlation and standard "t" test. Path correlation analysis was used to determine the contributions of the key climatic factors on PET.

The comparison of daily and monthly evaporation from the soil, from the two equations and microlysimeter data was done using regression and correlation analysis. Other computations were done using statgraphic, Free Lance, Lotus 123 and Quatro Pro. The results are presented in tables and graphs. In this study error of estimation is given as below:

$$\text{Error } (\%) = \frac{\text{PET Pan - PET BMN}}{\text{PET pan}} \times 100 \quad \ldots\ldots\ldots \quad (12)$$

and

$$\text{Error } (\%) = \frac{\text{PET lysimeter - PET BMN}}{\text{PET lysimeter}} \times 100 \quad \ldots\ldots\ldots \quad (13)$$

Table 3.0: Equations Selected for Comparative Analysis

Equations	Dependent variable	Climatic parameters	Country of origin
Blaney Morin Nigeria	Mean air temperature, Rel. humidity, and solar radiation	Temperature, Rel. humidity and solar radiation	Nigeria
Hamon	Possible hours of sunshine, sat. water vapor density and a regional coefficient	Saturation water vapor and density, hours of sunshine	U.S.A
Jensen Haise	Solar radiation, temperature, vapor pressure and elevation	Solar radiation, air temperature and vapor pressure	U.S.A
Penman	Net radiation, windspeed, vapor pressure	Net radiation, windspeed, air temp. and vapor press.	England
Makkink	Solar radiation, saturation vapor pressure and slope	Solar radiation and temperature	Netherland

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Soil Characterization and Classification of Experimental Site

An evaluation of morphological, physical and chemical properties of the soil were determined to describe the site where the evapotranspiration measurements were taken.

The soil of the experimental site was described and classified according to the US Soil Taxonomy system, as typic kanhaplustaff, fine loamy, Isohyperthermic. The main soil characteristics are presented in Appendix A and Table 4.0. The farm is located on a gentle sloping site of about 2% gradient. The soil is well drained, friable, porous and gravelly. The soil is weakly acid (pH 5.8) in the surface horizon. The pH appeared to decrease slightly (strong acid) with depth which suggests that the soil parent material is more acidic than the soil formed from it. The soil is commonly derived from basement complex rocks.

The surface horizon was loam dominated by sand over clay loam subsoils. The colour of the surface soil is dark yellowish brown (10 YR 4/3) tending to brownish yellow (10 YR 6/6) and strong brown (7.5 YR 5/6). The subsoil horizons have yellowish brown (10 YR 5/6) matrit colours. The structure is moderately developed and subangular blocky.

4.1.2 Physical Properties

The physical and chemical properties of the soil is presented in Table 4.0. The values of percent sand, silt and clay for each depth are also given in Table 4.0.

The sand content decreases with depth from 50% at the soil surface to 14% in the subsoils. Clay content increases with depth from 12% to 50% at the subsurface. The silt content is high and decreases from 38% at topsoil to 26% in the subsoils.

The higher sand fraction at the surface could be due to low clay content at the surfce as a result of clay eluviation. The high silt content of the soil could indicate the influence of aeolian deposition on the area (Kowal, 1968).

Higher clay content is recorded for the subsoils than the surface soils. The lower clay content of the surface soils is a characteristic that has been observed for most soils on Basement complex in Nigeria (Ojanuga, 1969, Leow and Ologe, 1982; Esu *et al*. 1987). This characteristic has been attributed to biological sorting of soil materials, downward eluviation of clay and erosion. The lower clay content of the topsoils relative to the subsoils could also mean a more intensive chemical weathering at the subsoil relative to the topsoils.

According to Jones and Wild (1975) increase in clay content with depth is thought to be related to climate such that the most pronounced textural B horizons are found in "leached ferrallitic soils" of the humid savannas of West Africa.

4.1.3 Bulk Density

The bulk density of the soil ranged from 1.48 to 1.75 g /cm^3 (Table 4.0). Bulk density values vary widely among the soil depths to reflect the difference in organic matter content and

clay content. These lower values in the surface increase subsequently with depth. The lower values of this range is due to the higher organic matter at the surface. The bulk density of the top surface of the soil compares with that obtained (1.53 g/cm^3) by Kowal (1968) for some Samaru soils.

4.1.4 Porosity

The total porosity and macroporosity of the soil ranged from 33.96% at the subsurface to 47.55% at the surface and 6.25% (topsurface) to 28.15% (subsoils) respectively (Table 4.0). There is a gradual decrease in these two properties of the soil with the depth from the surface. This is due to the texture of the soil the deeper the soil, the finer the soil particles. The total porosity and macroporosity values obtained compared favourably with those of Kowal (1970) who obtained total porosity values ranging from 36% in the subsurface to 46% at the topsoil of some Samaru soils.

4.1.5 Hydraulic Conductivity

Hydraulic conductivity is greatest near the soil surface with values ranging from 3.17 x 10^{-1} cm/sec at soil surface to 2.23 x 10^{-1} at the subsurface of the soil. The results according to Kowal (1970), Ogunwole (1995) and Wuddivira (1998) indicate that the surface soil is very permeable inspite of poor surface conditions and the pronounced tendency for capping under rainfall impact.

Some selected soil physical properties were correlated with each other and with measured PET. It was observed that moisture content (r = 0.52) and bulk density (r = 0.94) increase with the depth of the soil. Total porosity, macroporosity, hydraulic conductivity, depth, moisture content and bulk density correlated with each other. Microlysimetric PET increases with porosity (r = 0.26) available water (r = 0.073), hydraulic conductivity (r = 0.21) and moisture content at 0.1 bar (r = 0.18) but decreases with macroporosity (r = -0.075), depth (r = -0.13), bulk density (r = 0.27) and moisture content at 0.3 - 15 bars.

4.1.6 Volumetric Moisture Content

Table 5.0 shows that volumetric moisture of the soil increases with the depth and decreases with hydraulic conductivity and porosity. It ranged from 10.98% to 50-75% in the subsurface. More water is retained at 0.1 and 0.3 bars (field capacity) than any other bars.

4.2 Chemical Analysis

The results of the chemical analysis are shown in Table 4.0.

4.2.1 Organic Carbon

The soil is generally low in organic carbon content (Table 4.0). The range is 2.9 gkg^{-1} to 6.0 gkg^{-1}. This may be attributed to the rapid microbial mineralisation of added litter in the soil

due to high temperatures recorded all the year round in this zone (Mosugu, 1989). The generally low organic carbon content of tropical soils have also been attributed to low polymerization of humic compounds with stable components that commonly accumulate as complexes with soil clays. These humic compounds are therefore easily leached out of the soil system, thus accounting for their low organic carbon content (Ojanuga, 1971).

The major reason for the low organic carbon content of the soil are climate, vegetation and landuse over the years. The alternation of wet and dry seasons, characterised by intense insolation, especially during the dry season and the cause of depletion under continuous cultivation lead to a rapid biological decomposition and humification of organic matter which is promoted by the pronounced activity of micro-organisms, ants and termites, with improved aeration through cultivation. The result is loss of organic matter in the well drained soils.

4.2.2 Soil Reaction

The pH values of the soil horizons (Table 4.0) ranged between 5.7 and 6.0 with a mean of 5.8 in water and between 4.7 and 5.8 with a mean of 5.1 in 0.01M $CaCl_2$; indicating weakly acid soil reaction (Soil Survey Staff, 1951). The major factors responsible for this low pH include perhaps the acidic nature of the parent rocks; the rocks are rich in bases and as such when they weather, the end products are low in bases too. The sandy texture, coupled with low levels of organic matter content are known to encourage

quite an effective leaching of cations into the subsoils from the topsoils.

4.2.3 Available Phosphorus

Values of the available phosphorus are presented in Table 4.0. The values ranged from 0.41 at subsoils to 3.37 gkg^{-1} at the surface. The soil contains low levels of available phosphorus. Higher value of available phosphorus is recorded for the surface soil, followed by a sharp decrease in the subsoils. This higher amount of available phosphorus in the surface soil might be linked with higher content of organic matter in the soil surface. Bhat and Bouyer (1968), Bhat (1970), Oliver (1972) and Pichot et al; (1973) found that application of humified organic matter to different soil types (ferruginous, hydromorphic and ferralitic soils) from Senegal, the Malagasy Republic and the Central African Republic is known to have increase phosphate concentration in the soil solution. Esu (1982) made the same observation in Kaduna area of some soils, organic carbon content did not vary directly with amount of available phosphorus in these soils.

The inconsistence in accumulation of phosphate at the surface, a pronounced occurrence in the savanna, has been attributed to the decrease in the return of phosphorus to the soil surface as the vegetation becomes sparser (Enwezor and Moore, (1966); Ipinmidun (1972).

4.2.4 Cation Exchange Capacity

The cation exchange capacity (CEC) of the soil is low, ranging from 2.50 at topsurface to 4.83 cmol+kg^{-1}. This was measured using ammonium acetate (Table 4.0). The lowest values are recorded in the top surface owing to their low clay content. This is followed by an increase in the subsuface due to an increase in clay content.

The CEC of the soil is influenced by type and amount of clay and organic matter content - Jones and Wild (1971) found that the CEC of some savanna soils he studied was 3.68 cmol+kg^{-1} of carbon or organic matter.

Soils low in CEC have low fertility because of their inability to hold nutrients inadequate amounts especially where crops requiring high levels of nutrients are grown. A low CEC also implies that when nutrient such as calcium, potassium and sodium are applied as fertilizers, more of the cations are likely to be leached.

4.2.5 Exchangeable Bases

Exchangeable bases (Ca, Mg, K and Na), Table 4.0, are low reflecting the low cation exchange capacity of the soil. The major saturating bases in the soil is calcium, with a range of values 1.56 to 2.90 cmol+kg^{-1}. This is followed by magnesium 0.44 to 0.95 cmol+kg^{-1}. Potassium and sodium are low, with values 0.096 to 0.12 cmol+kg^{-1} for potasium and 0.011 to 0.054 cmol+kg^{-1} for sodium.

The low values of potassium and sodium suggest that these

cations are easily leached from the soil or that the parent materials of the soil are low in minerals containing these elements. The presence in soils of exchange sites which show specific affinity for Ca may be responsible for the predominance of Ca over the other cations in the soils (Becket, 1965). It may be also that of all the exchangeable cations, Ca is the least easily lost from the soil environment (Brady; 1974).

4.2.6 Base Saturation

The base saturation (Table 4.0) obtained from CEC of the soil by NH_4OAc method range from 78.5% at the surface to 98.4% in the subsurface, thus reflecting the very low corresponding CEC values. This range of values increase inconsistently with depth. However, the higher base saturation in the subsurface soil than in the surface may be attributed to the return of cations from the surface to the subsurface soil through the pumping effect of vegetation.

4.2.7 Exchangeable Acidity

The exchangeable acidity is generally very low in the soil ranging from 0.04 to 0.4 $Cmol+kg^{-1}$. The low value of exchangeable acidity is associated with the high base saturation. The low exchange acidity is also a reflection of the low amounts of exchangeable Al and H in the soil.

The chemical analyses show that topsoils are generally less acidic than subsoils, owing to exchangeable bases, especially calcium, being brought up from depth by plant roots to the soil

surface through plant litter incorporated into the soil surface. Another possible factor could be the result of decomposition of plant litter rich in bases in the surface may be associated with the leaching of exchangeable bases through drainage.

Table 4.0: Soil properties of the experimental site

A. Physical properties

Depth (cm)	Horizon	Particle size distribution			Bulk density (g/cm^3)	Available Water (mm)	Porosity (%)	Hydraulic conductivity mm/sec	Makro Porosity (%)	Soil Texture
		Sand 50-2000µm	Silt 2-50µm	Clay < 2µm						
0-15	aP	50	38	12	1.39	11.5	47.55	$3.17x10^{-1}$	28.15	loam
15-30	B/A	40	40	20	1.55	10.8	41.51	$2.82x10^{-2}$	22.61	loam
30-45	Bt1	30	42	28	1.60	8.6	39.62	$2.81x10^{-3}$	21.22	Clay loam
45-60	Bt2	30	38	32	1.67	6.1	36.98	$9.62x10^{-4}$	18.68	Clay loam
60-75	Btv	24	32	44	1.70	13.6	35.85	$6.2x10^{-4}$	8.75	Clay loam
75-90	Btv	18	34	48	1.74	8.1	34.34	$2.18x10^{-4}$	11.25	Clay loam
90-105	C	14	26	50	1.75	10.5	33.96	$2.23x10^{-4}$	6.26	Clay loam

B. Chemical properties

Depth (cm)	Horizon	Org. Carbon g/kg	Avai. P Bray 1 mg/kg^{-1}	pH Water	pH 0.01N $CaCl_2$	CEC $cmol+kg^{-1}$	Exch. Acidity $H+ Al^{3+}$ $cmol+kg^{-1}$	Base saturation %	Ca^{2+}	Mg^{2+} coml+k g^{-1}	K^+	Na+
0-15	Ap	6.0	3.37	5.8	5.2	2.50	0.40	85.6	1.56	0.44	0.12	0.021
15-30	B/A	3.8	0.87	5.7	4.8	3.55	0.40	88.90	2.57	0.44	0.097	0.04
30-45	Bt1	5.4	0.41	5.7	4.7	3.92	0.40	89.8	2.73	0.68	0.096	0.011
45-60	Bt2	3.4	0.87	5.6	5.0	4.83	0.04	78.5	2.81	0.81	0.12	0.045
60-75	Btv	3.1	0.56	5.4	4.6	4.604	0.04	98.3	2.90	0.88	0.10	0.054
75-90	Btv	2.9	0.60	5.2	4.5	3.90	0.04	98.4	2.85	0.95	0.08	0.047
90-105	C	2.6	0.49	5.0	4.4	4.49	0.04	98.87	2.83	1.11	0.075	0.046

Table 5.0: Volumetric moisture content (%)

Depth (cm)	Bars					
	0.1	0.3	P1	5	10	15
0-15	34.06	26.97	15.99	13.07	11.95	10.95
15-30	34.44	26.46	17.51	12.74	12.04	11.20
30-45	35.64	26.13	21.16	16.33	15.48	13.92
45-60	27.07	26.35	23.18	20.02	18.43	17.57
60-75	40.30	39.57	32.70	28.32	21.46	19.71
75-90	41.16	33.96	30.28	27.64	26.61	22.05
90-105	42.92	41.00	36.11	30.93	30.04	25.46

4.3 Meteorological Conditions

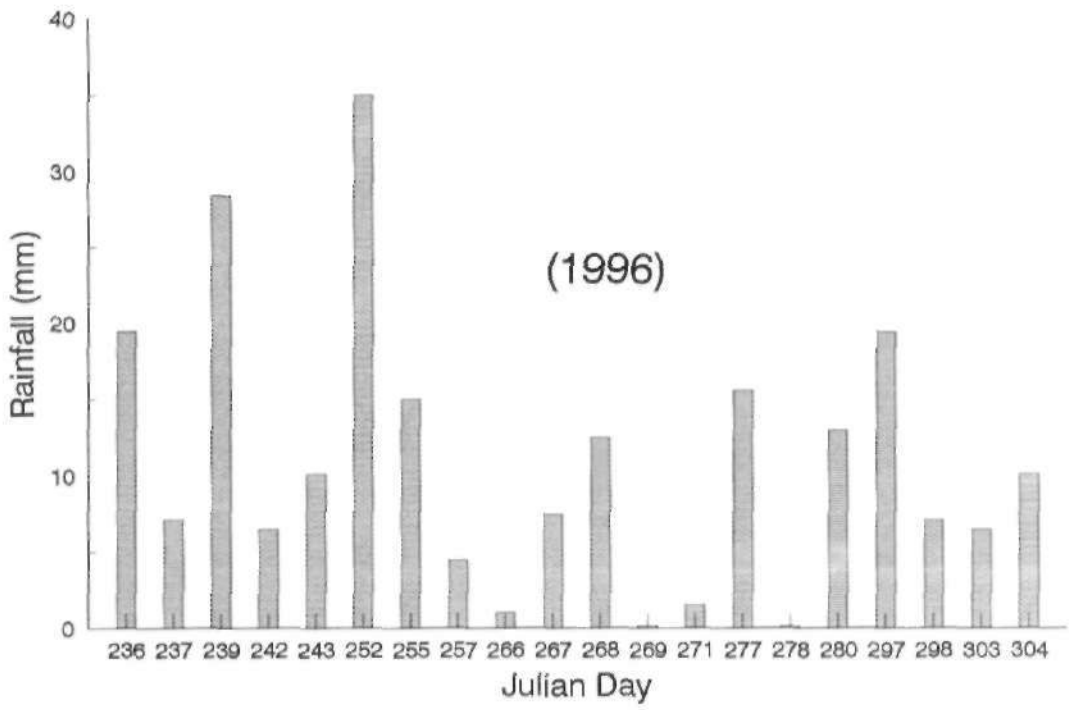
Climatic factors (relative humidity, wind speed, solar radiation, sunshine hours, soil and air temperatures, pan evaporation, and microlysimetric data) of the experimental site taken during the potential evapotranspiration measurements are presented in Appendix B.

Average daily relative humidity ranged from 32 to 88%. Relative humidity of 100% was not uncommon at night and led to dew formation which was not measured or accounted for in the experimental analysis. Windspeed tended to be high with a maximum daily average of 242.4 km/day. Solar radiation ranged from 4.4 to 22.4 MJ/M^2/day. The solar radiation was higher in October than the other months during the experiment. This is because by the end of September, the rain begins to cease in the Northern part of this country hence increase in sunshine hours and solar radiation. Pan evaporation ranged from 4.00 to 8.24 mm/day. Rainfall data are shown on the day of occurrence during the trials and as accumulation of all rainfall between trials. Total rainfall for the period from August 24th to October 7th 1996 amounted to 32.5% (265.2mm) and 52.5% (555.2mm) in 1997 of the annual rainfall. The year 1997 was wetter (1057.2mm) with a record of 87 rainy days extending late into October. The daily rainfall distribution for the two years are shown in Fig. 6.0.

The average soil temperature measured at 5cm, 10cm and 20cm depths for a near soil surface temperature ranged from 23-30°C. The soil temperature is higher at 5cm than 10cm and 20cm depths. This is due to the decrease of soil temperature with the depth.

Soil temperature was measured to the depth of 20cm due to the heat inputs and losses at the surface. It is in accordance with the findings of the Gaylon (1977) who observed that a bare dry soil surface will have large surface temperature fluctuations while fluctuation are greatest at the soil surface and decrease with increasing depth. Temperature fluctuations are greater at the soil-air interface than in air above or soil below. Soil surfaces under vegetation will show much smaller fluctuations (Foth, 1978). Average daily air temperature varied from 22.5 to 27.5°C.

Maximum temperatures are highest from March to June the peak of dry season in this zone. They are lowest in July and August; the wettest months of the year. The mean annual daily minimum temperature is 22°C.



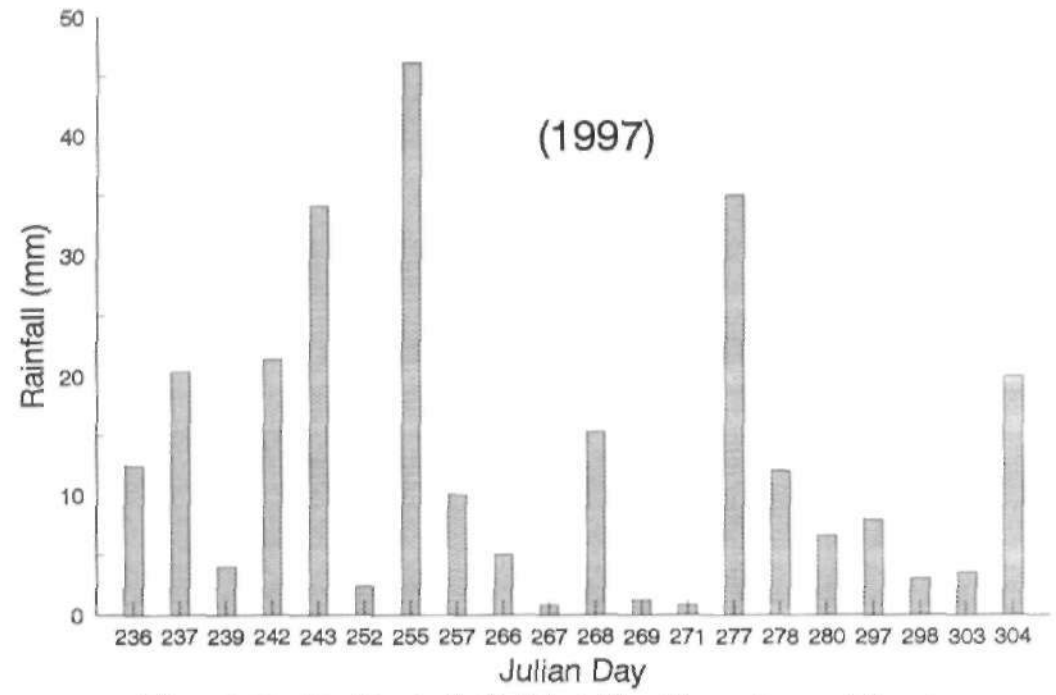


Fig.6:Daily Rainfall Distribution (mm/day)

4.4.0 Evapotranspiration

Potential evapotranspiration: Three methods were used for determining potential evapotranspiration. These were:

(a) Evaporation as measured from a class A evaporation pan.

(b) Potential evapotranspiration as measured from a *microlysimeter*.

(c) PET as calculated from Blaney Morin-Nigeria, Hamon, Jensen Haise, Penman and Makkink equations.

The results of the analysis of the five equations selected are divided into two sections. The first section presents the comparison of the PET estimates by the five selected equations with the pan evaporation at Samaru, Northern Guinea Savanna of Nigeria. The second section presents the comparison of the PET estimates with measured microlysimetric data.

The PET estimates are calculated using actual climatic data. Monthly variations of PET are obtained and statistical comparisons are presented in Fig. 8. Tables 9.0 and 11.0 comments on interpretation and implications of the results are given for each specific analysis.

4.4.1 Comparison of Potential Evapotranspiration (PET) and Evaporation Estimates

Input data from the experimental site are temperature, relative humidity, solar radiation, sunshine hours and windspeed. These are contained in Appendix B. The dry season (months), March, April and May represent the conditions of maximum expected evaporation and Potential Evapotranspiration (PET) as shown in

Table 9.0.

4.4.2 Yearly Distribution of PET and Evaporation Estimates

The data computed from five equations and for 30 years of monthly values represent 1800 bytes of data which are far too extensive to be included in this thesis. Therefore, only average monthly values for each equation are presented in Appendix C. Values of pan evaporation and microlysimetric data have also been included in Appendix C.

It is difficult, by simple observation to compare PET estimates obtain from different equations, especially since their behaviour changes from month to month. A graphical presentation of the results is shown in Fig. 7.0. All the equations show the typical sinusoidal shaped annual distribution of PET. The peak values occur generally during March, except for the Penman equation where they have been displaced to April (Fig. 7.0).

Four characteristics define each annual curve; the initial point at the beginning of the year, the rising limb during the dry season, the peak and the decreasing limb during the rainy season.

The least or minimal differences among the equations occur during the wet months or at the period of low PET demand. thus there was general agreement that, with the exception of evaporation pan readings, the meteorological measurements and equations tested showed smaller seasonal differences than the measured potential evapotranspiration (PET). The reason for this may be that there are some seasonal changes in the physiological state of the grass

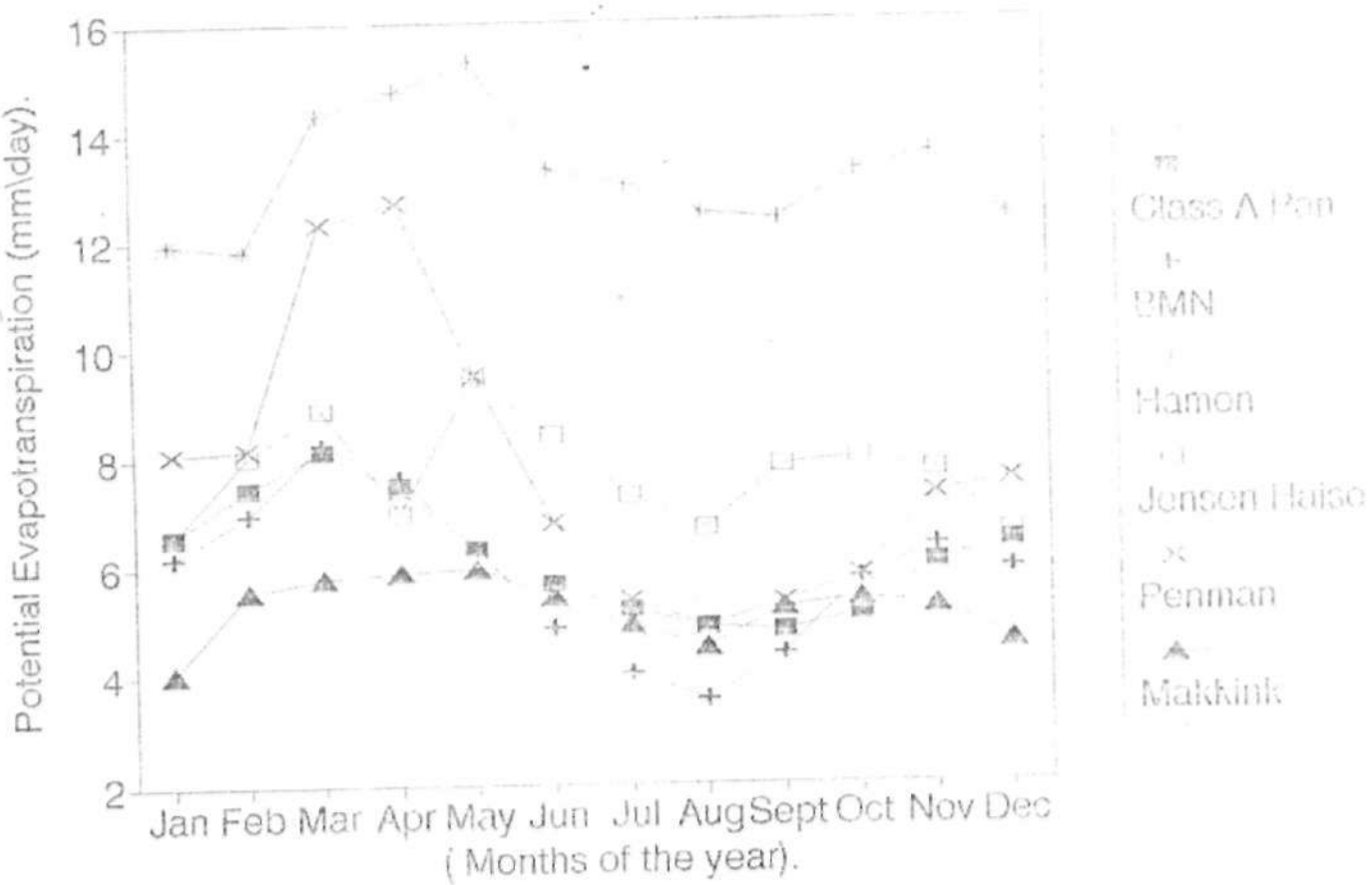


Fig. 7:Monthly distribution of PET.
(1965-1994).

cover which exercises some control of water loss. However, the more likely explanation is that in regions with comparatively small seasonal climatic differences it is necessary to measure directly the climatic factors controlling (PET) such as net radiation flux, temperature rather than to rely on empirical methods developed under different climatic conditions.

