HYDROLOGIC AND CROP RESPONSE TO TILLAGE UNDER SEMI-ARID CONDITIONS IN KENYA

By

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DECLARATION

I, ONCHOKE, WILFRED ONCHWARI, hereby declare that this is my original work and has not been presented for a degree in any other University.

..... 30/8/2000
.....

ONCHOKE, W.O DATE

This thesis has been submitted with my approval as University Supervisor.

..... 30/8/2000
.....

BIAMAH, E.K. DATE

DEDICATION

This thesis is dedicated first and foremost, to my Heavenly God who sustained, gave me good health throughout and increased my knowledge to understand and complete this Msc. Research Study. Secondly I remember my Wife Grace Mokune, our Children Sarange Mokamba and Moses and my Parents whose perseverance and sacrifice made it psychologically and materially possible for me to complete my education.

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LIST OF SYMBOLS AND ABBREVIATIONS

AASM	-	Actual (momentary) amount of available moisture (mm)
AASMRM	-	Available soil moisture under residue mulch (mm)
AASMCT	-	Available soil moisture under conventional tillage (mm)
AASMTR	-	Available soil moisture under tied ridging (mm)
AASMEST	-	Estimated available soil moisture (mm)
SMEST	-	Estimated soil moisture ($cm^3\ cm^{-3}$)
SMRM	-	Measured soil moisture under residue mulch ($cm^3\ cm^{-3}$)
SMCT	-	Measured soil moisture under conventional tillage ($cm^3\ cm^{-3}$)
SMTR	-	Measured soil moisture under tied ridging ($cm^3\ cm^{-3}$)
MSM	-	Measured soil moisture ($cm^3\ cm^{-3}$)
EMS	-	Number of intervals between emergence and beginning of mid-season stage of crop development.
ET_a	-	Actual rate of evapotranspiration ($ET_a \leq ET_m$) mm/d or mm/period.
ET_m	-	Maximum rate of evapotranspiration of a crop when soil water is not limited (mm/d or mm/period).
ET_o	-	Potential rate of evapotranspiration (mm/d or mm/period).
K_c	-	Crop coefficient.
L	-	Number of intervals elapsed since emergence.
LAI	-	Leaf Area Index of a crop (m^2/m^2)
LUSA	-	Land - Use System Analysis of soil moisture.
PREC	-	Gauged rate of rainfall (mm/d)
RD or D	-	Equivalent depth of uniformly rooted surface layer (mm).
RD_{init}	-	Equivalent rooting depth at planting or emergence (mm).

SMCR	-	Critical volume fraction of moisture in soil ($cm^3\ cm^{-3}$).
SMPSI	-	Volume fraction of moisture in soil ($cm^3\ cm^{-3}$).
SMPWP	-	Volume fraction of moisture at permanent wilting point ($cm^3\ cm^{-3}$).
TASM or S_a	-	Maximum possible amount of available moisture (mm).
ASI	-	Available Soil Water Index.
cH	-	Correction for harvested part on net total dry matter of a crop.
cL	-	Correction for crop development over time and leaf area on total dry matter of a crop.
cN	-	Correction for net dry matter (respiration) on gross dry matter of a crop.
F	-	Fraction of the daytime the sky is clouded.
G	-	Length (days) of total growing period of a crop.
K	-	Correction for crop species on gross dry matter of a standard crop.
K_y	-	Yield response factor.
PWP	-	Permanent wilting point
Q	-	Runoff (mm)
DP	-	Deep percolation (mm)
I	-	Interception (mm)
P_{eff}	-	Effective rainfall (mm)
P or R	-	Rainfall (mm)
YES	-	Yield Estimation System
CROPWAT	-	Crop water estimation Program
Wb	-	Actual depth of available soil moisture over the root depth at the beginning of a period

y_o	-	Gross dry matter production rate of a standard crop for a given location on a completely overcast (clouded) day (kg/ha/day)
Y_o	-	Gross dry matter production rate of a standard crop for a given location (kg/ha/day)
Y_{mp}	-	Maximum yield potential in tons/ha of dry weight for a high producing variety adapted to environment with growth factors not limiting.
Y_{me}	-	Maximum harvested yield in tons/ha of dry weight for a high yielding variety adapted to the environment and growth factors not limiting.
FAO	-	Food and Agriculture Organisation of the United Nations
ASAL	-	Arid and semi-arid lands
ANOVA	-	Analysis of variance
a.s.l.	-	Above sea level
CEC	-	Cation exchangeable capacity
ICRISAT	-	International Crops for Research Institute for the Semi-Arid Tropics.
UNEP	-	United Nations Environmental Program
TR	-	Tied ridging
CT	-	Conventional tillage
RM	-	Residue mulch
$SMPS_{init}$	-	Initial soil moisture (cm^3 cm^3)
SMDL (p)	-	Soil moisture depletion level
DT	-	Time interval (days)
GD	-	Crop growth period (days)
RAM	-	Readily available soil moisture (mm)
IR_{req}	-	Irrigation requirement (l/s/ha)

ABSTRACT

Effects of the rainfall variability on soil moisture (SM) over crop growth periods is a prerequisite for assessing and developing better soil moisture conservation practices in semi-arid areas. It was therefore necessary to quantify soil moisture variability as affected by rainfall availability for crop productivity. This lead to an investigation into hydrologic and subsequent crop responses. The study was based on data collected for Kalalu, Laikipia District during the short and long rains periods of 1988 and 1989 respectively. Maize and beans under three soil moisture management practices, namely tied ridging (TR), conventional tillage (CT) and residue mulch (RM) were studied.

Data on rainfall, soil moisture and crop yields were used. An estimate of soil moisture and crop yields were used. An estimate of soil moisture variability in the rhizosphere by Land Use Specific Analysis (LUSA) method, crop evapotranspiration by Crop Water Requirement estimation Program (CROPWAT), Available Soil Moisture Index (ASI) and LUSA Methods were made. Potential crop yields were estimated through Wageningen and Agro-Ecological zone Methods for maize and beans respectively. Actual yields were estimated through CROPWAT, YES and Doorenbos Methods. Comparison between rainfall, soil moisture, available soil moisture, crop evapotranspiration and crop yields under the three tillage practices and the two crops were made.

Increasing trends in soil moisture during both short and long rains period for the three tillage types were observed. The trend was more for the 1989 long rains season. Soil moisture during the short rains period in the three treatments reached their maximum within 18 days and remained constant for the next 20 days before declining with TR having the lowest declining rate. During the long rains, SM in both RM and CT reached their maximum within 43 days before declining while TR had a lower increasing rate reaching a maximum

within 53 days before declining at a lower rate than the other two. Generally SM during the short rains period was higher than that of the long rains.

Rainfall amount and distribution before and after tillage coupled with the tillage practices enhanced soil moisture with rainfall having more impact. There was little significant difference in cumulative crop water used under the three treatments. CROPWAT overestimated the crop water used during the long rains season. There was an overestimate of bean yields due to the unexpected high measured soil moisture. Major reduction in yield was due to water deficit. Water and temperature limitations were two major factors that reduced maize yields from 8.9tons/ha to 1.2tons/ha.

These analyses showed that quantification of soil moisture and consequent crop water used within the crop growth stages will facilitate the choice of appropriate tillage practices. Early tillage especially after harvesting was necessary for soil moisture retention and availability to the crop. A combination of residue mulch and tied ridging will facilitate better soil moisture distribution necessary to reduce water deficits and improver crop productivity.

1.0 INTRODUCTION

1.1 Scientific Background and Rationale

Changing land use patterns in semi-arid areas for example, through the removal of existing vegetative cover (e.g. clearing for cultivation) and intensive cultivation, may result in significant increases in runoff intensity, evaporation from bare soils and surface sealing thus reducing infiltration and soil moisture. The variation of soil moisture in a given area is dependent upon hydrologic, soil and land use changes which are related to soil moisture dynamics.

In marginal rainfall (semi-arid) areas of Kenya, low, unreliable, erratic, high intensity and poorly distributed rainfall and problem soils constitute major constraints to crop production which undergoes extreme yield variations as a result. Semi-arid soils, which are predominantly Luvisols and Acrisols, are considered to be problematic because their physico-chemical properties limit their uses for agricultural purposes. Some of the problems associated with these soils that limit agricultural production are limited soil water storage capacity, structural instability, high salinity and sodicity, soil hardsetting and crusting, high runoff and soil loss and low soil fertility which subsequently causes serious soil moisture deficits due to low infiltration. Depending on the soil type, upto 70 % of rainfall may be lost as surface runoff and hence significantly reducing effective rainfall. Soil crusting and hardsetting also inhibit seed germination and root penetration of the crops grown in the area.

In order to design improved and effective soil moisture conservation systems for semi arid conditions, an essential prerequisite is to understand the hydrologic system response in terms of soil moisture variation as a result of various processes of infiltration, runoff and evapotranspiration. In Kenya, a lot has been done in the area of soil moisture conservation

for crop and fodder production without proper understanding of the factor variability which would influence proper choice, design and applicability of soil moisture conservation practices for increased crop yields. This study attempted to develop and therefore contribute some knowledge of that understanding of soil moisture dynamics and its impacts on crop yield. The temporal variation of soil moisture is as a result of many factors, the main one being rainfall variation and its subsequent partitioning into various components of the water balance as influenced by the method of conservation, climate, vegetation/crop, soil type and slope of the area. The methods and knowledge gained may be used to set some criteria for the selection, prioritization and improvement of soil moisture conservation measures for specific areas. Some thorough understanding of soil moisture dynamics is necessary for meaningful and scientific strides in recommending improved water management practices for specific semi arid areas of Kenya.

The ability to quantify soil moisture and its impacts on crop production in semi-arid areas is essential for their proper management. Of importance is an understanding of soil moisture variation during the crop growth periods and how this affects crop production under different changes in land use.

The dominant soils of semi arid areas (Luvisols and Acrisols) have high clay content which exhibit very strong surface sealing and crusting properties. The dominant clay minerals are Kaolinites and Illites. Generally, these soils have a low organic matter content, high surface runoff and low infiltration.

Application of simple appropriate methods for soil moisture estimation and measurement of an experimental plot/farm would facilitate some better understanding of this dynamic soil property and lead to the development of improved water management practices for such soils. The existing feasible interventions for increasing infiltration and storage of soil

moisture in semi arid environments include application of manure, maintaining ground cover (e.g. mulching), use of termite activity to improve rain penetration and for regeneration of vegetation (Mando, 1991), modification of soil micro conditions (e.g. conventional tillage) and increasing surface water storage through tillage (e.g. tied ridges).

In this study simple models or programs were used to estimate crop water use and yield.

1.2 Conceptual Framework of Farming System Response to Tillage and Crop Production.

Farming system soil moisture is part of the dynamic processes of the hydrologic cycle. In a semi-arid environment, the physical system (e.g. a farmers plot) could be defined in terms of inflow and outflow processes and also those processes which occur within the system according to the spatial and temporal variabilities in soil moisture among other factors within homogenous areas of microscale (see fig.1). This system is what should be considered to be containing the major problem affecting the ordinary farmer and hence should be well understood in the mitigation against seasonal agricultural water deficits which often extend to critical crop growth stages and hence significantly affecting crop performance and yield. Principally, the analysis of the dynamic processes of the physical system, requires consideration of the functional relationships between the pertinent variables characterizing the processes and those defining the corresponding state of the system (Stewart and Faught, 1984).

The problem of soil moisture status in semi arid environments requires attention from an array of scientific disciplines, e.g. geology, engineering, geography and soil science. For example geologists would attempt to study soil moisture in relation to parent material and soil

characteristics within a large time scale; geographers/hydrologists would look at climate (rainfall and temperature) in relation to infiltration; soil scientists would be concerned with soil properties in relation to soil moisture storage. Some of these disciplines have made little effort to relate soil moisture deficits to variations in climate (e.g. rainfall) and crop production. In order to understand the system response due to variation of rainfall in terms of soil moisture and its consequent crop production under different soil management practices, simple simulation methods should be employed on a simple homogenous area and in a small scale (e.g. a small farm unit or plot). It has been found that soil moisture dynamics is influenced by: unknown system heterogeneities and anisotropies; inadequate knowledge of physical behaviour; unknown time dependence of system parameters and approximations/assumptions introduced for computational economy and therefore application of complex models on large scale may not have a corresponding accuracy on the results. Simple simulation methods can provide the means of bringing together all information about processes involved with the view to giving an integrated response of the whole system to some particular excitation without much loss of accuracy as compared to the complicated methods (Schouwenaars, 1990).

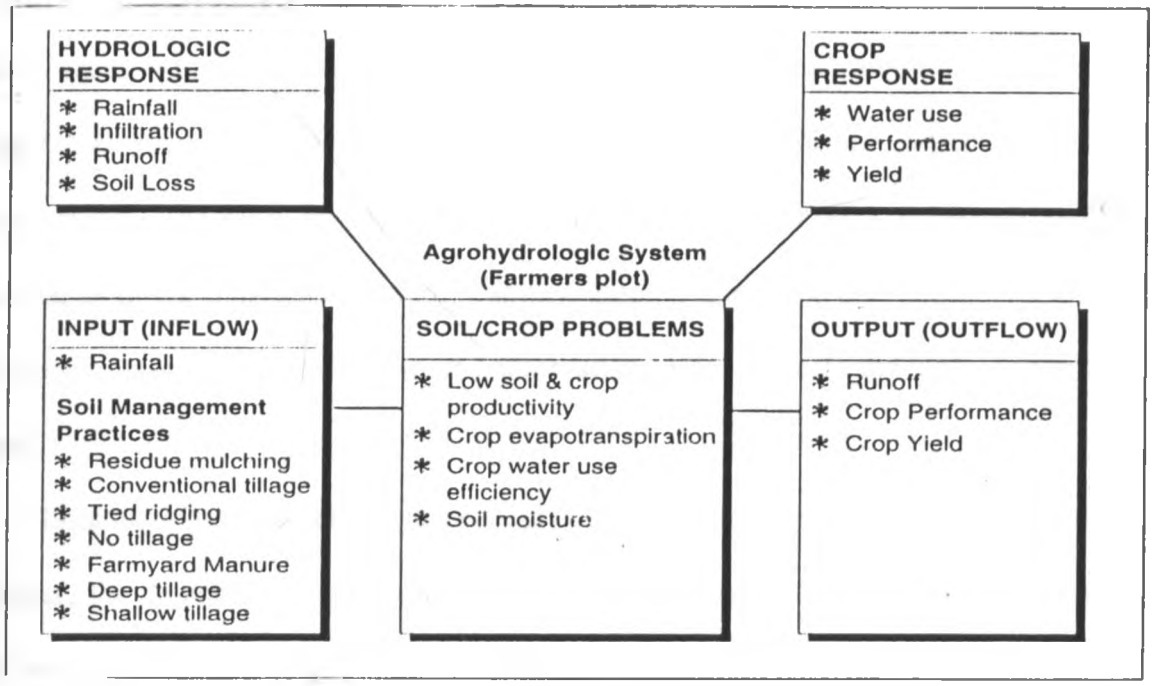

Fig. 1 Conceptual framework of a farming system (Biamah and Onchoke, 1996).

1.3 Water Conservation Research Problem(s), Questions, Objectives and Scope of Study

1.3.1 Research Problem(s)

High rate of crop failure and low yields which occur in semi arid areas of the country has always created a lot of concern. The most important reason advanced is soil moisture deficits due to mostly low, erratic and high intensity rainfall, high surface runoff rates, high evaporation rates, low infiltration of rainfall water and poor soils with low storage capacities. The problem of soil moisture shortage has been compounded by the recurrence of seasonal agricultural drought which significantly affect crop production (Stewart and Faught, 1984).

Some of the main methods of soil moisture conservation measures for improved crop production used in semi-arid areas are tillage and residue management techniques such as conventional tillage, residue mulching and tied ridging. It is important for farmers to

understand the impacts of these simple and cheap methods on soil moisture conservation. The choice of these measures would vary according to soil properties and rainfall characteristics, and the extent to which they increase infiltration and hence soil moisture in terms of amount and distribution. Therefore the appropriateness and applicability of these measures should be seen in terms of the enhancement of infiltrability, amount stored and distributed over critical crop growth stages and therefore which conservation measure yields the highest returns as a result.

Since there has been a rapid increase in both human and livestock population in semi-arid areas, the demographic pressure arising therefore means that more land has been put under crop production. Some of the crops that are grown in these areas include: maize, beans, sorghum and millet. Crop production under these limited moisture conditions requires land management practices that conserve both soil and moisture (Liniger,1989). Good recommendations of appropriate and effective soil and water management practices means that crop production can be sustained and increased in these areas. This study attempts to answer mainly one pertinent question: To what extent do some of the available soil and water management practices used in semi-arid areas increase and conserve soil moisture and what is the impact of the conserved moisture (under these dryland conditions) on crop production?

1.3.2 Research Questions

1. Given some soil type, rainfall, and maize and beans' maximum evapotranspiration, how can the soil moisture be estimated?
2. Given seasonal daily rainfall, how does it relate to the estimated and measured soil moisture in the profile and the subsequent crop evapotranspiration under different soil management practices (mulching, conventional tillage and tied ridging) over two crop

growth periods?

3. Given that the most commonly cultivated crops in semi arid areas of Kenya are maize and beans, what are maximum evapotranspiration rates over their crop growth periods?

4. Given estimated and measured soil moisture variations over crop growth period, what are the available soil moisture variations and actual crop evapotranspiration rates and also what is the impact of the actual water used by the crop on crop production in terms of final yield for the above mentioned crops?

1.3.3 Research Objectives

1.3.3.1 Overall Objective

To assess how seasonal rainfall variation over crop growth periods for maize and beans affects measured and estimated soil moisture in profile under three different soil management practices; and its availability for optimal crop production (crop water use and productivity).