However, in view of the large regional differences in the amount of rainfall in Nigeria and to a lesser extent, in the rate of potential evapotranspiration and the amount of available water held in the rootzone, this value of PET computed for Zaria cannot be considered to be of general application. It does however, illustrate the need for reliable measurements of or methods of estimating PET before making any assessment of the water resources or requirements of an area.

If pan evaporation is considered to integrate all climatic parameters which affect PET, the shape of pan evaporation curves should yield slopes which are characteristic of the location. Pan evaporation has been related to PET mainly using correlation factor such as presented by Jensen (1970), Hagan (1967) and Stanhill (1961).

A generally recognized weakness of empirical methods is that their validity is restricted to conditions similar to those under which they were developed. It is very necessary to generalise these models formulated in Zaria (BMN) and outside Nigeria to all of Nigeria, through comparison of PET predicted by BMN, Hamon, Jensen Haise, Penman and Makkink models with observed PET or open-water evaporation. It was also considered important to compare

PET predicted by the BMN model and the Penman model considered to be the premier evapotranspiration model in use.

Figs 8-12 show the predicted performance of the BMN, Hamon, Jesnen Haise, Penman and Makkink models in comparison with measured data, pan evaporation (Table 6). If the models were perfect, the points in the graphs should all fall along the line of perfect fit.

From design and safety standpoints, Duru (1984) recommended that a model that over predicts should be preferred to one that underpredicts. Thus, for economic considerations the better model is one that over predicts to a lesser degree. It is evident from Figs 8-12 that the BMN model (r = 0.92) is the best predictor, under Zaria, Nigerian conditions, followed by Penman (r = 0.90) and Makkink (r = 0.69) models Hamon (r = 0.51) and Jensen Haise (r = 0.46) models overpredict too high.

To aid visual presentation, a least square linear regression analysis was performed with pan evaporation multiplied by a factor of 0.7 as measured PET, as the independent variable and PET predicted by the BMN, Hamon, Jensen Haise, Penman and Makkink models as the dependent variables regression equation has the form:

$$Y = a + bx$$

The accuracy of prediction by each models may be judged by the slope b and the intercept a of the regression line, with values of 1.0 and 0.0 indicating perfect agreement between predicted and observed values. The degree of association r, known as the correlation coefficient gives the reliability to be Fig.8

Table 6: Mean monthly predicted PET and measured Pan evaporation

Month					Computed
	Pan	BMN	Hamon	J. Haise	Penman
Jan	6.58	6.20	11.95	6.56	8.07
Feb	7.45	6.99	11.80	8.03	8.16
Mar	8.14	8.24	14.32	8.89	12.30
Apr	7.42	7.63	14.76	7.00	12.67
May	6.33	6.32	15.28	9.43	9.51
Jun	5.66	4.86	13.29	8.40	6.80
Jul	5.11	4.00	12.98	7.28	5.35
Aug	4.84	3.52	12.47	6.70	4.84
Sept	4.78	4.34	12.94	7.83	5.30
Oct	5.06	5.73	13.23	7.96	5.80
Nov	6.04	6.34	13.55	7.72	7.30
Dec	6.41	5.90	12.37	6.55	7.53
Total	73.88	70.07	158.94	92.35	93.63
Mean	6.16	5.84	13.25	7.70	7.80

Table 7.0: Monthly ratios of BMN, Hamon, Jensen Haise, Penman and M kkink to the Pan evaporation

Months	Equations				
	BMN	Hamon	J. Haise	Penman	Makkink
Jan	0.94	1.82	1.00	1.23	0.61
Feb	0.94	1.58	1.08	1.10	0.74
Mar	1.01	1.76	1.09	1.71	0.71
Apr	1.03	1.99	0.94	1.71	0.80
May	1.00	2.41	1.49	1.50	0.94
Jun	0.86	2.35	1.48	1.20	0.96
Jul	0.77	2.51	1.41	1.03	0.94
Aug	0.73	2.58	1.38	1.00	1.09
Sept	0.91	2.71	1.64	1.01	1.09
Oct	1.13	2.61	1.57	1.15	1.06
Nov	1.05	2.24	1.28	1.21	0.87
Dec.	0.92	1.93	1.02	1.17	0.71

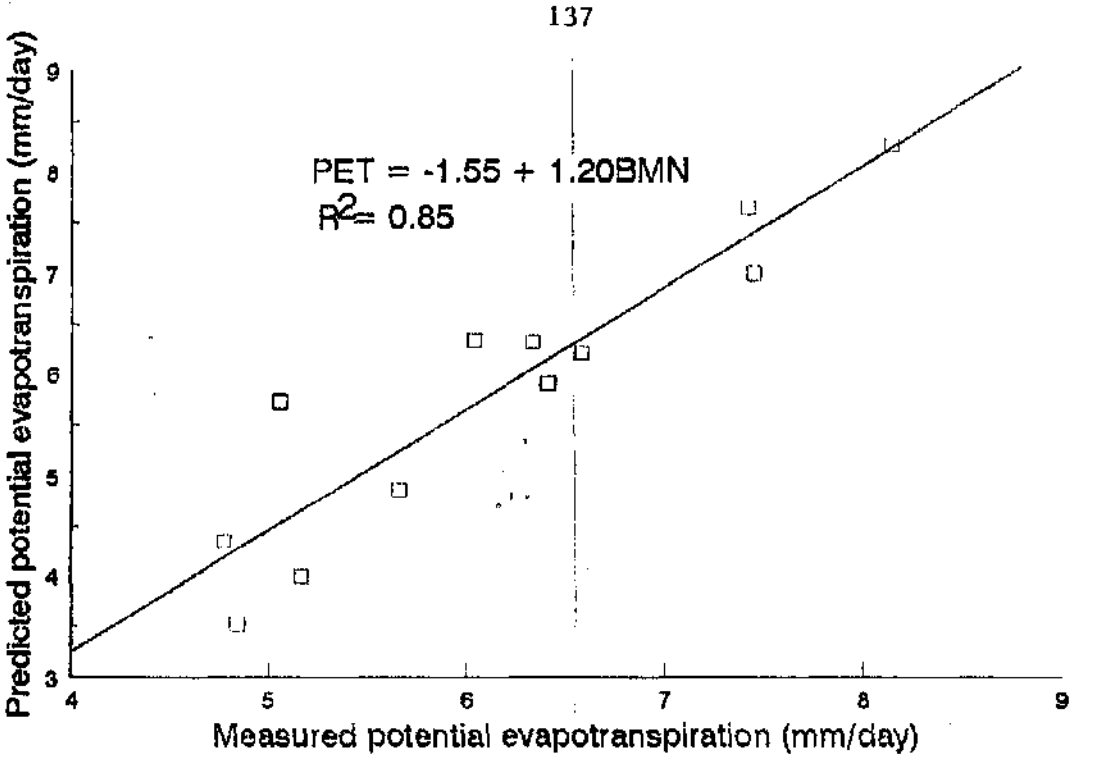


Fig.8a: Regression of BMN equation on pan evaporation

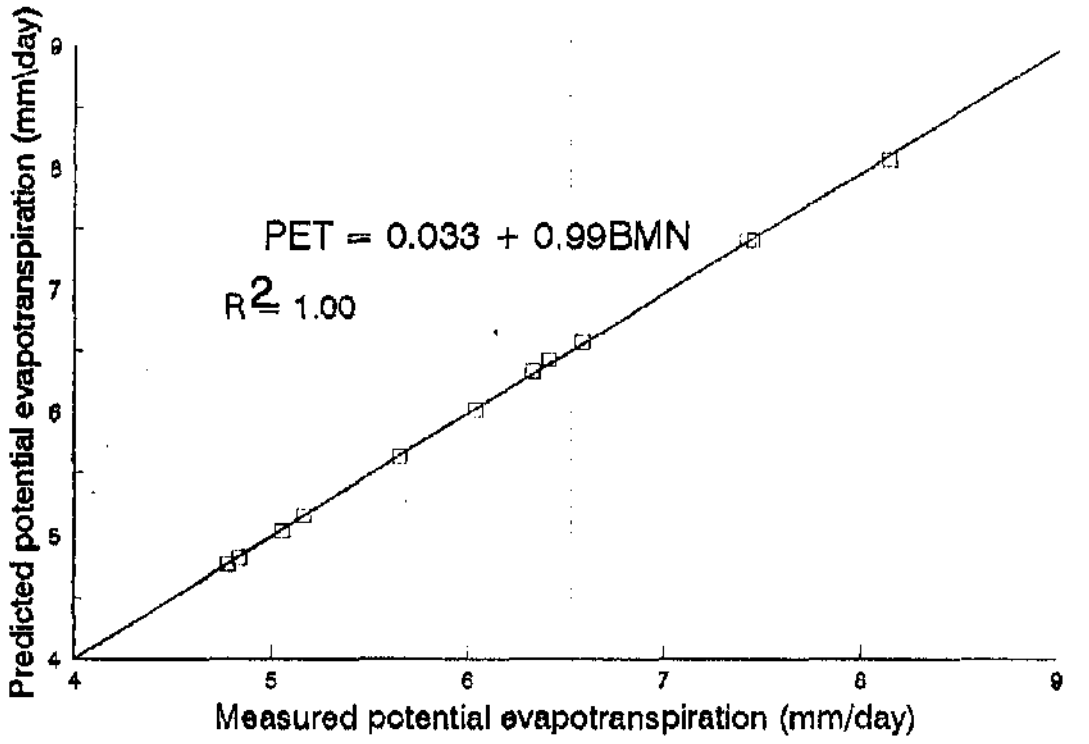


Fig.8b: Regression of adj.BMN equation on pan evaporation

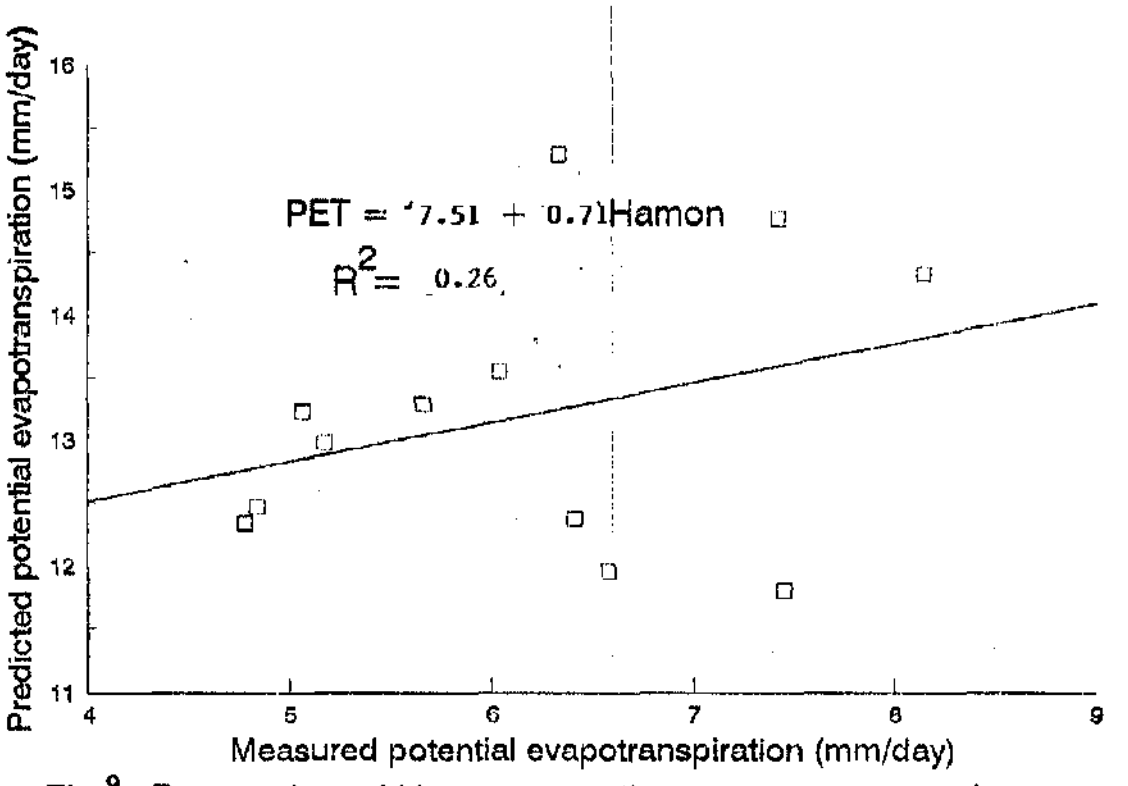


Fig. 9: Regression of Hamon equation on pan evaporation

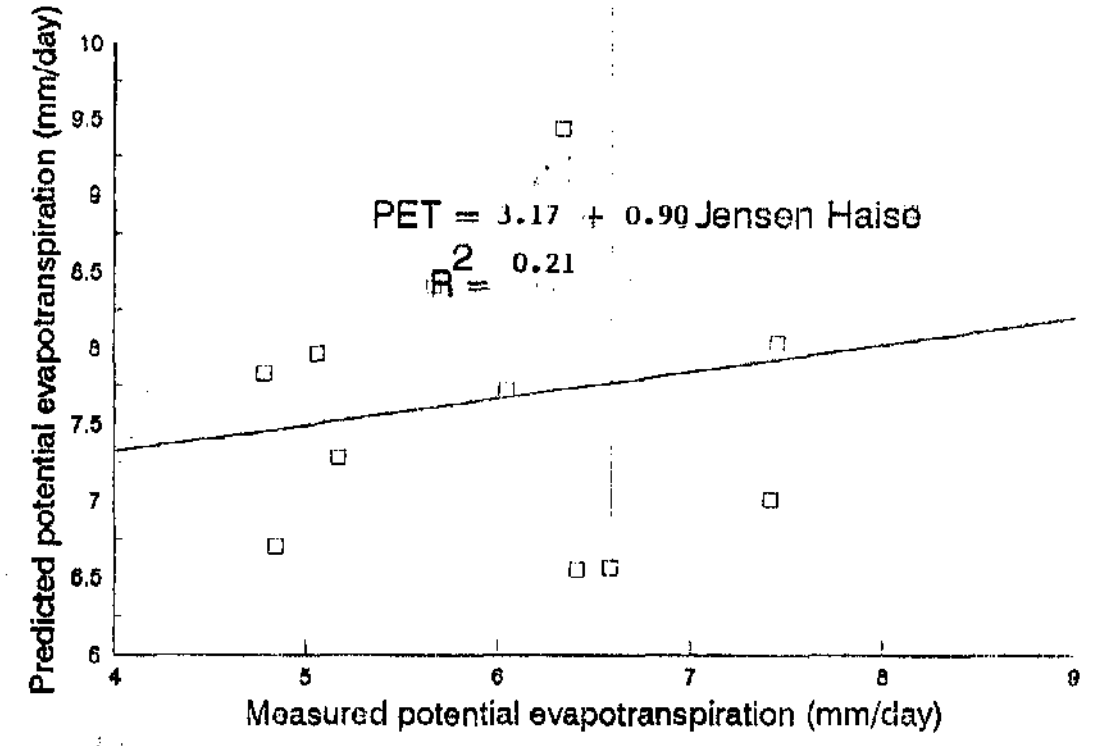


Fig. 10 Regression of Jensen Haise equation on pan evaporation

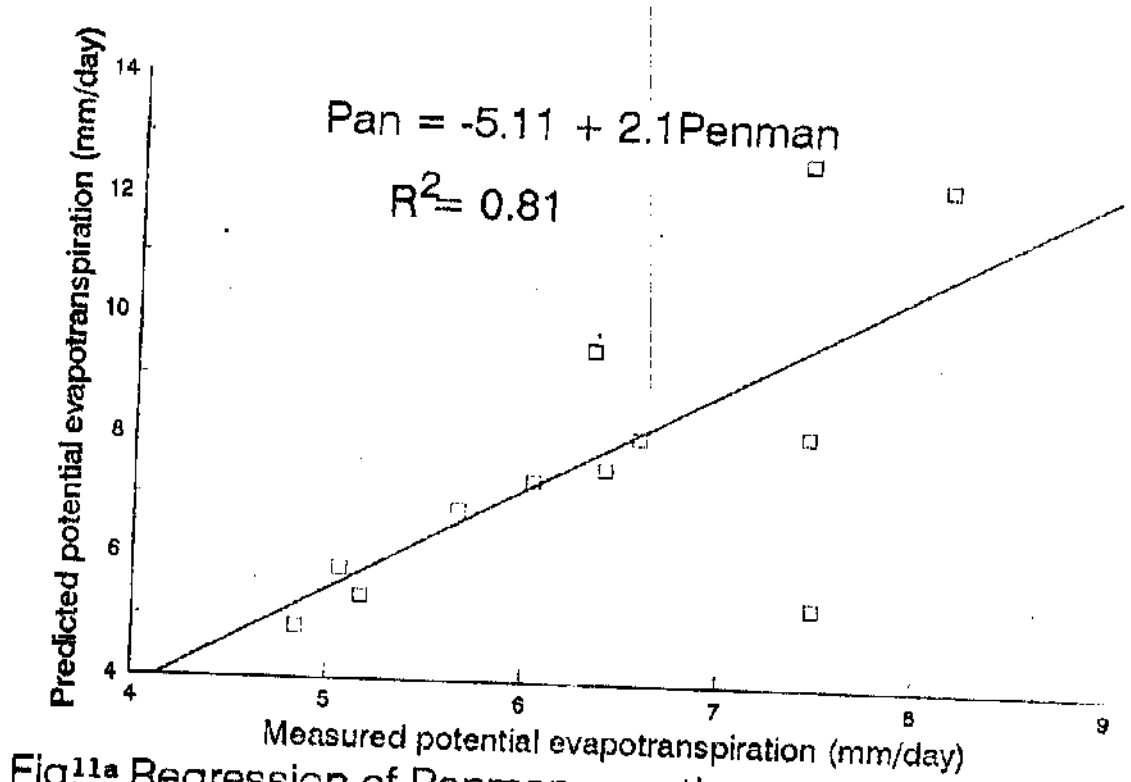


Fig.11a Regression of Penman equation on pan evaporation

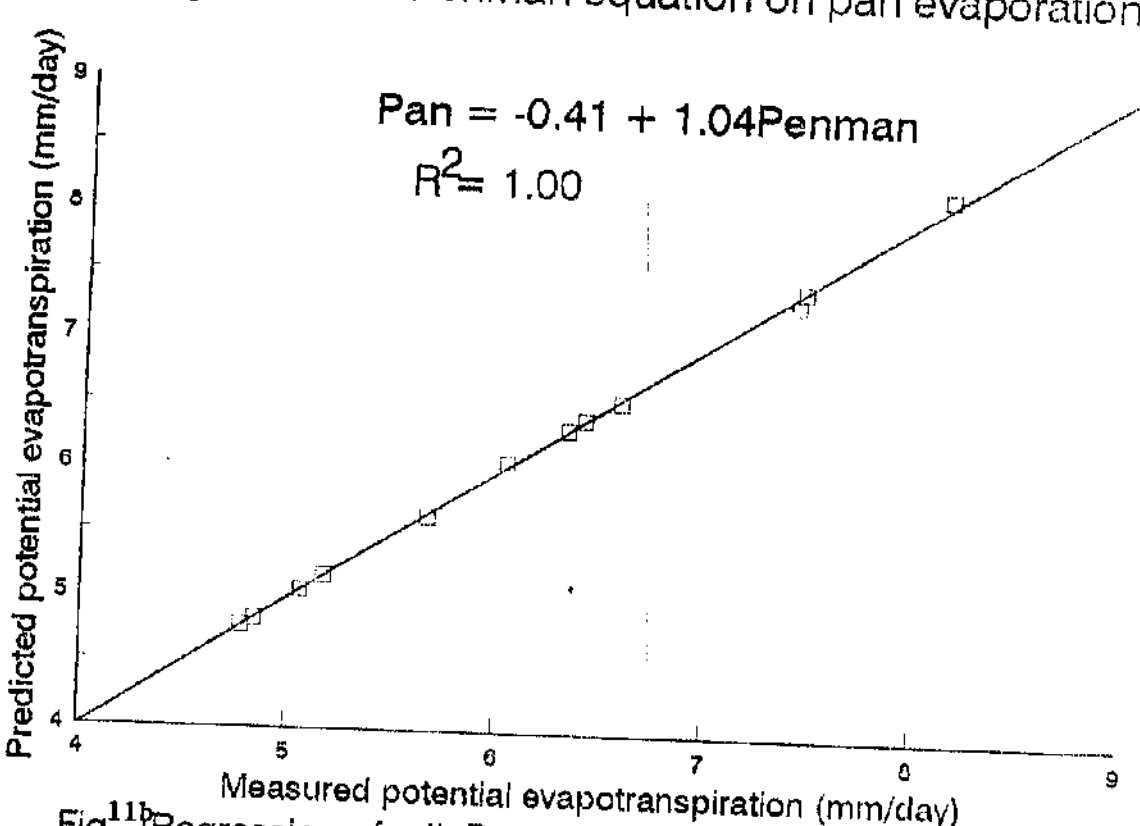
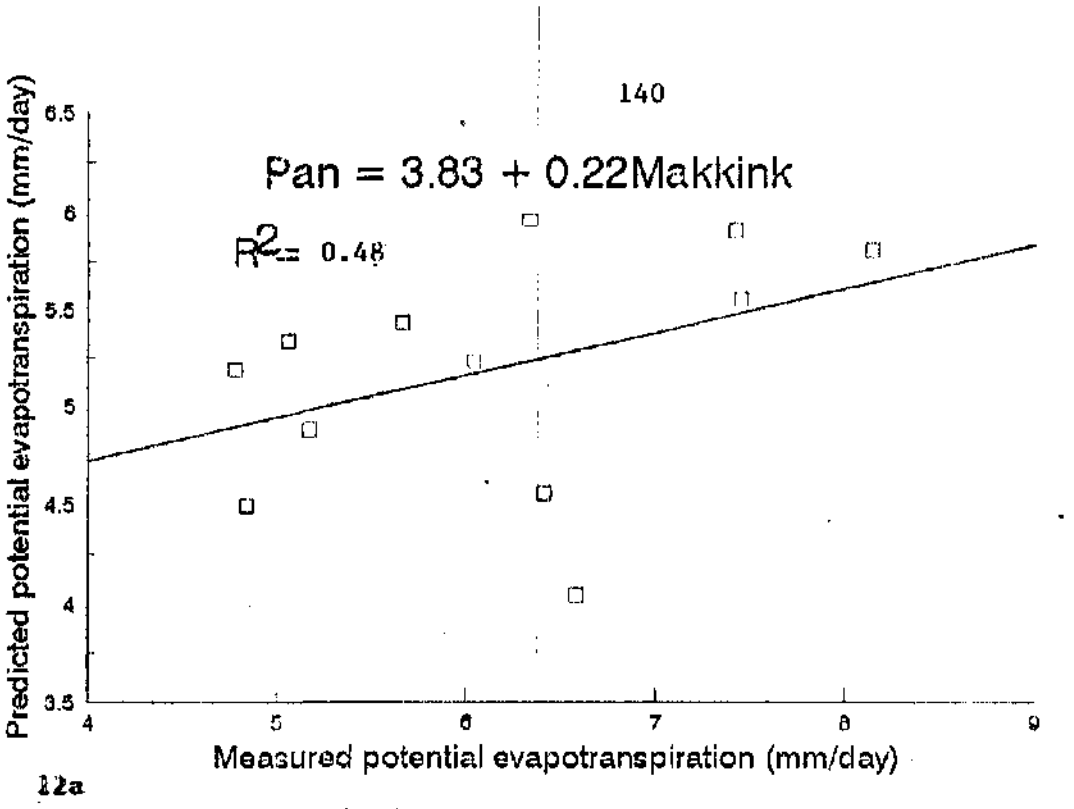
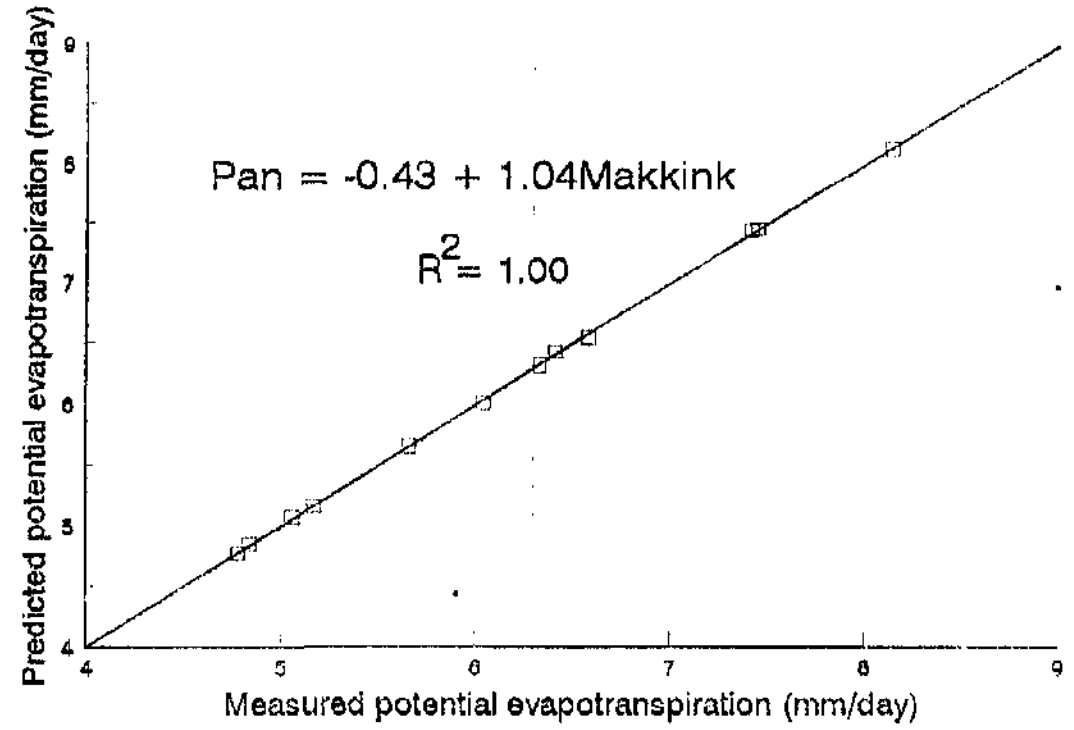


Fig.11b Regression of adj. Penman equation on pan evaporation



12a

Fig. : Regression of Makkink equation on pan evaporation



12b

Fig. : Regression of adj.Makkink equation on pan evaporation

expected of the predictor. Table 8 summaries the statistical analysis with observed PET from pan evaporation.

The correlation coefficients for the BMN model are consistently higher than those for the Hamon, Jensen Haise, Penman and Makkink models. The slopes and intercepts of the regression line for the BMN model are closer to the ideal. The Penman and Makkink models are also good predictors of PET since their coefficient of correlations are more than that of Hamon and Jensen Haise models. Table 6.0 is a summary of the predicted PET and pan evaporation monthly means used in the comparative analysis.