1.3.3.2 Specific Objectives

1. To analyze rainfall/measured and estimated soil moisture relationships under different soil management practices (residue mulching, conventional tillage and tied ridging).
2. To estimate soil moisture variations over two crop growth periods using Land Use Specific Analysis (LUSA) method and then compare the results with actual measured soil moisture in profile.
3. To estimate, by use of Crop Water Requirement Program (CROPWAT), potential and maximum evapotranspiration rates of maize and beans and relate them to measured

and estimated soil moisture variation under the above mentioned soil management practices during two crop growth periods at Kalalu, Laikipia.

4. To estimate potential yields of maize and beans by the 'Wageningen' and Agro-Ecological Zone Methods.

5. To estimate available moisture from the measured and estimated soil moisture and also subsequent actual evapotranspiration.

6. To estimate the actual yields of maize and beans by use of Yield Estimation System (YES), CROPWAT and Doorenbos Methods.

1.3.4 Scope of Study

This study is a systematic soil water analysis to evaluate the yield benefits derived from some of the already existing soil water management practices used in semi-arid areas in Kenya. It is a quantitative assessment of soil moisture responses of these soil water management practices and includes crop water requirements, water balance and yield estimations. The study starts by looking into two seasonal rainfall variations and one of the water balance components, soil moisture with a view to finding out how the variation affects two test crops, maize and beans, in terms of their final yields. This study was based on data from an experimental site at Kalalu, Laikipia. The data included climatic and measured soil moisture on experimental plots during the short rains of 1988 and long rains of 1989 when beans and maize were planted respectively.

2.0 REVIEW OF LITERATURE

2.1 Rainfall in Semi-Arid Areas of Kenya

Farming in semi arid areas mostly rely on rainfall as the sole water supply. The characteristics of rainfall are major factors in water conservation in these areas. Average annual rainfall amount and variability during the rainfall season and amounts of rainfall per storm all affect the water conservation process.

The limited soil water supply in these areas is far too complex than the case of too little rainfall. More often than not crop yields and returns are far below the levels that actual rainfall amounts could support. The soil moisture constraint here is rooted in the variability and unpredictability of seasonal rainfall characteristics in terms of the following factors (Stewart et al., 1981): onset and end of rain dates; rainfall amounts; rainfall duration; rainfall intensity; and rainfall distribution.

Conservation of water in the soil from rainfall on the land requires (i) movement of water into the soil and (ii) control of soil water losses. This conservation involves conserving water from a highly variable and unpredictable source. Therefore the true nature of limited soil moisture supply in semi arid areas is rooted in seasonal variability and unpredictability. Tremendous variability means recurrent drought with increasing frequency as one moves to lower rainfall zones (Stewart and Faught, 1984).

2.2 Effective Rainfall

Natural rainfall can contribute significantly in meeting consumptive use requirements of crops, provided the knowledge of effective rainfall is available. Effective rainfall is the portion of total rainfall that assists in meeting the consumptive water use requirements of

growing crops (Avinash et al., 1988). The other portion of the rain may be lost through surface runoff, deep percolation or evaporation. Also Dastane (1974) defines effective rainfall as the portion of the total seasonal/annual rainfall which is used directly and/or indirectly for crop production at the site where it falls without pumping. The factors that influence effective rainfall are:- soil management practices; meteorological parameters; land; soil; ground-water; drainage channel; and crop characteristics. High intensity rainfall increases runoff and lessens infiltration thus reducing effective rainfall. Well distributed rainfall in frequent light showers is more effective.

Increase of temperature, radiation, wind velocity and decrease in humidity enhance evapotranspiration and encourage greater soil moisture deficit. The enhanced soil moisture deficit results in a greater proportion of effective rainfall (Dastane, 1974).

On level land, rain water has a higher opportunity of infiltrating than on sloping land. Therefore rolling and undulating land favour high effective rainfall. Increased soil water holding capacity has an increased fraction of effective rainfall. The soil water holding capacity depends on soil depth, texture, structure and organic matter content and therefore any modification of these would correspondingly change the effective rainfall. The higher the soil moisture deficit the higher the effective rainfall because there is high demand for water by the crop.

Physical and chemical properties of soil water, e.g. depth, turbidity, and viscosity of water, and the nature of dissolved salts influence infiltration and hence effective rainfall (Dastane, 1974).

Effective rainfall is high when the ground water table is deep and low when it is shallow. Before the onset of rains, the water table may be deep but rises to the surface during the rainy season. Thus the contribution of ground water to crop water needs is

variable and the proportion of effective rainfall varies with it. If the groundwater is saline, effective rainfall increases since salts are diluted.

Bunding, terracing, ploughing, ridging and mulching reduce runoff and therefore increase effective rainfall while random practices may reduce it (Dastane, 1974).

The degree of ground cover, rooting depth and stage of growth influence the rate of water uptake by crops. Crops with high uptake rates create greater soil moisture deficits and hence a higher effective rainfall. Rainfall just before crop harvesting, rainfall which reduce yields and which results in deterioration of a crop are ineffective (Dastane, 1974).

Effective rainfall is calculated on the basis of probability of occurrence from records over a long period of time. It is utilized in planning cropping patterns in dryland farming, irrigation project planning and operation, drainage design and planning soil water conservation programmes (Martin, 1992).

From the foregoing, effective rainfall is a concept which is easy to understand but very difficult to determine. Nevertheless methods exist for estimating effective rainfall including; direct field monitoring techniques, empirical techniques (equations, tables and charts), and soil water balance methods.

If all possible pathways of rainfall disposition are considered, then effective rainfall can be estimated and this is indeed a very complex concept. In fact, the working definition used will vary with the discipline involved (Dastane, 1974). Effective rainfall will then mean one thing to a hydrologist interested in predicting flood runoff and a different thing to a scientist involved in irrigation scheduling. There are limited procedures available for estimating effective rainfall and their use calls for expediency rather than judgement.

2.3 Measurement and Estimation of Effective Rainfall

All effective rainfall measurement and estimation methods are based on representations and varying degrees of simplification of the hydrologic cycle. The processes are; rainfall, interception, infiltration and runoff, evapotranspiration, redistribution (downward) of soil water, and deep percolation.

The equation for the conservation of mass (water) in the soil profile is expressed as (Avinash et al., 1988):

$$\Delta V = R - (I + Q + ET + DP) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

Where;

ΔV	=	the change in soil water storage (in mm of water)
R	=	rainfall in mm
Q	=	runoff in mm
ET	=	evapotranspiration in mm
DP	=	deep percolation in mm.
I	=	Interception in mm

All these quantities occur over a time period Δt.

Effective rainfall (P_{eff}) is defined in the model as being that portion of total rainfall that infiltrates into the soil profile and does not contribute to deep percolation. This can be expressed as:

$$P_{eff} = R - (I + Q + DP) \quad . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

Effective rainfall may also be estimated through the following methods:- fixed percentage of rainfall; dependable rain (empirical form); empirical formula; and USDA Soil Conservation Service (Martin, 1992).

2.4 Soil Moisture in Profile

The variable amount of water contained in a unit mass or volume of soil, and the energy state of water in the soil are important factors affecting the growth of plants. There is therefore a need to determine the amount of water in the soil in order to understand its hydrological and biological relationships. There are several methods of directly or indirectly measuring soil moisture (Hillel, 1980a) but there are no universally recognized standard methods of measurement and no uniform way to compute and present the results of soil moisture measurements.

Water constitutes one of the most important constraints to increasing food production in our hungry world. So tenuous and delicate is the balance between the demand for water by crops and its supply by rainfall that even short term dry spells often reduce production significantly and prolonged droughts can cause total crop failure and mass starvation (Hillel, 1980b). The role which soil moisture plays in the production of agricultural crops is complex and the interacting processes involved in crop growth and subsequent yield do not easily render themselves to quantification. Hence several attempts have been made to understand crop response to water through modelling of plant-soil-water systems and some success has been met. A proliferation of soil water models have been developed ranging from physically based models (Nimah and Hanks,1973; Nwabuzor, 1988) to empirically-based models. The high number of models has been accentuated by the development of computer technology which offers a fast and accurate solution to hitherto complex and time consuming algorithms.

Despite the development of several models on plant-soil-water relations, Schouwenaars (1990) says that most of these models use descriptions of site specific characteristics which are global and therefore certain model parameters can only be presented in terms of probability and hence he questions the validity of studying the plant-soil-water

relations which are part of a complex process in detail. He suggests that simple water balance models should be used to keep track of the soil moisture within a crop's root zone. Driessen quoted by Van Keulen and Wolf, (1986) says that this can be done by the aid of a water balance equation, which compares for a given period of time, incoming water in the rooted surface soil with outgoing water and quantifies the difference between the two as a change in the amount of soil moisture stored.

2.5 Significance of Soil Water Conservation

The problem of soil water losses through surface runoff and evaporation is one of the major limiting factors in agricultural production in semi arid areas of Kenya. In these areas short intense storms coupled with prolonged dry spells make crop production difficult if not impossible. Without some measures to reduce surface runoff during and after rainfall events, enhance surface storage, infiltration and water holding capacity of the soil, and minimize evaporation losses during dry periods chances of crop failure are high.

Direct evaporation from the soil constitutes a major pathway of water loss which is considered wasteful since it does not contribute to crop production. Upward movement of water due to evaporation not only reduces the storage of plant-available water but also deposits salts within the root zone (Mwendera, 1992). Thus it is important to device ways of minimizing evaporation for a successful agricultural production. Appropriate soil management techniques for soil and water conservation are needed and these differ according to soils and ecological zones. In semi arid areas, the choice of any soil management system is clear, that is all rainfall must be retained by techniques which reduce runoff, improve infiltration and increase the water holding capacity of the soil to benefit crop growth (Stewart and Faught, 1984).

One of the main objectives of any tillage operation is to optimise soil water intake rate and moisture retention capacity for increased crop production (Gitau and Biamah, 1995)

Some of the appropriate tillage and residue/manure management practises used in semi-arid areas to improve infiltration and hence conserving soil moisture for plant growth include maintenance of ground cover (e.g. cover cropping and mulching), modification of soil surface macro conditions (e.g.zero, minimum, conventional and conservational tillage) and increasing surface water storage by runoff impounding structures (e.g tied ridges, U and V shaped micro basins (Alria et al., 1991). Another practice involves the incorporation of organic manure into the soil. This practice significantly increases infiltration and moisture holding capacity.

2.6 Soil Water Management Practices

The problem of soil water management especially in semi arid areas may be accomplished through tillage or soil surface management to prepare a desired seedbed. Judiciously used, tillage can be a powerful tool to alleviate some soil-related constraints to crop production, e.g. compaction, crusting, low infiltration, poor drainage, unfavourable soil moisture and temperature regimes, disposal of undesirable biomass and wastes, and pest management. Improperly used, tillage can lead to deterioration of soil structure, reduced infiltration, accelerated runoff and erosion, water pollution, and degradation of soil and environment (Lal, 1991 and Alria et al., 1991).

Soil tillage is therefore a basic and an important component of agricultural production technology. In addition to preparing the desired seedbed, tillage is needed to manage crop residue, mix fertilizer in the soil, improve aeration, alleviate compaction and optimize soil temperature and moisture regimes. The exact nature of tillage operations, however, is soil

and crop specific (Lal 1991).

There is now a greater need to attain agricultural sustainability than ever before in fragile ecosystems and marginal lands of the country. Productivity and land carrying capacity of the arid and semi arid lands (ASAL) are low, but the demographic pressure and demands on limited resources are high. As a consequence resources are used to the limit, and risks of soil and environmental degradation are high. The issues of agricultural sustainability in these areas are: risks of desertification due to degradation and aridization of soil and environment, perpetual drought stress, high risks of crop failure, nutrient deficiency and soils of low fertility, soil compaction and low capacity of land. Some of the main technologies for sustainable management of soil and water resources for the ASAL areas are: rough ploughing, tied ridges and mulching. Residue mulch enhances sustainability through its effects on soil and water conservation, maintenance of soil organic matter at favourable level, and enhancement of the activity of soil fauna. Soil inversion or ploughing reduces the compactness of semi arid areas by mechanical loosening to alleviate compaction, increase infiltration capacity, conserve water in the root zone, increase deep root system development, and decrease risks of soil erosion by wind and water (Lal, 1991).

2.6.1 Conventional Tillage

Conventional tillage is the loosening of the soil either by using machines or hand tool so that the loosened soil can enhance infiltration rates, water holding capacity, root development and also remove weeds (Muchiri 1989 quoted in Gicheru 1990). It is a common practice used by many farmers in Eastern Africa. Normally seedbed preparation involves primary tillage operations with no secondary tillage until weed control (Beasley et al. 1984). The plain hoe (Jembe) is the most common implement for manual tillage in Eastern Africa

though some times the forked hoe is also used.

Larson (1962) observed that the loose mulch formed as a result of hoeing is not stable enough to withstand heavy storms. Furthermore the surface feeding roots of the crop may be destroyed. Hulugalle and Maunya, (1991) were of the view that soil degradation associated with mechanized conventional tillage can be minimized with zero tillage. However, the success of such a move will wholly depend on the soil type and the availability of organic matter.

Appropriate measures for soil and water conservation are often site specific and vary from place to place. For Kaolinitic clay soils, Latham and Ahn. (1987) recommended tillage after harvest in order to minimise evaporation and maximise on the soil water intake rate. On the other hand, Harte (1984) observed an increase in bulk density due to tillage on red brown earth in New South Wales. Furthermore mechanized agricultural systems used in Southern Brazil and West Africa's semi arid areas have been observed to accelerate soil erosion, deplete plant available nutrients and reduce crop productivity (Castro et al., 1991; Hulugalle and Maunya, 1991).

The break down of soil structure and the loss of fertility especially on dusty, fine sandy soils, particularly when dry; on very heavy, sticky soils are possibly the most serious consequences of conventional tillage. However, tillage can improve the structure of heavy soils (Morgan, 1986).

2.6.2 Crop Residue Mulch

Many definitions of mulch have been given (Jacks et al. 1955; Moody et al. 1969; Unger 1975; Stigter 1987; and Othieno and Ahn, 1980) but they all point to the fact that mulch makes an ideal cover to protect the soil against erosive raindrops, modify soil

temperature, reduce loss of water by surface evaporation, reduce weed emergence, add nutrients for growing plants and encourage earth worms and other desirable soil fauna. Mulch also increases organic matter in the soil and reduces runoff velocity.

Mulching affects crop growth indirectly through reducing evaporation, improving soil physical properties and hence improving infiltration. Provision of a rough surface also increases the infiltration opportunity time. In this way, runoff is reduced by mulching. Mulch is known to increase the water holding capacity of the soil (Unger, 1975).

It has been shown that during a prolonged drought, mulching helped to conserve soil moisture up to 90 cm depth in tea plots (Othieno and Ahn, 1980). Several other researchers have reported increase in soil moisture as a result of mulching (Black, 1973; Unger, 1978; Pereira and Jones, 1964). It is important to note that the low temperatures under surface residues may do more damage to the crop than water conservation benefits (Ulsaker and Kilewe, 1984).

Materials used for mulching include crop leaves and stalks, coffee husks, sawdust, napier grass and banana trash. Soil and water conservation are the most important reasons advanced for mulching (Pereira and Jones, 1964).

2.6.3 Tied Ridging

Tied ridging is an effective and simple practice in controlling runoff especially when they are constructed along the contour. Tied ridges bond water so that it has time to infiltrate into the soil profile. They were found to be sufficiently effective in controlling runoff on Chromic Luvisols at Katumani (Njihia, 1979). Pereira et al. (1958) found out that tied ridges in a semi arid area do not improve the resistance of soil to surface sealing, but may impede surface flow of water within the furrow, thus allowing more time for water to infiltrate.

2.7 Dryland Tillage Research in Kenya

Tillage research studies conducted in semi-arid areas of Kenya have focused on the effects of some tillage practices on soil and moisture conservation for increased crop production. These tillage methods are: mulching, farmyard manuring, tied ridging, zero tillage, conventional tillage and contour furrows. A few of the methods will be discussed here.

Dryland tillage research conducted at Katumani (Marimi 1978; Njihia 1979; Muchiri and Gichuki, 1982; Kilewe and Ulsaker, 1983) found that conventional tillage, tied ridges, bench terraces, residue mulch and farmyard manure were sufficiently effective in controlling runoff through increased surface water storage, breakdown of soil surface crust, improved infiltrability and moisture retention characteristics of the soils.

Pereira et al. (1954) also found out in an experiment that 10 cm mulch of elephant grass on a coffee plantation produced after 2 years an infiltration rate equal to that of 5 years under elephant grass. Also Pereira et al. (1958) in a water conservation study in a semi-arid area, established that tied ridges improved infiltration by allowing more time for impounded water to penetrate.

Marimi (1978) at Katumani, Machakos found out that zero tillage and tied ridging operations improved infiltrability and moisture storage of the soil. Significantly higher dry matter and grain yields of maize and beans were obtained in tied ridged plots as opposed to low yields in other plots. Minimum tillage gave the lowest crop yields. He also found out that with a seasonal rainfall of 171 mm, there was grain yield of maize from tied ridges and stover mulch plots.

Njihia (1979) at Katumani, Machakos monitored effects of tied ridges, conventional tillage, crop residue mulch and farmyard manure on soil and moisture conservation. Maize

stover mulch was sufficiently effective in controlling runoff through increased the time available for infiltration. Maize stover also helped minimize evaporation. Tied ridges effectively controlled runoff. Conventional tillage with or without farmyard manure lost about 40% of the storm rainfall. A grain yield of maize was realized from the tied ridged and stover mulch plots for a seasonal rainfall of 171 mm. No grain was harvested from conventional tillage with or without farm manure.