Table 7.0 shows the monthly ratios of the five equations to the pan evaporation. The ratios of the slope of each equation to pan evaporation slope for early months of the year, the peak, and rainy season are presented in Table 7.0. The ratios close to one (1) have been underlined. BMN model predicted satisfactorily or close to the pan evaporation from January to June and September to December. It underpredicts PET only in July and August. This may be due to low radiation and sunshine hours during these two months (wettest months of the year). It is essential, therefore, to have an accurate prediction of PET, so as to determine irrigation requirements accurately. The BMN model gives a better seasonal fluctuation of PET. It is also observed that the Hamon and Jensen Haise relationships yield ratios which are larger than 1. Hamon model overestimated PET in all the months of the year. Jensen Haise predicted PET satisfactory from January to April and December. It overpredicted from May to November. It appears likely that there is some systematic error in one of the empirical

Table 8: Statistical parameters - correlation of measured pan Pet wit predicted PET by different methods

Prediction	Independent variable	a	b	r	N
BMN	Measured Pet	-1.55	1.20	0.92	"
Hamon	"	11.69	0.25	0.26	"
J. Haise	"	6.63	0.17	0.21	"
Penman	"	-5.11	2.10	0.90	"
Makkink	"	3.79	0.23	0.48	"

Correlation equation: $Y = a + bx$

Table 9.0: Mean monthly pooled PET (mm) determined by 5 empirica formula for the period 1965-1974 at Samaru

Month	Mean	Ranking
March	1486.5	a
April	1438.8	b
May	1394.7	c
February	1215.9	d
November	1204.2	d
June	1163.4	e
October	1141.8	e
January	1116.6	f
December	1107	f
September	1068	g
July	1034.4	h
August	960.6	i

terms of Jensen Haise equations which leads to overestimates during low PET and to underestimates during high evaporation/PET. One such likely error could be in the method of calculating solar radiation, the most important term in the two equations. This points to the desirability of measuring the radiation terms in Jensen Haise equations in place of calculating it from other parameters. Penman model tends to overpredict PET during the dry season (March - May, November and January) and predicts satisfactorily for the rests of the months. Makkink equation underestimates PET from January to March and December, months of dry season and period of high PET rate. It estimates satisfatorily from April to November.

A plot of monthly PET for 1965-1994 (Fig. 7.0) produces a sinusoidal type curve with distinct maxima and minima. The BMN method best duplicates the pattern of variation maxima and minima as compared to the measured class A pan evaporimeter. The curves of PET predicted by this method and the measured PET have a strong intensity of association. The methods of Penman and Jensen Haise gave comparable to each other. Hamon method overestimates PET through out the year, while Makkink method underestimates during the dry season.

The monthly values of PET (1965-1994) for January, March, April and August are presented in Fig. 7.0. These average values indicate the variation of PET throughout the year. For the months of January, the values of PET show large differences except for BMN only. The BMN and Jensen Haise equations have mean values close to pan evaporation value plus or minus one standard

deviation of the pan evaporation mean. The Makkink equation is one or more standard deviation below the pan evaporation mean. The Penman and Hamon equations are one or more standard deviations above the pan evaporation mean.

The peak PET and evaporation values were obtained for March. The comparison shown in Fig. 7 is therefore important for its effect on irrigation project design in terms of PET and crop water requirement. March is also the month that shows the largest differences between mean PET values for the equations studied. Again, the BMN and Jensen Haise equations show the closest systematic agreement with pan evaporation in March.

Comparing the results for the month of April, it is observed that the BMN, Jensen Haise and Makkink equations are plus or minus one standard deviations of the mean value of pan evaporation. The Penman and Hamon equation overestimates pan evaporation by about 27% and 115.13%, respectively. PET values from Makkink equation always fall short of pan evaporation except in September and October when it is above pan evaporation estimates but remain within one standard deviation of the mean value. The Penman and Hamon do deviate much from pan evaporation values. Penman equation is close to pan evaporation only in months of June to December but deviated so much in months of January to May. BMN equation estimated below the pan evaporation from months of July to August. In months of June to November, Makkink and Penman equations compared favourably with pan evaporation but below it from Janaury to March. This may be as a result of high solar radiation because of seasonal changes.

Daily potential evapotrationspiration (PET) measured by microlysimeters has been included in Fig. 20. The information, however, is based on only two years records (Table 16). The comparison with microlysimetric data shows that these set of equations - Jensen Haise (R^2=0.28) and Hamon (R^2=0.34) overestimates PET in all the months (Figs. 13-17) . Makkink equation (R^2 = 0.26) overestimates PET also but has good agreement with BMN (R^2 = 0.68), Penman equations (R^2 = 0.37) and microlysimetric PET in the month of September as well as overestimates in months of August and October. In all the figures, the pan evaporation has been included to allow comparison among the equations, good agreement is also obtained for the BMN, Penman equations and the microlysimetric data in months of September and October. BMN, Penman, Hamon, Jensen Haise and Makkink equations show values above microlysimetric values in the months of August. Only BMN and Penman equations estimate PET close to microlysimetric PET. Adjustment factors for BMN, Penman and Makkink equations for the month of August is presented on Table 13b.

The result of this study is in agreement with previous research findings of Duru 1984 who recommended that BMN is suitable for estimating PET under Samaru conditions. However, it disagrees with Ramalan and Owonubi 1995 who recommended Jensen Haise equation as a good estimator of potential evapotranspiration in Samaru

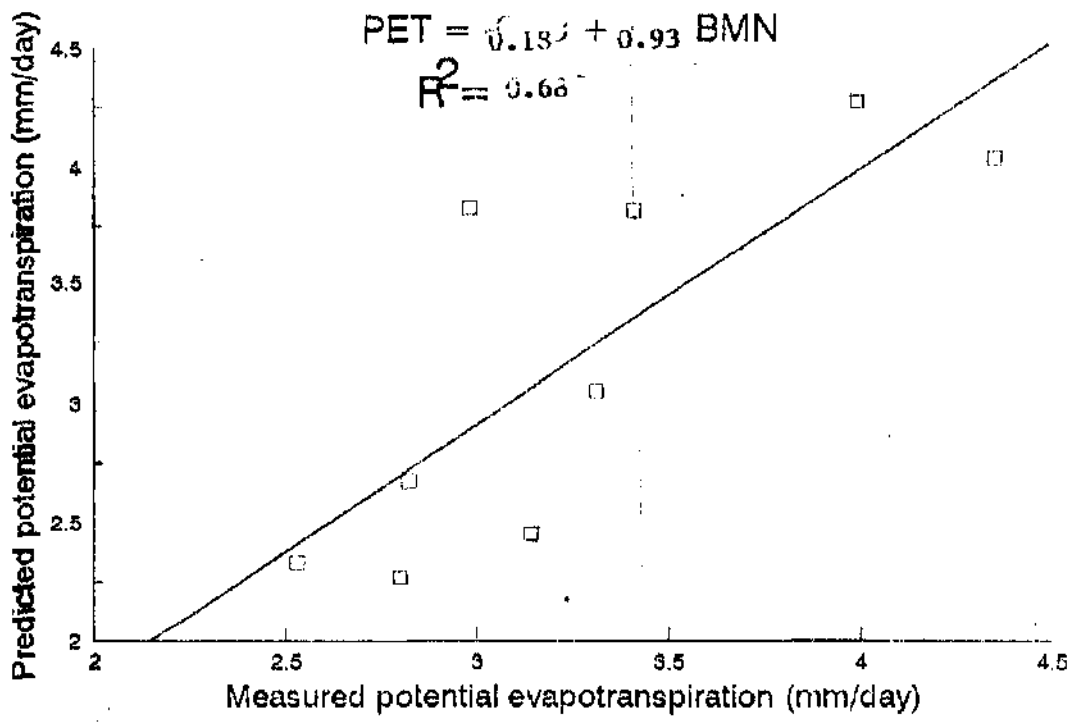


Fig. 13a :Regression of BMN equation on microlysimetric PET.

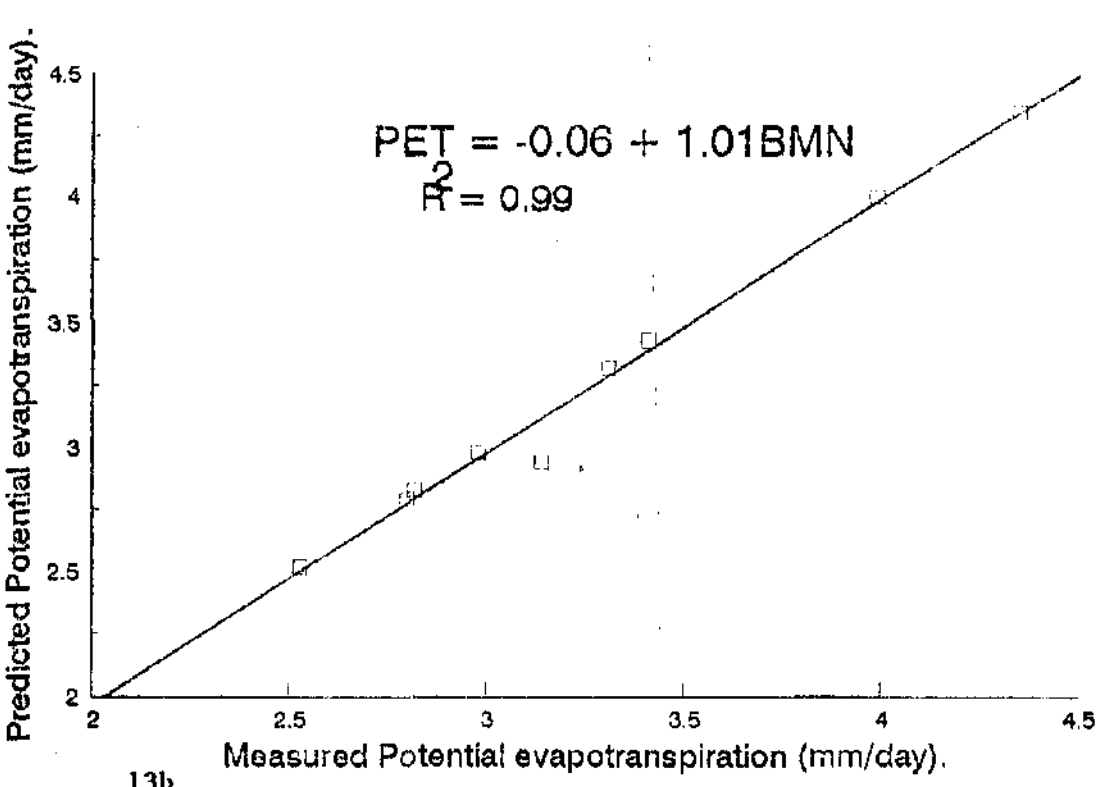
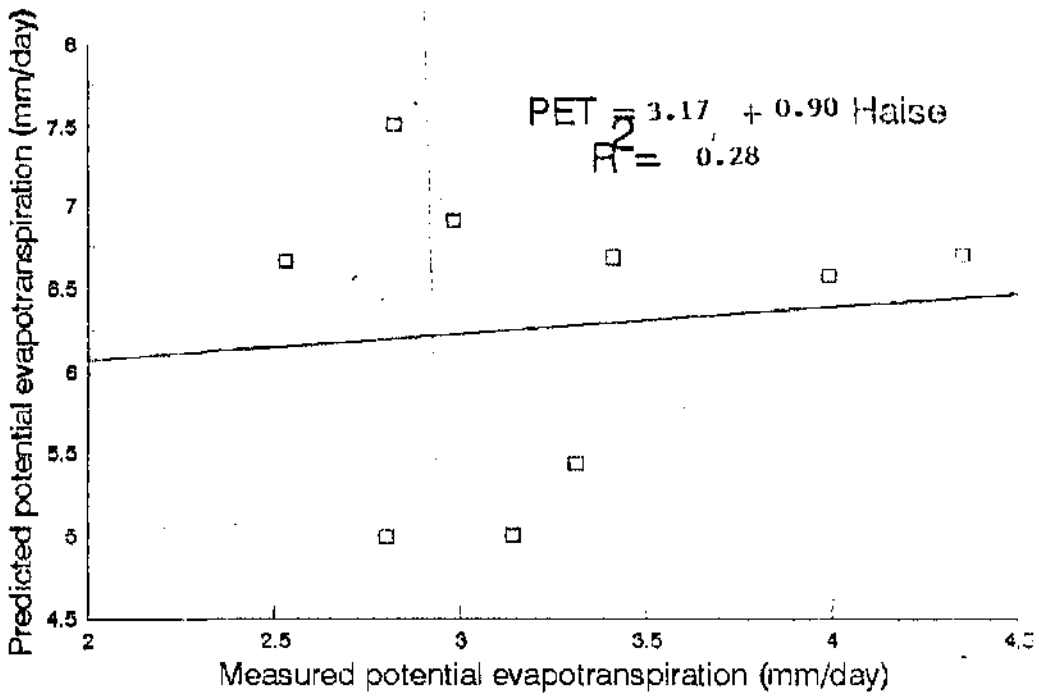
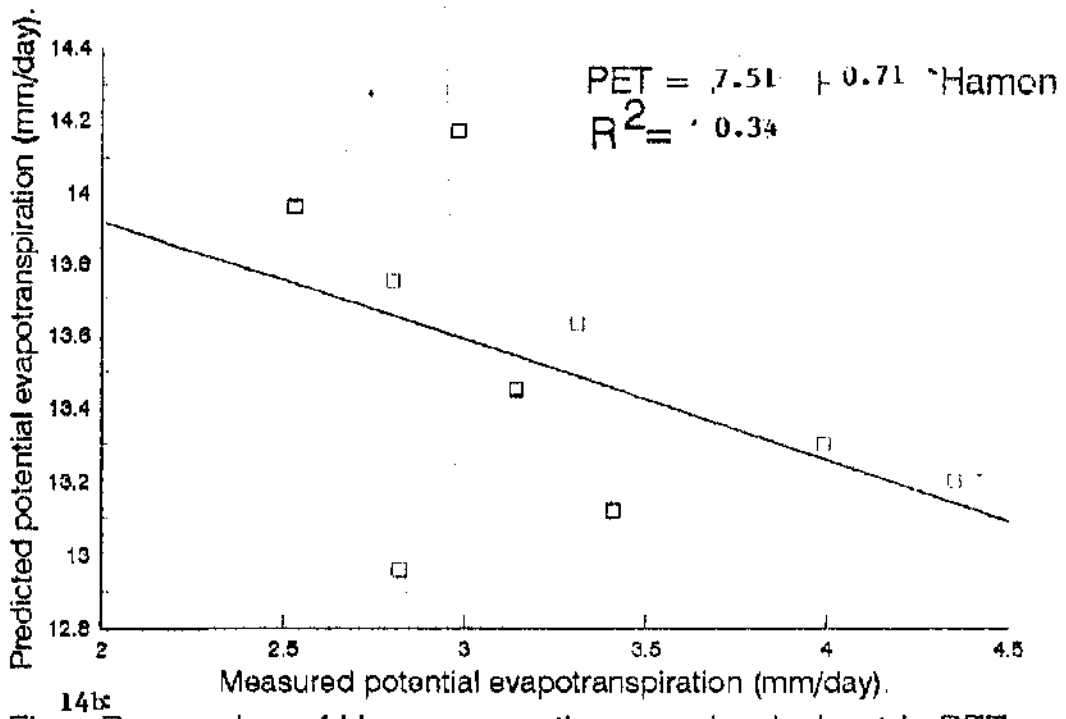


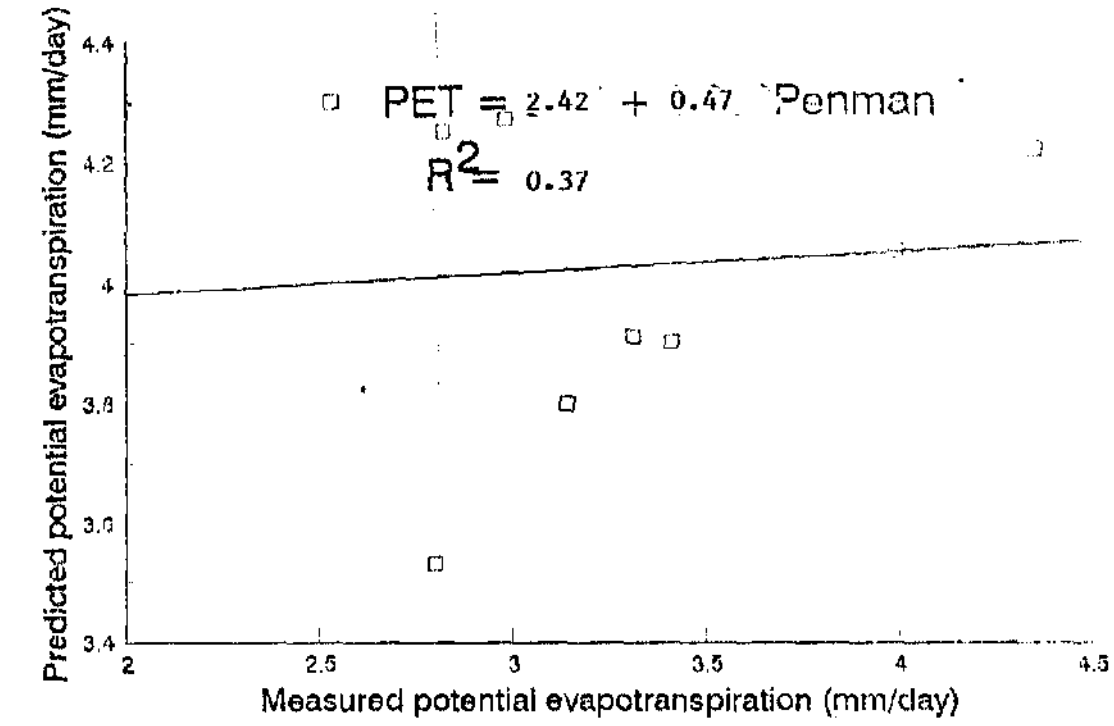
Fig. 13b :Regression of adjusted BMN equation on microlysimetric PET.



14a Fig. :Regression of Jensen Haise equation on microlysimetric PET.

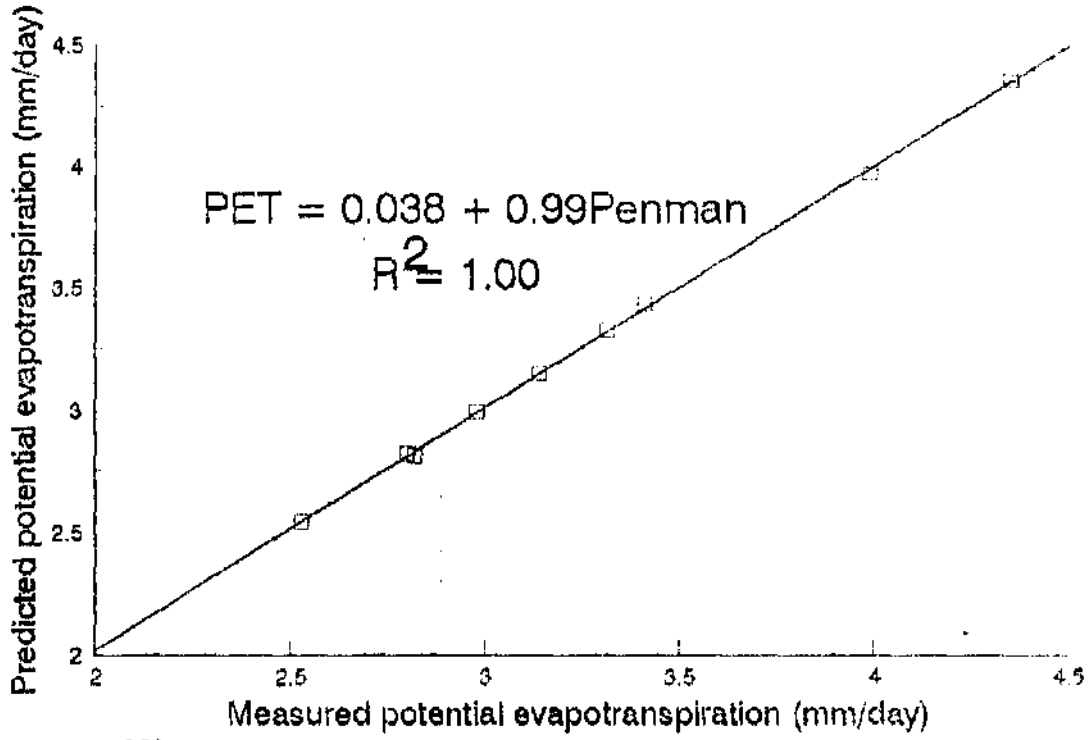


14b Fig. :Regression of Hamon equation on microlysimetric PET.



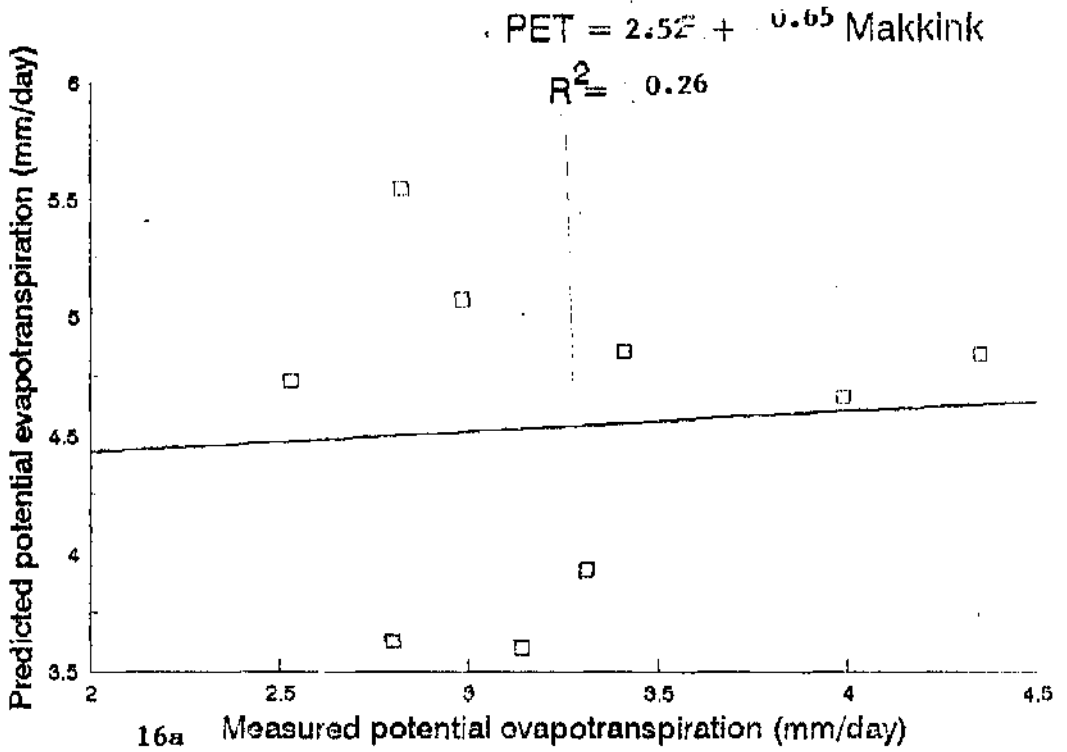
15a

Fig. Regression of Penman equation on microlysimetric PET



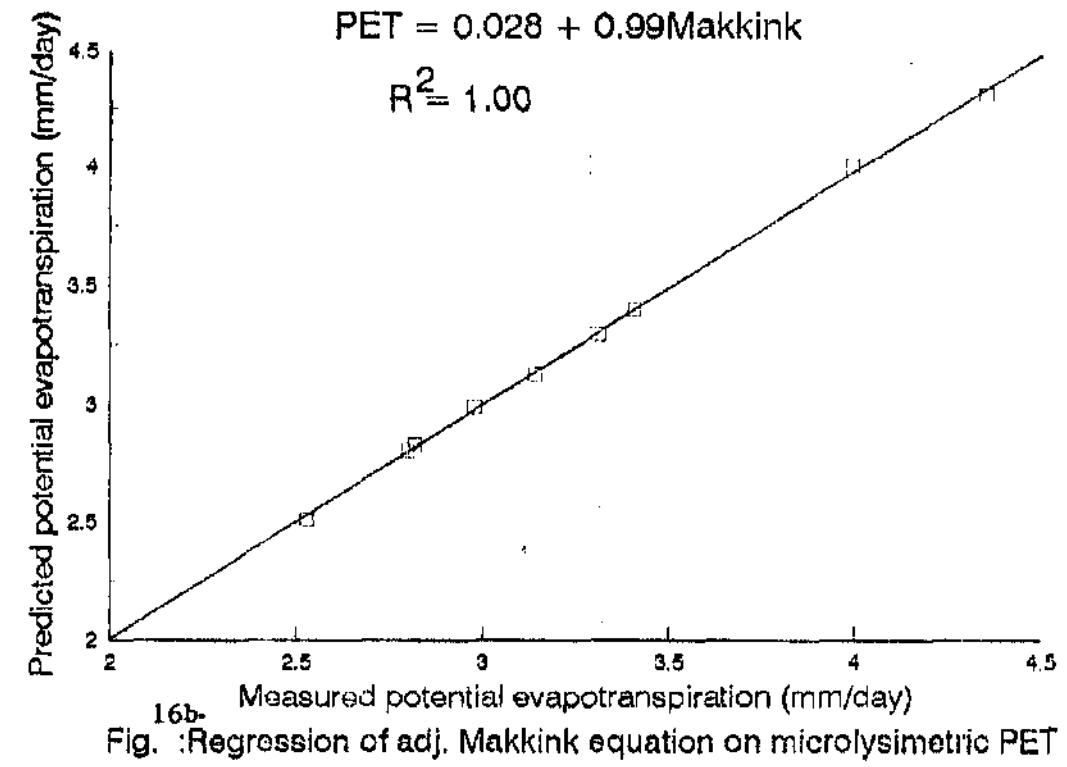
15b

Fig. Regression of adj. Penman on Microlysimetric PET



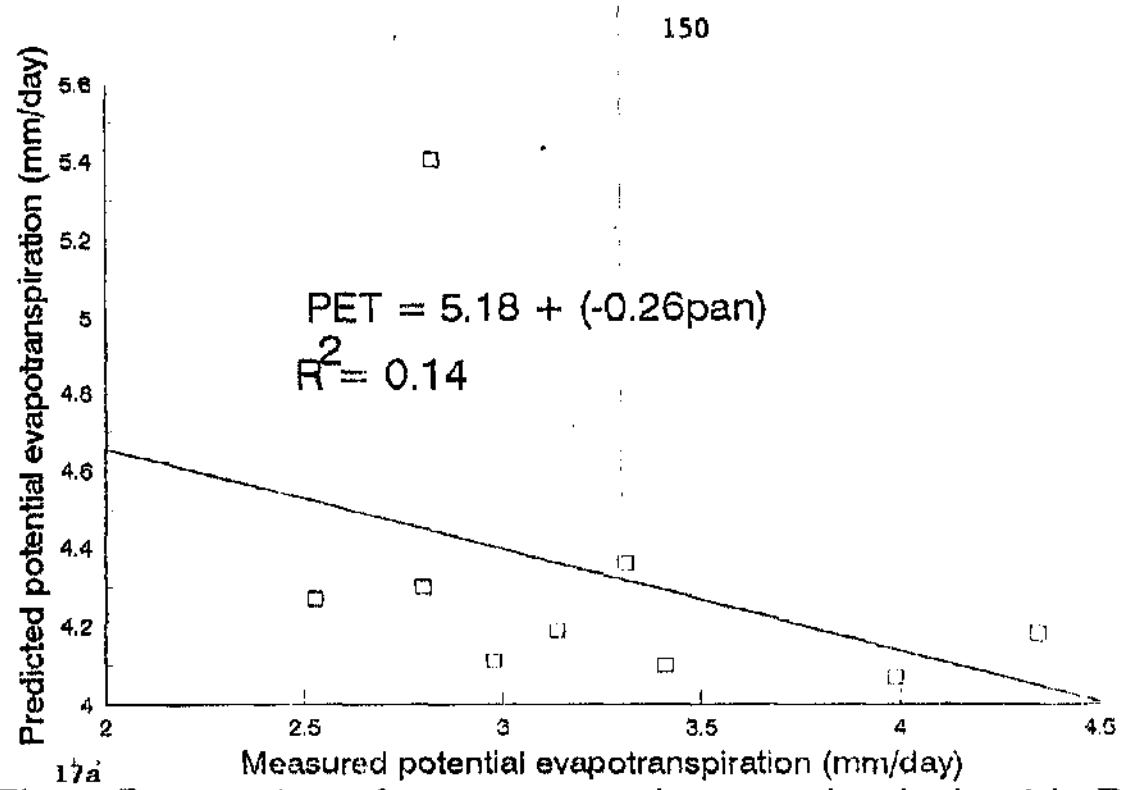
16a

Fig. :Regression of Makkink equation on microlysimetric PET



16b

Fig. :Regression of adj. Makkink equation on microlysimetric PET



17a

Fig. : Regression of pan evaporation on microlysimetric PET

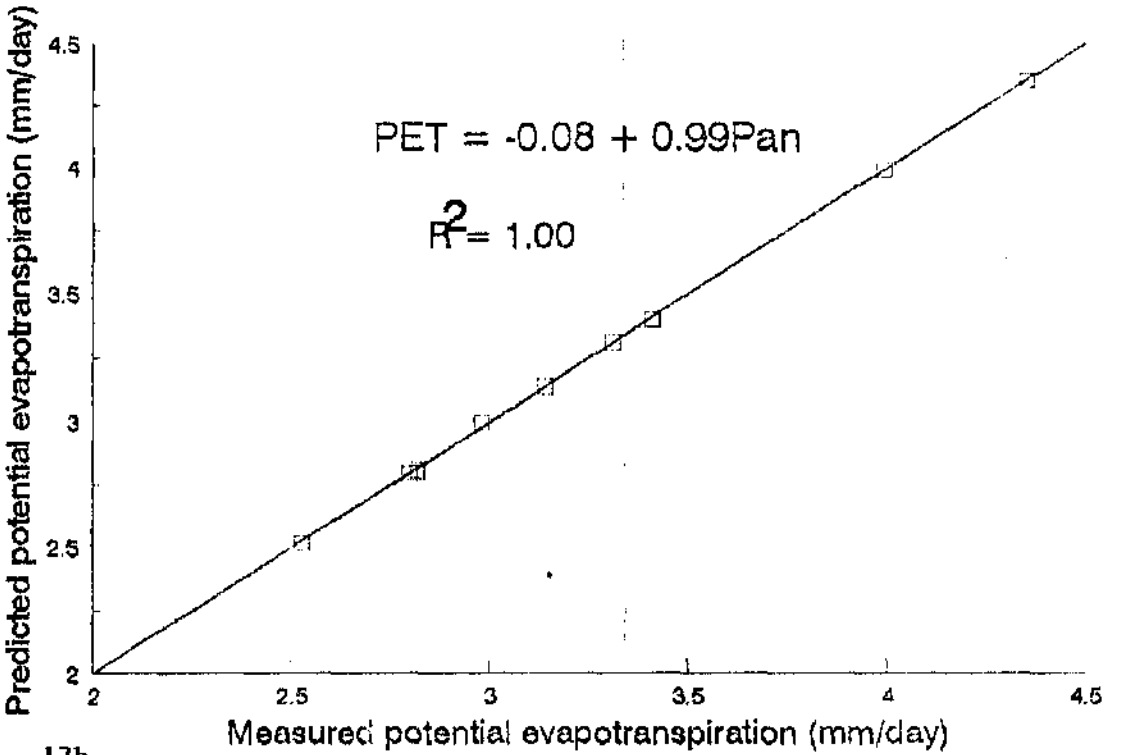


Fig.[17b]: Regression of pan evaporation on microlysimetric PET

climatic conditions. It was observed that Hamon method developed in the temperate climate of North Eastern United States of American over predicts evapotranspiration in subhumid semi-arid and arid climate; that the Makkink method is not very suitable for climatic conditions where the radiation is high. The Makkink method estimate is low (in some months) because of the large climatic differences compared to the area in which it was derived: Makkink method among the radiation methods are nearly always in phase with the monthly variation in measured PET and did not yield unusually high estimates. When considering all radiation methods evaluated they generaly tend to underestimate PET because most were derived undercool coasted conditions (Jensen 1973).

The Penman method generally gives the best approximation of actual evapotranspiration. Of the other three methods except BMN method; Penman's appears to enjoy the widest popularity. This may be so because it incorporates factors which conceptually appear to have a bearing on evaporation. Another reason is that the Penman method is capable of computing PET over relatively short periods of time - as short as one day (Duru and Adewuyi, 1979). This quality makes it more useful for irrigation planning. Some of the other methods predict PET over a full growing season that may involve many months. Penman method is the most complex of the simulation methods. These discrepances in Penman method pointed out is rather intended to highlight the argument that the method, while apparently the best simulator of (potential evapotrnaspiration is none the less difficult to use. Penman PET estimate is close to measured values except from January to June

when it is about 2mm/day too high when the radiation and temperature are relatively high. This observation is not in agreement with those of Stanhill (1963) and Duru (1984), that the Penman over predicts PET during the rainy season (June - September) and underpredicts during the dry months (December - April) when the evapotranspiration rate is high. The radiation methods are usually low except for the Jensen Haise method which has elevation adjustment. However, estimates of this method are high after April as shown on Table 6.0.

One other significant finding is that the radiation - based method by Jensen Haise is not potentially good PET model for Zaria. It is possible that by incorporating locally determined coefficient or adjustment factor into this method, it will predict PET accurately.

The result of this study shows the methods of BMN, Penman and Makkink to give a good estimate of PET under Zaria conditions. BMN method, however, lagged about 1.17 $mmday^{-1}$ in July and 1.32 $mmday^{-1}$ in August. The PET water requirements as predicted by Penman and Jensen Haise is practically the same with average monthly values of 7.70 mm/day (Jensen Haise) and 7.8 mm/day (Penman). The Penman method has several draw backs. First; many meteorological parameters are needed. Second, the method is tedious.

The analysis of variance establishes that the five equations are statistically different at the 95% confidence limit. This is important for the purposes of the study, but it shows that the equations are tested under statistically different climatic

conditions. The interraction among equations and climatic condition appears highly significant and shows that the equations are behaving differently depending upon the climatic conditions.

Analysis of variance for each method.

In comparing daily PET estimated by the five methods over 30 years at Samaru with pan evaporation, significant differences between the methods were observed. The BMN method was very significantly different from others; when their means were ranked, there was a highly significant difference between the Hamon method and others. Jensen Haise and Penman were significantly the same, while pan evaporation, BMN and Makkink methods were statistically the same. Hamon, Jensen Haise and Penman methods tend to overestimate PET above the pan evaporation.

The Hamon equation was grouped separately from the other equations because of the extreme over estimation of the PET values as compared to the general mean of all the equations. The results of the analysis for all methods are presented in Table 10.0. Each pair of equations is compared to determine if they are statistically equivalent or the same. For the conditions of Samaru, all equations give statistically different monthly means (Table 9), when mean monthly PET were ranked the results was as follows: March, April, May, Febraury, November, June, October, January, December, September, July and August. PET is highest in March and lowest in August.

The comparison of the BMN and Penman equations with microlysimetric data yields similar results for the month of September. Good agreement is also observed between the

microlysimetric PET and the BMN estimate of PET from September to October. BMN and Penman equations show close agreement themselves particularly for wet and early dry seasons.

The data was also analysed for every ten years as follows. For 1965-1974. There is a significant difference among the months. The month of March gave the highest, followed by April, and August being the lowest. There is also a highly significant difference between the methods. Hamon method gave the highest value, followed by Jensen Haise, Penman and Makkink gave the lowest estimate. The coefficient of variation (C.V = 13.8), standard error (1.086) estimates are shown on Table 11.0. The graph is shown in Fig. 19.0.

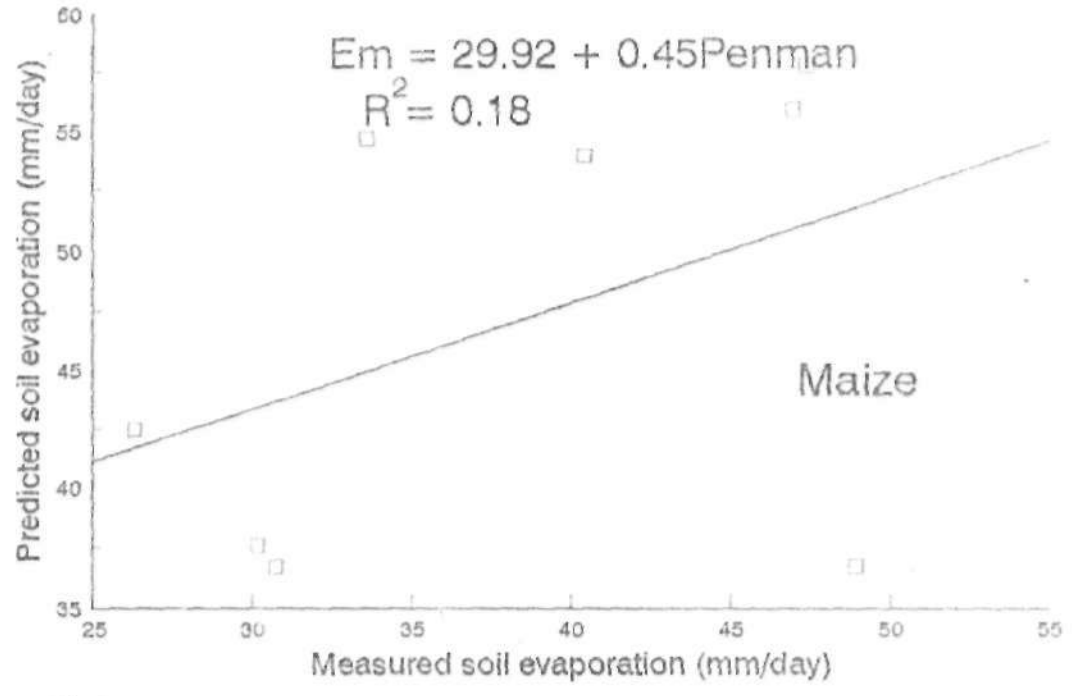


Fig. 18a : Regression of Penman equation on soil evaporation

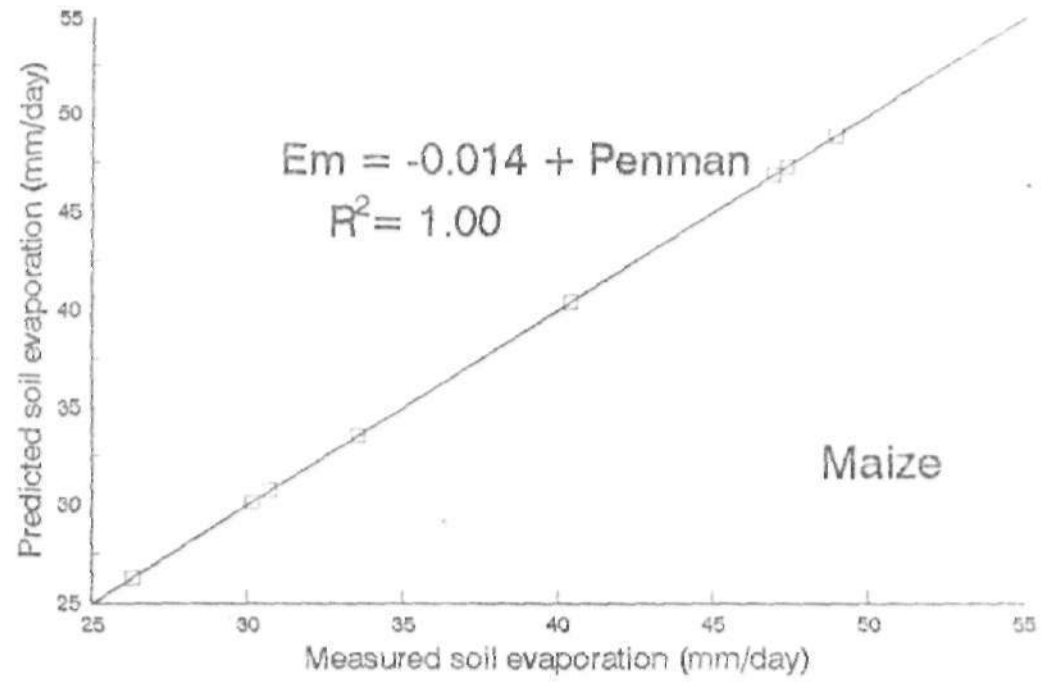


Fig. 18b : Regression of adj. Penman on soil evaporation

Table 10.0: Mean daily PET(mm) measured by five methods

Methods	Years											
	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
BMN	5.75	5.69	5.75	5.74	5.85	8.83	5.40	5.75	5.96	5.76	5.70	4.41
Hamon	13.18	13.10	13.71	13.73	13.63	12.46	14.83	13.24	11.85	12.3	12.99	12.20
J. Haise	8.55	9.08	8.70	8.77	9.59	8.73	8.87	8.96	9.77	7.12	7.27	7.46
Penman	8.82	8.74	5.29	8.38	8.32	8.31	8.34	8.20	8.39	8.13	7.74	7.63
Makkink	5.61	5.51	8.51	5.40	5.52	5.29	5.37	5.45	5.41	5.14	5.26	5.37
Mean	8.38	8.44	8.40	8.40	8.58	8.12	8.56	8.32	8.28	7.69	7.79	7.41

Table 10.0 contd: Mean daily PET (mm) measured by five methods

Methods	Years											
	1981	1982	1983	1984	1985	1986	1987	1988	1939	1990	1991	1992
BMN	5.90	5.69	7.04	5.55	5.96	5.87	6.38	6.17	6.04	6.04	6.65	5.76
Hamon	13.19	12.45	13.80	13.08	12.0	13.22	13.1	12.98	12.69	13.54	13.34	13.14
J. Haise	8.0	7.22	7.78	6.94	6.67	8.4	7.84	6.9	7.78	8.06	7.47	6.51
Penman	7.86	8.01	8.78	7.95	8.00	7.82	8.73	7.90	7.68	8.55	7.23	7.4
Makkink	5.39	5.13	5.30	5.02	4.77	4.24	5.55	4.92	5.25	5.38	5.18	4.71
Mean	8.07	7.70	8.54	7.71	7.48	7.91	8.32	7.77	7.89	8.31	7.97	7.50

	Methods	Mean	Ranking
2.	Hamon	13.10	a
3.	J. Haise	7.963	b
4.	Penman	7.930	b
6.	Pan evaporation	6.148	c
1.	BMN	5.826	c
5.	Makkink	5.301	c

Table 11: C.V. standard error, F=ratio, DF for every ten years.

Years	CV	SE	DF	F-ratio	for months ratio
1965-1974	13.2	1.036	11	5.45**	at F table = 2.40
Methods	13.8	1.086	4	86.32**	at F table = 6.61 %
1975-1984	14.1	1.080	11	7.055**	
Methods	13	0.407	4	101.51	
1985-1994	19.9	1.52	11	5.28**	
Methods	12.9	0.662	4	36.76**	

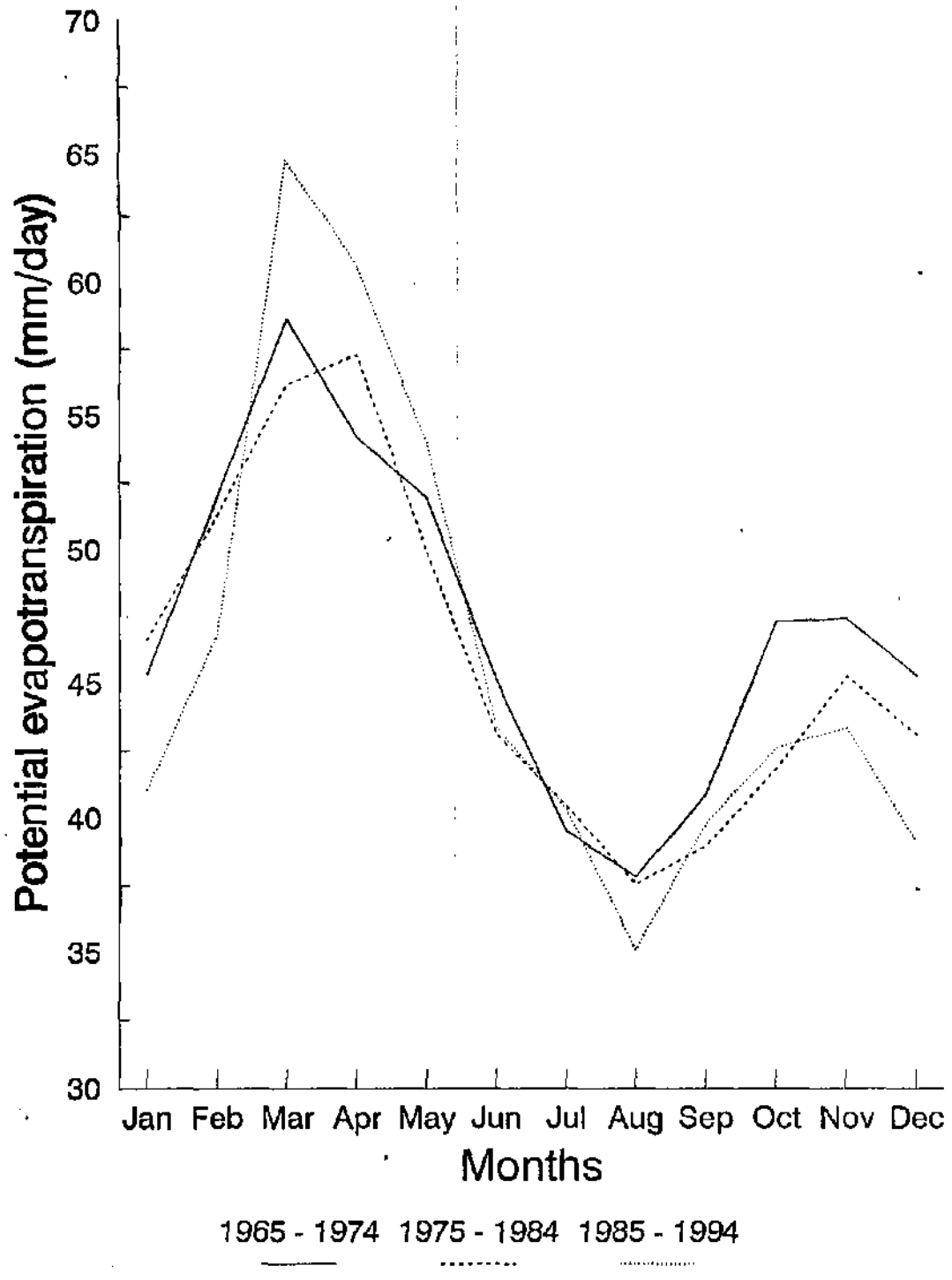


Fig.19:Decade variation of potential evapotranspiration (mm\day)

1975-1984: There is a significant difference (P = 0.05) among the months. Month of April estimated the highest PET, followed by March and August estimated the lowest. Ther is also a highly signifiicant difference among the methods, when their means were compared using least significant difference (LSD) t 5%, the results are as followed: Hamon (13.3), Penman (7.92), Jensen Haise (7.78), class A pan (6.29) BMN (5.69) and Makkink (5.16mm).

1985-1994: There is a significant difference among the months at 5%. Months of March and April have the highest PET while August has the lowest. There is also a highly singificant difference among the methods as in the other decades.

There is a highly significant difference among the 30 years at 5%. When their means were compared using LSD, 1983 estimated the highest PET. Years, 1969, and 1971 are significantly the same. This was followed by 1965, 1966, 1967, 1968, 1972, 1973, 1979, 1987 and 1990 which are significantly the same. There is no significant difference among the years 1970, 1974, 1975, 1977, 1978, 1980, 1981, 1982, 1984, 1986, 1988, 1989 and 1991. 1985 and 1993 are significantly the same: PET estimation was lowest in 1994. This is shown on Table 12.

4.4.3 Comparison of Estimates with measured Potential Evapotranspiration

The distribution patterns for PET by both adjustment and non-adjustment BMN equation compared with pan and microlysimeter measurements. There is a highly singificant difference among the

Table 12: Mean yearly pooled potential evapotranspiration determined by the five equations

S/No	Years	Mean	Ranking
1.	1983	8.32	A
2.	1971	8.15	a,b
3.	1969	8.105	a,b
4.	1966	7.98	a,b,c
5.	1965	7.97	a,b,c
6.	1987	7.96	a,b,c
7.	1968	7.95	a,b,c
8.	1990	7.95	a,b,c
9.	1973	7.94	a,b,c
10.	1967	7.91	a,b,c
11.	1972	7.91	a,b,c
12.	1979	7.87	a,b,c
13.	1977	7.815	a,b,c,d
14.	1981	7.83	a,b,c,d
15.	1970	7.78	a,b,c,d
16.	1980	7.69	a,b,c,d
17.	1989	7.69	a,b,c,d
18.	1991	7.67	a,b,c,d
19.	1978	7.59	a,b,c,d
20.	1986	7.59	a,b,c,d
21.	1982	7.52	a,b,c,d
22.	1984	7.52	a,b,c,d
23.	1992	7.51	a,b,c,d
24.	1975	7.48	a,b,c,d
25.	1988	7.48	a,b,c,d
26.	1974	7.46	a,b,c,d
27.	1993	7.36	b,c,d
28.	1985	7.26	b,c,d
29.	1976	7.15	c,d
30	1994	6.94	D

CV = 8.45, R^2 = 0.95, SE = 0.65, at 5%

Table 13a: Mean-Monthly adjusted BMN, Penman and Makkink equation for Pan evaporation

Month	Adjusted BMN	Adj.Makkink	Adjusted Penman
Jan	6.57	6.59	6.54
Feb	7.41	7.44	7.43
Mar	8.16	8.12	8.12
Apr	7.40	7.43	7.48
May	6.32	6.31	6.37
Jun	7.40	5.65	5.64
Jul	5.64	5.16	5.14
Aug	4.82	4.85	4.84
Sept	4.77	4.77	4.77
Oct	5.08	5.07	5.05
Nov	6.02	6.06	6.06
Dec	6.43	6.42	6.40

Table 13b: Adjustment factors for BMN, Penman and Makkink equation for microlysimetric PET

Month	BMN	Penman	Makkink
Aug.	0.93	0.75	0.66
Sept.	1.13	0.86	0.82
Oct.	1.12	0.81	0.70

days (P = 0.05) for every ten days when the data was analysed using analysis of variance (Anova). The coefficient of variations among the days was 16.6% with standard error of 0.89. Coefficient of variation of the interraction between the days and methods is 14.9% with standard error of 0.8. There is very highly significant difference between the methods at 5% when the means of the methods were compared with LSD, the results were as followed, Hamon (12.83), Jensen Haise (5.98), Makkink (4.33), Class A Pan (4.11), Penman (3.87), microLysimeter (3.11) and BMN (3.07). The results showed that BMN predicted closest to microlysimeter than any other method.

When the predicted methods were correlated with the measured data of microlysimeter and class A pan evaporation, BMN was highly correlated (r = 0.92) with pan evaporation, followed by Penman (r = 0.90) BMN is significantly correlated (r = 0.68) with microlysimeter only.

4.4.4 Determination of Adjustment factors for BMN, Penman, Makkink and Monteith.

Blaney- Morin Nigeria (BMN), Makkink and Penman equations estimated PET close to pan evaporation and microlysimetric data in this study. Monteith equation was better to estimate soil evaporation than Penman equation. Therefore, adjustment factors are determined for both BMN, Penman, Makkink and Monteith equations so that they can predict PET and soil evaporation, respectively, as accurate as pan evaporation and microlysimetric

data.

The computer program gives the estimates of PET and soil evaporation by BMN, Penman, Makkink and Monteith equations; corresponding daily measured PET from pan and microlysimeter readings were obtained. Daily values of PET and soil evaporation for both methods were summed up into monthly values for the years 1965 - 1994 and 1996 - 1997, respectively. From these, ratios of pan to BMN , microlysimeter to BMN and Monteith were computed and averaged over the thirty years and two years. These were used as adjustment factors as presented in Table 16. The BMN, Penman, Makkink and Monteith equations were recomputed with the adjustment factors multiplying each daily estimates. The summation repeated for monthly and annual ratio of estimates to measured PET and evaporation calculation. The monthly mean values were compared using analysis of variance (ANOVA), regression and correlation.