Muchiri and Gichuki, (1982) at Katumani found that contour furrowing, bench terracing and conventional tillage operations effectively conserved soil moisture. In their study they showed that conventional furrows, wide furrows and mini benches retained all the runoff within the furrows and increased infiltration opportunity time after the rainfall. Wide furrows (1 m wide) had the highest soil moisture content followed by conventional tillage during both the short and long rains. These furrows had significantly higher maize grain yield than all the other tillage methods.

Liniger (1989) at Kalalu, Laikipia observed that the reduction of runoff and evaporation loss was a significant factor in the mulched plots. He found out that there was storage of plant available water between 45 and 110% higher in the mulched plots than under conventional tillage. Mulching was also reported to have increased yields by 45% when compared to similar yields under conventional tillage.

Gicheru (1990) at the same place found out that crop residue mulching (despite lagging behind in seedling emergence) had better crop performance and yield when compared to conventional and tied ridging methods. The tied ridge plots had the lowest amount of soil moisture and hence the poorest crop performance and yield (due to no runoff to impound and high evaporation water losses from increased soil surface area.)

Nagaya (1993) in Katumani, Machakos in Kenya found out that tillage and farmyard manure application enhanced rain infiltration, reduces soil loss and improves soil moisture during the onset of rains.

Gitau (1994) working in Illuni. Machakos also found out that deep tillage increased rainwater infiltration through depressional storage of surface runoff while shallow tillage resulted in high soil moisture storage due to reduced soil disturbance.

Sishekanu (1996) at Katumani Machakos investigated the influence of tillage depths and farmyard manure on soil erosion and moisture found out that a combination of tillage and farmyard manure reduced surface runoff and soil loss hence increasing soil moisture.

2.8 Crop Water Use

As mentioned above, the relationship between crop, climate, water and soil are complex and many biological, physiological, physical and chemical processes are involved. Doorenbos and Kassam, 1979 say that for practical purposes the knowledge must be reduced to a manageable number of major components to allow meaningful analysis of crop response to water at the field level.

A definition of a few terms on the major components follows:

2.8.1 Concept of Crop Water Requirements

This is defined by Doorenbos et al. (1977) as the depth of water needed to meet the water loss through evapotranspiration of a disease-free crop, growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment.

2.8.2 Potential Evapotranspiration (ET_o)

Rosenberg (1974) defines it as the evaporation from an extended surface of short green crop which fully shades the ground, exerts little or negligible resistance to the flow of water, and is always well supplied with water. This definition can be compared to the one which Doorenbos and Pruitt, (1977) have given as being reference crop evapotranspiration which 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.

The definition of potential evapotranspiration presupposes no internal plant resistance to water. Evidence of significant stomatal influence on evapotranspiration in sugar cane and in dry beans suggest a major influence of stomatal resistance on evapotranspiration (Rosenberg, 1974).

The phrase "well supplied with water" in the definition of potential evapotranspiration means no soil imposed restrictions reduce the meteorologically determined rates of water use. Marlatt et al. quoted in Oketch (1991) showed that decreasing soil moisture availability reduces the rate of evapotranspiration below the potential. Hence potential evapotranspiration cannot prevail if the soil is not well supplied with water and depending on the crop, may not exist for any important part of the growing season (Rosenberg, 1974).

2.8.3 Maximum Crop Evapotranspiration (ET_m)

Maximum crop evapotranspiration (ET_m) refers to conditions when water is adequate for unrestricted crop growth and development. It represents the rate of maximum evapotranspiration of a healthy crop, grown in large fields under optimum agronomic and water management. Evapotranspiration is related to evaporative capacity of the air as

controlled by temperature, which is expressed as potential or reference evapotranspiration (ET_0) and calculated to predict the effect of climate on crop evapotranspiration. The method used for ET_0 calculation is Penman-Monteith which is preferred since it is supported by sound theoretical basis. Maximum crop Evapotranspiration (ET_m) is related to ET_0 by empirically determined crop coefficients (K_c) when crop water requirements are fully met. Crop coefficients increase during the development stages, (Martin, 1992). (Berger, 1983) says that K_c varies according to the crop considered and its stage growth. In order to determine the K_c values, the length of the different stages of crop growth must be known. The following equation is normally used:

$$ET_m = K_c \times ET_o$$

2.8.4 Actual Evapotranspiration (ET_a)

The demand for water by the crop must be met by the water in the soil, via the root system. The actual rate of water uptake by the crop from the soil in relation to its maximum evapotranspiration is determined by whether the available water in the soil is adequate or whether the crop will suffer from stress inducing water deficit. Also the rate of actual evapotranspiration from say a cropped land surface depends on the effect of climate (accounted for in potential evapotranspiration), type of crop, crop growth stage and the growing season.

2.8.4.1 Determination of Actual Evapotranspiration (ET_a)

Actual evapotranspiration (ET_a) of a crop in relation to the maximum evapotranspiration (ET_m) is determined by the availability of water in the root zone and water extraction ability via the root system (Driessen and Konijn, 1992). In order to determine

actual evapotranspiration, the level of the available soil water must be considered. Adequate soil water availability is present when $ET_a = ET_m$. A crop water deficit and possible crop-induced stress occurs when $ET_a < ET_m$. Available soil moisture may be defined as the fraction (p) to which the total available soil water S_a may be depleted without causing ETa to become less than ETm. The value of the fraction (p) depends on the crop type, the magnitude of ET_m and the soil characteristics e.g. texture of the profile in the root zone and compactness or permeability of layers (Doorebos and Kassam, 1979).

2.8.5. Total Available Soil Moisture

Doorenbos and Kassam (1979) define the total available soil water (S_a) as the depth of water in mm/m soil depth between the water content at field capacity (SMFC is at soil water tension of 0.1 to 0.2 atmosphere) and the soil water content at wilting point (SMPWP or at soil water tension of 15 atmosphere). Other sources use different tension ranges, for different textural classes:- 0.1 bar for coarse texture soils and 0.33 bar for moderately and fine textured soils (Jamison and Kroth, 1958; Colman, 1947).

Soil texture is a major factor in determining available soil water. However, soils with identical soil texture may vary considerably in total available water (S_a) in the soil root profile. A representative S_a value should be selected to compensate for layered soils in which dense layers restrict water holding capacity and distribution. Normally actual field observations and additional sources are recommended for better selection (Schultink 1987).

The articles by Ritchie (1981) suggest that variations in potential extractable soil water, (the difference between highest field-measured water content of a soil after plants stop extracting water) might be less extreme than suggested by Doorenbos and Kassam (1979).

Hillel (1980b) says that the rate of water uptake by a crop depend on the ability of

the roots to absorb water from the soil with which they are in contact, as well as on the ability of the soil to supply and transmit water toward the roots at a rate sufficient to meet transpiration requirements. These, in turn, depend on following:-

(i) Properties of the plant e.g. rooting density, rooting depth, and rate of root extension, as well as the physiological ability of the plant to continue drawing water from the soil at a rate needed to avoid wilting while maintaining its vital functions even while its own water potential decreases.

(ii) Properties of the soil e.g. hydraulic conductivity-diffusivity-matric suction-wetness relationships.

(iii) Meteorological conditions which dictate the rate at which the plant is required to transpire and hence the rate at which it must extract water from the soil in order to maintain its own hydration. What this means is that the crop water uptake is not an exclusive function of the content or potential of soil water.

2.8.6 Readily Available Soil Moisture

Not all water held between FC and PWP can be considered as equally available to plants. Milthorpe (1960) suggests that at tensions up to 1 bar water is freely available to most crops, whilst Hensen et al. (1980) consider that 75 percent of the available water capacity can be easily extracted. A rule of thumb is that the total readily available water capacity value is half to two thirds of the total available water capacity of a profile. The proportion of water held at the low tensions expressed by the total readily available water capacity may sometimes be more important than the total available water capacity in determining crop response to soil moisture conditions. It is this readily available water held at low tensions within the larger soil pores which is particularly affected by soil structural conditions.

2.8.7 Yield Response to Water

The primary yield response is a function of crop water requirements and water deficits experienced during critical crop growing phases. The quantification of this relationship is possible when empirical data on crop moisture requirements, maximum yield, moisture deficit and resulting actual yield are available. Plant stress resulting from moisture deficits is determined by several variables, including rainfall and actual evapotranspiration. Plant moisture stress can be quantified by the rate of actual evapotranspiration (ET_a) in relation to the maximum evapotranspiration (ET_m).

ET_m and ET_a can be quantified for most crops and most climatic zones. If ET_a equals ET_m, crop moisture requirements are fully met. If $ET_a < ET_m$, water supply is insufficient and yield will be reduced in most crops.

The extent to which moisture deficit will reduce crop yield is largely determined by the crop species and the length and timing of the growing season.

Doorenbos and Kassam (1979) propose an empirically-derived yield response relationship. When crop water demand exceeds supply, actual evapotranspiration will be less than maximum ($ET_a < ET_m$) the resulting crop stress will affect growth and, ultimately, harvestable yield. The significance of water stress as a yield reducing factor will depend on the magnitude, the crop type, timing of the deficit during the crop development stages, and finally, its duration.

To quantify the yield response to variable water supply conditions, the yield response factor (K_y) is introduced. It relates relative yield decrease

$$\left(1-\frac{Y_a}{Y_m}\right) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

to relative evapotranspiration deficit

$$(1-\frac{ET_a}{ET_m}) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (4)$$

Water deficit may occur throughout the growing period or during individual crop development stages (i.e establishment, vegetative, flowering, yield formation, or ripening).

The relationship is finally written as:

$$(1 - \frac{Y_a}{Y_m}) = K_y(1 - \frac{ET_a}{ET_m}) \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (5)$$

Where:

Y_a = actual harvested yield

Y_m = maximum harvested yield

K_y = yield response factor

ET_a = actual evapotranspiration

ET_m = maximum evapotranspiration

Although the relationship looks simple and tenable, care should be taken on results obtained by using such equations of characterization of crop response to inputs of water so called crop-water production functions because they are largely empirical, site specific, and their inclusion or omission of other production inputs such as climatic parameters, crop nutrients, soil salinity, disease and pest influences will make them give widely varied estimates of yield levels from the actual (Sinclair et al., 1984).

2.9 Yield Estimations

Several people have developed models to predict crop yields. A micrometeorological approach to yield prediction was taken by Kanemasu et al. (1976; 1978) based on the interrelationships among solar radiation, temperature, potential transpiration, and leaf-area

index. Still other models to predict evapotranspiration and yield have been proposed by Nimah and Hanks, (1973).

In Kenya a few examples of yield estimations and measurements especially for maize have been done. Stewart (1982), working in Katumani area, Machakos under the Dryland Cropping Systems Research Project, did experiments on the relationships between water availability and yields of maize and beans. From his experiments it was found that yields of maize and beans increase linearly with applied water until their requirements for water were satisfied. Yields then remained constant when rainfall plus irrigation was 250 mm and 590 mm for beans and maize respectively.

Shisanya (1988) utilised FAO methods developed by Frere and Popov (FAO, 1986) and Doorenbos and Kassam, (1979) to predict maize yields at Kakamega District, Kenya.

The first prediction method he used utilises the water requirements satisfaction index (I). The index indicates the extent to which the cumulative water requirements of (for example) an annual crop is satisfied at any stage of the crop growing season. The index (I) is calculated as follows.

Shisanya (1988) assumed that at the beginning of the growing season, sowing takes place when there is ample moisture in the soil. The index (I) is thus assumed to be 100 and remains at this level until either a water surplus of more than 100 mm or a deficit occurs. Surplus of the index (I) is reduced during the first decade (10 day period) to 97 and remained at this level until a further stress period occurred. If say, after the second decade the water reserves fell to 480 mm and there was a deficit of 20 mm, then the quotient between the water deficit 20 mm and the total water requirements 500 mm was made and gave a value of 0.04 or 4% of the water requirements which was not satisfied and the previous index figure went down from 97 to 93.

The calculation continued by decade until the crop matured, corresponding to the end of the growing season. It must be borne in mind that the index (I) start at 100 and thereafter only remains at 100 or fall if water deficit periods occur during the vegetative cycle. Even if the water deficit is, compensated for afterwards, the index will not increase.

At the end of the growing season, (I) reflected the cumulative water stress endured by the crop during successive decades, the higher the final index (I) the lower the water stress. Assuming a linear relationship, (I) was linked to the final yield of maize after knowing the average yield maximum of maize (Y_{mp}) in each agro-ecological zone or from historical records. For example if Y_{mp} was 50 bags/ha and (I) was 78 this represents a 22% yield reduction. Therefore the final yield of maize expected is 39 bags/ha (Shisanya, 1988). The accuracy of this model depends on how accurately Y_{mp} and crop water use are estimated. The index nevertheless gives a good estimate of the yield.

The second method used was that developed by Doorenbos and Kassam, (1979) and is as explained in 2.8.7 above.

The two methods don't take into account factors other than water requirement and only the first method has limited sensitivity to excess water.

Ministry of Agriculture yield estimates is based on a district sampling procedure using the quadrant method prior to harvest, Shisanya (1988).

A comparison made in Kakamega, by Shisanya (1988) using the above methods, between seasonal rainfall and Ministry of Agriculture yield estimates for a period (1970-1985) showed that there was no correlation between total seasonal rainfall and maize yield. For example in 1984 rainfall was about 1300mm but this was concentrated within a short period resulting in about 3.5tons/ha. In 1971 rainfall of 700mm with much better distribution gave 4.7tons/ha. Low yields could occur with a high rainfall amount falling within a short

period, followed by a prolonged dry spell like in 1980. This confirms that the distribution of rainfall throughout the season is more important for maize than total seasonal amount.

2.10 Potential and Maximum Yield Production

Potential crop production is defined (Van Keulen and Wolf, 1986) as the total dry matter production of a green crop surface that, during its entire growth, is optimally supplied with water and all essential nutrient elements, and grows without interference from weeds, pests and diseases.

Doorenbos and Kassam, (1979) define maximum yield as the harvested yield (expressed in biomass or dry matter) of a high-producing variety, well adapted to the given environment, including the time available to reach maturity without stress-inducing constraints (insufficient water or nutrients, pests and diseases) under good farm management.

Climatic factors affecting maximum yield are temperature, rainfall, solar radiation and length of growing season. Special requirements may exist relative to specific temperatures and day length during certain stages of crop development. Doorenbos and Kassam, (1979) provide a summary of major crop requirements. Water availability and temperature affect the length of the growing season, while variations in moisture supply within the season affect actual crop yield during critical stages in development (Schultink 1987). Some crops require a periodic deficit to aid flowering or fruit development. The maximum yield calculation may be carried out by use of "Wageningen" method, based on the earlier work of De Wit (1965).

Berger (1983) says that the potential yields for the region around Kalalu for maize and beans are 26 bags and 13 bags per acre respectively. Optimum yields are around 44 and 60 percent of the potentials for maize and beans respectively.

2.11 Optimum Yield Levels

In semi arid areas the time of planting is considered optimal if it optimizes the water supply for the ensuing growth period of the crop. This optimization is described by Berger (1983) as the minimization of the crop water deficit and thus the reduction in yield. The time of planting can only be given statistically by analysis of many rainfall records.

The yield which results from this procedure is called the optimal yield as opposed to the potential yield. The potential yield is always set at 100 percent, and the optimal yields are consequently below that figure.

Yields realised by the small scale farmers are lower than optimal yields due to the difficulty of selecting the optimal time of planting plus other factors affecting yield. The optimal time of planting during the long rains (around Kalalu area) is end of March and early April. In view of the low yields of maize it can be said that maize is not very adapted to the ecology of the area but is grown because it holds a high position as a staple food for the people. The hybrid maize varieties show slow rate of growth and flowering and yield formation are delayed until the next rainy seasons. It is always advisable to plant shortly before the onset of the rains, (Berger 1983). For short rains the optimum planting period is end of October and mid-October for maize and beans respectively.

2.12 The "Wageningen" Method (Doorenbos and Kassam, 1979)

It is based on a simplified water availability - yield relationships which have been tested extensively for a wide range of climatic conditions for four crops, alfalfa, maize, sorghum and wheat. The method is further based on work by Slabbers (1978) who established that linear relationships could be successfully used to establish a cause and effect relationship between dry matter production estimates and water yield. He used a

mathematical approach to convert dry matter estimates into predictable yields. To do this, it was assumed that maximum dry matter production occurs at ET_m.

Production potential estimates are based on De Wits (1965) work using radiation and evapotranspiration data. For application to agricultural crops corrections are required using crop-dependent constraints and expressions of the effect of temperature, growth efficiency (respiration) and for harvested portion of the final yield. All yields are expressed as experimental yields (Y_{me}). The procedure for calculation of Y_{me} for maize is shown under methodology.

The estimate can, however, be adjusted to actual field conditions (see YES, CROPWAT, and Yield Response Factor Relationships).

2.13 "Agro-Ecological zone" Method

Since the above 'Wageningen' method can only be applied for the crops mentioned it was therefore used for maize in this study. A different method was selected for beans which is the Agro-ecological zone Project. The method is described by Dorenboos and Kassam, (1979).

Potential yields are calculated for a standard crop according to De Wit (1965) concept as explained above. Corrections are made for genetically-controlled crop growth under identical climatic conditions. Presumably; climatic crop requirements are met and variables such as water, nutrients, salinity, pests and disease will not affect potential yield. Under actual farming conditions, yield losses will occur due to adverse climatic conditions over short periods, limited water and nutrient supply, and problematic farm operations including land preparation, weeding and harvesting. These constraints are complex and it is difficult to quantify their effects on yield. However, when compared to actual farmers' yields, the

calculated potential yield (Y_{mp}) will give an indication of the efficiency in agricultural production. The procedures for calculating potential yield (Y_{mp}) are:- calculate the gross dry matter production of a standard crop (Y_o) as in the 'Wageningen' method; make corrections for crop species and temperature variations; make corrections for crop development over time and for leaf area (cL); make corrections for net dry matter production (cN); and make corrections for harvested yield (cH).

The standard crop leaf relationship (cL) is calculated using a leaf area index (LAI) for a mature crop which is assumed to represent five times the surface of the total ground area. The time factor incorporated into this relationship reflects the average growth rate during the five portions of the production cycle.

In concluding this chapter, it has been deduced from the aforegoing that there has been little research done in terms of soil moisture quantification over crop growth periods in the semi arid areas. It is necessary to know the impacts of soil water management practices on soil moisture in these areas where water deficit is a norm rather than an exception. The reduction of the water deficits through maximum use of rainfall is a priority for increased productivity.

3.0 RESEARCH APPROACH AND METHODOLOGY

3.1 Research Study Area

3.1.1 Introduction

The data used in this study was collected from earlier research and meteorological information collected for Kalalu, Laikipia. The site was chosen for the purpose of applying an evaluative framework for the study of assessing the impacts of soil water on crop yield. It was also supported by the appropriate soil water conservation methods used mostly in semi-arid areas. The methods of the study chosen are easily and systematically applicable to the site and the earlier experiments done. The site has physical characteristics considered relatively homogeneous at the level of detail supported by the soil management practice evaluation. The area is related to existing soil and water management uses, associated farming systems and estimated crop production potential based on the land use alternatives and crops grown.

A brief description of the site will suffice to bring into picture of what kind of area is being dealt with. The Kalalu area faces a limited available soil moisture supply for crop production and depend mainly on traditional rainfall. There is great need of practising appropriate water-conservation techniques for rain-fed land use to curb losses of precious rain water. Since there are no other water sources or are scarce which can be used for irrigation, the consequences of mismanaging rain water would be recurrent crop failures and problems of Environmental degradation leading to declining productivity, a worldwide problem in the semi-arid tropics (ICRISAT and UNEP, 1986).

3.1.2 Characteristics of the Kalalu Experimental Site

The site is found within the semi-arid highlands of Laikipia located on the Western and North-Western foot slopes of Mt. Kenya between 1,600 and 2200 m a.s.l.

The climate of this area is semi-arid and falls within Agroclimatic Zone IV/6 (Sombroek and Braun, 1980). The Agro-ecological zone is lower Highland zone 4: Cattle-Sheep-Barley, Jaetzold and Schmidt (1983).

3.1.3 Agrometeorological Data from the Experimental Site

The data records were collected from a nearby agrometeorological station which is about 200 m from the experimental site. The station was established in 1985. The data available was on rainfall, evaporation, temperature, relative humidity, wind run, sunshine hours and radiation.

3.1.4 Soils

The soils at Kalalu are classified as ferric Acrisol. They are deep, well drained, reddish brown in colour and of clay type (Desaules 1983 and Gicheru 1990). The slope varies from 2-5 percent. The geology of the area is based on the Mt Kenya volcanic (phonolites).

The original vegetation consisted of cedar montane sclerophyll forest (Trapnell et al. 1976) but most of it has been cleared.

3.1.5 Land Use

The ratio of crop to grazing land varies from 2:1 to 1:4 while the percentage of plots settled is 80 percent and the average size of plots is 5.8 ha (Kohler 1983).

3.1.6 Rainfall

The median rainfall (1942-75) of Kalalu is 700 mm/year and ranges from 416 mm to 1,160 mm and the distribution is trimodal. The long rains start in March and end in May. Short rains start in October and end in November. The continentals come in July to August. The growing period of long rains (longer than 100 days) are on average 76 percent (Flurry 1985).

The mean annual rainfall of the Experimental Site is 749.5 mm based on a 3 year period (1986-1988) and that based on 54 years observations is 711.4 mm (Gicheru, 1990).

The driest month of the area is February with an average rainfall of 1.3 mm and the wettest month is April with an average rainfall of 187.8 mm (Gicheru 1990)

3.2 Experimental Layout and Design

As mentioned above some of the research data used here was from the past research conducted by Gicheru (1990). The layout and design of this experiment is briefly described here below.

A Completely Randomized Block Design (CRBD) with three treatments and three replicates was used. Each plot was of size 4 m x 10 m and an access tube installed at the centre to a depth of 120 cm to enable soil moisture measurements by a neutron probe.

The three treatments were conventional tillage (CT), residue mulching (RM) and tied ridging (TR). Maize stover was used as mulch at a rate of 3 tonnes/ha. The mulch was randomly applied on each plot. Tied ridges had a spacing of 40 cm for beans during short rains (1988) and 75 cm for maize spacing during the long rains period of 1989. One conventional operation was done before planting using hoes to a depth of 20 cm.

Soil moisture content was monitored on a weekly basis using neutron probe. The field

capacity and the wilting point moisture contents as determined in the field differed with depth probably due to some errors as the conditions were not controlled and also as a result of inaccurate neutron probe calibration and measurements Gicheru, (1990). Also the difference was probably due to the different textural variations with depth.

Table 1 Bulk density (kg/m^3) and available soil moisture (percent volume) of a ferric Acrisol (Gicheru, 1990).

Soil depth (cm)	Bulk Density (kg/m^3)	Field Capacity (% v/v)	Wilting Point (% v/v)	Available Water (% v/v)
0-30	1300	43.6	35.7	7.9
30-60	1200	45.2	27.9	17.3
60-90	1300	39.2	31.3	7.9
90-120	1400	36.1	32.1	4

The soils show a high initial infiltration rate of about 14 cm/hr and final infiltration rate of 0.9 cm/hr.

From the analysis of variance (ANOVA) of soil moisture it was found out that there was no significant difference between blocks i.e. replicates. With this in mind, the average soil moisture values were used in this study and were calculated per each treatment and depth representing the soil moisture at those particular depth levels as per the crop root growth rates during the dates when they were measured.

Field capacity water content is the maximum water content that a soil will hold following free drainage. Usually, soil is at field capacity one to two days after saturation.

On the other hand, wilting point is defined as the soil moisture content at which plants wilt permanently. The difference between the moisture content at field capacity and wilting point constitute the available water capacity.

3.3 Research Approach

Figure 2 shows the approach followed in this study. The study was subdivided into mainly three phases. The phases were:- hydrologic system response; crop water use; and yield response to water.

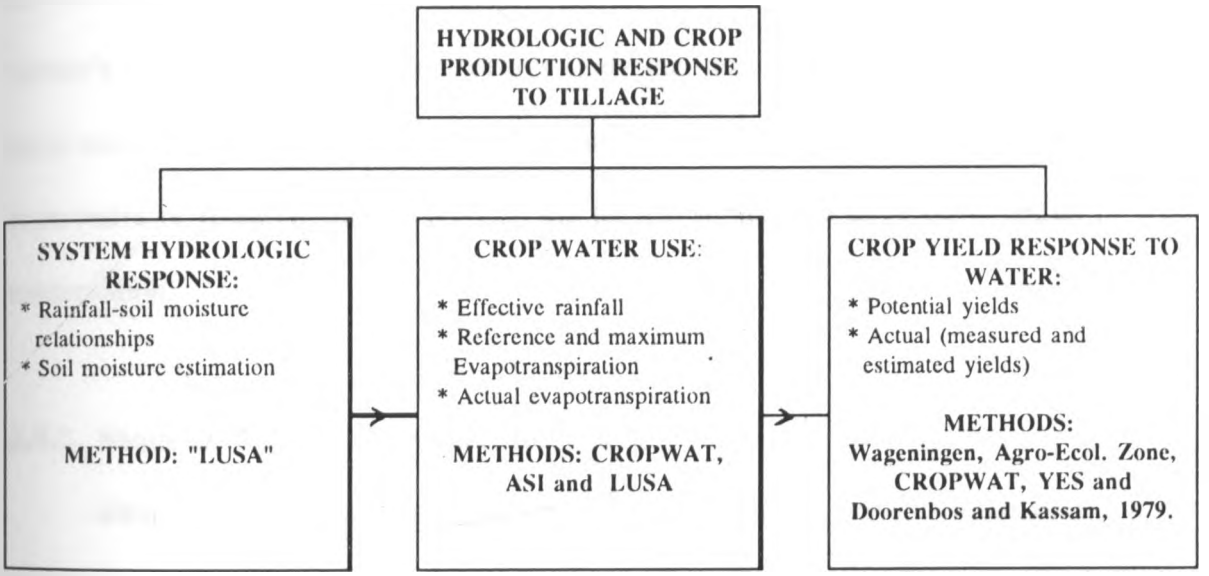

Fig. 2 Flow chart of research approach

The three phases of this study were based on available research data and collected meteorological data for Kalalu, Laikipia.

3.3.1 Definition of a Physical System

A 'Physical System' in this study represents the original experimental plots. It may be partially or fully (depending on the quantity and detail of variables characterizing the

system considered) described in terms of inflow and outflow processes and also that which occur within it. The assumptions are that:- the system was set in a farmer's terrace plot; and also that within a terrace the following factors were constant or nearly so (the site has deep homogeneous and adequately draining soils and since it is situated in flat and level terrain (terrace) there is no lateral flow of water and no water logging).

The analyses done take one rainfall season and corresponding crop season separately at a time.

It should be noted here that the fact that most semi arid areas are flat and therefore terraces are normally wide, the experimental plot can reasonably be said to represent a farmer's plot. So whatever results of this study that may be obtained from the experimental plot can be extrapolated to a small farm unit within the same area where the experiment or research was done and if the farmer applied the same technologies of water conservation.

3.3.2 Sequence Used of Research Methods

First a simple method (LUSA) was applied to simulate the soil water level variations in the soil and its results compared to historical measured soil moisture data under the three different soil water conservation options. The same method was used to estimate actual evapotranspiration using estimated and measured soil moisture. Further by using other methods (see figure 2 above) the impacts of the soil available water to the crop was assessed in terms of crop yield. Further explanation is given below.

3.4 Method Selection and Requirements

Soil moisture and crop yield estimation methods are important in the field of agriculture. In addition, soil moisture is also important in hydrology and environmental engineering. The reason for this is the significant role which soil moisture plays in food production, groundwater reserves and in the modification of the environment.

Any method of the production capacity of (dryland) crops must therefore keep track of the soil moisture content to determine when and to what degree a crop is exposed to water stress.

When plant-soil-water methods are developed and applied, a thorough knowledge of biochemical and ecological processes involved must be known. In most cases and areas this is not possible and therefore simple soil moisture methods should be used.

The choice of the best methods that can be applied under the three phase studies as mentioned above was based on their availability and data requirements, simplicity in terms of user friendly programs and to what extent of detail of information about the various processes involved and expected output required.

For the first phase of the study on system hydrologic response in terms of soil moisture estimation, a simple simulation dynamic method LUSA is used (Driessen and Konijn, 1992) to get the variation in soil water content within the crop root zones during the test crops growing periods. The method was used to estimate the soil moisture and actual crop evapotranspiration from the estimated and measured soil moisture.

For the second phase of the study on crop water use, CROPWAT Program was used for the estimation of effective rainfall, reference and maximum crop evapotranspiration. This program gives reasonable results by use of simple meteorological data which were collected from the site.

For the third phase of the study on crop production and its response to water, first an estimate of potential yields was determined by use of Wageningen and Agro-Ecological Zone methods (Doorenbos and Kassam, 1979). By applying three methods i.e. CROPWAT, which gives yield reductions as a result of water deficit under rainfall conditions, YES which gives an estimate of yield as an index as a result of insufficiency of several other factors among water and lastly Doorenbos and Kassam (1979) method which is used for determining yield reduction at various crop growth stages as a result of water deficits only. The reductions are then applied on the potential yield estimations to give an estimate of expected yields at the time the experiment was done. The results were then compared among themselves and with the measured actual harvested yields for maize and beans.

3.5 Collected Research Data

3.5.1 Soils Data

Measured soil moisture at the site was used for analysis as explained in the various methods described below. Also the following information was used: rooting depth, selected physical and chemical properties as per the printout in the YES Program.

3.5.2 Agro-Climatic Data

This was collected from the site and for seasons the experiments were conducted. This included rainfall, evaporation, relative humidity, windrun, sunshine hours and radiation.

3.6 Research Methodology

3.6.1. Comparison of Monthly Rainfall

Rainfall figures for the site were collected and compiled from Literature and the meteorological station situated near the site. The actual monthly data for short and long rains of 1988/89 and 1989 respectively for the site and for the time the earlier research was done was compared with the available long term averages. Daily rainfall values were compiled for two crop growth seasons. The rainfall variation was then compared to the measured soil moisture variations and also with estimated values.

3.6.2 Estimation of Soil Moisture and Actual Evapotranspiration

This was done for the growing seasons for maize and beans. LUSA method was used for the analysis.

3.6.2.1 Assumptions

The assumptions are that the site where the research was done belong to land unit with deep homogeneous and adequately draining soils in flat and level terrain (no lateral flow of water and no waterlogging) and only one rain season is chosen at a time.

3.6.2.2 Procedure

1) First a determination or knowledge of the date of planting for the test crops is required.
2) Knowledge of the initial soil moisture ($SMPS_{init}$) is found from the measured soil moisture.

3) Calculation of the maximum evatranspiration (ET_m) is done by use of CROPWAT program.

4) Knowing maximum evapotranspiration (ET_m) and crop group, the depletion level, p, is calculated as explained by Doorenbos and Kassam (1979) who have tabulated indicative values of p for combinations of crop groups depending on drought-tolerance and ET_m (see table 2).

Table 2 Groups of crops with similar drought resistance (Doorenbos and Kassam, 1979)

CROP GROUP	REPRESENTATIVE CROPS
1	Onion, Peppers, Potato
2	Cabbage, Pea, Tomato
3	Phaseolus bean, groundnut, rice, Sunflower, Water melon, wheat
4	Cotton, Maize, Sorghum, Soya, Sugarbeet, tobacco.

Table 3 Depletion fraction (p) as a function of crop group and maximum rate of evapotranspiration, ET_m (Doorenbos and Kassam, 1979).

	ET_m (cm d^{-1})								
Crop Group	<0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	>=1.0
1	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
2	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
3	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
4	0.875	O.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40

(5) Establish the amount of available moisture in the rooting zone at the time of germination by substituting the initial soil moisture content SMPSint for SMPSI and RDint for RD in the following equation.

$$AASM = (SMPS_i - SMPWP) \times RD \quad (6)$$

Where:

AASM = Actual (i.e. momentary) amount of available moisture (cm).

SMPSI = Actual volume fraction of moisture in the root zone $cm^3\ cm^{-3}$.

(6) Calculation of critical soil moisture (SMCR) as defined by Doorenbos and Kassam, 1979. It expresses the moisture content at which stomata start closing and is a function of the total available soil moisture (TASM).

SMCR = (1-p)(SMFC-SMPWP)+SMPWP

Where:

SMFC = Volume fraction of moisture in soil at field capacity ($cm^3\ cm^{-3}$)

SMPWP = Volume fraction of moisture at permanent wilting point ($cm^3\ cm^{-3}$)

SMCR = Critical volume of moisture in soil ($cm^3\ cm^{-3}$)

p = depletion fraction

(7) Consider the values of SMPSI and RD invariant for the duration of one time interval. Compare actual volume fraction of moisture in the root zone ($cm^3\ cm^{-3}$) SMPSI (in this case $SMPS_{int}$) with SMCR and then calculate the actual evapotranspiration ET_a from the following equations (Driessen and Konijn, 1992). Update the value of AASM by adding the water influx (Rain) and subtracting the (calculated) water losses in the interval (see 8 below). The updated value of

AASM and the updated value of RD can be used to calculate an updated value of SMPSI which is then considered invariant over the next interval (see 9 below) and so on.

If

$$SMPSI \geq SMCR \quad => \qquad ET_a = ET_m \quad . \; . \; . \; . \; . \quad (7)$$

$$Else \quad if \qquad SMCR > SMPSI > SMPWP \quad => \quad (8)$$

$$ETa = (SMPSI - SMPWP) * \frac{(ET_m - 0.05ET_0)}{SMCR - SMPWP} + 0.05ET_0 \quad . \; . \quad (9)$$

$$Else \qquad ET_a = 0.05ET_0 \quad . \; . \; . \; . \; . \; . \quad (10)$$

Meaning that the water loss is entirely through evaporation and is arbitrary set equal to ($0.05ET_0$).

Where:

ET_o = potential or reference rate of evapotranspiration and the rest is as explained above.

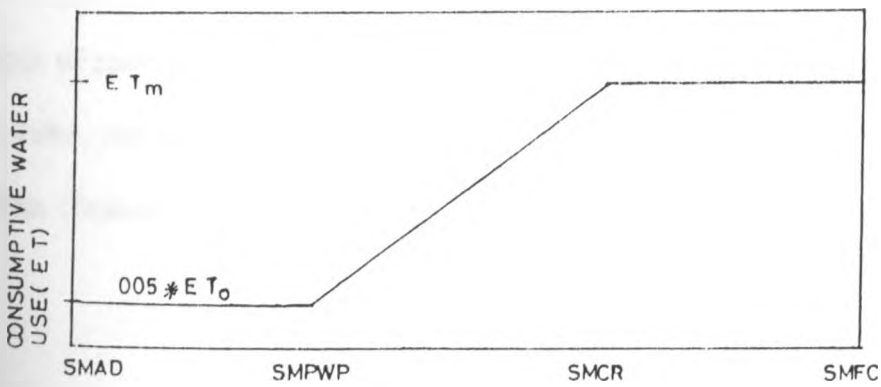

Fig. 3 Schematized relationship of ET_a to SMPSI

(8) Determination of rooting depth at the end of the interval chosen:

(a) Choice of time interval (DT)

Good results are obtained if the difference between the temporarily-fixed state variable(s) and the true variable(s) is kept small. The state variables must be frequently updated: the interval must be chosen short enough to handle the dynamics of the system under study.