Table 15 shows the longterm mean-monthly ratios of potential evapotranspiration (PET) by BMN, Penman and Makkink to that measured by pan and microlysimeter at Samaru. There was a great improvement of accuracy of estimations as a result of adjustment factors in the three equations. Mean monthly error of estimations fall within $\pm$13% for all months for BMN method with adjustment factors. However, the mean ratios were low between 10.73 to 0.94) in most of the months. Figs. 21-24 show graphical comparisons of PET by both methods with or without adjustment factors for each of

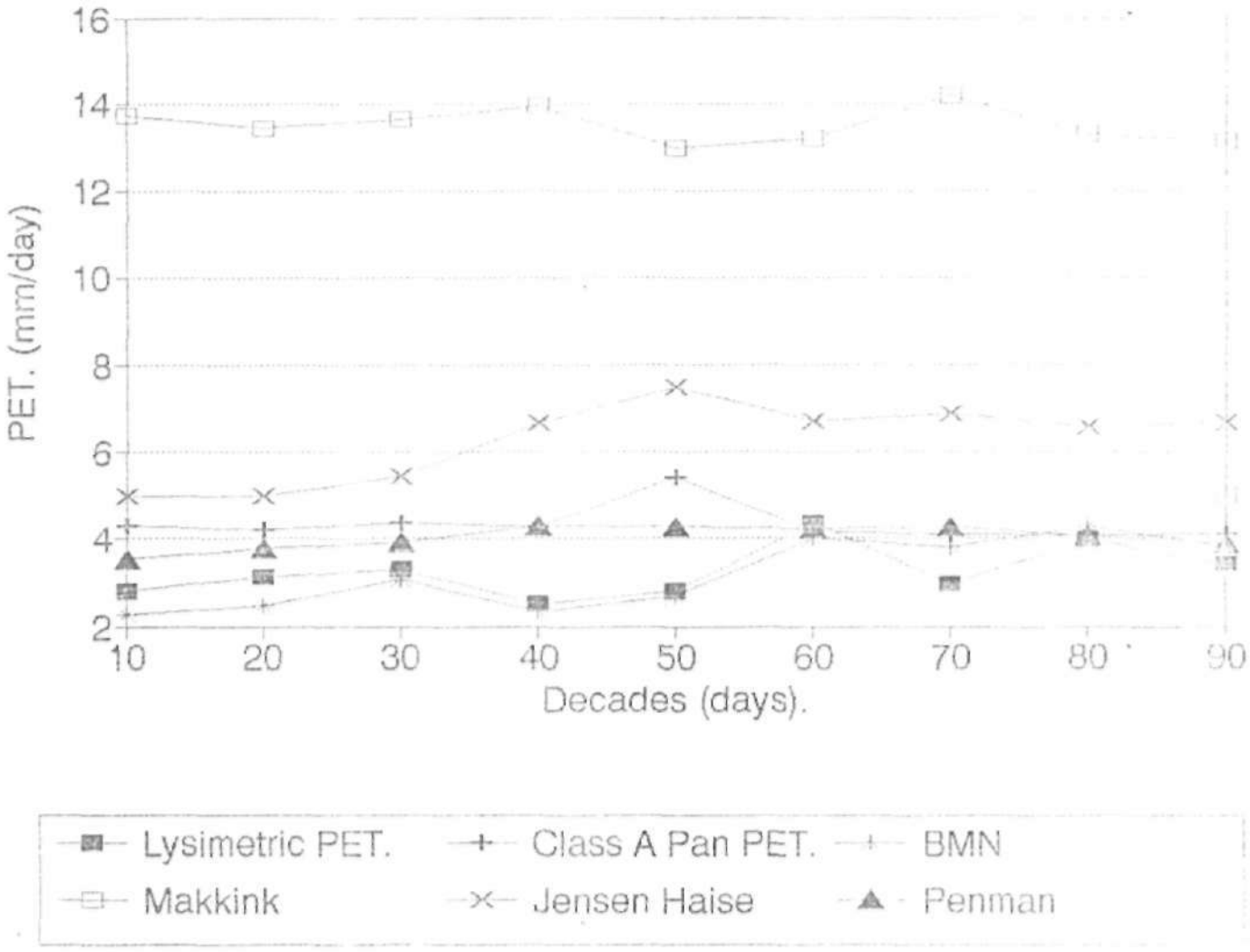
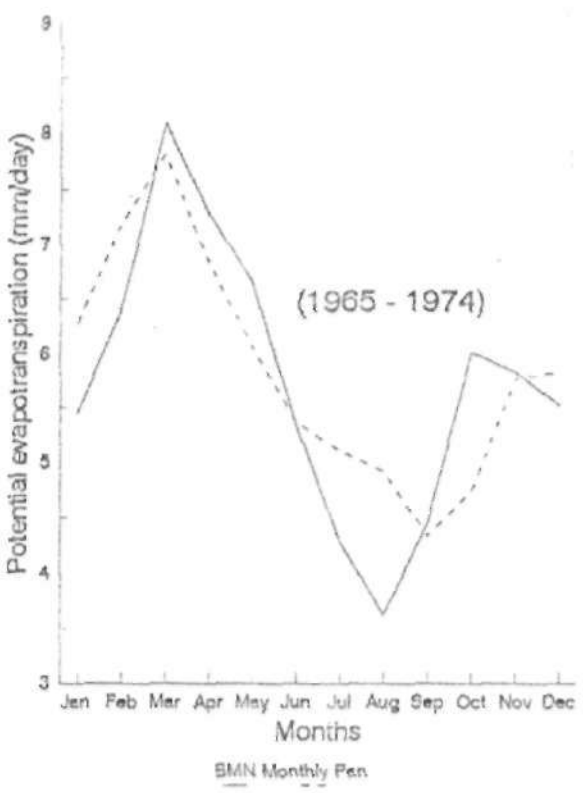
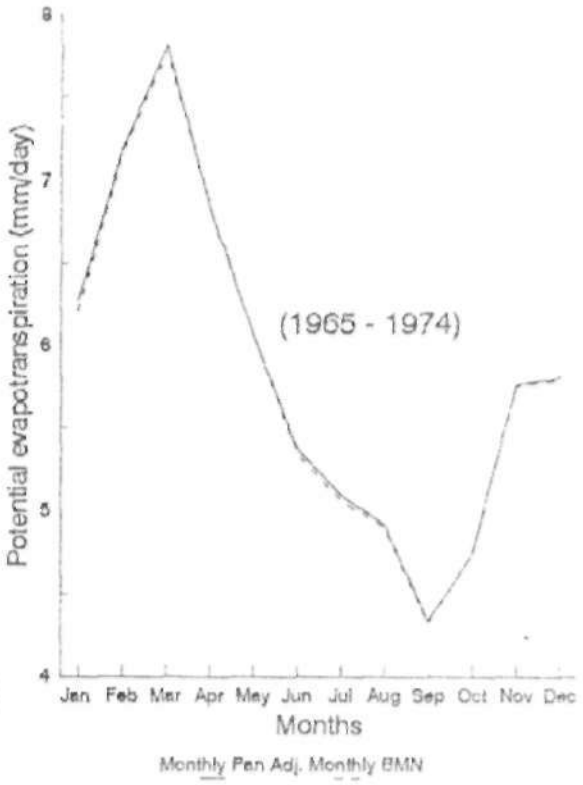


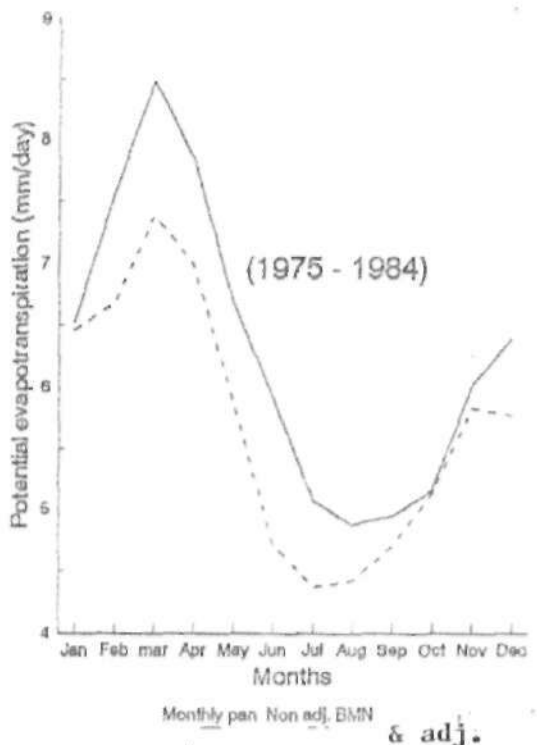
Fig. 20: Mean daily potential evapotranspiration mm/day, (1996 - 1997)



BMN Monthly Pan



Monthly Pan Adj. Monthly BMN



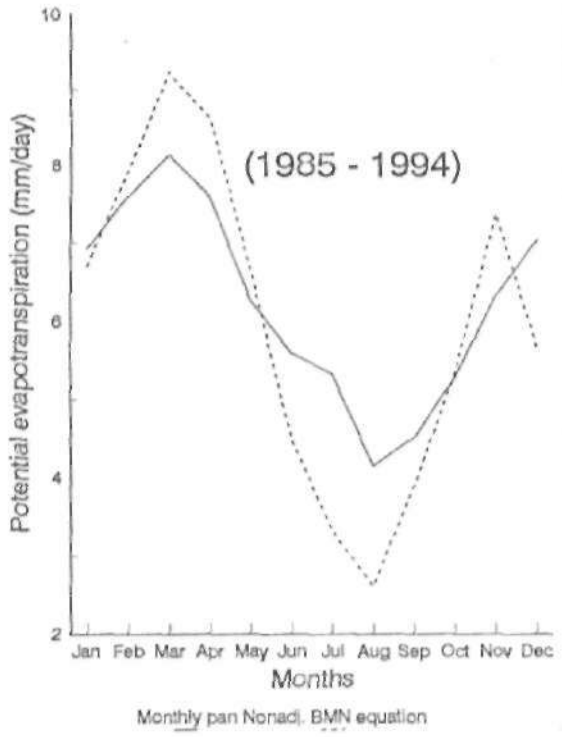
Monthly pan Non adj. BMN



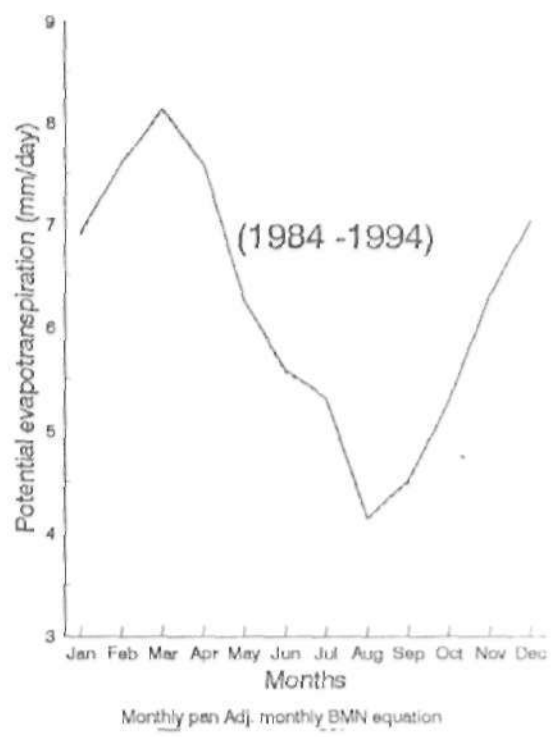
Monthly pan Adj. monthly BMN

& adj.

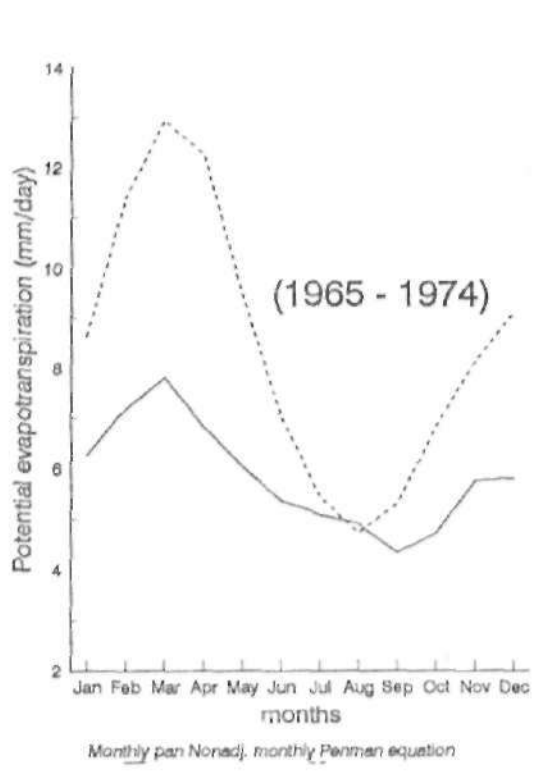
Fig. 21 Non-adj. monthly BMN Equation



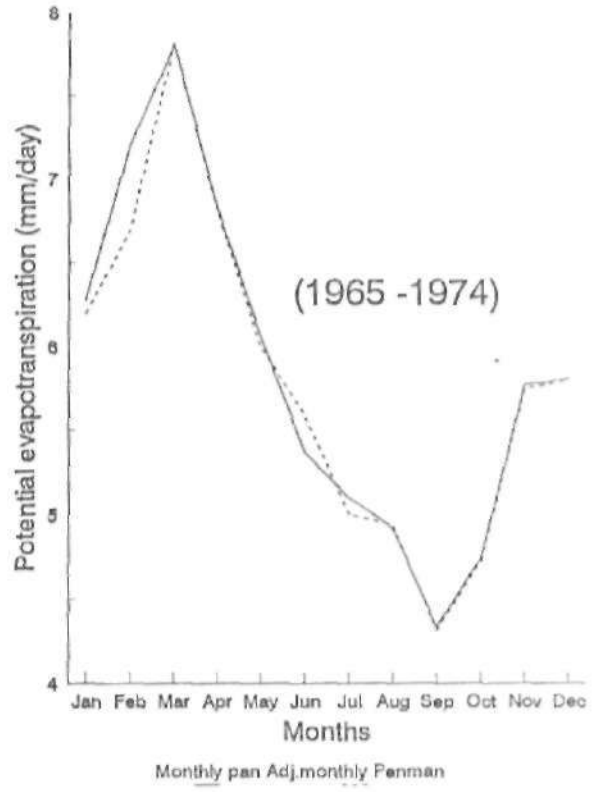
Monthly pan Nonadj. BMN equation



Monthly pan Adj. monthly BMN equation

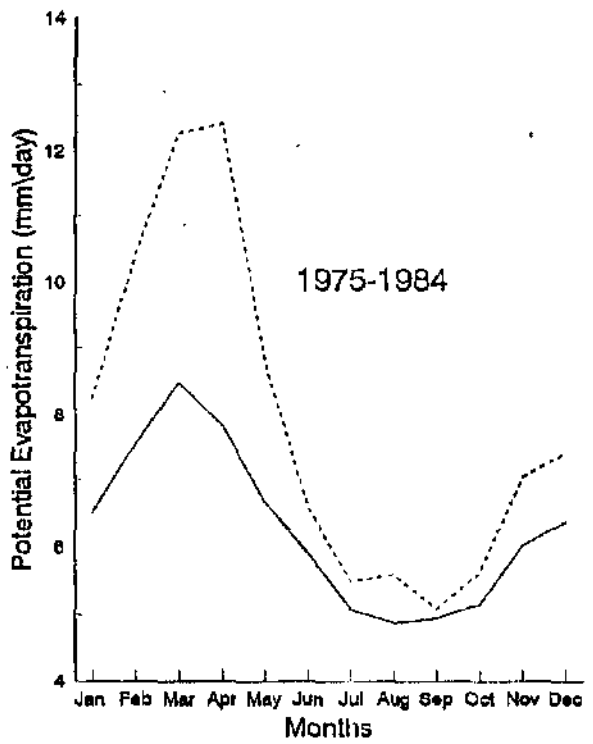


Monthly pan Nonadj. monthly Penman equation

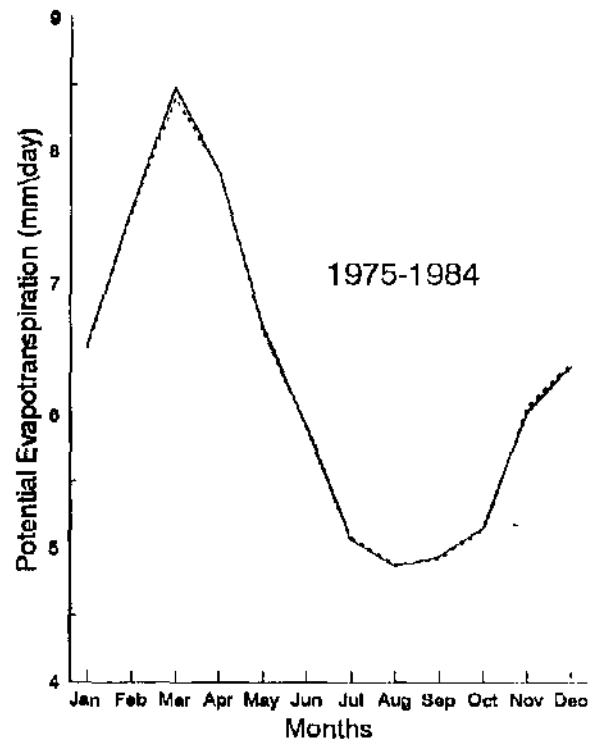


Monthly pan Adj.monthly Penman

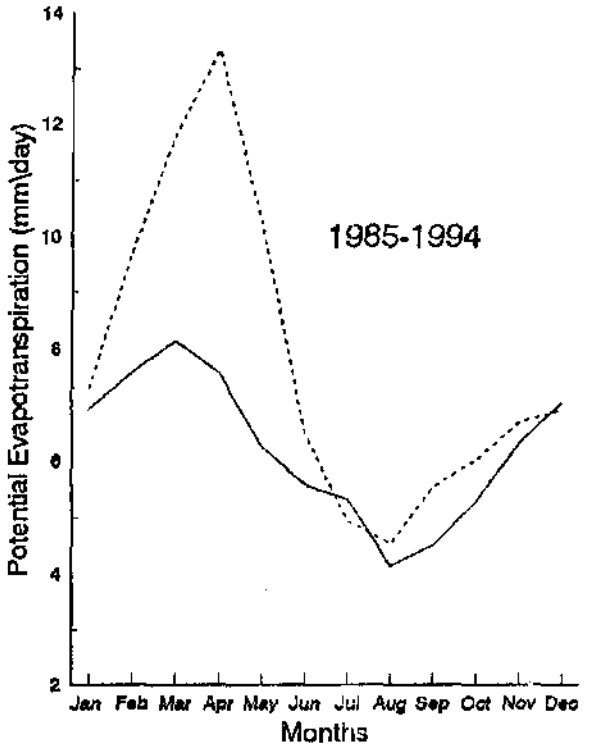
Fig. 21B: Non-adj. and adj.BMN and Penman equations



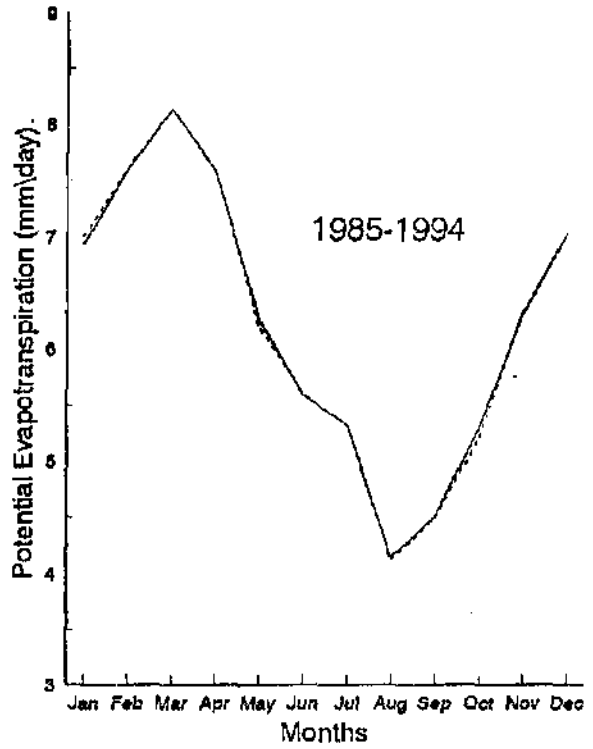
Non-adj. Penman Equation.



Adj. monthly Penman Equation.



Non-adj. monthly Penman Equation

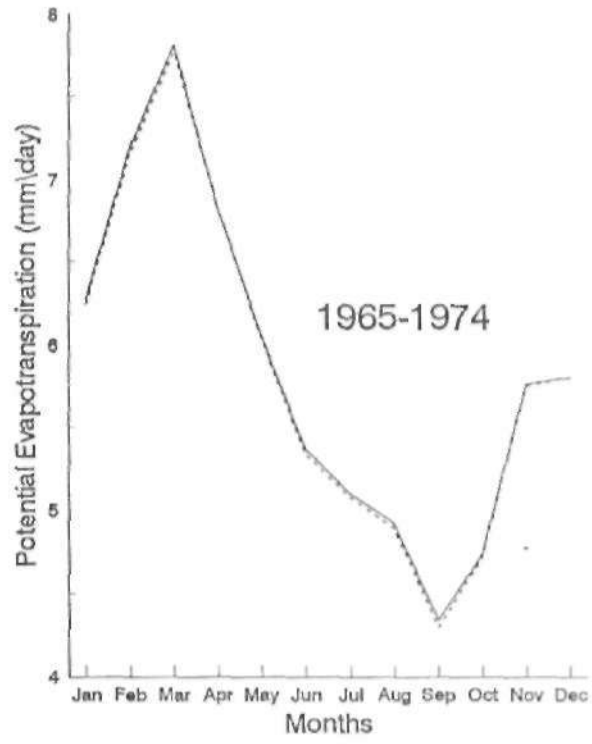


Adj. monthly Penman equation.

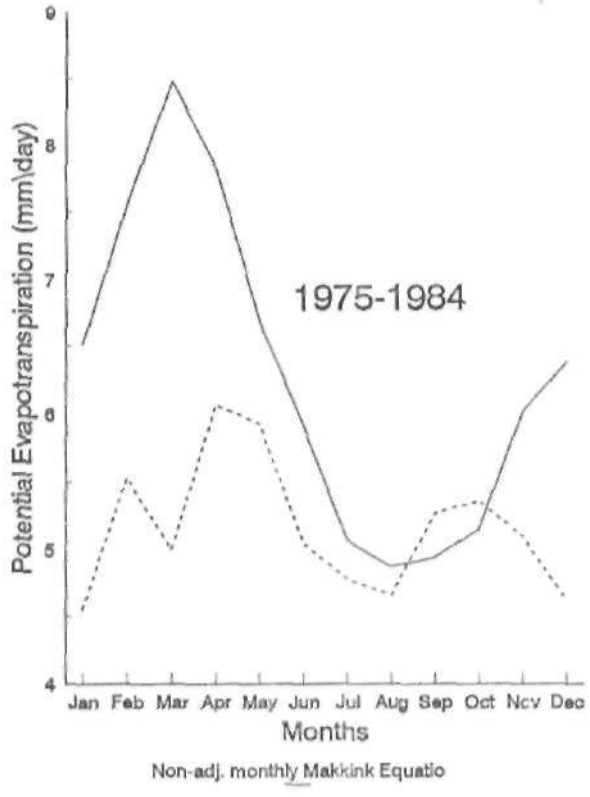
Fig.22: :Non-adj. & adj.monthly Penman equation.



Non-adj.monthly Makkink Equation



Adj.monthly Makkink Equation.



Non-adj. monthly Makkink Equatio

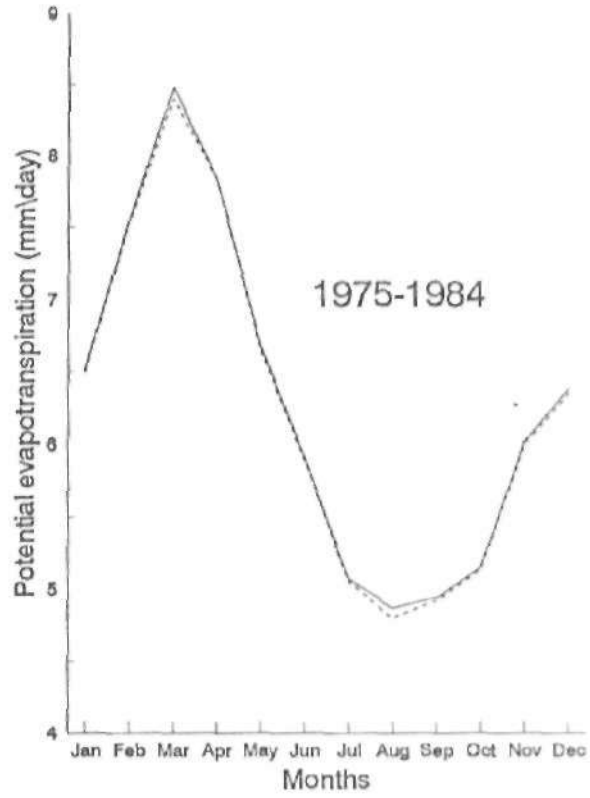
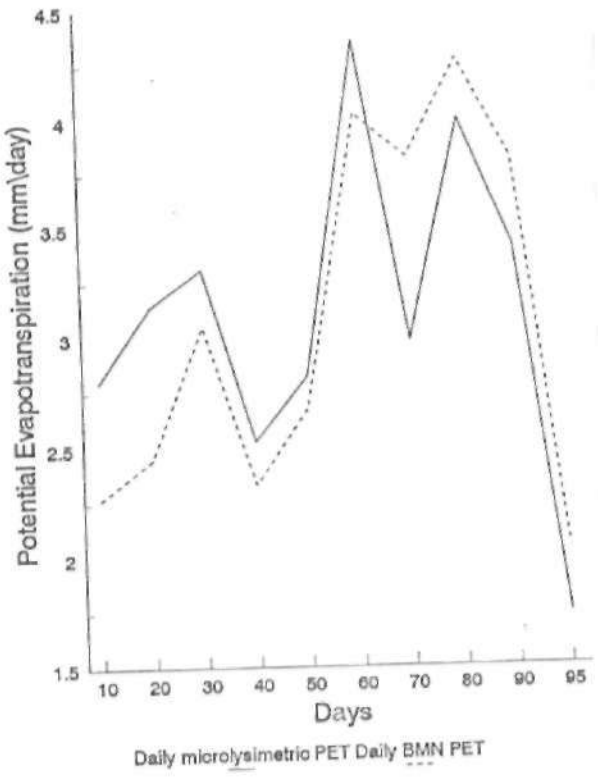
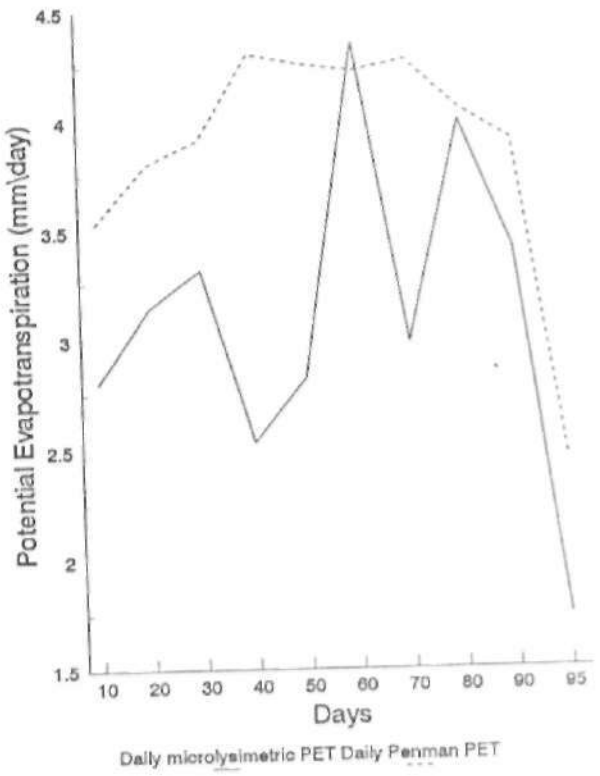


Fig. 23a ;Non-adj. & adj.monthly Makkink equation.





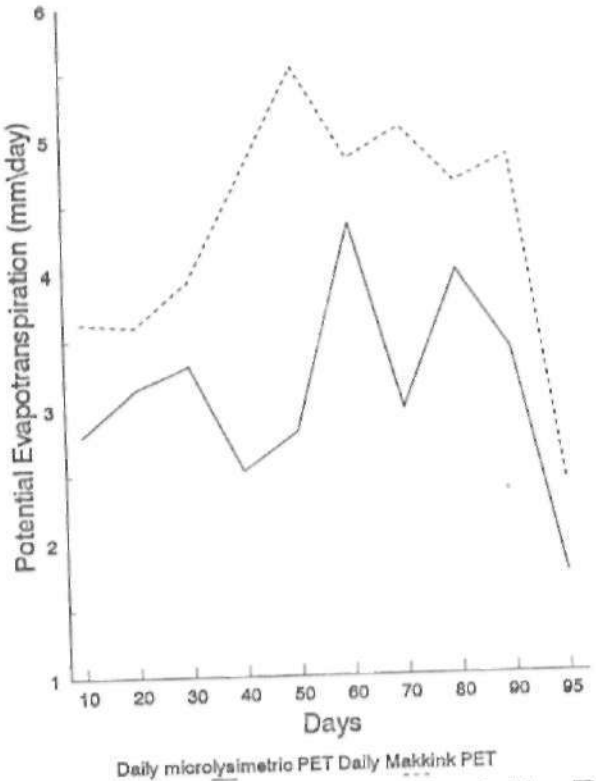


Fig. 23b :Non-adj. daily Penman & Makkink equations.

the decade. It was observed from these figures, that the monthly patterns were similar from year to year. PET are high in the first and last quarter of each year. It was lower for the period of April to September and lowest in the month of August. The peak often occur in the months of March. According to Jagtap et al (1995), this may be as a result of high incident solar radiation due to low cloud cover.