The choice of DT is dictated by the analytical accuracy pursued and the dynamics of the system under study but also by the resolution of the available data. A set interval of 10 days was used in this study.

(b) Adjusting rooting depth (RD)

Most annual food crops have an initial rooting depth of 4 to 10 cm upon emergence (depending on seed size and depth of planting or sowing); the roots are assumed to grow at fixed rates to reach their maximum depth (RDm) early in the mid-season development stage (EMS). Normally, the roots are not evenly distributed over the rooted surface soil. So, the rooting depth used in the calculations (RD) is not the true rooting depth but represents an equivalent depth of rooting, over which roots are thought to be uniformly distributed.

Depth of rooting increases during a crop cycle from the initial value (RDint) to a maximum value, reached at mid-season development stage (EMS) and arbitrarily set equal to 0.7* RDm (Driessen and Konijn, 1992).

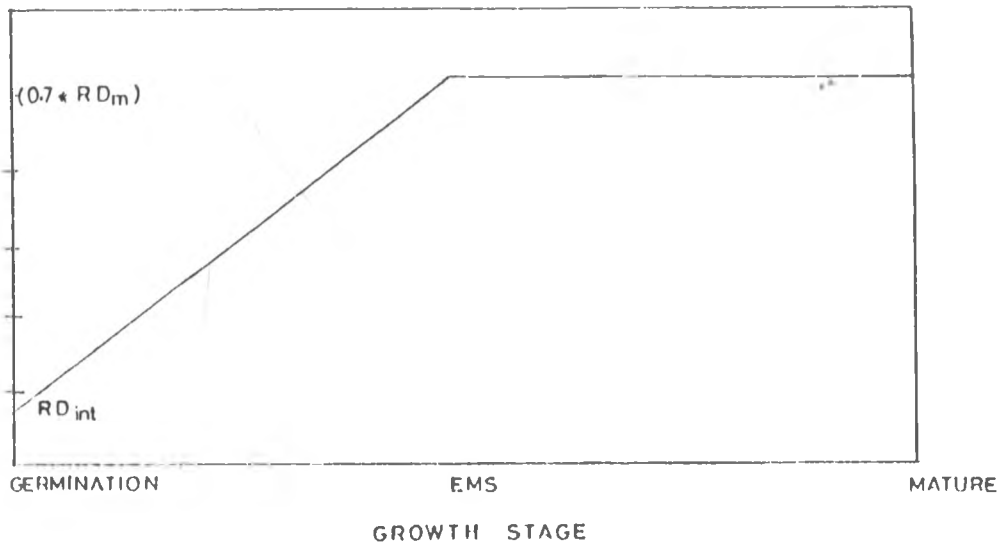

Fig. 4 Schematized equivalent rooting depth (RD) over the crops growing season.

The horizontal axis is a time axis, it runs from emergence or planting time to the total growth duration (GD), the moment at which a full cycle is completed. This horizontal axis is divided into time intervals, each labelled with a segmented number, L. For example if EMS is reached after 5 intervals have elapsed since germination, and the length of the intervals (DT) chosen is 10 days, then the mid-season stage of crop development starts after L * DT = 50 days. The pattern of figure 4 is mathematically described as follows:

$$If \quad L < EMS \quad => \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (11)$$

$$RD = RD_{init} + (0.7 * RD_m - RD_{init}) * \frac{L}{EMS} \quad . \; . \; . \; . \qquad (12)$$

Else

$$RD = 0.7 * RD_m \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad (13)$$

Where :

L = number of intervals elapsed since emergence.

EMS = number of intervals between emergence and beginning of mid-season stage of crop development.

RD = equivalent rooting depth (cm)

RDm = maximum rooting depth (cm)

$RD_{init.}$ = rooting depth at planting or emergence (cm)

Since there were no observed values for RD_{init} and RD_m available the values in the following table were used.

Table 4 Indicative values for initial rooting depth and the maximum rooting depth (cm) of maize and bean crops (Doorenbos and Kassam, (1979); Landon, (1991); and Van Keulen and Wolf, (1986)).

Crop	Rooting Depth (cm)	
	Initial	Maximum
Bean	7 - 10	100 - 150
Maize	10	100 - 170

(9) **Calculation of actually available moisture (AASM)**

AASM = (SMPSI - SMPWP) * RD + PREC * DT - ETa * DT

Where:

AASM = actual (i.e momentary) amount of available moisture (cm)

SMPSI = Actual volume fraction of soil moisture in root zone (cm^3 cm^{-3})

RD = equivalent rooting depth at the end of the interval (cm)

PREC = rate of rainfall during the (past) interval (cm/d)

ET_a = calculated actual rate of evapotranspiration (cm/d)

DT = length of interval in days, (d).

(10) **Calculation of total available soil moisture (TASM)**

TASM = (SMFC - SMPWP) *RD

Where:

TASM = Maximum possible amount of available moisture (cm)

SMFC = Volume fraction of soil moisture at field capacity (cm^3 cm^{-3})

SMPWP = Volume fraction of soil moisture at permanent wilting point (cm^3 cm^{-3})

RD = equivalent depth of a homogeneously rooted surface layer (cm)

(11) **Comparison of AASM and TASM**

If AASM > TASM => AASM = TASM

If SMPSI < SMPWP => AASM = 0

(12) Finally the value of SMPSI at the end of the time interval is established and assumed valid for the entire next interval, with

(New)

$$SMPSI = \frac{AASM}{RD} + SMPWP \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (14)$$

The dependent variable AASM is calculated anew for each interval in the crop cycle and signifies the state of the system during an interval. AASM is a state variable. The state-variable technique allows description of availability and consumptive needs for water in a dynamic way.

3.6.3 Estimation of Effective Rainfall, Reference and Maximum Evapotranspiration by CROPWAT Program.

CROPWAT is a computer program developed by Martin (1992) for FAO to calculate crop water requirements from climatic and crop data. Procedures for calculation of the crop water requirements are mainly based on methodologies presented in FAO Irrigation and Drainage papers No 24 "Crop water requirements" and No 33 "Yield response to water." The program includes a method for estimating reference crop evapotranspiration, ET_0, adopting the approach of Penman-Monteith.

3.6.3.1 Calculation of Potential Evapotranspiration (ET_0)

The following data is to be supplied:

(a) Basic information on the climatic station, country name, station name, altitude, latitude and longitude.

(b) Monthly climatic data on temperature, relative humidity, daily sunshine and windspeed. The results of ET_0 calculations are then presented together with the climatic data as in appendix 6.

3.6.3.2 Calculation of Crop Water Requirements

The following data input was required:

Monthly data on reference evapotranspiration (ET_0) and rainfall. The actual monthly rainfall values were used. For getting crop water requirements, the contribution of rainfall was set to zero. This gives the total crop water requirement which then would come from either rainfall or irrigation depending on the availability of either or their combination.

3.6.3.3 Calculation of Effective Rainfall (P_{eff})

Actual monthly rainfalls during the crop growth periods were used and from CROPWAT Program the rainfall efficiency was taken as a fixed percentage of rainfall. The method of fixed percentage of rainfall was chosen and any rainfall reduction was due to losses to surface runoff and deep percolation. The effective rainfall could be estimated according to the following relation in the absence of actual measured data:

$$P_{eff} = a.\ P$$

where 'a' is a fixed percentage given by the user to account for losses from runoff and deep percolation (Martin, 1992).

For the crop water requirement calculations, 10-day values of ET_0 and P_{eff} are used. To convert monthly data to 10-day values, a linear interpolation is carried out. Values of the first and third decades are found by interpolation with the preceding and successive month respectively. To compensate for deviations on the maximum and minimum months, a reiteration is carried out to fulfil the condition that the 3 decade values average the given monthly average.

3.6.3.4 Input of Crop Data

The crop data used was that which was available and was obtained from both the research sites and literature. The data required was:

(a) Lengths of the individual growing stages: Initial phase (A), development stage (B), mid-season (C) and late season (D).

(b) Crop factors (K_c) for initial stage, mid-season and at harvest were given. The values were extracted from (Mesy and Kalders, 1985)

Also additional data required was:

i) Rooting depth (RD).

Initial rooting depth and that of full development was given as indicated in table 4.

ii) Allowable depletion (p) is calculated as explained under methodology. The depletion level at various stages allow the calculation of the readily available moisture (RAM) content on the root zone.

iii) Yield response factor (K_y). To assess the effect of drought stress on yield, the K_y factor was given for each growth stage (Martin Smith, 1992).

(d) Planting date

Actual planting dates for maize and beans at Kalalu were given.

3.6.3.5 Irrigation Water Requirements

Crop water requirement being the daily water needs of a crop. It represents the daily uptake of soil moisture from the root zone due to evapotranspiration. The calculation of crop water requirements is carried out per decade. For reasons of simplicity all months are taken to have 30 days, subdivided into 3 decades of 10 days.

The average daily maximum crop evapotranspiration, ET_m is determined according to:

$$ET_m = K_c \cdot ET_o$$

Where Kc are crop factors at various crop stages (Mesy and Kalders, 1985) and Martin (1992).

Crop Evapotranspiration per decade is calculated by multiplication of the number of effective crop days. This will normally be 10, except in the first and last decade when planting date and harvest date do not necessarily coincide with the beginning or end of the decade. Knowing the P_{eff} and ET_m then the difference which is a deficit required to meet crop water requirements is denoted as 'Irrigation requirement', IR_{req} in this Program. i.e.

$$IR_{req} = ET_m - P_{eff}$$

The Program at this stage continued with the calculation of irrigation scheduling for maize and beans crops. This scheduling was used to simulate field irrigation programs under water deficiency conditions, in this case rainfed conditions i.e given the rainfall amount the program controls it and supplies the crop with the same amount as shown in CROPWAT printout, (appendix 6).

3.6.3.6 Data Input for Irrigation Scheduling

The calculation of irrigation scheduling by the Program was based on the water balance on which in a daily basis, the incoming and outgoing water flow (evapotranspiration, rain) in the root zone of the soil profile was being monitored. For the calculations data on crop evapotranspiration, rainfall, crop and soil were used.

(a) Crop water requirements.

These were calculated from ETo and Kc values as explained above.

(b) Rainfall

Actual monthly rainfall data was used.

(c) Crop data

Rooting depth, allowable depletion (p) and yield response factor were used (appendix 6).

(d) Soil data.

i) Total Available Soil Moisture Content (TASM), defined as the difference in soil moisture content between field capacity and wilting point. It represents the ultimate amount of water available to the crop and depends on texture, structure and organic matter content of the soil expressed in mm/m. Kalalu soil which was predominantly clay (66 t0 70% clay - see appendix 7), a value of about 160 mm/m was expected (see Table 5) but a value of 107 mm/m was used as calculated from measured soil moisture by Gicheru (1990).

Table 5 Indicative available soil moisture for different soil textural classes (Martin Smith, 1992).

	Coarse	Sandy	Loamy	Clayey
TASM	60	100	140	180 mm/m

ii) Initial soil moisture depletion (% TASM) at the start of the growing season. 0 percent represents a fully wetted soil profile and 100 percent soil at wilting point. In most cases only an estimate could be made of the initial soil moisture, depending on previous crop and periods preceding fallow or dry season. A value of 100 percent was used for maize and 99 percent for

beans as calculated from the measured soil moisture.

iii) For maximum rooting depth, the default value set arbitrarily at 900 cm indicates no soil depth limitation. A value of 120 cm for both test crops was used as measured by Gicheru (1990).

iv) Maximum rain infiltration rate allows an estimate of the surface runoff for the effective rain calculation and is expressed in mm/day. It limits the maximum amount of rain which can infiltrate the soil on any one day, as a function of rain intensity, soil type and slope class. A value of 216 mm/day was used as measured by Gicheru (1990).

3.6.3.7 Rainfall Only Option for Scheduling

The scheduling program allows a range of options, depending on the specific application the user is aiming at and the conditions and restrictions the field system imposes. The option chosen here was one of timing which relates as to when the rainfall was to be applied or supplied i.e. under rain fed conditions with no irrigation supply but using only rainfall as the sole source of water and assuming full control of the supply. This option took the monthly rainfall as given under the climatic data considered above and was spread regularly over the month, in six rainfall showers. The printout gave a 10-day overview in deficit, evapotranspiration and rainfall losses. The total monthly rainfall was taken and applications were simulated by two applications for each decade on day 3 and day 7 of half the 10 daily rainfall. For each rainfall an account was kept of which part of the rainfall was lost by runoff determined by the maximum rain infiltration rate and the deep percolation determined by the soil moisture depletion in the root zone.

Actual evapotranspiration was equal to the calculated maximum evapotranspiration

as long as soil moisture content had not reached the critical level as given by the allowable depletion (p). Beyond this level actual crop evapotranspiration was reduced proportionally to soil moisture depletion.

Values for total and readily available soil moisture, as determined by root depth, allowable depletion and total available soil moisture, were calculated on daily basis. Furthermore, by summation of daily values an account was kept of actual and maximum evapotranspiration for growing stage and the total growing period.

Gross irrigation applications from given irrigation efficiency were converted into a permanent field supply in l/sec/ha over the irrigation interval i.e. if the water supply (i.e. rainfall in this case) was to be given continuously.

Purpose of irrigation scheduling chosen was to evaluate crop production under rainfed conditions when the rainfall was distributed as explained above.

3.6.3.8 Rainfall Only Scheduling Output

For the final output, accounts on the number of irrigation, interval periods and irrigation losses and yield reductions were kept (Appendix 6). The output also included information on the irrigation calender, the total water used and yield reductions as a result of the option chosen. Also an evaluation of the scheduling efficiency was given.

3.6.4 Monthly Actual Evapotranspiration (ASI Method)

The effect of inadequate water varies by crop group and growing stage. Crops with a dry harvested portion have a higher tolerable range of fraction (p) to which the available soil moisture (S_a) may be depleted while ET_a remains equal to ET_m. Under conditions of limited water supply, an estimate of ET_a can be determined via the

calculation of the available Soil Water Index (ASI).

The (ASI) indicates when during the month soil moisture is adequate to meet crop water requirement ($ET_a = ET_m$). By combining ASI, ET_m and the remaining available soil water, [(1-p) S_a * D] an estimate of mean monthly ETa can be determined. This requires calculation of the ASI, adjustment of ET_a based on the reference tables provided by Doorenbos and Kassam (1979).

An estimate of mean monthly actual evapotranspiration (ET_a) for maize and beans was thus calculated:

$$ASI = \frac{P_{eff} + Wb - (1-P)S_a.D}{Monthly\ ET_m} \quad . \ . \ . \ . \ . \ . \quad (15)$$

P_{eff} = effective rainfall, mm/month

Wb = actual depth of available soil water at the beginning of the month, mm/root depth.

$(1-P)S_a.D$ = depth of remaining available soil water when

$ET_a < ET_m$, mm/root depth

ET_m = maximum evapotranspiration, mm/month.

Assumption

When $P_{eff} \leq 30\ ET_m$, then the P_{eff} fully contribute to the evapotranspiration and no deep percolation or runoff will occur; also mean monthly ET_a is only affected by the total of P_{eff} and Wb and not by their distribution over the month.

When

$$ASI \geq 1 \Rightarrow \quad ET_a = ET_m \quad . \ . \ . \ . \ . \ . \quad (16)$$

When

$$ASI < 0 \quad => \quad \frac{ET_a}{ET_m} \quad . \; . \; . \; . \; . \; . \; . \qquad (17)$$

is so small that crop growth is hardly possible except when ET_m is low and the remaining available soil water $[(1-p)S_s.D]$ is high.

3.6.5 Estimation of Maize and Beans Yields

For yield estimates following steps were followed.

(1) Calculation of maximum yield of a crop.

(2) Determination of maximum Evapotranspiration.

(3) Determination of actual Evapotranspiration.

(4) Calculation of estimated yield

3.6.5.1 The 'Wageningen' Method

Calculation Procedure

The procedure is described by Doorenbos and Kassam, (1979). A summary is given here.

Steps followed for the calculation

(a) Dry matter production is calculated for a standard crop (Y_o) by use of De wit (1965) method based on radiation and corrections applied as follows:-

(b) Site climate effect, (ET_m (ea-ed))

(c) Crop species (K)

(d) Temperature (cT)

(e) Harvested part (cH)

The mathematical equations used are:

(a) Dry matter production of a standard crop (Y_o).

$Y_o = F.y_o + (1-F)\ y_c$ where

where

Y_o = Gross dry matter production of a standard crop, Kg/ha/day

F = fraction of the daytime the sky is clouded, fraction; or $F = (R_{sc} - 0.5R_s)/0.8R_{sc}$

Where R_{sc} is the maximum active incoming shortwave radiation on clear days in cal/cm²/day and R_s is the actual measured incoming shortwave radiation on cal/cm²/day.

y_o = Gross dry matter production rate of a standard crop for a given location on a completely overcast day, Kg/ha/day

y_c = Gross dry matter production rate of a standard crop for a given location on a clear (cloudless) day, Kg/ha/day

Corrections applied to Y_o:

(a) Climate effect (ET_m (ea-ed))

where

ET_m = maximum evapotranspiration in (mm/day)

ea-ed = vapour pressure deficit in mean daily mbar over the growing period (appendix 5)

(b) Correction for crop species (K)

K is empirically derived crop constant with a value of 1.9 for maize.

(c) Correction of temperature (cT)

The production given as Y_o is presented for standard temperature conditions. For actual mean daily temperature during the total growing period, a crop-specific temperature correction (cT) is applied to obtain net dry matter production (Ydm) taking into account 40 percent total energy required by the plant for growth and maintenance process (respiration).

(d) Correction for harvested part (cH)

Only part of the total dry matter is harvested. When maize is grown for grain, only a fraction of the total dry matter is harvested. The ratio between net total dry matter and harvested yield is given as the harvested index (cH). For maize, it varies between 0.4-0.5.

In summary, the production Y_{me} under experimental conditions of a high-producing, climatically adapted maize crop grown under optimum climatic condition is:

$Y_{me} = 1.9 \cdot cH \cdot cT \cdot G \cdot Y_0 \cdot ET_m/(ea-ed)$ Kg/ha

G = total growing period in days.

3.6.5.2 Agro-Ecological Zone Method

Calculation procedure

a) Calculation of gross dry matter production of a standard crop (Y_0) as above.

b) Correction for species and temperature.

The gross dry matter production is crop specific and temperature dependent. The production rate y_m can be larger or smaller than 20Kg/ha/hr as assumed for the standard crop. The production rates for a standard bean crop in y_m in Kg/ha/hr is given in table 6.

Table 6 Production rates (y_m in Kg/ha/hr) for standard bean crop at different mean temperatures (°C) (Doorenbos and Kassam, 1979).

Mean temp	5	10	15	20	25	30	35	40	45
Rate	5	15	20	20	15	5	0	0	0

By use of De Wit (1965) method the value of y_0 and y_c can be adjusted as follows.

a) When $y_m > 20$ Kg/ha/hr =>

$$Y_0 = F(0.8 + 0.01y_m)y_0 + (1 - F)(0.5 + 0.O25y_m).\ y_c \text{ Kg/ha/day}$$

i) When $y_m < 20$ Kg/ha/hr =>

$$Y_0 = F(0.5 + 0.025y_m)y_0 + (1 - f)(0.05y_m)y_c \quad \text{Kg/ha/day}$$

c) Correction for crop development over time and leaf area (cL). The LAI considered here is at the time of maximum growth, Driessen and Konijn (1992) suggest a LAI of 5 to mean complete ground cover at the time of maximum growth.

Table 7 Corrections for LAI (Doorenbos and Kassam, 1979)

LAI	1	2	3	4	>= 5
Correction	0.2	0.3	0.4	0.48	0.5

d) Correction for Net Dry Matter Production (cN)

cN = 0.5 to 0.6 for most crops.

e) Correction for harvested part (cH).

Bean grain cH = 0.25 - 0.35

In summary potential yield (Y_{mp}) of a high producing, climatically adapted variety grown under constraint free conditions over a growing period of G days is :-

i) When $y_m > 20$ Kg/ha/hr

$$Y_{mp} = cL.\ cN.\ cH.\ G.\ [F(0.8 + 0.01y_m)\ y_0 + (1 - F)(0.5 + 0.025y_m)\ y_c]$$

Kg/ha

ii) When $y_m < 20$ Kg/ha/hr

$$Y_{mp} = cL.\ cN.\ cH.\ G.\ [F(0.5 + 0.025y_m)\ y_0 + (1 - F)(0.05y_m)\ y_c]\ \text{Kg/ha}$$

The terms are as explained under Wageningen Method.

LAI means Leaf area per soil surface area.

3.6.5.3 Actual Yield Estimate Method (Doorenbos and Kassam, 1979)

Production of a crop is a reflection of the compounded sufficiency of all land characteristics and qualities in a land-use system. If we assume that all other factors are not limiting apart from the land quality water adequacy then it means water supply does not meet crop water requirements and actual evapotranspiration (ET_a) is less than maximum evapotranspiration (ET_m). Under this condition a crop's production situation is known as a water-limited production potential, Driessen and Konijn (1992).

When ET_a is less than ET_m then the water stress induced causes an ultimate drop in yield (Doorenbos and Kassam, 1979). In actual situations the crops yield response to water is interrelated with other agronomic factors and therefore in a sense cannot be analyzed independently if the other factors are limiting.

Assuming that there are no other constraints apart from water the response of for example a maize crop to water supply is simply and normally quantified through a yield response factor (K_y) as explained by Doorenbos and Kassam, 1979. The factor relates

relative yield decrease ($1-Y_a/Y_m$) to relative evapotranspiration ($1-ET_a/ET_m$) i.e.

$$(1 - \frac{Y_a}{Y_m}) = K_y(1 - \frac{ET_a}{ET_m}) \quad . \; . \; . \; . \; . \; . \; . \; . \qquad (18)$$

Where:

Y_a = actual harvested yield

Y_m = maximum harvested yield

k_y = yield response factor

ET_a = actual evapotranspiration

ET_m = maximum evapotranspiration

The magnitude and duration of water deficit is usually expressed to correspond to the individual crop growth periods. Any precise defined stress-day and drought indices prove difficult. The value of k_y for different crops is based on the evaluation of numerous research results and is given by Doorenbos and Kassam (1979). Also different k_y values are given for different crop growth stages.

3.6.5.4 Yield Estimation System (YES) Method (Jan Pit, 1993)

YES is a computer-based simulation Program capable of predicting yield indexes for various crops for user selected locations and agro-Ecological zones. The crops can be grown under rainfed or irrigated conditions. The Program is linked with a data base of optimum crop requirements containing agro-climatic and soil to predict yield response in terms of an index for any location. The data base can be extended by the user and the resulting yield response index will be more accurate than before. Depending on what crop production factor(s) one is analyzing the Program's data requirements may vary and may include the following:

Location identification, temperature, rainfall, relative humidity, wind velocity, solar radiation, sowing dates, crop type, length of growing stages, soil texture and rooting depth.

The YES program was used to estimate the yield index for maize over the month of April when it was planted during the earlier experiment. The way the Program works is that first, crop(s) which are already connected to the data base are chosen and then depending on what factor one is interested to analyze, its actual values at different crop growth periods are entered. The program then compares the parameters so entered with the optimum values in the data base. These will result in an index value between 0 and 100 percent for each parameter. For instance Maize requires an average temperature of 22 to 25°C. If a site has a mean temperature of 17°C then this will result in an index value of 75 percent. If several factors are entered then the combined indices of all the factors or parameters indicates how suitable the site is for that particular crop in terms of a final index which shows the percent of the potential yield is remaining. Therefore for the Kalalu area the water sufficiency factor was analyzed. The following information was entered for analysis:

a) Location: station name of the site, latitude in degrees (minutes and N or S), longitude in degrees (minutes and E or W), and altitude in metres.

b) Climate:

For each crop growth month the total precipitation and evaporation in mm were used. Also required was number of raindays. Evaporation was calculated using Penman's method. It required the minimum and average temperature, the humidity, the solar radiation, the windspeed and the altitude as inputs (see appendix 7). For interest other input data on other factors can be entered if available e.g. that related to soils.

4.0 RESULTS AND DISCUSSION

4.1. Monthly Rainfall Distribution, Short and Long Rains Periods (1988/89) at Kalalu

Figure 5 & 7 shows that the total rain for 4 months which coincided with the bean crop growth period was 210 mm. The total mean monthly rainfall based on six years (1986-1991) for the same period was 167 mm. The actual monthly rainfall for the months considered of November 1988 to February 1989 was therefore higher by 43 mm. Based on the six years, it was concluded that the bean crop growth period was above average in terms of rainfall.

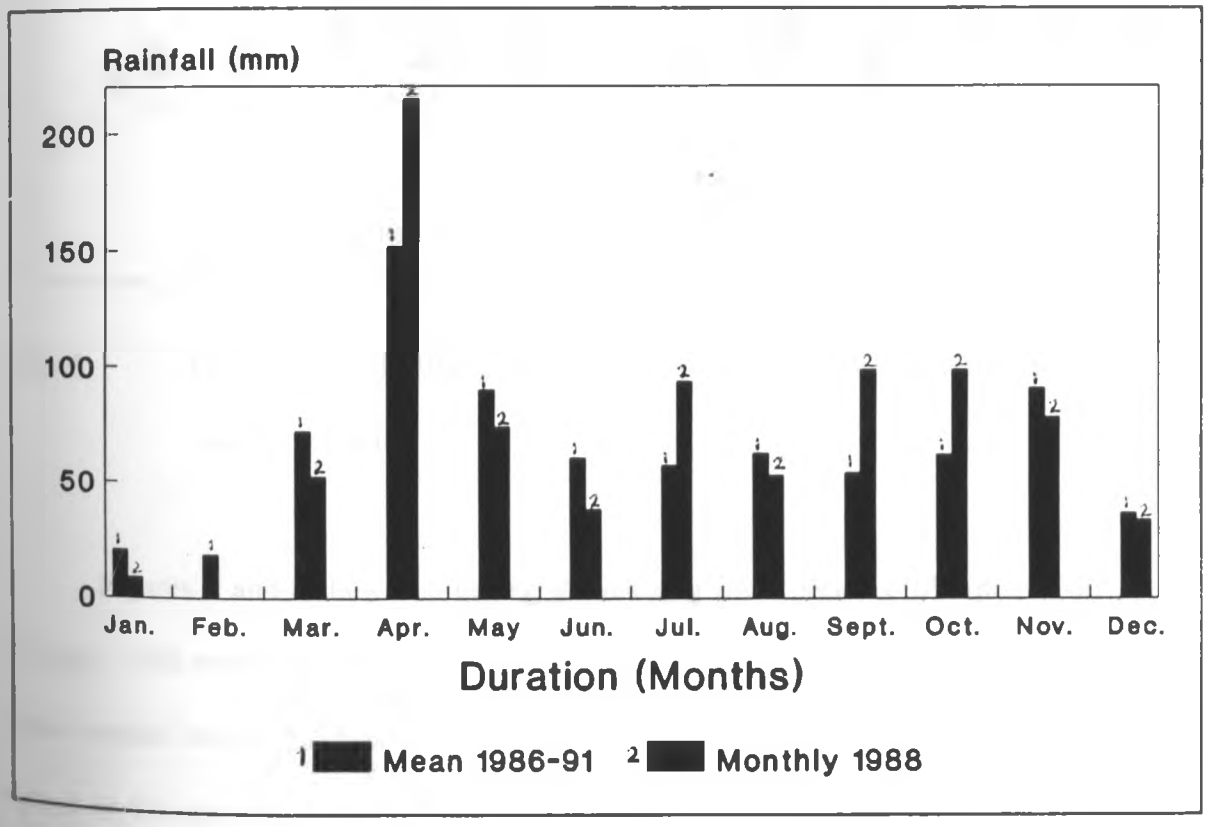

Fig. 5 Comparison of 1988 monthly rainfall with mean monthly rainfall of (1986-1991) for Kalalu.

Comparing the 210 mm rainfall which occurred during the bean growth period with mean monthly rainfall of 144 mm based on 54 years (Figure 6 & 8), the crop growth period had more rain than the long term mean.

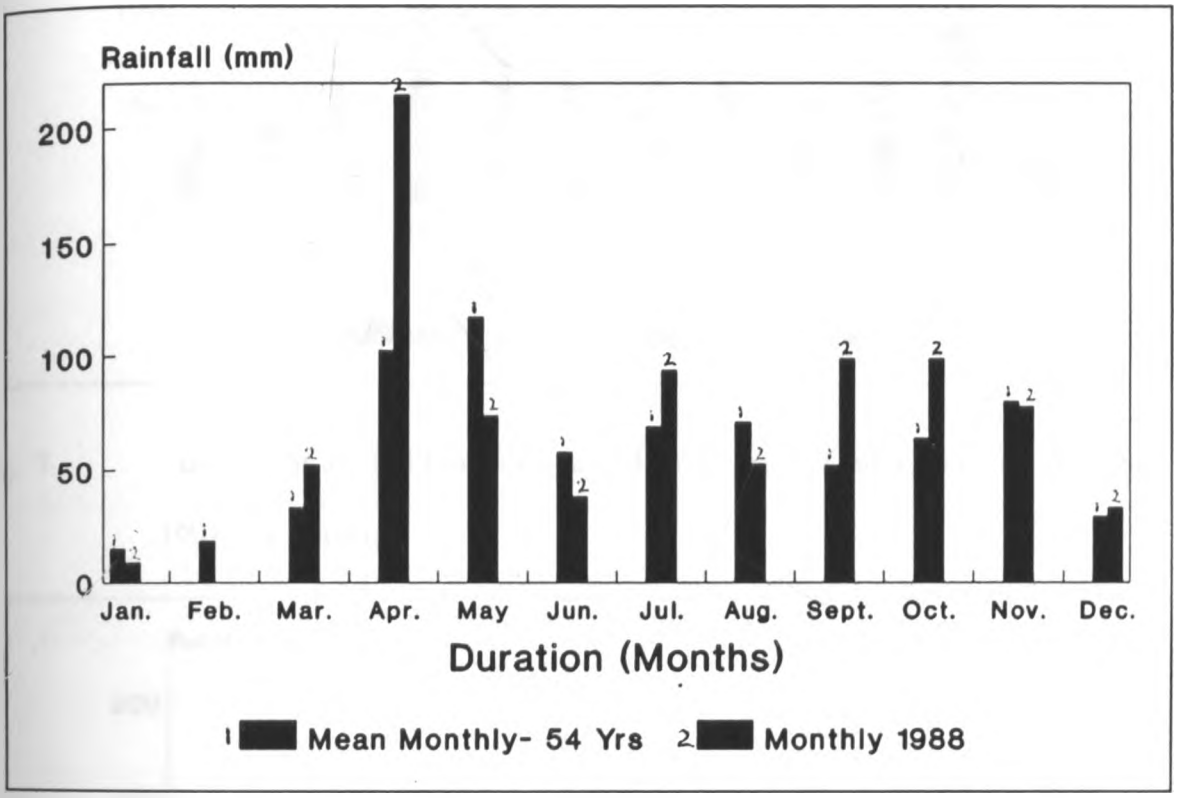

Fig. 6 Comparison of 1988 monthly rainfall with mean monthly rainfall of 54 years for Kalalu

Figures 7 and 8 show that during the maize growth period (10th April to 30th October, both months inclusive), the actual amount of rainfall was 523 mm. The total mean rainfall was 538 mm and 434 mm based on six and 54 year periods respectively. Based on the six year period the actual total rainfall was nearly the same whereas it was higher than that based on the 54 year period. So the season could be said to have been above average in this respect.

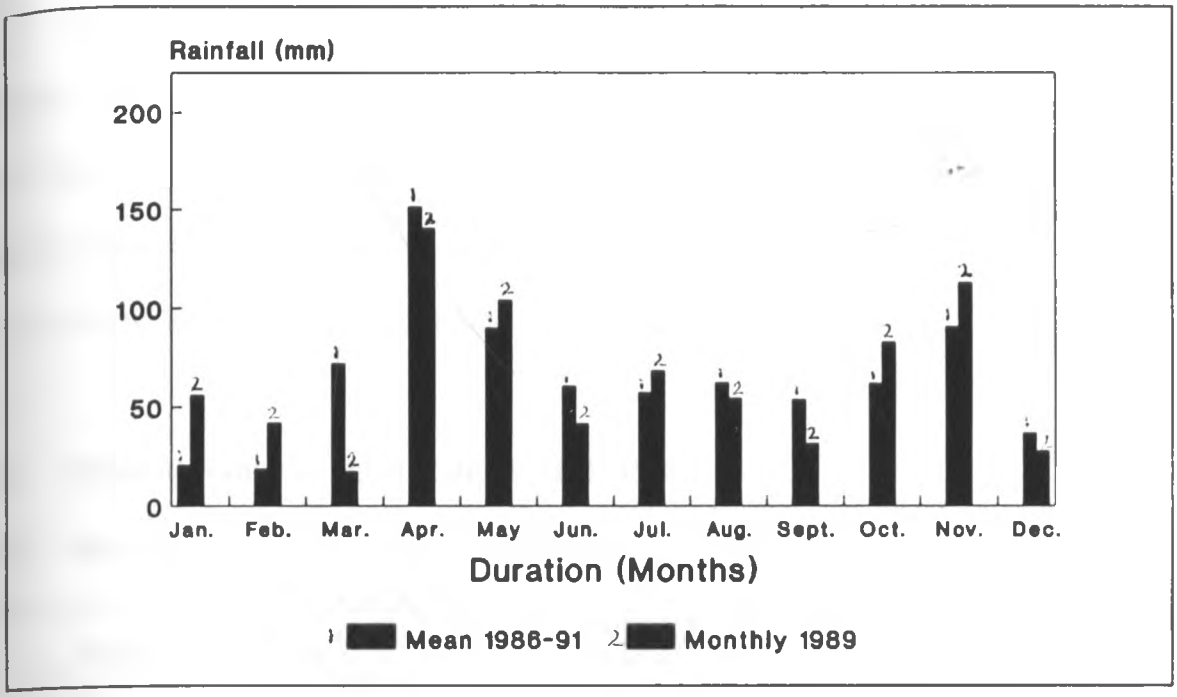

Fig. 7 Comparison of 1989 monthly rainfall with mean monthly rainfall of (1986-1991) for Kalalu.