Mean seasonal error of estimates are presented on Table 14.0. For the period of November to March, the mean seasonal error of estimations improved from 7.66% to -2.63% and from 10.25% to 1.15% for the period of April to October. On yearly basis, the error of adjusted BMN improves highly from a longterm mean of 4.9% to 0.11%, when adjustment factors were introduced. Monthly estimates were highly correlated with measured values in all the years as it is observed in Table 15.0, the coefficient of determination (R^2). The values of coefficient of variation were computed and these were less than 16% for the 30 years. This shows that the adjusted BMN can evaluate PET accurately. The accuracy and precision being shown by low C.V. values. The slope of relationship of adjusted BMN estimates to measured PET by class A pan was computed using regression analysis as included in Table 15.0 and all are less than one. The intercepts are very near to zero. This means that monthly PET can be predicted to between 89-100% accuracies.

The equation relating BMN equation to microlysimetric PET is given by:

Microlysimetric PET (Y) = 1.38 + 0.59 BMN

Table 14: Mean seasonal error of estimates for Pan evaporation

Period	Nov. - March		April - October	
	Without factor	with factor	Without factor	with factor
	+ 7.66%	2.63%	+10.25	1.15%
	Microlysimeter Aug. - Oct			
	Without factor	with factor		
	+4.41%	0.60%		

Table 15: Annual Ratio, mean PET with C.V, R^2 and Regression result for adjusted BMN equation at Samaru

Year	Ratio 1	Mean Annual BMN (mm)	Total Mean PET Pan (mm)	Ratio 2	C.V	R^2	Slope (b)	Inter-cept. a
1965	0.98	69.02	70.62	1.02	13.47	0.37	0.68	0.14
1966	0.99	68.23	68.61	1.01	15.44	0.43	0.67	0.14
1967	1.06	69.05	65.11	0.95	8.78	0.34	0.65	0.17
1968	1.02	68.93	67.80	0.98	14.96	0.20	0.68	0.17
1969	1.02	70.15	68.63	0.98	6.89	0.18	0.67	0.12
1970	0.96	69.97	72.57	1.04	10.70	0.25	1.16	-0.17
1971	0.88	64.75	73.28	1.13	9.0	0.33	0.73	0.18
1972	0.98	68.94	70.11	1.02	10.55	0.44	1.27	-0.22
1973	0.95	71.54	75.31	1.06	8.5	0.45	0.77	0.21
1974	0.92	69.12	75.47	1.09	15.58	0.42	0.74	0.18
1975	0.96	68.35	71.03	1.02	15.71	0.38	0.70	0.16
1976	0.76	52.86	69.83	1.32	15.95	0.55	1.0&	-0.19
1977	0.93	67.88	73.20	1.08	10.82	0.33	0.74	0.20
1978	0.94	66.68	71.19	1.07	7.88	0.26	0.69	0.15
1979	0.94	67.82	72.26	1.07	8.27	0.48	0.74	0.21
1980	0.95	68.20	71.69	1.05	6.1	0.37	1.03	-0.16
1981	0.89	70.83	79.96	1.12	12.82	0.29	1.14	-0.23
1982	0.86	68.25	79.96	1.17	12.47	0.0.7	0.73	0.11
1983	0.98	84.42	86.48	1.02	7.50	0.35	0.93	0.33
1984	0.84	66.62	78.94	1.18	14.16	0.60	0.88	0.34
1985	0.97	71.51	74.1	1.03	8.61	0.15	0.70	0.12
1986	0.99	70.49	71.48	1.01	12.99	0.41	0.75	0.24
1987	1.04	76.60	73.94	0.96	15.45	0.26	0.76	0.22
1988	1.02	74.03	72.27	0.98	13.59	0.31	0.75	0.22
1989	1.00	80.1	80.1	1.00	13.35	0.35	0.83	0.25
1990	0.98	72.49	73.51	1.01	15.86	0.30	0.77	0.24
1991	1.08	79.8	73.88	0.92	12.24	0.065	0.68	0.097
1992	0.76	69.07	90.54	1.31	15.23	0.011	0.78	0.033
1993	0.99	76.13	76.73	1.01	14.24	0.064	0.68	0.064
1994	0.97	62.93	64.88	1.03	12.72	0.30	1.14	-0.27

Table 16: 1996-1997 Monthly predicted and measured PET (mm/day)

Month	micrôly-simeter	BMN	Hamon	J. Haise	Pen	Makk
Aug.	63.79	68.58	282.31	131.96	85.15	96.23
Sept.	89.74	79.48	375.07	153.68	104.16	108.92
Oct.	143.15	142.47	757.61	283.94	175.62	205.29

Table 17: 1996-1997 Monthly ratios of the 5 equations to the microlysimetric PET

Month	BMN	Hamon	J. Haise	Penman	Makkink
Aug.	1.08	4.43	2.07	1.33	1.51
Sept.	0.89	4.18	1.71	1.16	1.21
Oct.	1.00	5.27	1.98	1.23	1.44

$P < 0.001$, R^2 (adj.) = 0.99

S = 0.38

Pan evaporation, X = -1.55 + 1.20 BMN

$P < 0.001$, R^2 = 90%, SE = 0.58

For Penman equation to microlysimetric PET

Y = 2.58 + 0.17 Penman

R^2 = 1.000, SE = 0.62

Pan evaporation, X = -0.051 + 1.007 Penman

R^2 = 99.97%, SE = 1.17

For adjusted Makkink equation to microlysimetric PET

Y = 0.5 + 0.99 Makkink

Pan evaporation, X = 3.79 + 0.23 Makkink

R^2 = 0.95 SE = 14

P = 0.52

In general, it is concluded from the data presented in the tables that all the equations transform the climatological data into statistically different sets of PET values. Under subhumid condition such as obtains in Samaru, (Northern Guinea Savanna) none of the five equations yielded similar results for monthly values of PET.

There is agreement among some equation for particular months. These are mainly the BMN and Penman equations, Penman and Jensen Haise equations. The comparisons, however, are not favourable for the dry season, which is period of greatest interest for irrigation studies and design purposes.

The yearly averages and long term maximum expected PET values

are statistically different for all equations. This is particularly important in determining the adequacy of a water supply for irrigation projects.

It is shown by the data presented that some equations will yield similar results of PET for the wet season. This indicates that there are several equations that may be used for certain types of hydrological studies requiring information during the wet season.

The BMN equation is generally estimated from mean air temperature and relative humidity. Sensitivity to relative humidity increase with temperature. The equation yielded high values of PET at high temperature and low values of PET at low temperture as compared with pan evaporation. It is expected that this equation will behave in this way in warm arid conditions and give low estimates of PET at lower temperatures. The equation peaks rapidly with high temperatures.

It is suggested in order to improve the BMN relationship, that a variable coefficient be included in the equation in such a way as to increase both the temperature sensitivity and the relative humidity sensitivity at low and medium temperature conditions. It is a matter of introducing adjustment factor from the ratio of BMN to pan evaporation.

Three of the equations, Penman, Makkink and BMN are solar radiation dependent. There is a favourable comparison between the BMN and Penman equations and the pan evaporation data, for most of the months (majority of the year). Hamon equation overestimates

both pan evaporation and microlysimetric data for the entire months of the year.

Penman relationship has the best theoretical basis for estimating PET of the five equations studied (Duru, 1979). The Penman vapor pressure deficit sensitivity has a large effect on PET but its temperature sensitivity is low compared with all other relationships.

The Jensen Haise method, which uses only two climatic variables, is the equation that offers the best substitute to the Penman relationship when adequate input data for the Penman equation are not available. The accuracy of the Jensen Haise equation, when measured solar radiation data do not exist, will depend directly upon the precision with which this parameter can be estimated.

The Makkink equation yields systematic results very much below the other three solar radiation equations. The largest influence is obtained for the lowest temperature and highest solar radiation conditions. This behaviour explains the low values of PET obtained for wet conditions. This equation may be improved by increasing the sensitivity of PET to temperature as the temperature increases.

Hamon equation which is the function of possible day sunshine hours and saturated vapor density and a regional coefficient can be improved by introducing an adjustment factor or reducing the regional coefficient.

4.5.0 Correlation and Path Coefficient Analyses

4.5.1 Correlation

A simple correlation analysis was done to determine the relationships between microlysimetric PET, pan evaporation, climatic factors and within climatic factors (Table 18.0). There was significant (at P = 0.01) positive correlations between lysimetric PET and air temperature in both years, soil temperature in 1996, relative humidity in both years, radiation in 1997, sunshine hours in 1996 combination of wind speed and relative humdity in both years. The climatic factors have significant positive correlation with pan evaporation - windspeed, air and soil temperatures, air temperature and relative humidity, air temperature and sunshine hours, soil temperature and relative humidity, soil temperatutre and solar radiation, soil temperature and sunshine hours, solar radiation and sunshine hours. Solar radiation and air temperature had the highest correlation coefficient (0.893 and 0.742) and soil temperature (0.117) had the lowest correlation coefficient with microlysimetric PET. Relative humidity had the lowest correlation with the other climatic factors tested.

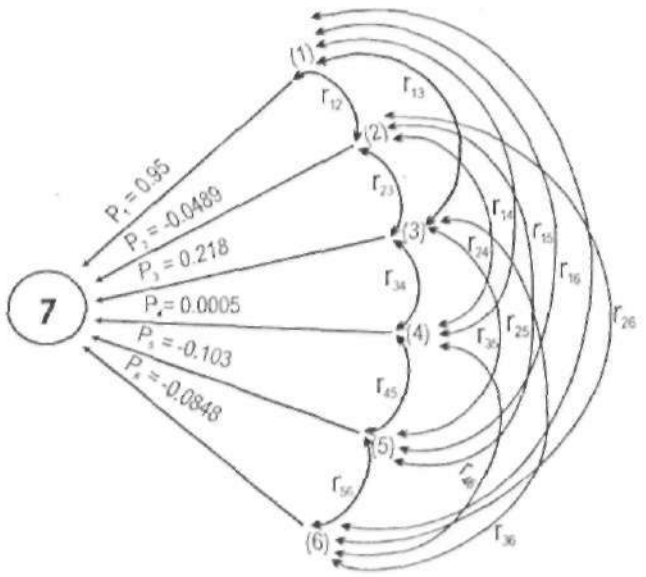
4.5.2 Contribution of Climatic Factors on Microlysimetric PET and Pan Evaporation

Direct effect (Pi) and coefficient of correlation rij of air temperature, windspeed, relative humidity, sunshine hours, soil temperature, solar radiation, microlysimetric potential

evapotranspiration (PET) and pan evaporation are given in Fig. 25a and 25b for 1996 and 25c and 25d for 1996 and 1997 respectively. The direct and indirect contributions are given in Table 19.0 and results are discussed with reference to this table.

Windspeed and Potential Evapotranspiration (PET).

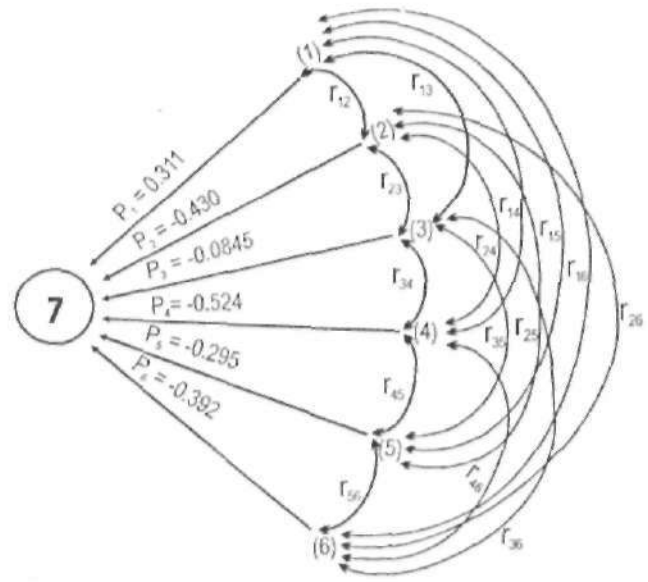
Total contributions of windspeed were found to be -0.101 and 0.217 for microlysimetric PET and, 0.365 and 0.284 for pan evaporation in 1996 and 1997; respectively (Table 19.0) when these contributions were examined for direct and indirect effects it was observed that the direct contribution of the total windspeed was in microlysimetric PET as compared with 0.365 and 0.284 for pan evaporation. The indirect contribution via temperature was found to be positive in almost the entire two years except for microlysimetric PET in 1997. The contribution was very small and ranged from 0.00557 to -0.0861 for microlysimetric PET and 0.049 to 0.01716 for pan evaporation. The indirect contribution of windspeed via soil temperature was positive in microlysimetric PET and pan evaporation during 1996 and 1997, respectively. It ranged from -0.01199 to 0.204 in PET and 0.00465 to -0.249 in pan evaporation. The total contribution of air temperature on potential evapotranspiration was found to be 0.0406 and 0.274 for microlysimeter in 1996 and 1997, respectively and correspondingly -0.502 and 0.246 for pan evaporation.



r12 = -0.441
r13 = 0.155
r14 = -0.481
r15 = -0.517
r16 = -0.438
r23 = 0.661
r24 = -0.911
r25 = 0.878
r26 = 0.773
r34 = -0.552
r35 = 0.584
r36 = 0.526
r45 = -0.637
r46 = -0.707
r56 = 0.769

(a): 1996 Microlysimetric PET.

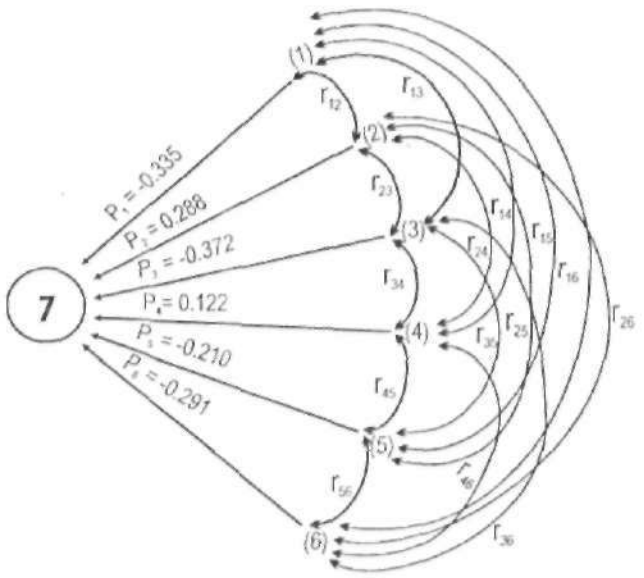
(1) Windspeed
(2) Air temperature
(3) Soil temperature
(4) Relative humidity
(5) Solar radiation
(6) Sunshine hours.



r12 = 0.441
r13 = 0.336
r14 = -0.284
r15 = -0.428
r16 = -0.228
r23 = 0.961
r24 = -0.715
r25 = 0.878
r26 = 0.773
r34 = -0.814
r35 = 0.602
r36 = 0.632
r45 = -0.584
r46 = -0.818
r56 = 0.764

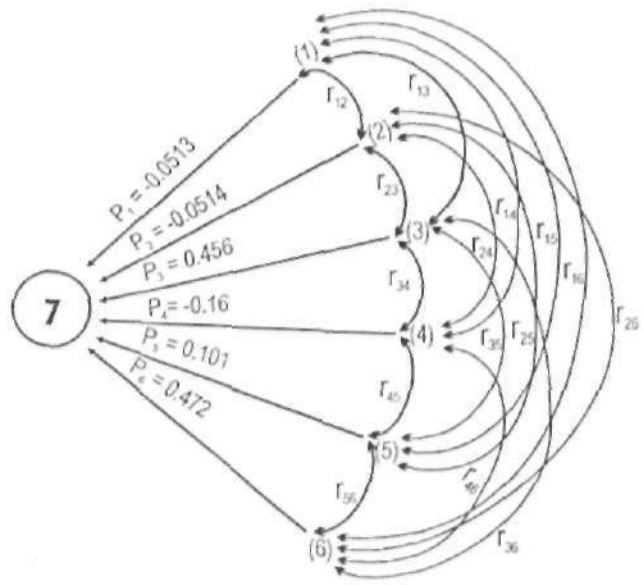
(b): 1996 Pan evaporation.

Fig24.: Contribution of windspeed (1), air temperature (2), soil temperature (3), relative humidity (4), solar radiation (5) and sunshine hours (6) to microlysimetric PET (a) and pan evaporation (b) in 1996.



r_{12} = 0.399
r_{13} = 0.548
r_{14} = 0.463
r_{15} = -0.319
r_{16} = -0.341
r_{23} = 0.508
r_{24} = -0.863
r_{25} = 0.878
r_{26} = 0.773
r_{34} = 0.552
r_{35} = 0.584
r_{36} = 0.526
r_{45} = -0.367
r_{46} = -0.707
r_{56} = 0.709

c): 1997 Microlysimetric PET.



r_{12} = 0.315
r_{13} = 0.458
r_{14} = 0.363
r_{15} = -0.119
r_{16} = -0.184
r_{23} = 0.703
r_{24} = 0.931
r_{25} = 0.776
r_{26} = 0.634
r_{34} = -0.584
r_{35} = 0.694
r_{36} = 0.572
r_{45} = 0.486
r_{46} = 0.087
r_{56} = 0.566

d): 1997 Pan evaporation.

Fig. 25 Contribution of windspeed (1), air temperature (2), soil temperature (3), relative humidity (4), solar radiation (5) and sunshine hours (6) to microlysimetric PET (a) and pan evaporation (b) in 1997.

Air Temperature and PET

The direct contributions of air-temperature were positive (0.288) in 1997 and negative (-0.0489) in 1996 for microlysimeter and 0.43 and -0.0574 in both years for pan evaporation (Table 19.0). The range in the pan evaporation was wider when compared with the microlysimeter PET due to a large variation in the available moisture. The indirect contribution via windspeed was very small (-0.0355 and 0.03287) for the pan when compared with the microlysimeter (0.01083 and 1.00). The indirect effect of air temperature via soil temperature was only negative in 1997 for microlysimeter and in 1996 for pan evaporation.

Soil Temperature and PET

The direct contribution of soil temperature on potential evapotranspiration (PET) was negative and very low for microlysimeter and pan evaporation in 1997 and 1996 respectively (Table 19.0). It was 0.218 and -0.372 for microlysimeter and -0.0845 and 0.456 for pan evaporation. Indirect contribution of soil temperature via windspeed was found to be more erratic for both microlysimeter and pan evaporation in 1997 and 1996 (0.180 and 0.1552) as well as 1996 (microlysimeter) and for pan evaporation (0.00525 and 0.02811) in 1997. The indirect contribution of soil temperature via air temperature was -0.01765 and 0.0873 for pan evaporation. The total contribution of soil temperature on microlysimeter was lower (0.206 & -0.007) in

comparism with pan evaporation (-0.257 and 0.467).

Relative Humidity and PET

The Total contribution of relative humidity was found to be lower in pan evaporation (-0.048 and -0.140) when compared with the microlysimeter (0.110 & 0.170) Table 19.0. The direct contribution of relative humidity was found to be higher (0.0005 and 0.122) for microlysimeter when compared with pan evaporation (-0.524 and -0.16) the contribution of relative humidity via solar radiation was found to be negative only in 1997 for pan evaporation. The contribution was very small for microlysimeter and pan evaporation (0.0656 and 0.0239) and (0.188 and -0.0182), respectively. Contribution of relative humidity via sunshine hours was positive (0.0439 and 0.0239) for microlysimeter and (0.288 and 0.0387) for pan evaporation.

Solar Radiation and PET

The direct contributions of solar radiation were negative (-0.103 and -0.295) in 1996 for both microlysimeter and pan evaporation but positive in 1997 (0.21 and 0.161) Table 19.0. The range in 1997 was much wider when compared with the 1996 evaporation. Indirect contribution of solar radiation via relative humidity was very small in microlysimeter (-0.000319 and 0.0139) for both years when compared with pan evaporation (0.334 and -0.256). The indirect contribution of solar radiation via sunshine hours was (-0.0599 and -0.0329) for microlysimeter and -

0.392 and 0.0406 for pan evaporation. The total contribution of solar radiation on microlysimeter and pan evaporation was found to be -0.163 and 0.191 and (-0.353 and -0.054), respectively.

Sunshine Hours and PET

The total contributions of sunshine hours were found to be -0.157 and 0.283 for microlysimeter and -0.271 and 0.472 for pan evaporation (Table 19.0) when these contriutions were examined for direct and indirect effects it was observed that the direct contribution of the total sunshine hours was -0.0848 and 0.291 for microlysimeter and -0.556 and 0.472 for pan evaporation. The indirect contribution of sunshine hours via relative humidity was very small for microlysimeter (0.000259 and 0.010) when compared with pan evaporation (0.271 and 0.273). There was a very small contribution of total sunshine hours via solar radiation (-0.0727 and -0.273) for pan evaporation.

4.5.3 Percentage Contribution of Climatic Factors on Potential Evapotranspiration

Simple correlation coefficient between microlysimetric PET and pan evaporation, climatic factors and within climatic factors are given in Tables 18-20 while Table 20 gives the direct and combined percentage contribution of climatic factors on potential evapotranspiration.

In microlysimetric PET, the lowest contribution of 0.000025% and 1.49% were made by relative humidity in 1996 and 1997,

respectivley. Relative humidity contributed maximum value of 27.46% and 2.56% to pan evaporation. Similarly, windspeed directly contributed 0.9% and 11.22% to microlysimetric PET, 9.67% and 0.26% to pan evaporation.

Sunshine hours directly contributed 0.72-8.47% to microlysimetric PET, which were 30.91% and 22.28% in pan evaporation. The direct contributions of soil temperature to PET and pan evaporation were 4.75% and 13.84%, 0.71% and 20.79% respectively. Solar radiation directly influenced PET and pan evaporation. Its contributions were 1.06 and 4.47, 8.70 and 2.59%, respectively.

The combined contributions of windspeed and air temperature were -17.89% and 5.77% in the microlysimetric PET while they were 3.05 and -0.18 in the pan evaporation. The combined effect of windspeed and soil temperature ranged between -1.50 to -13.66 in microlysimeter and from 0.29 to 2.56 in pan evaporation. Thus there was an inconsistency in contribution even within the two methods. Similarly combined contributions of windspeed and relative humidity were -2.83% and 1.77% in microlysimeter and -11.90% and 0.43% in pan evaporation. The combined effect of windspeed and radiation were smaller (-2.90% and 0.27%) in microlysimeter compared with 9.49% and -0.03% in pan evaporation. Combined contributions of windspeed and sunshine hours were -4.65 and 6.65 in microlysimeter, 15.15 and 1.65% in pan evaporation.

The combined contributions of air temperature and soil temperature to microlysimetric PET were negative in both years (-

0.77 and -6.49) when compared with 2.61% and -1.59% in pan evaporation. A combined effects of air temperature and solar radiation on PET and pan evaporation was found to be negative in the two years of experimentation; they were extremely low (-0.48% and -0.27%) in PET when compared ith the pan evaporation (-4.19 and 0.04%). The combined contributions of air temperature and sunshine hours were found to be -0.92 and 4.21% in PET and (-8.08 and -1.36%) in pan evaporation.

When soil temperature and relative humidity were combined, their contributions were 2.99% and 3.49% to PET, -11.60 and 5.60% to pan evaporation. The combined contributions of soil temperature and solar radiation were -1.62% and 2.36% in PET and (0.63 and -2.22%) in pan evaporation. A combined effect of soil temperature and sunshine hours were much higher in pan evaporation (0.24 and 16.96%) than in PET (-0.63 and -8.53%). Similarly combined contrihbutions of relative humidity and solar radiation were 16.79% and 0.58% in PET, (-19.63 and -0.58%) in pan evaporation. The combined effect of relative humidity and sunshine hours were higher (30.18% and 0.58%) in lysimetric PET than pan evaporation (30.18 and -1.24%). A combination of solar radiation and sunshine hours contributed 23.16% and 10%) in PET and (23.16% and -1.31) in pan evaporation. Thus, what the total contributions (direct and combined) in microlysimetric PET accounted for were found to be 52.28 and 55.70% as against 87.03% and 67.85% in pan evaporation. This leaves the unaccounted residual effect as 47.72% and 44.3% in microlysimetric PET and 13%

and 32.15% in pan evaporation.

The highest contribution on microlysimetric PET and pan evaporation was through sunshine hours which ranged from -0.271 to 0.472. Direct contribution of the total sunshine hours was remarkably higher in the pan evaporation than in the microlysimetric PET. The indirect contribtuion via relative humidity appeared to account for most of the 1997 contribution. Indirect contribution, sunshine hours to pan evaporation and PET via solar radation was found to be very small and negative. This was followed by the total contribtuion of soil temperature which was distinctly higher in pan evaporation when compared with the microlysimeteric PET. The total contribution of each of the climatic factor is very low and negative in 1996. This is as a result of well distributed rainfall which supplied adequate moisture and moderate temperature in 1996. The direct effects of the climatic factors to PET and within themselves in both PET and pan evaporation is higher in 1997 than 1996.

In conclusion, whereas climatic factors contributed significantly to the PET and pan evaporation, the solar radiation and sunshine hours are the most important contributing factors. Sunshine hours contributed more in pan evaporation than microlysimetric PET because pan evaporation has no leaf resistance. It acts like an open lake, therefore, water evaporates easily and more due to its large surface area.