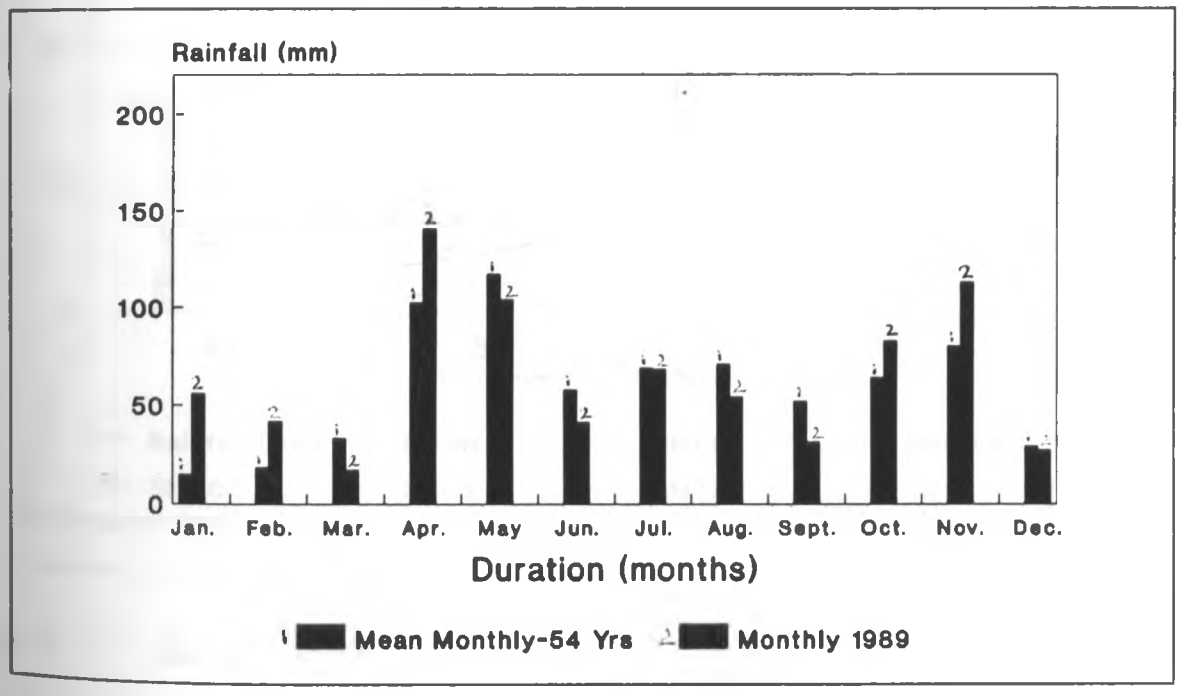

Fig. 8 Comparison of 1989 monthly rainfall with mean monthly rainfall of 54 years for Kalalu.

From CROPWAT (appendix 6) effective rainfall estimation was found as 97 percent for the rain which occurred within the maize crop growth period (10th April 1989 to 1st November 1989) and this was 476 mm. The actual rainfall amount was 449.6 mm and the reason for the high figure in CROPWAT is that the program considered some of the rainfall which fell in the first decade of the month of April.

4.2 Seasonal Rainfall, Short Rains Period, 1988

4.2.1 Seasonal Rainfall Distribution, Short Rains Period, (1988) at Kalalu, Laikipia

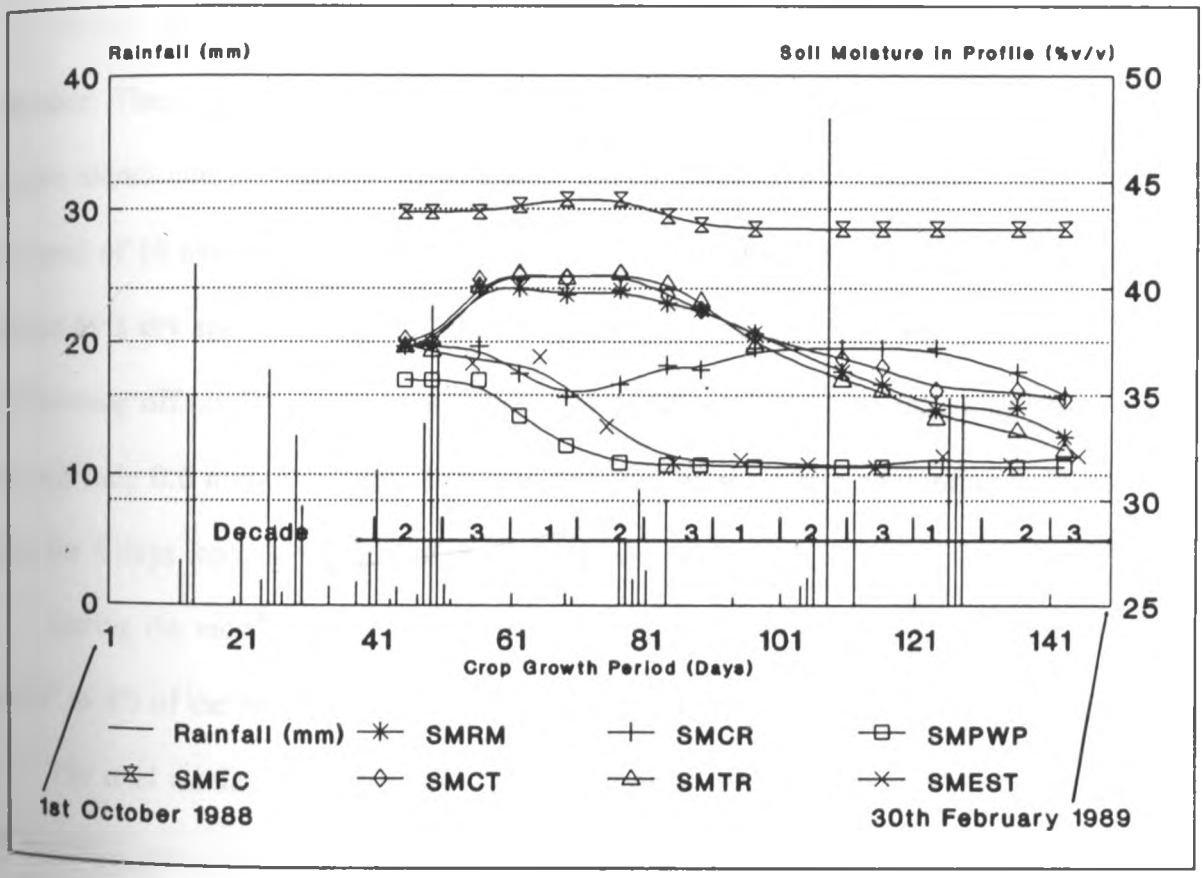

Fig. 9 Rainfall and soil moisture in profile during bean crop growth period (October 1988 to February 1989)

The abbreviations in Fig. 9 for soil moisture in (cm^3 cm^{-3})are as follows:

SMRM - Measured soil moisture under residue mulch

SMCR - Critical soil moisture, below which the crop experiences water stress.

SMPWP - Soil moisture at which crops wither irreversibly.

SMFC - Soil moisture measured immediately after free drainage

SMCT - Measured soil moisture under conventional tillage

SMTR - Measured soil moisture under tied ridging.

Figure 9 shows that there was no rainfall during the 1st eleven days of the month of October. There were 23 raindays with a total amount of 176.5 mm rainfall from 12th the same month upto 22nd day of the following month (November). Thereafter, there was a dry spell of 16 days followed by 2 days of light rainfall amounting to 1.6 mm. This was followed by a dry spell of 6 days till the 16th of December when there was rain for six days finishing off on 24th of December. From 25/12/88 to 13/1/89 the following year there was only 0.6 mm of rainfall. This was followed by some rain amounting to 55 mm falling for 5 days from 14th to 22nd of the same month of January.

During the month of February 1989 there was only 42 mm of rainfall within three days (6th to 8th) of the month otherwise the rest of the month was dry.

The total rainfall that fell within the bean growth period (from 10th November to 25th February) was 172.4 mm and all of it was estimated by CROPWAT to be effective rainfall (appendix 6). This result tallied with what Gicheru (1990) found that there was no runoff and therefore also agreeing with Avinash et al. (1988) definition of effective rainfall as the portion of total rainfall that infiltrates into the soil profile and does not contribute to deep percolation. The result was further confirmed by the fact that there was

no time when soil moisture was equal to or more than the total available soil moisture (TASM) which would mean that the excess moisture should have percolated. The fact that soil moisture varied within the treatments probably could be attributed to other factors e.g. interception and consequent evaporation thus bringing about a difference in infiltrated rain and also probably due to errors in measurement using the neutron probe.

The above rainfall distribution led to the following soil moisture variation under three treatments of residue mulch, conventional tillage and tied ridging. Bean crop was planted on all the plots of the treatments.

4.2.2 Seasonal Soil Moisture Variability, Short Rains Period, (1988) at Kalalu, Laikipia

Beans were planted on 10th of November slightly less than a month after the on-set of the rains, (Fig. 9). On 15th of November, the amount of soil moisture measured was about the same within the three treatment plots, SMTR = 37.3 % v/v, SMCT = 37.6 % v/v and SMTR = 37.3 % v/v. These moisture levels were above the permanent wilting point moisture (35.7 %). Two were the same as SMCR (37.3 % v/v) except for SMCT.

Figure 9 shows that a higher proportion of the initial stage of bean growth development occurred during the 16 dry days of the month of November. However, moisture variation for the three treatments continued to rise at a declining rate above SMCR upto around 10th of January.

The initial low soil moisture, and subsequent increase during planting and/or germination time could be attributed to either the tillage and/or the rainfall which fell immediately after the first measurement of the moisture on 15th of November. The response of soil moisture to rainfall showed a time lag between them. The former lagged

behind the latter and that was partly the reason why the moisture continued rising and remaining at a high level even within the dry spell. It could be deduced that although there was the time lag, the initial response of soil moisture to the previous rainfall was not as expected. It started with low values but steadily rose probably because most of the earlier rainfall was lost. Due to the tillage the subsequent rainfall was allowed to infiltrate which then caused the aftermath rise in soil moisture. Alternatively, probably there was some initial error in soil moisture measurement. If the former was true and considering the time lag of soil moisture to rainfall, then it would be recommended that land preparation and treatment should have been done earlier before the onset of rainfall and then followed by the planting of the crop to avoid losing some of the soil moisture.

The rise in soil moisture during the above mentioned dry period could also be attributed to the fact that as the rooting depth of the crop increased it was utilizing the soil moisture at the middle depth (30-60 cm) which seemed to be having a higher retention capacity for water. The difference between SMPWP and SMFC (Table 2) at this range was highest. The 0 - 30 cm depth difference was small but then increased to some level within the middle soil depth after which it declined slightly and remained approximately constant throughout. This fact could probably be explained by a variation of soil texture and the fact that the topmost part was exposed to excessive drying thus rapidly losing moisture by evaporation.

In all treatments, SMCR level increased with both time and rooting depth of the crop. In addition, the increase was caused by a decreasing soil moisture depletion level, (p). There was a slight decrease of SMCR towards the end of the growing season due to an increase of (p).

After about mid-January 1989, the soil moisture for the three treatments fell below SMCR but above SMPWP till the end of the growth period. During this period the crop experienced water stress and this coincided with the middle and late bean crop growth stage. From the yield response factor the crop had gone through the most critical development (flowering) stage where the factor was highest. The yield response factors gave an indication of the impact on yield due to water stress and for beans, it is in the order: development (1.1), middle (0.75) and both initial and late stage (0.2).

There was no time the soil moisture reached field capacity thus indicating that the rainfall was not excessive or that there were other unaccounted for losses. Nevertheless it was 100 percent effective (Dastane, 1974)

From around 26th November upto around end of December (34 days), the SMTR level was above that of SMCT and SMRM. This period coincided with the dry spell with little or no rainfall and therefore it seemed the response was due to the rainfall which fell around planting and/or germination time. The fact that tied ridging had higher soil moisture than the other treatments could probably be due to high rainfall which fell during the 3 days of 18th November to 20th November (between the 48th day and 50th day) as shown in figure 9. Tied ridging might have prevented some small runoff which was not registered and thus allowing more rain to infiltrate and hence higher soil moisture. During the same period, SMRM was the least among the three levels. Same reasoning could be advanced that some small runoff was partially assimilated within the channels of conventional tillage lines and this gave rise to higher soil moisture than in residue mulching where the same little runoff probably was held within the mulch trash only to evaporate and hence decreased moisture content.

The trend above was contrary to what was expected. It is clear that, depending on the amount, duration and distribution of rainfall and at what stage in time in relation to the setting up of the three soil water conservation practices it was difficult to predict the sequence as to which method was better than the other or alternatively there were issues which could not be explained.

After around the 100th day or 10th January until the end of the crop growth period SMTR was lowest and SMCT highest. During this apparent second phase, conventional tillage seemed to have done better probably because it was capable of conserving the past little rainfall since the soil was loose and therefore could allow more infiltration than the other treatments. The amount of crop cover in each of the three treatments might have influenced direct evaporation which probably caused tied ridging plots with less cover (Gicheru, 1990) to have higher evaporation rates and therefore least soil moisture level.

Generally there was a decline in moisture level in all the treatments because of reduced rainfall and increased rates of bean crop evapotranspiration thus causing higher corresponding soil moisture extraction rates.

The estimated soil moisture varied from 31.5 % v/v to 37.4 % v/v. It was lowest as compared to the measured ones probably due to several reasons as explained elsewhere in this thesis. SMEST was above SMPWP nearly throughout and as from the 80th day (figure 9) they asymptotetically ran close each other with the SMEST slightly above SMPWP. From planting day and for the next 35 days the SMEST was above SMCR. This period came within the initial and start of the middle stages of the crop growth development.

4.2.3 Seasonal Available Soil Moisture, Short Rains Period (1988) at Kalalu

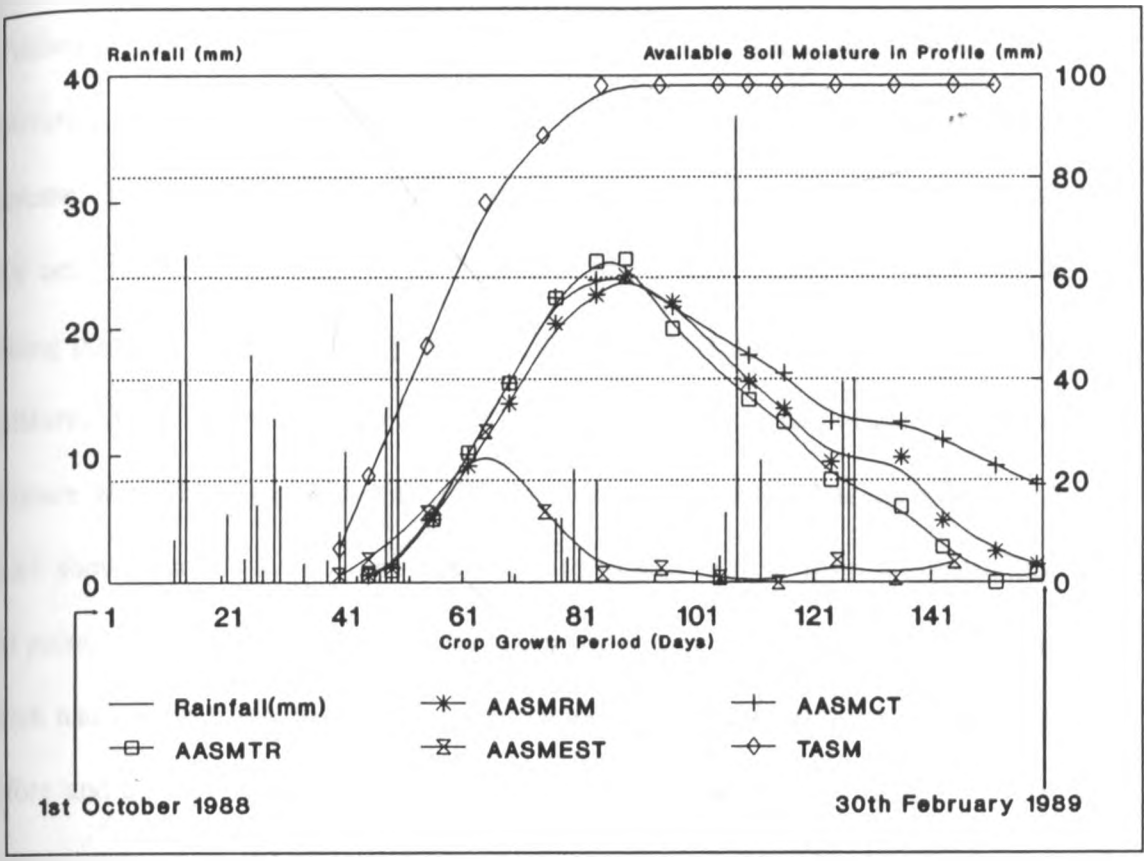

Fig. 10 Rainfall and available soil moisture during bean growth period (October 1988 to February 1989)

Figure 10 shows that the total available moisture the soil could hold during the bean crop growth period varied from 6.7 mm to a maximum of 98.0 mm corresponding to an equivalent (effective) rooting depth of the crop of 8.5 cm to 87.5 cm respectively. The accuracy of the figures were as good as the values of SMPWP and SMFC used.

Within the crop growth period, AASMEST varied from 0.0 mm to 29.6 mm and AASMCR from 1.4 mm to 60.3 mm on 3rd of December. Similarly AASMCT varied from 1.6 mm to 60.3 mm on 3rd of December and AASMTR from 1.4 mm to 63.6 mm on around the 3rd decade of December.

The trend of the variation of available moisture was nearly the same as the variation in soil moisture and same reasons for the difference apply. The available moisture rose steadily from the 45th to 90th day and thereafter showed a continuous decrease. The highest available moisture for the three treatments therefore appeared to have occurred at around the end of December or 90th day (figure 10). This was the turning point of the initial steady increase due to increasing rooting depth and soil moisture. After this point, the effective rooting depth remained constant and also soil moisture was decreasing with time. This position can be termed as an inflection point which shows maximum soil moisture response to past rainfall from the beginning upto that point. The point indicates the maximum accumulation of available soil moisture which had not been lost through deep percolation and evapotranspiration by the crop. Before and after this point, the available moisture decreased. It is possible to have several of such peaks of available moisture depending on the rainfall amount, distribution and the level of the crops rooting depth with time. The position of the peak did not depend on the treatment which meant that the response was due to rainfall among other factors if any.

AASMEST was lowest as compared to AASMRM, AASMCT and AASMTR. It increased from the 40th day until 70th day when it started declining steadily till the 85th day where it remained slightly above zero for the rest of the crop growth period. Same reasons advanced for SMEST low values applied here also.