Table 18.0: Simple correlation coefficient between microlysimetric PET, pan evaporation, climatic factors and within climatic factors

Climatic factors	PET		Pan	
	1996	1997	1996	1997
1. PET vs windspeed	0.201	0.188	0.365**	0.284
2. PET vs air temperature	.742**	0.274**	0.502	0.446**
3. PET vs soil temperature	0.496**	0.117	0.501	0.667**
4. PET vs rel. humidity	0.410**	0.395**	0.548	0.490
5. PET vs solar radiation	0.893	0.691**	0.853	0.754
6. PET vs sunshine	0.657	0.483**	0.471	0.572**
Windspeed vs air temp	0.441	0.399	0.411	0.315
Windspeed vssoil temperature.	0.155	0.548	0.336	0.458
Windspeed vs rel. humidity.	0.481**	0.463**	0.284**	0.363**
Windspeed vs solar radiation.	-0.517	-0.319	0.428	-0.119
Windspeed vs sunshine	-0.438	-0.341	-0.228	-0.184
Airtemp vs soil temp.	0.661**	0.508**	0.961**	0.703**
Airtemp vs Rel. humidity	0.911**	-0.863	0.715**	0.931
Airtemp vs Solar radiation.	0.878	0.776	0.878	0.776
Airtemp vs sunshine	0.773	0.634**	0.773	0.634**
Soil temp vs Rel. humidity	0.552**	-0.484	0.814**	-0.584
Soil temp vs solar radiation	0.584**	0.444	0.602**	0.694**
Soil temp vs sunshine	0.526**	0.494**	0.632**	0.572**
Rel. humidity vs solar rad	-0.637	0.595**	-0.584	0.486**
Rel. humidity vs sunshine	-0.707	0.661**	-0.518	0.087**
Solar radiation vs sunshine	0.769**	-0.574	0.764**	0.566

Significant at P = 0.01

Table 19.0: Direct and indirect contributions of climatic factors on microlysimetric PET and pan evaporation at Samaru (1996 to 1997)

Climatic factors	Microlysimetric PET		Pan	
	1996	1997	1996	1997
1. Windspeed and PET				
Direct contribution P1	-0.095	-0.335	0.311	-0.0513
Indirect contribution via air temp.	0.00557	-0.0861	0.040	0.0172
Indirect contribution via soil temp.	-0.01199	0.204	0.00465	-0.249
Total	-0.101	0.217	0.365	0.284
2. Air temperature and PET				
Direct contribution P2	-0.0489	0.288	-0.43	-0.0514
Indirect contribution via windspeed	0.01083	0.100	-0.0355	0.03281
Indirect contribution via soil temp.	0.0787	-0.113	-0.0365	0.1557
Total	0.0406	0.274	-0.502	0.246
3. Soil temperature and PET				
Direct contribution P3	0.218	-0.372	-0.0845	0.456
Indirect contribution via windspeed	0.005225	0.180	-0.1552	0.2871
Indirect contribution via air temp	-0.01765	0.0873	-0.0173	-0.01739
Total	0.206	-0.007	-0.257	0.467
4. Relative humidity & PET				
Direct contribution P4	0.0005	0.122	-0.524	-0.16
Indirect contribution via windspeed	0.0656	0.0239	0.188	-0.0182
Indirect contribution via air temp	0.0439	0.0239	0.288	0.0387
Total	0.11	0.170	-0.048	-0.140

Table 19.0 contd: Direct and indirect contributions of climatic factors on microlysimeteric PET and pan evaporation at Samaru (1996 to 1997)

Climatic factors	Microlysimetric PET		Pan	
	1996	1997	1996	1997
5. Solar Radiation and PET				
Direct contribution P5	-0.103	0.210	-0.295	0.161
Indirect contribution via Rel. hum..	-0.000319	0.0139	0.334	-0.256
Indirect contribution via Sunshine	-0.0599	-0.0329	-0.392	0.0406
Total	-0.163	0.191	-0.353	-0.054
6. Sunshine and PET				
Direct contribution P6	-0.0848	0.291	-0.556	0.472
Indirect contribution via rel. hum.	0.0000259	0.010	0.271	0.273
Indirect contribution via solar rad.	-0.0727	-0.0181	0.014	-0.273
Total	-0.157	0.283	-0.271	0.472

Table 20.0: Direct and combined contribution of climatic factors on microlysimetric PET and pan evaporation presented as percentage

Climatic factors	PET		Pan vaporation	
Direct contribution $(Pi)^2$	1996	1997	1996	1997
Windspeed (P1)	0.90	11.22	7.67	0.26
Air temperature (P2)	0.24	8.29	16.49	0.33
Soil temperature (P3)	4.75	13.84	0.71	20.79
Relative humidity (P4)	0.000025	1.49	17.46	2.56
Solar radiation (P5)	31.06	24.47	36.70	2.59
Sunshine hours (P6)	0.72	8.47	30.91	22.28
Combined contribution				
Windspeed and airtemp	-17.89	5.77	3.05	-0.18
Windspeed and soil temp	-1.50	-13.66	0.29	2.56
Windspeed and Rel. hum.	-2.83	1.77	-11.90	0.43
Windspeed and solar rad.	-2.90	0.27	9.49	-0.03
Windspeed and sunshine	-4.63	6.65	15.15	1.65
Airtemp and soil temp.	-0.77	-6.49	2.61	-1.59
Airtemp and solar temp.	-2.42	1.19	22.05	0.31
Airtemp and solar rad.	-0.48	-0.27	-4.19	0.04
Air temp and sunshine	-0.92	4.21	-8.08	-1.36
Soil temp and Rel. hum	2.99	3.49	-11.60	5.60
Soil temp and solar rad.	-1.62	2.36	0.63	-2.22
Soil temp and sunshine	-0.63	-8.53	0.24	6.96

Table 20.0 contd: Direct and combined contribution of climatic factors on lysimetric PET pan evaporation presented as percentage

Climatic factors	PET		Pan evaporation	
Direct contribution	1996	1997	1996	1997
Relative hum. and sunshine	30.18	0.58	23.16	-1.24
Rel. hum. and solar rad.	16.79	0.58	19.63	-0.58
Solar rad. and sunshine	3.16	10.00	30.18	1.31
Total	82.28	75.70	90.00	87.85
Residual (1-P1r17-P2r27-P3r37-P4r47-P5r57-P6r67)	17.72	24.31	10.00	12.15
Grand Total	100.00	100.00	100.00	100.00

4.6. Soil Evaporation

The Penman model was used to compute daily evaporation rate from the soil surface, (ES), evaporation rate from plant leaves, transpiration (Ep) and total evaporation rate from soil and plant surfaces, evapotranspiration (E). The daily values of rainfall (P), leaf area index (LAI) and potential evaporation rate above the plant canopy (Eo) used in the equation are given in Appendix D with the computed values of soil surface evaporation, transpiration and total evaporation. The daily evaporation measurements (Em) made with the microlysimeter and deviation of total evaporation from microlysimeter data are also given in Appendix D.

The deviation of the calculated total evaporation from microlysimetric evaporation in Appendix D show that the absolute error on moist days was less than 1mm/day. Those deviations above 1mm/day point out a problem associated with the use of daily rainfall in the model when soil surface evaporation is calculated during drying. It was assumed that the rainfall was received at the beginning of the day, and therefore soil surface evaporation was calculated as if the surface was freely evaporating for the entire day. However, the amounts of rainfall recieve on these days did not begin to fall until about mid day. Since the soil was relatively dry before the rainfall was received, soil surface evaporation would be expected to be lower than the value predicted by the model.

The total eaporation calculated for the study period was

303.23 and 311.33mm which compared with measured water loss of 192.25m and 191.35mm for maize and sorghum, respectively Table 21. The total evaporation was overestimated. The soil evaporation was amounted to 28.65% and 23.68% of the total evaporation for maize and sorghum, respectively.

One limitation of some of the equations used in the Penman model is the apparent over prediction of total evaporation on days when the canopy is in advanced stage of development and the soil surface is wet. The most likely source of error is the prediction of transpiration from equation (8) in chapter three.

Other sources of inaccuracy in the model are the methods used to calculate potential evaporation rate above the plant canopy (Eo) and potential evaporation rate below the plant canopy at the soil surface (Eos). The use of daily averages for air temperature, wind speed and vapor pressure decreases the accuracy of potential evaporation rate above the plant canopy.

When Penman and monteith equations were compared with measured data, Monteith equation has an excellent agreement with measured data for both maize and sorghum only that it overestimated evaporation in the months of August for sorghum and September for maize. The evapotranspiration was improved with an adjustment factor for each month, for the two equations as presented on Table 21. The estimated sorghum yield (13,192Kg/ha was much higher than the actual sorghum yield (3,023Kg/ha) with water use efficiency of 59.80%. Likewise the estimated maize yield of 12,743Kg/ha was higher than actual maize yield of 6802.5Kg/ha

(Table 24). Both sorghum and maize yields were overestimated. An adjustment factor is determined for each of the yield, and the yields were improved.

Table 21a : Soil evaporation beneath the crops (1996-1997)

Species	Site	Duration	Cumulative values				
		(days)	Eo	E	Es	Ep	Ei
Maize	Samaru	82	381.53	303.23	86.87	216.36	*n
Sorghum	Samaru	82	381.53	311.33	73.71	237.62	*n

n = negligible

Microlysimetric Pet (Em) = 191.35mm Sorghum
= 192.95mm maize

Table 21b: Monthly ratios of Penman and Monteith equations to microlysimetric Pe

Month	Sorghum		Maize	
	Non-adj. Pen	Adj. Pen	Non-Adj. Pen	Adj. Pen
August	1.54	0.65	1.54	0.65
September	1.29	0.77	1.32	0.78
October	1.11	0.90	1.13	1.03
Month	Sorghum		Maize	
August	1.30	0.78	1.03	0.96
September	1.13	1.00	1.24	0.8
October	1.08	0.99	1.10	1.00

Table 22a: Predicted and measured yields

B	Yp	Y Maize yield	WUE Kg/harm	Actual grain yield	ET	Pet	G
1.11	12743.11	6802.5 kg/ha	59.80	3023.33	151.68	261.51	13192 kg/ha

Table 22b: Adjustment factor for the estimated yields

Estimated grain yield		Estimated maize yield	
Non-adjusted	Adjusted	Non-adjusted	Adjusted
4.36	0.23	1.87	0.54

CHAPTER FIVE

SUMMARY AND CONCLUSION

5.1 Summary

This research was carried out to estimate potential evapotranspiration by various empirical methods reported to be reliable in the tropical environment and identify the best suitable empirical method for estimating potential evapotranspiration in the Northern Guinea savanna zone of Nigeria.

Five equations developed in different parts of the world have been used to calculate potential evapotranspiration (PET) under Samaru climatic conditions. The equations used are the Blaney Morin Nigeria (BMN) from Nigeria, Hamon and Jensen Haise from United States, Penman from England, and Makkink from the Netherlands.

Thirty years (1965-1994) data from meteorological station of the Institute for Agricultural Research (IAR), ABU, Zaria were used to compute the PET estimates. The predictive efficiency of the five PET models was examined against measured microlysimetric PET and open pan evaporation (for two years, 1996-1997).

The PET estimates were compared with pan evaporation and microlysimetric PET, using regression, correlation analysis and Analysis of Variance. The statistial comparison shows that the

PET estimates of all the five equations are significantly different for dry season conditions for the location used in the study. Some equations yield statistically similar results during the wettest months of the year. The similarities were also observed from October to March.

BMN, Penman and Makkink equations are the most appropriate methods with which to estimate PET in subhumid environment of Nigeria. Hamon and Jensen Haise equations were found to over estimate in all climatic conditions tested. BMN equation is the simplest, most accurate and consistent. It is recommended for application as best satisfying the objective of the study.

It is suggested, based on the results of the comparisons that most of the equations can be improved in order to make them agree more closely with measured PET values. Adjustment factors have been determined for BMN, Penman and Makkink equations so that they can estimate as precisely and accurately as the measured PET. It was observed that PET is highest in March, the warmest month of the year. Followed by April and May the beginning of the rainy season. It is lowest in August the peak of rainy season in this zone. Selected meteorological factors, various physical and chemical properties were determined.

Path correlation analysis indicates that PET is

influenced in this order: sunshine > Soil temperature > relative humidity > air temperature > windspeed > solar radiation while pan evaporation is influenced in this manner: soil temperature > sunsine hours > relative humidity > air temperature, > windspeed > solar radiation. When some physical properties of the soil are correlated with measured PET,it was observed that PET increases with available water, hydraulic conductivity, total porosity and moisture content at field capacity (0.1 bar).

Penman and Monteith equations were used to compare with the measured soil evaporation beneath maize and sorghum crops. Monteith equation was closer to measured soil evaporation than Penman. However, adjustment factors were developed for both equations.Equation relating adjusted BMN, Penman and Makkink equations to pan evaporation, and microlysimetric PET were:

Microlysimetric PET, (Y) = 1.38 + 0.59 BMN..(R^2 = 99%)
= -0.08 + 0.99Pan ..(R^2 = 100%)
= 2.58 + 0.17Penman .(R^2 = 100%)
= 0.5 + 0.99 Makkink ..(R^2 =100%)

Pan evaporation, (x) = -0.051 + 1.007Penman .....(R^2 =99.97%)
= 3.79 + 0.23 Makkink .....(R^2 = 95%)
= 0.033 + 0.99 BMN .....(R^2 = 99.98%)

Equations relating adjusted Penman and Montheith equations to microlysimetric evaporation are given below: Microlysimetric PET (maize) = -7.94 + 0.93 Monteith
= -5.93 + 1.033 Penman
Microlysimetric PET (sorghum) = -7.60 + 1.12 Penman
= 1.52 + 0.99 monteith

5.2 Conclusion

The following conclusions can be drawn (from the

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statistical comparison and the comparison with pan evaporation and the microlysimetric data) from this study:

1. BMN, Penman and Makkink equations are the most appropriate to estimate PET in subhumid regions such as Samaru in Northern Guinea Savanna of Nigeria.
2. The principal characeristics of the equation are summarized in Table 22.0.
3. The applicability of the equations as a function of the type of meteorological information available is summarized in Table 24. The information contained in Tables 22.0 and 23.0 should be useful to the designer to select the most appropriate equation to use for the calculation of PET.
4. BMN: Because of its high sensitivity to temperature and relative humidiy at high temperatures, the BMN equation will give a high PET at high temperature and low PET estimate at low temperature.
5. Hamon: The equation generally tends to overestimate pan evaporation and microlysimetric data for the entire months of the year, especially at high temperatures. The drier the climatic conditions, the more sensitive the equation becomes to temperature.
6. Jensen Haise: The equation offered good

agreement with the Penman equation. It is the best substitute for the Penman equation when adequate input data are not available for use with the Penman equation. If actual solar radiation data are not available, solar radiation values estimated from Tables and cover are satisfactory.

7. Penman: The Penman equation has the best theoretical basis to estimate PET. It is very sensitive to the way in which the wind function and the vapor pressure are evaluated.

8. Makkink: The equation generally underestimates PET during dry season at Samaru climatic conditions.

9. Comparison of evaporation estimates of the Monteith and Penman equations at Samaru shows that Monteith equation (which contains surface resistance that reflect incoming solar radiation reaching the soil through the crop) estimates soil evaporation better than Penman's for an open water surface. An adjustment factor is incorporated into the equation so that it can predict PET as accurately as the measured data.

10. Microlysimetric PET increases with total porosity, available water, hydraulic conductivity and moisture content of the soil at field capacity.

5.3 RECOMMENDATION

It is suggested, based on theoretical analysis and from the results of data and the contributions of each of climatic factor that most of the equations can be improved in order to agree more closely with measured PET. The objective of the improvement of the equations is to allow the irrigation project designers the choice of selecting two or more dependable equations if climatic information are available.

The following are specific suggestions for improvement.

BMN: The BMN equation maybe improved by decreasing the sensitivity of the equation to temperature and relative humidity at high temperature and increase its sensitivity at lower temperature. The use of the monthly adjustment factors in Table 13b of this study would also improve the equation.

Hamon: It is suggested that the correlation factors with climatic variables be calibrated for each region where the equation is used. An appropriate regional coefficient is recommended.

Penman: It is recommended that the logarithmic wind function be used to determine the wind function. This will require further research into the evaluation of the roughness length, Zo. Application of the monthly adjustment factors in Table 13b can help to improve the Penman equation.

Makkink: The estimated PET of the Makkink equation could be improved markedly if temperature sensitivity were made constant with temperature for each value of the mean annual solar radiation. Application of adjustment factors in Table 13b can help to improve the Makkink equation.

Table 23.0: Correlation coefficient, standard error of estimate (SE), R^2 for sorghum and maize

	Sorghum	SE of estimate	R^2
Adj. monteith	1.00	1.22	99.84
Adj. Penman	0.97	9.03	93.63
	Maize	SE	R^2
Adj. Monteith	1.00	2.034	106
Adj. Penman	1.00	0.21	100

Table 24.0: Characteristics of the 5 Equations

Equation	Sensitivity	Precision	Accuracy	Observations
BMN	Sensitive to temp.and elative humidity at high temp.	Moderatel y high	High	To predict pan evaporation and lysime at sub humid condition Recommended for irrigation studies at subhumid regions
Hamon	High temp. and possible hours of daylight	Low	Low	Overestimates pan evaporation and lysime at sub humidconditions Needs further studies t be recommended
Jensen	Moderate to temp. and solar radition	Moderae	Moderate to high	Recommended whenev solar radiation could bc estimated
Penman	High to change in vapor pressure low to temp., wind and rel. humidity	High	High	Recommended whene the climatic informatio is available.
Makkink	Inverse and low to temp. moderate to solar radiation	Low	Moderate to high	Recommended for irrigation studies.

Table 25.0: Applicability of PET equations as a function of the type of meteorological information available

Climatic conditions as given by temp.				Climatic information available						Eq
Temperature range of				r.h %	Sol. Rad.	Wind	Sun Hrs	K	KP	
<10	10-20	20-30	>30							
			Yes	Yes						BM
Yes	Yes	Yes				Yes	Yes			Ha
Yes	Yes	Yes	Yes		Yes					Jer
Yes	Yes	Yes	Yes	Yes	Yes	Yes				Pe
Yes	Yes	Yes			Yes					Ma

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APPENDICES

Appendix A: Experimental site soil profile description.

The description of the soil profile is presented as follows:

Parent materials : Colluvial-coessial

Drainage : Well drained

Relief slope : Gently sloping (2%)

Vegetaion : Short grasscover thickly vegetated

Horizon	Depth (cm)	Description
	0-15	Pale brown 10YR 6/3, moist; 10YR 6/4 dry) loamy sand to sand loam. Subangular blocky
	15-30	Dull yellowish brown (10YR 4/3, moist, 10YR 6/3, dry) loam, subangular slightly hard, plastic and sticky wet.
	30-45	Yellowish brown (10Y 5/4, moist; 10YR 6/6, dry) loam very friable moist.
	45-60	Yellowish brown 10YR 5/6, moist, 7.5YR 6/8, dry) lay loam, fine coarse subangular blocky structure, hard dry, fine clay cutans on ped faces.
	60-75	Very pale brown (10YR 7/3, moist; 7.5YR 5/6, dry) clay loam texture medium coarse subangular blocky, slightly firm moist plasti and sticky wet.
	75-90	Strong brown 7.5YR 5/6, moist; 7.5YR 5/8, dry) clay loam; moderae to strohg medium coarse subangular blocky structure, hard dry, firm moist
	90-105	Very pale brown (10YR 7/3, moist; 7.5YR 5/6, dry) clay loam. Thick clay cutan pores, hard (dry), sticky when wet friable moist
Classification:		Typic kanhaplusaff, fine loamy, isohyperthermic

Appendix B: Climate information

Date	Wind speed km/hr	Air temp. °C	Soil temp. °C	Relat. humidity %	Solar radiation	Sunshine	Pan Evap. mm/day	Lysimeter mm/day
20/8/96	124.05	24.0	26.0	86.0	9.3	2.0	5.59	3.52
22/8/96	95.54	23.0	24.0	77.0	7.4	2.1	6.04	4.55
23/8/96	111.38	25.0	26.0	76.0	4.7	2.4	6.21	2.03
24/8/96	133.90	25.0	26.0	75.0	5.2	1.2	6.04	1.94
25/8/96	115.94	24.0	23.0	80.0	7.4	1.4	5.95	1.90
26/8/96	77.34	25.0	24.0	75.0	9.2	8.4	5.90	1.75
28/8/96	59.60	24.5	24.0	77.0	10.0	8.2	5.81	3.87
30/8/96	94.50	24.0	26.0	78.0	7.2	8.8	5.81	1.43
2/9/96	131.88	24.5	25.0	77.0	12.4	-9.0	5.68	2.15
5/9/96	110.91	23.5	28.0	76.0	4.8	0.1	8.26	4.81
6/9/96	118.17	27.5	27.0	75.0	6.6	4.0	5.86	4.73
7/9/96	165.90	26.5	29	78.0	8.0	5.0	5.95	2.25
8/9/96	154.94	25.5	28	78.0	5.2	3.0	6.12	2.17
10/9/96	165.70	23.0	27.0	77.0	10.2	1.9	5.95	4.24
13/9/96	100.64	24.0	29.0	73.0	11.7	7.4	6.08	3.92
14/9/96	74.64	26.0	28.0	75.0	8.4	5.1	6.04	3.55
15/9/96	81.90	24.5	27.0	73.0	6.4	2.5	5.99	2.57
16/9/96	148.04	23.5	27	73	4.4	1.4	5.81	2.36
17/9/96	134.04	24.5	26	78	7.3	1.3	5.86	1.32
19/9/96	51.32	24.0	30	77	14.3	7.2	5.95	4.53
21/9/96	103.87	24.0	27	80	13.6	3.6	6.17	2.71
23/9/96	78.08	26.0	26	75	16.4	1.5	6.04	1.01
27/9/96	85.60	24.5	29	77	17.3	5.7	5.95	3.83
28/9/96	81.20	25.5	29	67	18.3	6.0	6.26	2.59
29/9/96	68.21	24.5	28	74	14.3	7.2	6.08	1.96
30/9/96	65.20	25.5	27	66	16.3	7.6	6.17	1.85
2/10/96	112.81	26.0	28.0	73	11.3	4.5	4.70	4.74
3/10/96	60.60	25.5	28.0	70	10.2	0.3	4.63	4.93
4/10/96	60.18	26.0	28.0	66	13.6	2.2	4.35	4.89
5/10/96	72.67	25.0	28.0	62	16.6	9.0	4.28	4.54
6/10/96	54.72	26.0	27.0	68	16.1	7.7	4.26	4.09

Date	Wind speed km/hr	Air temp. °C	Soil temp. °C	Relat. humidity %	Solar radiation	Sun-shine	Pan Evap. mm/day	Lysimeter mm/da
7/10/96	7.043	26.0	27.0	68	16.6	8.6	4.07	3.32
8/10/96	57.97	25.0	29.0	72	15.2	9.0	4.19	3.17
9/10/96	53.0	27.0	29.0	68	12.7	6.3	4.44	2.87
10/10/96	91.75	25.5	28.0	73	12.1	3.6	4.28	2.33
11/10/96	74.11	26.0	28.0	72	21.0	7.9	4.10	1.60
15/10/96	92.41	25.5	28.0	79	12.8	6.3	4.32	1.63
16/10/96	63.70	25.5	28.0	81	14.8	4.8	4.35	1.96
17/10/96	64.99	25.0	28.0	69	19.6	8.0	4.17	2.17
18/10/96	67.90	26.5	28.0	74	18.2	5.7	4.54	2.13
20/10/96	74.31	26.0	27.0	63	22.4	8.8	4.19	3.20
21/10/96	94.86	25.0	28.0	71	16.9	10.5	5.04	2.72
22/10/96	69.76	23.5	27.0	43	13.0	8.5	5.63	3.68
23/10/96	51.63	24.0	27.0	40	17.0	7.2	5.88	2.32
25/10/96	62.22	24.5	27.0	35	17.5	7.8	5.47	2.67
26/10/96	106.12	24.5	27.0	37	20.4	8.0	5.29	2.76
28/10/96	72.81	23.0	298.0	33	21.3	9.8	6.10	1.88
29/10/96	136.23	21.5	28.0	32	22.3	9.1	6.12	2.00
30/10/96	54.77	21.5	25.0	41	22.3	10.8	6.32	3.22
31/10/96	66.45	22.0	25.0	32	22.3	8.5	5.94	1.89
18/10/97	108.56	23.8	68.50	9.84	8.0	5.81	2.86	28
21/10/97	102.98	24.5	77.5	9.08	8.5	5.90	4.59	28
23/10/97	59.22	24.8	74	9.99	9.8	5.95	4.15	28
24/10/97	87.53	24.7	67.5	8.64	5.3	5.81	3.76	28
25/10/97	71.22	24.8	70.5	9.77	9.0	6.12	3.23	28
26/10/97	105.55	24.8	70	7.43	4.5	5.86	2.29	28
27/10/97	74.53	25.5	67	8.91	6.1	6.12	5.54	28
28/10/97	79.38	25.5	62.5	9.91	9.1	6.08	3.81	29
29/10/97	93.11	25.2	62.5	8.47	6.6	6.04	3.47	29
30/10/97	74.66	24.8	68.5	9.27	9.1	6.17	2.63	29
31/10/97	69.51	25.1	64.5	7.23	3.4	5.90	1.95	28

Appendix C: Measured average daily PET and pan evaporation and corresponding values computed by different methods (mm/day)

Date	Measured		Computed				
	PET	Pan evap. mm/day	BMN	Hamon	J. Haise	Penman	Makkink
20/8/99	3.52	3.91	1.57	13.70	3.39	2.27	2.49
22/8/99	4.55	4.23	1.93	12.91	3.35	2.71	2.50
23/8/99	2.03	4.35	2.07	14.46	3.80	2.48	2.74
24/8/99	1.94	4.23	2.12	14.46	2.90	2.67	2.08
25/8/99	1.90	4.17	1.84	13.70	3.17	3.85	2.32
26/8/99	1.75	4.13	2.12	14.46	6.08	4.82	4.37
28/8/99	3.87	4.07	2.00	14.46	8.08	4.92	5.90
30/8/99	1.43	4.10	1.93	13.70	8.38	4.77	6.14
2/9/96	2.15	3.98	3.86	13.19	8.61	4.97	6.29
5/9/96	4.81	5.78	3.28	12.47	1.95	1.86	1.43
6/9/96	4.73	4.10	4.33	15.59	5.37	4.18	3.82
7/9/96	2.25	4.17	1.47	14.75	6.00	5.08	4.18
8/9/96	2.17	4.26	2.23	13.95	4.30	3.95	3.08
10/9/96	4.24	4.17	2.77	11.78	3.19	2.44	2.36
13/9/96	3.92	4.26	2.99	13.19	8.29	4.84	5.96
14/9/96	3.55	4.23	3.36	12.47	7.30	4.32	5.35
15/9/96	2.57	4.19	1.25	13.95	5.99	4.53	4.23
16/9/96	2.36	4.10	2.24	13.19	3.79	2.41	2.77
17/9/96	1.32	4.77	1.28	12.47	2.88	2.65	2.12
19/9/96	4.53	4.23	2.54	13.19	2.91	3.59	2.12
21/9/96	2.71	4.32	2.08	12.47	7.16	4.03	5.34
23/9/96	1.01	4.23	3.19	14.47	4.53	3.84	3.32
27/9/96	3.83	4.17	3.11	13.95	5.90	4.92	4.23
28/9/96	2.59	4.30	2.78	13.95	3.20	2.44	2.26
29/9/96	1.96	4.26	1.96	13.19	8.37	4.92	6.02
30/9/96	1.82	4.32	3.72	13.19	6.16	4.22	4.64
Total	52.55	77.34	48.44	241.41	95.90	60.36	69.44
Mean	2.96	4.07	2.69	13.41	5.33	3.35	3.86

Date	Measured		Computed				
	Lysimeter	BMN	Hamon	J. Haise	Pen	Makkink	Pan
2/10/96	4.74	3.12	**13.95**	5.19	2.38	3.67	4.70
3/10/96	4.93	3.27	**13.95**	2.10	2.80	1.51	**4.53**
4/10/96	**4.89**	3.56	**13.95**	3.52	**4.81**	2.49	4.35
5/10/96	4.54	3.71	**13.19**	8.21	4.70	5.91	**4.28**
6/10/96	**4.09**	3.43	13.95	7.52	**4.77**	5.32	4.26
7/10/96	3.32	3.43	**13.95**	8.18	4.70	5.78	4.07
8/10/96	3.17	**3.25**	13.19	8.21	4.42	5.91	4.19
9/10/96	2.87	**2.79**	**14.75**	5.09	3.05	3.53	4.44
10/10/96	2.33	**2.12**	13.95	4.47	4.57	3.21	4.78
11/10/96	1.60	**1.85**	13.95	7.67	3.99	5.42	4.10
12/10/96	1.63	**1.06**	13.95	6.41	3.73	4.60	4.32
16/10/96	1.96	**1.21**	13.95	5.33	4.54	3.82	4.35
17/10/96	2.17	**4.17**	**2.05**	13.19	7.51	3.99	5.40
18/10/96	2.13	**4.51**	**2.12**	14.75	6.16	5.22	4.34
20/10/96	3.20	**4.19**	**2.66**	13.95	8.33	5.29	6.02
21/10/96	2.72	**5.04**	**2.84**	13.19	9.27	4.50	6.67
22/10/96	3.68	**5.63**	**3.25**	12.47	7.47	3.96	5.58
23/10/96	2.32	**5.88**	**2.60**	12.47	6.73	4.08	4.93
25/10/96	2.67	**5.47**	**2.43**	13.19	7.25	4.95	5.30
26/10/96	2.76	**5.29**	**2.84**	13.19	7.39	4.92	5.40
28/10/96	1.88	**6.10**	**1.79**	**12.91**	**8.23**	5.12	6.15
30/10/96	3.22	**6.32**	**3.17**	11.12	**8.45**	3.49	6.55
31/10/96	1.89	5.94	1.81	11.12	7.13	3.36	5.43
x	**2.99**	110.54	2.63	**13.40**	**6.76**	4.23	4.91
Total	68.71	4.81	60.38	308.2	155.84	97.34	112.94
1/8/97	1.99	**4.08**	3.65	**13.66**	6.12	4.74	4.53
2/8/97	2.64	**4.10**	**3.91**	**13.66**	**3.21**	2.42	2.38
3/8/97	3.37	**4.26**	**3.81**	**15.29**	**7.87**	**3.73**	5.64
5/8/97	3.31	**3.91**	4.14	13.66	**5.94**	4.54	4.42
7/8/97	2.46	4.32	3.87	14.46	7.67	3.80	5.57

Date	Measured		Computed				
	Lysimeter	BMN	Hamon	J. Haise	Pen	Makkink	Pan
10/8/97	2.86	4.07	3.67	13.66	6.22	5.03	4.77
17/8/97	2.65	3.98	3.19	13.66	8.89	5.60	6.52
22/8/97	3.87	4.10	4.03	14.46	10.32	4.67	7.42
23/8/97	3.31	4.04	3.94	14.46	8.27	5.21	5.95
25/8/97	4.85	4.19	3.76	15.29	9.10	4.20	6.53
26/8/97	5.07	4.19	7.60	15.29	7.10	4.84	5.09
27/8/97	3.28	4.07	3.67	12.91	4.21	2.86	3.19
28/8/97	3.17	4.26	3.76	14.46	7.89	5.02	5.68
Total	42.8	53.57	53.00	170.46	92.81	56.66	67.69
$\bar{X}$	3.29	4.12	4.08	13.11	7.14	4.36	5.21
2/9/97	1.41	3.94	3.53	12.47	4.60	2.70	3.13
3/9/97	5.27	4.23	2.87	12.47	2.78	5.72	1.75
8/9/97	2.97	4.04	2.64	13.95	5.25	4.94	3.[illegible]
9/9/97	5.68	4.04	2.93	12.47	7.04	4.83	4.57
11/9/97	3.63	4.04	2.95	13.95	5.33	3.45	3.62
12/9/97	4.82	4.07	3.45	13.19	4.78	3.68	3.25
13/9/97	3.42	4.07	2.83	12.47	7.88	4.92	5.45
27/9/97	3.77	4.00	3.56	14.75	7.37	4.75	5.12
28/9/97	4.01	4.10	3.56	14.75	10.25	5.73	7.23
30/9/97	2.25	3.91	2.72	13.19	2.50	3.05	1.80
Total	37.19	36.37	31.04	133.66	57.78	43.8	39.48
$\bar{X}$	3.72	3.64	3.104	13.37	5.78	4.38	3.95
1/10/97	5.37	4.26	6.75	13.95	9.27	4.74	6.55
6/10/97	5.31	4.07	4.28	12.47	4.87	2.86	3.66
8/10/97	3.30	4.10	8.32	11.12	5.99	3.69	4.55
10/10/97	3.98	4.04	4.18	13.19	7.46	3.57	5.40
11/10/97	3.41	4.07	4.06	13.19	8.16	4.55	5.91
12/10/97	2.94	4.04	2.58	13.19	6.89	3.71	4.94
14/10/97	3.94	4.00	4.77	13.19	3.61	3.13	2.60
15/10/97	2.91	4.10	3.77	13.19	5.69	3.12	4.13

Date	Measured		Computed				
	Lysimeter	BMN	Hamon	J. Haise	Pen	Makkink	Pan
18/10/97	2.86	4.07	2.60	12.41	7.23	3.56	5.33
21/10/97	4.59	4.13	4.04	13.19	7.74	4.02	5.66
23/10/97	4.15	4.17	4.39	13.19	8.73	5.80	6.32
24/10/97	3.76	4.07	4.75	13.19	5.55	3.73	4.03
25/10/97	3.23	4.28	4.50	13.19	8.16	4.43	5.91
26/10/97	2.29	4.10	2.59	13.19	5.00	2.93	3.62
27/10/97	5.54	4.28	5.10	13.95	6.27	4.00	4.49
28/10/97	3.81	4.26	4.57	13.95	8.42	6.44	6.04
29/10/97	3.47	4.23	4.56	13.19	6.56	5.53	4.69
30/10/97	2.63	4.32	3.44	13.19	8.23	4.70	5.96
31/10/97	1.95	4.13	2.84	13.19	4.27	3.72	3.06
Total	74.44	78.72	82.09	449.38	128.1	78.28	92.85
$\bar{X}$	3.92	4.14	4.32	13.13	6.74	4.12	4.89

Appendix D:: Summary of daily estimates of evaporation from sorghum for a 32 day period

1996	Lai.	(mm) Rainfall	Eo	Es	Ep	E	Em	E-Em
24/8	0.03	19.4	2.81	2.31	0	2.31	2.75	-0.44
25/8	0.05	7.1	5.62	3.51	0	3.51	3.88	-0.37
26/8	0.06		4.22	3.11	0	3.11	3.01	0.1
27/8	0.08		2.32	2.06	0	2.06	2.88	-0.82
28/8	0.09		1.62	1.34	0	1.34	1.00	0.34
29/8	0.10		1.12	1.07	0	1.07	1.03	0.4
30/8	0.11	6.5	4.22	3.27	0.20	3.47	3.45	0.02
31/8	0.12	10.1	1.12	1.04	0.30	1.34	0.59	0.75
	Total	43.1	23.05	17.71	0.50	18.21	18.59	
8/9	0.15		1.82	1.74	0.40	2.14	1.98	0.16
9/9	0.18	35.0	5.92	2.74	0.80	3.54	2.57	0.97
10/9	0.22		5.32	1.04	0.9	1.94	2.20	-0.26
11/9	0.27		5.32	0.84	1.00	1.84	2.57	-0.7
12/9	0.32	15.0	2.62	0.74	0.88	1.62	1.46	0.16
13/9	0.38		3.22	0.64	1.10	1.74	2.13	-0.39
14/9	0.45	4.5	3.72	0.54	0.97	1.51	0.66	0.85
22/9	1.26		4.12	0.74	2.37	3.11	3.00	0.11
23/9	1.37	1.0	4.27	0.63	2.60	3.23	3.53	-0.3
24/9	1.48	7.5	4.07	0.60	2.61	3.21	3.21	0
25/9	1.58	12.5	3.97	0.55	2.66	3.32	3.12	0.21
26/9	1.61	0.1	3.47	0.50	2.41	2.91	3.10	-0.19
27/9	1.80		3.87	0.50	2.82	3.32	3.12	0.20
28/9	1.91	1.5	4.17	0.50	3.16	3.66	3.56	0.1
29/9	2.02		2.27	0.40	1.78	2.18	2.00	0.18
30/9	2.13		3.97	0.40	3.22	3.62	4.02	-0.4
31/9	2.23		4.27	0.40	3.57	3.97	3.67	0.3
	Total	77.1	66.39	13.5	33.25	46.75	45.78	
1/10	2.34		2.27	0.40	1.95	2.35	3.15	-0.8
2/10	2.45		4.29	0.30	3.80	4.10	4.00	0.10
3/10	2.55		5.05	0.25	4.58	4.83	4.78	0.05
4/10	2.67	15.6	2.40	0.25	2.24	2.49	3.15	-0.66
5/10	2.76	0.1	3.60	0.20	3.43	3.63	3.71	-0.08
6/10	2.85		4.8	0.20	4.66	4.86	4.78	0.08
7/10	2.96	13.0	5.2	0.20	5.17	5.37	5.29	0.08
	Total	**28.7**	**27.61**	**1.8**	**25.83**	**27.63**	**28.86**	

Maize

1996	Lai.	(mm) Rainfall	Eo	Es	Ep	E	Em	E-Em
24/8	0.035	19.4	2.81	1.86	0	1.86	1.78	0.08
25/8	0.050	7.1	5.62	3.19	0	3.19	3.02	0.17
26/8	0.060		4.22	3.00	0	3.00	2.98	0.02
27/8	0.07		2.32	2.16	0	2.16	2.00	0.16
28/8	0.08		1.62	1.05	0	1.05	1.35	-0.3
29/8	0.09		1.2	1.03	0	1.03	1.00	0.03
30/8	0.10	6.5	4.22	3.02	0	3.02	3.14	-0.12
31/8	0.11	10.1	1.12	1.08	0.03	1.11	1.23	-0.12
	Total			16.39	0.03	16.42	16.5	
8/9	0.20		1.82	1.51	0.19	1.70	1.68	0.02
9/9	0.23	35.0	5.92	3.91	0.74	4.65	4.70	-0.05
10/9	0.27		5.32	1.95	0.82	2.77	2.75	0.02
11/9	0.32		4.32	1.31	0.99	2.30	2.25	0.05
12/9	0.37	15.0	2.62	1.21	0.57	1.78	1.80	-0.02
13/9	0.43		3.22	1.11	0.80	1.91	1.71	0.02
14/9	0.50	4.5	3.72	1.01	0.60	1.61	1.81	-0.2
22/9	1.31		4.12	1.37	2.44	3.81	3.51	0.31
23/9	1.42	1.0	4.27	1.17	2.67	3.84	3.75	0.09
24/9	1.53	7.5	4.07	0.96	2.68	3.64	3.70	-0.06
25/9	1.64	12.5	3.97	0.76	2.73	3.49	3.52	-0.03
26/9	1.74	0.1	3.47	0.58	2.48	3.06	3.87	-0.81
27/9	1.85		3.87	0.56	2.87	3.43	3.39	0.04
28/9	1.96	1.5	4.17	0.53	3.21	3.74	3.78	-0.04
29/9	2.07		2.27	0.50	1.81	2.31	2.25	0.06
30/9	2.18		3.97	0.48	3.27	3.75	3.82	-0.07
	Total			18.92	28.87	47.79	48.29	
1/10	2.29		2.27	0.45	1.93	2.38	2.00	0.38
2/10	2.40		4.29	0.42	3.75	4.17	4.27	-0.1
3/10	2.51		5.05	0.41	4.54	4.95	4.98	-0.03
4/10	2.62	15.6	2.40	0.40	2.22	2.62	2.53	0.09
5/10	2.73	0.1	3.60	0.40	3.41	3.81	3.72	0.09
6/10	2.84		4.80	0.40	4.65	5.05	5.00	0.05
7/10	2.95	13.0	5.2	0.30	5.16	5.46	5.56	-0.1
Total				2.78	25.66	28.44	28.06	
Mean		148.9		38.09	54.56	92.65	92.85	

				Sorghum				
1997	Lai.	(mm) Rainfall	Eo	Es	Ep	E	Em	E-Em
1/8	0.04		5.73	3.39	0	3.39	2.60	0.79
2/8	0.05		4.43	2.75	0	2.75	3.40	-0.65
3/8	0.06	12.4	6.41	2.46	0	2.46	2.51	-0.05
4/8	0.07		3.06	2.19	0	2.19	2.33	-0.14
5/8	0.08	20.4	5.97	2.47	0	2.47	1.79	0.68
6/8	0.09		3.98	2.00	0	2.00	1.89	0.11
7/8	0.10	4.0	4.67	2.45	0	2.45	1.99	0.46
15/8	0.91	21.4	2.84	1.62	1.30	2.92	2.56	0.36
16/8	1.02		3.13	2.02	1.56	3.58	2.58	1.00
17/8	1.14	34.1	2.25	1.77	1.21	2.98	1.72	1.26
18/8	1.26	2.3	5.56	2.7	1.00	3.70	3.00	0.70
19/8	1.38	46.1	4.20	0.9	2.57	3.47	3.54	-0.07
20/8	1.48	10.0	5.30	0.7	3.40	4.1	3.96	0.14
21/8	1.59		6.44	1.5	3.50	5.00	4.55	0.45
29/8	1.70	5.0	5.9	1.2	5.30	4.5	3.26	1.24
30/8	1.81	0.8	6.30	0.8	4.61	4.31	4.39	-0.08
31/8	1.92	15.3	6.60	0.9	5.0	5.9	5.32	0.58
	Total	171.8	82.77	31.82	27.45	58.17	51.39	
8/9	2.03	1.2	4.70	0.7	3.7	4.4	3.57	0.83
9/9	2.15	0.8	5.38	0.6	4.18	4.78	3.54	1.24
10/9	2.27	35.0	4.27	0.6	2.61	3.21	2.98	0.23
11/9	2.39	12.0	6.0	0.7	2.7	3.40	3.01	0.39
12/9	2.52		6.7	0.6	4.5	5.1	4.08	1.02
13/9	2.64	6.6	4.00	0.5	3.71	5.21	3.98	1.23
14/9	2.76		4.45	0.5	3.24	3.74	3.02	0.72
22/9	2.88		5.16	0.4	3.05	3.45	3.95	-0.5
23/9	2.98	7.9	6.4	0.4	5.39	5.79	4.58	1.21
24/9	3.02	3.0	6.2	0.4	4.24	4.64	3.65	0.99
25/9	3.14		4.7	0.3	4.44	4.14	4.25	-0.11
26/9	3.26		4.9	0.3	4.16	4.46	3.96	0.5
27/9	3.38		5.42	0.3	3.84	3.14	2.32	0.82
28/9	3.48		5.58	0.25	3.11	3.36	3.14	0.22
29/9	3.60	3.5	6.88	0.25	4.69	5.94	4.10	1.84
30/9	3.72	70	6.53	0.20	6.01	6.21	5.46	0.75
	Total		87.27	7.0	63.57	69.97	59.59	

1997	Lai.	(mm) Rainfall	Eo	Es	Ep	E	Em	E-Em
1/10	3.82		6.00	0.20	6.74	6.94	6.80	0.14
2/10	3.94	7.5	4.74	0.20	5.59	5.79	4.17	1.62
3/10	4.06	0.9	6.65	0.15	5.65	5.80	6.58	-0.78
4/10	4.17		5.48	0.14	4.68	4.82	3.96	0.86
5/10	4.28	23.0	3.25	0.12	4.02	4.14	3.73	0.41
6/10	4.38		4.97	0.11	3.24	3.12	3.35	-0.23
7/10	4.52	0.8	5.81	0.10	5.43	5.53	4.46	1.07
15/10	4.62		4.27	0.10	3.22	3.23	2.68	0.55
16/10	4.75	5.5	6.67	0.10	6.60	6.70	6.25	0.45
17/10	4.85	9.5	6.88	0.10	6.00	6.10	4.32	1.78
18/10	4.97	3.4	5.79	0.10	5.09	5.19	4.75	0.44
19/10	5.09	23.6	4.62	0.09	4.02	4.11	3.89	0.22
20/10	5.20		6.83	0.09	6.33	6.42	5.56	0.86
21/10	5.30		5.52	0.08	5.12	5.20	5.05	0.15
29/10	5.53		5.84	0.07	5.24	5.31	4.82	0.49
30/10	5.53		5.84	0.07	5.24	5.31	4.82	0.49
31/10	5.65		6.66	0.06	6.01	6.07	5.68	0.39
Total		74.2	94.64	1.88	87.02	88.58	80.37	
GT		316	264.68	40.7	178.04	216.72	191.35	
1/8	0.02		5.73	4.71	0	4.71	4.00	0.71
2/8	0.03		4.43	3.63	0	3.63	3.27	0.36
3/8	0.04	12.4	6.41	3.05	0	3.05	3.00	0.05
4/8	0.05		3.06	2.30	0	2.30	1.98	0.32
5/8	0.06	20.4	5.97	2.83	0	2.83	2.15	+0.68
6/8	0.07		3.98	2.41	0	2.41	2.79	-0.38
7/8	0.08	4.0	4.67	2.76	0	2.76	2.50	+0.26
15/8	0.18	21.4	2.84	1.61	0.25	1.86	2.00	-0.14
16/8	0.29		3.13	2.88	0.52	3.4	2.*7	0.53
17/8	0.41	34.1	2.25	1.44	0.54	1.98	1.73	0.25
18/8	0.53	2.3	5.56	2.76	0.86	3.62	3.59	0.03
19/8	0.65	4.6.1	4.2	1.17	1.49	2.66	2.36	0.93
20/8	0.77	10.0	5.3	1.00	2.14	3.14	3.00	+0.14
21/8	0.87		6.44	1.3	2.17	3.47	3.59	-0.12
29/8	0.99	5.0	5.9	1.11	2.87	3.98	2.98	1.00
30/8	**1.10**	**0.8**	**6.3**	**0.9**	**3.30**	**4.20**	**3.50**	**0.7**
31/8	**1.22**	**15.3**	**6.6**	**0.10**	**3.72**	**3.82**	**3.96**	**0.14**
Total				**35.96**	**17.86**	**53.82**	**49.27**	

30/8	1.10	0.8	6.3	0.9	3.30	4.20	3.50	0.7
31/8	1.22	15.3	6.6	0.10	3.72	3.82	3.96	-0.14
Total				35.96	17.86	53.82	49.27	
1997	Lai.	(mm) Rainfall	Eo	Es	Ep	E	Em	E-Em
8/9	1.99	1.2	4.7	0.8	2.65	3.45	2.99	1.46
9/9	2.10	0.8	5.38	0.7	3.33	4.03	3.97	0.06
10/9	2.22	35.0	4.27	0.7	3.56	4.26	3.63	0.63
11/9	2.34	12.0	6.0	0.8	3.16	3.96	3.52	0.44
12/9	2.44		6.7	0.7	4.92	5.62	5.38	0.24
13/9	2.56	6.6	4.00	0.6	3.64	4.24	3.41	0.83
14/9	2.68		4.45	0.6	3.16	3.76	3.55	0.21
22/9	2.80		5.16	0.5	2.96	3.46	3.00	0.46
23/9	2.92	7.9	6.4	0.5	5.31	5.81	4.99	0.82
24/9	3.04	3.0	6.2	0.5	4.27	4.77	4.64	0.13
25/9	3.16		4.7	0.5	4.47	4.97	4.66	0.31
26/9	3.27		4.9	0.4	4.17	4.57	4.97	-0.4
27/9	3.37		5.42	0.4	2.83	3.23	2.28	0.95
28/9	3.42		5.58	0.4	3.05	3.45	3.56	-0.11
29/9	3.54	3.5	6.88	0.4	4.62	5.02	4.80	0.22
30/9	3.64		6.53	0.4	5.35	4.75	5.52	-0.23
				8.9	61.45	69.35	64.87	
1/10	3.72		6.00	0.35	5.84	6.19	6.99	-0.8
2/10	3.82	7.5	4.74	0.35	4.69	5.04	4.95	0.09
3/10	3.94	0.9	6.65	0.30	4.29	4.59	3.59	1.00
4/10	4.06		5.48	0.30	4.58	4.88	4.86	0.02
5/10	4.18	23.0	3.25	0.30	5.00	5.30	5.00	0.30
6/10	4.30		4.97	0.25	5.78	6.03	5.99	0.04
7/10	4.42	0.8	5.81	0.25	4.76	4.51	4.21	0.3
15/10	4.54		4.22	0.25	3.28	3.53	3.07	0.46
16/10	4.66	5.5	6.67	0.20	5.57	5.77	5.97	-0.2
17/10	4.78	9.5	6.85	0.20	4.47	4.67	4.06	0.61
18/10	4.90	3.4	5.79	0.20	3.76	3.96	4.32	-0.36
19/10	5.02	23.6	4.62	0.20	2.28	2.48	2.98	-0.5
20/10	5.14		6.83	0.16	5.40	4.46	4.24	0.22
21/10	5.26		5.52	0.16	5.70	3.86	4.56	-0.70
29/10	5.40		4.74	0.15	5.71	4.86	4.02	0.84
30/10	5.52		5.84	0.15	5.38	5.53	5.17	0.31
31/10	5.64		6.66	0.15	6.00	4.15	4.83	-0.68
Total	**14.2**		**3.92**	**82.49**	**79.81**	**78.81**		
Mean		**264.68**	**48.78**					
G/Total	**316**			**161.80**	**202.98**	**192.95**		

Appendix E: Summary of daily estimates of soil evaporation from sorghum and maize

Date	SORGHUM				MAIZE			
1996	Lai	Eo	Pet	Em	Lai	Eo	Pet	Em
24/8	0.03	2.81	3.21	2.75	0.035	2.81	2.01	1.78
25/8	0.05	5.62	1.74	3.88	0.050	5.62	1.74	3.02
26/8	0.06	4.22	2.28	3.01	0.06	4.22	2.28	3.98
27/8	0.08	2.32	2.68	2.88	0.07	2.32	2.68	2.00
28/8	0.09	3.62	2.95	3.00	0.08	3.62	2.91	3.35
29/8	0.10	3.12	3.9	13.03	0.09	3.12	3.91	3.28
30/8	0.11	4.22	4.15	3.45	0.1	4.22	4.15	3.14
31/8	0.12	3.89	2.78	3.51	0.11	3.89	5.04	3.23
8/9	0.15	4.35	3.09	3.88	0.20	1.82	3.09	1.68
9/9	0.18	3.89	5.49	3.45	0.23	5.92	3.10	4.70
10/9	0.22	1.94	1.52	2.00	0.27	5.32	1.52	2.75
11/9	0.27	5.32	3.42	2.57	0.32	5.32	3.52	2.25
12/9	0.32	2.62	4.38	1.46	0.37	2.62	4.38	1.80
13/9	0.38	3.22	3.19	2.13	0.43	3.22	3.27	1.71
14/9	0.45	3.72	3.34	3.10	0.5	3.72	2.73	1.81
22/9	1.26	4.12	4.05	3.00	1.31	4.12	4.05	3.51
23/9	1.37	4.27	3.14	3.53	1.42	4.27	3.14	3.75
24/9	1.48	4.07	3.54	3.21	1.53	4.07	3.54	3.70
25/9	1.58	3.97	3.39	3.00	1.64	3.97	3.39	3.52
26/9	1.61	3.47	4.23	3.10	1.74	3.47	4.23	3.87
27/9	1.80	3.87	3.33	3.12	1.85	3.87	3.33	3.39
28/9	1.91	4.17	3.72	3.56	1.98	4.17	3.72	3.78
29/9	2.02	2.27	4.54	2.00	2.07	2.27	4.54	2.25
30/9	2.13	3.97	4.62	4.02	2.18	3.97	4.62	3.82
1/10	2.34	2.27	4.10	3.15	2.29	2.27	4.12	2.00
2/10	2.45	4.29	4.27	4.00	2.40	4.29	4.27	4.27
3/10	2.55	5.05	2.85	4.73	2.51	5.05	2.85	4.98

Date	SORGHUM				MAIZE			
1996								
	Lai	Eo	Pet	Em	Lai	Eo	Pet	Em
4/10	2.67	2.40	3.35	3.15	2.62	2.40	3.35	2.53
5/10	2.76	3.60	2.96	3.71	2.73	3.60	5.56	3.72
6/10	2.85	4.8	5.26	4.78	2.84	4.80	5.26	5.00
7/10	2.96	5.2	5.65	5.29	2.95	5.2	5.65	5.56
1997								
1/8	0.04	5.73	1.84	2.60	0.02	5.73	1.55	4.00
2/8	0.05	4.43	3.96	3.40	0.03	4.43	2.80	3.27
3/8	0.06	6.41	2.72	2.51	0.04	6.41	1.27	3.00
4/8	0.07	3.06	3.32	2.33	0.05	3.06	1.78	1.98
5/8	0.08	5.97	3.33	1.79	0.06	5.97	1.81	2.15
6/8	0.09	3.98	3.59	1.69	0.07	3.98	2.45	2.79
7/8	0.10	4.67	2.25	1.99	0.08	4.67	1.92	2.50
8/8	0.91	2.84	3.81	2.56	0.18	2.84	3.63	2.00
9/8	1.02	3.13	4.22	2.58	0.19	3.13	3.50	2.87
24/8	1.14	2.25	4.00	1.72	0.41	2.25	3.93	1.73
25/8	1.26	5.56	4.81	3.00	0.53	5.56	3.67	3.59
26/8	1.38	4.20	4.00	3.54	0.65	4.20	3.92	2.36
27/8	1.48	5.30	2.39	3.96	0.77	5.3	3.24	3.00
28/8	1.59	6.44	4.62	4.55	0.87	6.44	4.71	3.59
29/8	1.70	5.90	5.31	3.26	0.99	5.9	4.71	2.98
30/8	1.81	6.30	4.02	4.39	1.10	6.3	2.47	3.50
31/8	1.92	6.6	4.54	5.32	1.22	6.6	3.48	3.96
8/9	2.03	4.7	4.52	3.57	1.99	4.70	4.54	2.99
9/9	2.15	5.38	5.80	3.54	2.10	5.38	5.80	5.97
10/9	2.27	4.27	5.34	2.98	2.22	4.27	5.22	3.63
11/9	2.39	6.00	4.71	3.01	2.34	6.0	4.88	3.52
12/9	2.52	6.7	4.47	4.08	2.44	6.7	4.45	5.38
13/9	2.64	4.00	4.94	3.98	2.56	4.00	5.08	3.41

Date 1997	SORGHUM				MAIZE			
	Lai	Eo	Pet	Em	Lai	Eo	Pet	Em
14/9	2.76	4.45	5.10	3.62	2.68	4.45	5.21	3.55
22/9	2.88	5.16	5.72	3.95	2.8	5.16	5.76	3.00
23/9	2.98	6.4	5.44	4.58	2.92	6.4	5.46	4.99
24/9	3.02	6.2	5.09	3.65	3.04	6.2	5.25	4.64
25/9	3.14	4.70	5.02	4.25	3.16	4.7	4.88	4.66
26/9	3.26	4.90	6.39	3.96	3.27	4.9	6.79	4.97
27/9	3.38	5.42	5.22	2.32	3.37	5.42	5.34	2.28
28/9	3.48	5.58	6.73	3.14	3.42	5.58	6.54	3.56
29/9	3.60	6.88	5.90	4.10	3.54	6.88	6.14	4.80
30/9	3.72	6.53	3.23	5.46	3.64	6.53	3.35	5.52
1/10	3.72	6.00	6.76	6.99	3.82	6.00	6.77	6.80
2/10	3.82	4.74	6.15	4.95	3.94	4.74	6.07	4.17
3/10	3.94	6.65	6.74	3.59	4.06	6.65	6.66	6.58
4/10	4.06	5.48	5.51	4.86	4.17	5.48	5.44	3.96
5/10	4.18	3.25	6.36	5.00	4.28	3.25	6.29	3.73
6/10	4.30	4.97	2.02	5.99	4.38	4.98	4.82	3.35
7/10	4.42	5.81	6.69	4.21	4.52	5.81	6.57	4.46
15/10	4.54	4.22	2.25	3.07	4.62	4.22	4.78	2.68
16/10	4.66	6.67	5.02	5.97	4.75	6.67	6.00	6.25
17/10	4.78	4.85	4.00	4.06	4.85	6.85	6.28	4.32
18/10	4.90	5.79	6.11	4.32	4.97	5.79	4.95	4.75
19/10	5.02	4.62	3.20	2.98	5.09	4.62	3.88	3.89
20/10	5.14	6.83	5.27	4.24	5.20	6.83	6.25	5.56
21/10	5.26	5.52	5.38	4.56	5.30	5.52	4.98	5.05
29/10	5.40	4.74	4.71	3.01	2.34	6.0	4.88	3.52
30/10	5.52	5.84	4.96	5.17	5.53	5.84	5.06	4.82
31/10	5.64	6.66	6.15	4.83	5.65	6.66	6.35	5.68