4.2.4 Seasonal Crop Water Use, Short Rains Period (1988) at Kalalu

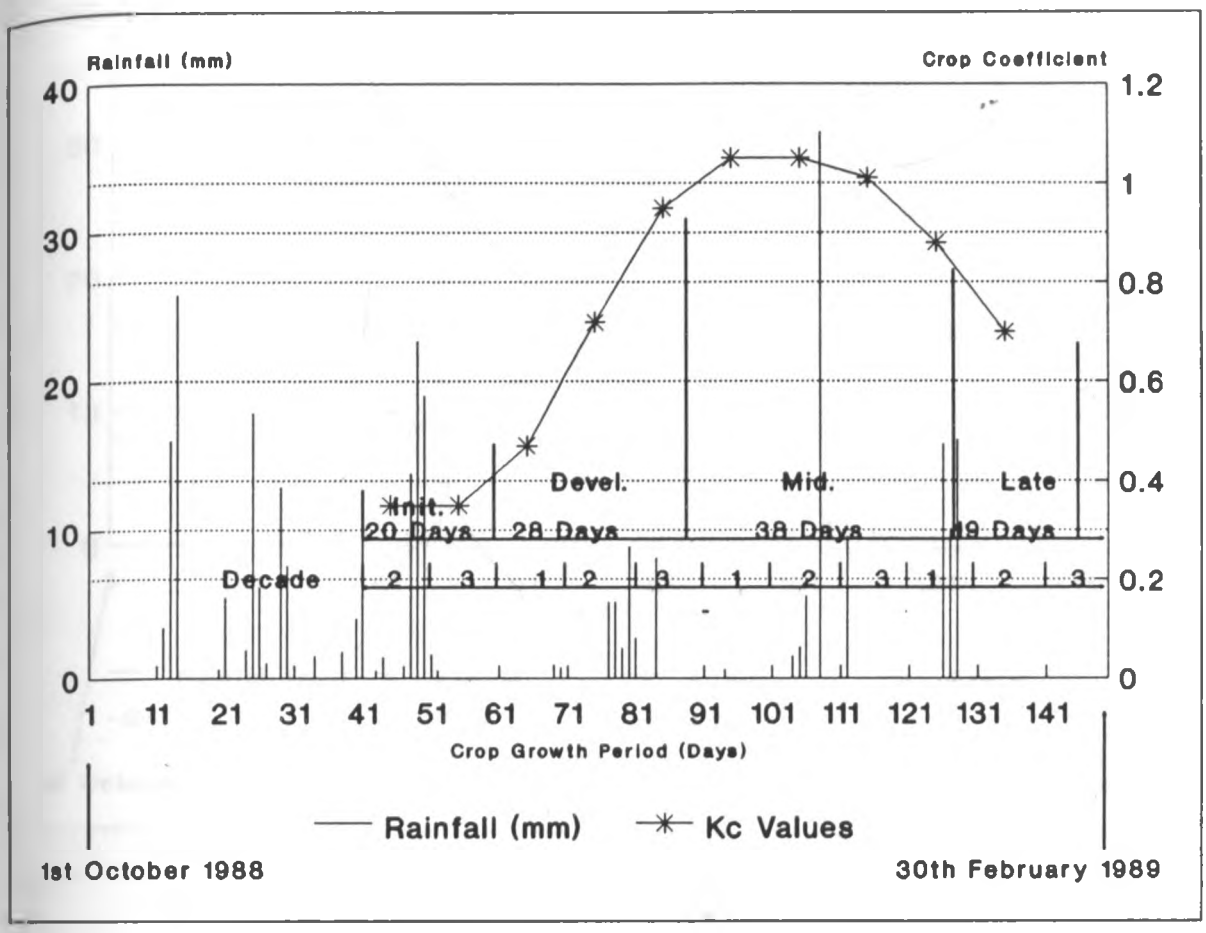

Fig. 11 Rainfall and crop coefficient over bean growth period (short rains, 1988) at Kalalu.

Figure 11 shows the trend of Kc values during the different bean growth periods. The higher the Kc value the higher the crop water requirement and this can be seen to be highest during the middle growth stage.

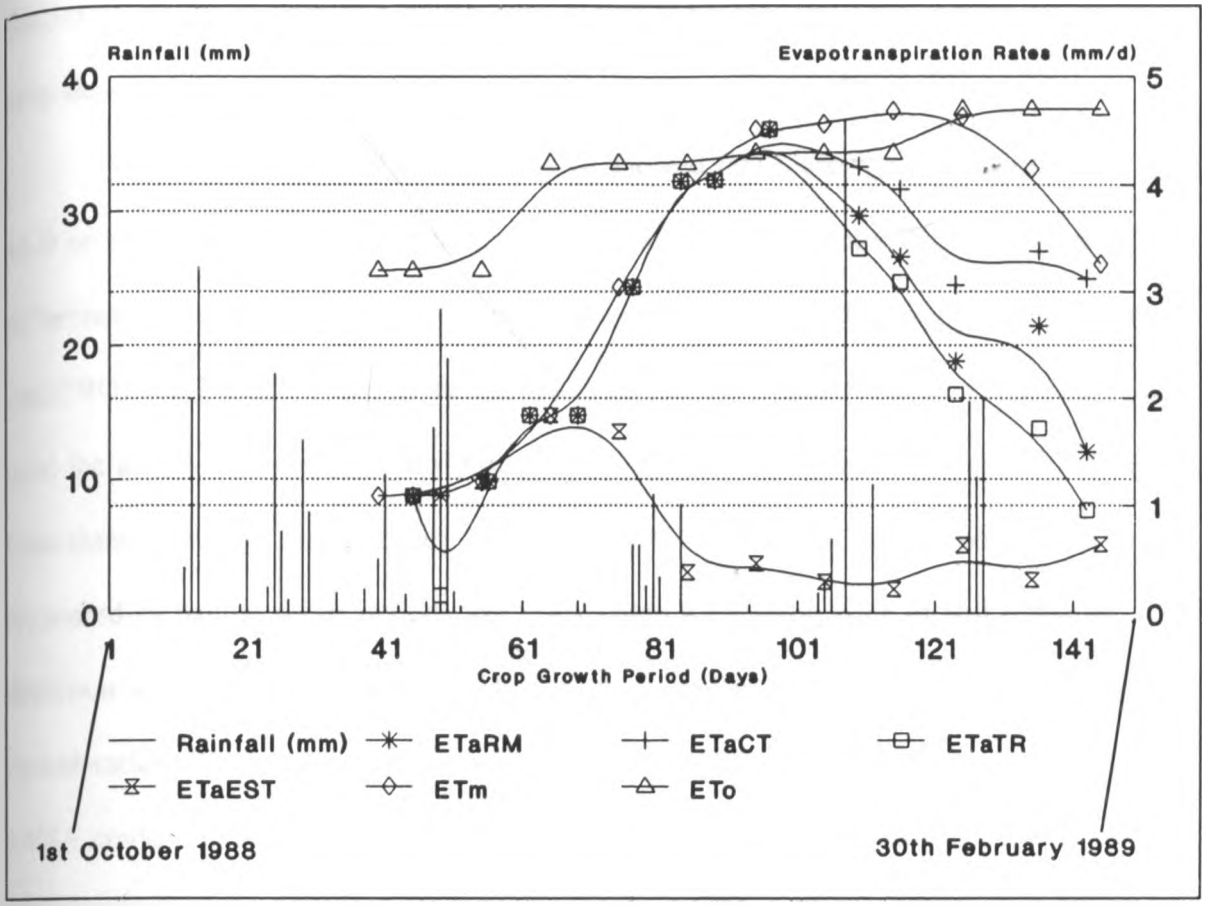

Fig. 12 Rainfall and evapotranspiration rates during the bean crop growth period (October 1988 to February 1989) at Kalalu.

Figure 12 shows that the reference evapotranspiration which indicated the climatic evapotranspiration demand during the period considered, varied from a value of 3.2 mm/day to 4.7 mm/day towards the end of the bean crop growth period. At the same time, the maximum evapotranspiration, ET_m varied from 1.09 mm/d to 3.26 mm/d at the end of the growth period. Between the 97th day and 116th day, ET_m was greater than ET_o since the K_c values were greater than one (see fig.11).

From the 45th day upto the 97th day, the actual evapotranspiration rates (ET_a) for the three treatments were equal to maximum evapotranspiration (ET_m) of the crop. This meant that available soil water for that period (about 50 days) was enough to supply the

maximum water requirements of the crop during the initial and development stages of the crop development.

The CROPWAT results (Appendix 6) showed that there was a reduction of ET_m of 14.0 percent and 44.4 percent during the initial and development stages respectively. This difference from the ET_a calculated by use of LUSA method with measured soil moisture and CROPWAT could probably be attributed to two main factors. One, LUSA method used the actual measured soil moisture whereas CROPWAT used redistributed rainfall (two showers within each decade). For CROPWAT some decades with no rainfall were registered as having water deficits and it also used a constant value of soil moisture depletion level (p) of 0.5 whereas LUSA method used larger values during the period in consideration. Therefore it was possible for CROPWAT to register water deficit where LUSA could not. Secondly, there seemed to be unexplained high levels of measured soil moisture as compared with the long rains season. LUSA method was expected to give more reliable ET_a values on condition that the actual soil moisture values used were accurately measured. The trend of LUSA method results tallied well with that of the ASI method.

The total water used by the crop as per the CROPWAT Program was about 154 mm, LUSA method with measured soil moisture gave 284 mm for residue mulch, 310 mm for conventional tillage and lastly 262 mm for the tied ridging. LUSA method with estimated soil moisture gave a total water used by the bean crop as 88 mm.

The total water used by the crop as calculated by ASI method (Table 8) followed the same trend as for the LUSA method i.e residue mulch 281 mm, conventional tillage 297 mm and tied ridging 279 mm.

Table 8 ET_m and ET_a (mm/ crop growth stage) values during various crop growth stages (short rains, 1988) at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	LUSA with SMM			ASI			LUSA with SMEST
				RM	CT	TR	RM	CT	TR	
Init	20	23.1	19.9	22.45	22.45	15.94	23.1	23.1	23.1	23.1
Dev	28	81.0	45.0	70.3	70.3	70.3	53.2	54.88	55.16	38.34
Mid	38	173.3	69.9	146.82	156.83	142.19	140.9	144.44	142.06	14.28
Late	19	76.3	27.7	44.41	60.56	33.28	63.65	74.48	58.33	12.02
Total	105	353.7	154.4	283.98	310.14	261.71	280.85	296.9	278.65	87.74

4.2.5 Seasonal Crop Water Use Sufficiency, Short Rains Period, (1988) at Kalalu.

Table 9 Water sufficiency (%) as estimated by various methods (short rains, 1988) at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	(LUSA with SMM)			ASI			LUSA with SMEST
				RM	CT	TR	RM	CT	TR	
Init	20	23.1	86	97	97	69	100	100	100	100
Dev	28	81.0	56	87	87	87	66	68	68	47
Mid	38	173.3	36	85	90	82	81	83	82	8
Late	19	76.3	36	58	79	44	83	98	76	16
Total	105	353.7	44	80	88	74	79	84	79	25

All the above results are given for each crop growth stage and for total average at the end of the crop growth period during the short rains 1988 at Kalalu.

4.3 Seasonal Rainfall, Long Rains Period, 1989 at Kalalu, Laikipia

4.3.1 Seasonal Rainfall Distribution, Long Rains Period, (1989) at Kalalu

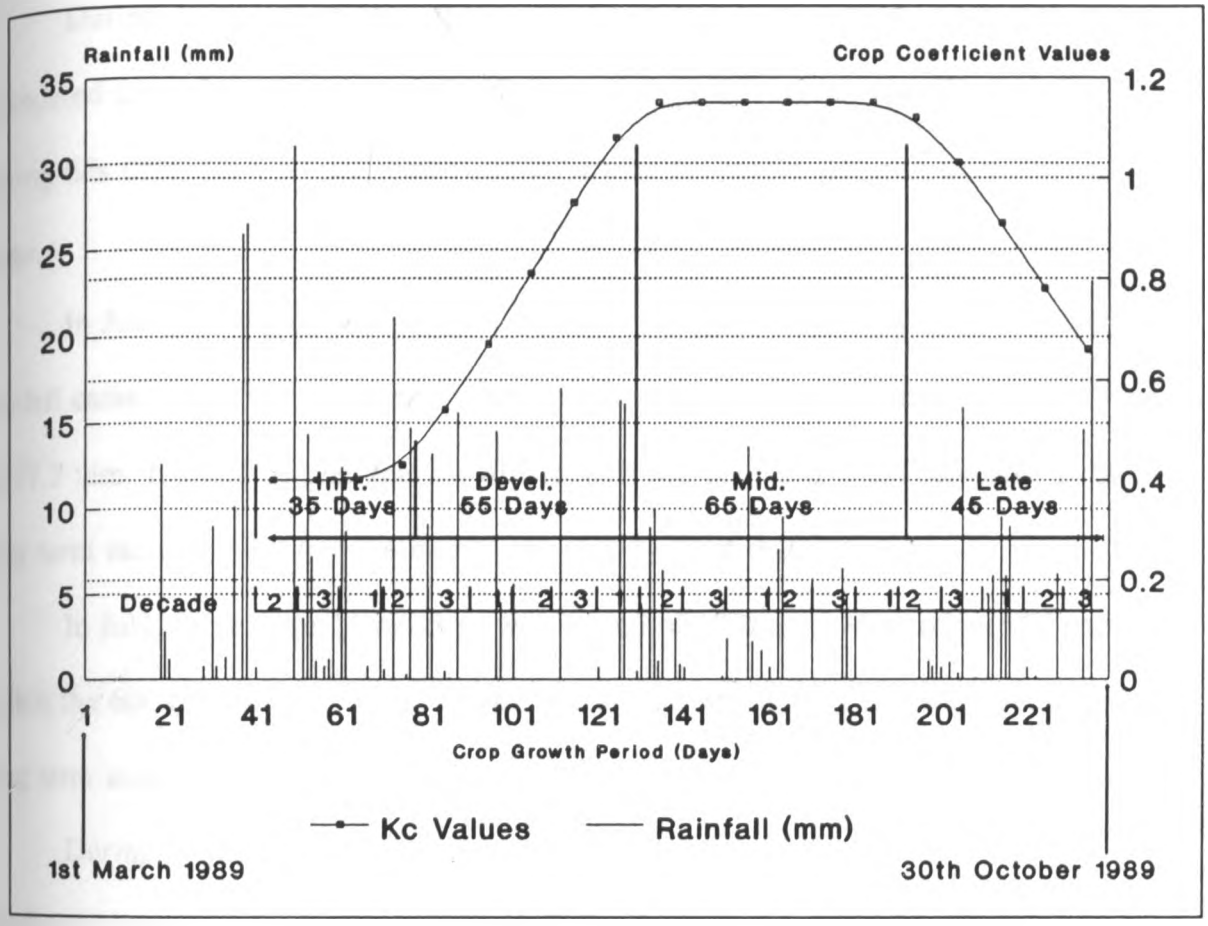

Fig. 13 Rainfall and crop coefficient during maize crop growth period (10th April 1989 to 30th October 1989) at Kalalu

Figure 13 shows that rainfall started on 19th of March and for the next 3 days the amount was 16.6 mm. After this, there were 7 days of dry spell followed by 0.8 mm on 29th of the same month. The total rainfall during the month was 17.4 mm. and as compared with the long term mean rainfall of 33.6 mm it could be said that it was drier than normal.

During the month of April, there were 15 raindays most of it coming during the 1st 9 days and the last 10 days. The total amount of rainfall was 140.5 mm and as compared to the long term mean of 102.5 mm, the month was normal.

During the month of May, there were 13 raindays with a total of 104 mm. Compared to the long term mean of 117.4 mm the month was average. The rainfall during this time was well distributed and most of it fell within the crop development stage.

In June, the amount of rain was 41.6 mm falling in only 4 days. Most of the rainfall came within the first decade of the month followed by one rainday on 22nd June of 17.7 mm. It could be seen that the distribution was poor and when compared to the long term mean of 57.9 mm the month was slightly drier than the mean.

In July, there were 11 raindays with a total of 68.4 mm. Most of it (68.2 mm) fell within the 6th and 20th day of the month. The month was normal as compared with the long term mean of 69.1 mm.

During the month of August there were 9 raindays with a total of 54.4 mm. September had 31.5 mm occurring in 9 days and lastly October had 11 raindays with a total of 82.8 mm. These months had slightly less, drier and wetter than the long term mean rainfall of 71.1 mm, 52.1 mm and 64.1 mm respectively.

During the maize growth period (from 10th of April to 1st of November) the total amount of rainfall which fell was 449.6 mm. CROPWAT gave a corresponding result of 487 mm. This was about the same as the total amount of rainfall which occurred between and inclusive of the months of April to October. The effective rainfall was 476 mm. The reason why the CROPWAT values were higher than actual rainfall was that the Program took the total monthly rainfall and redistributed into six showers per month i.e. twice in

each decade. For each rainfall event an account was kept of which part of the rainfall was lost by runoff and deep percolation otherwise the balance was cumulatively kept until the last decade at which point the total rainfall not lost was taken as effective. The effective rainfall was higher than the total actual rainfall during the crop growth period because some of the rainfall in the first decade of April was brought forward into the second decade. The crop growth period started at the second decade of April.

4.3.2 Seasonal Soil Moisture Variability Long Rains Period (1989) at Kalalu

Figure 14 shows that SMFC remained at 43.6 percent v/v from the 37th day till the 62nd day. Thereafter it rose gradually to 44.4% at the 92nd day and then decreased to 42.4 percent at the 133rd day at which level it remained till the end of crop growth period. The initial increase was due to the fact that within the 30-60 cm soil depth the available water capacity was highest as shown in table 1.

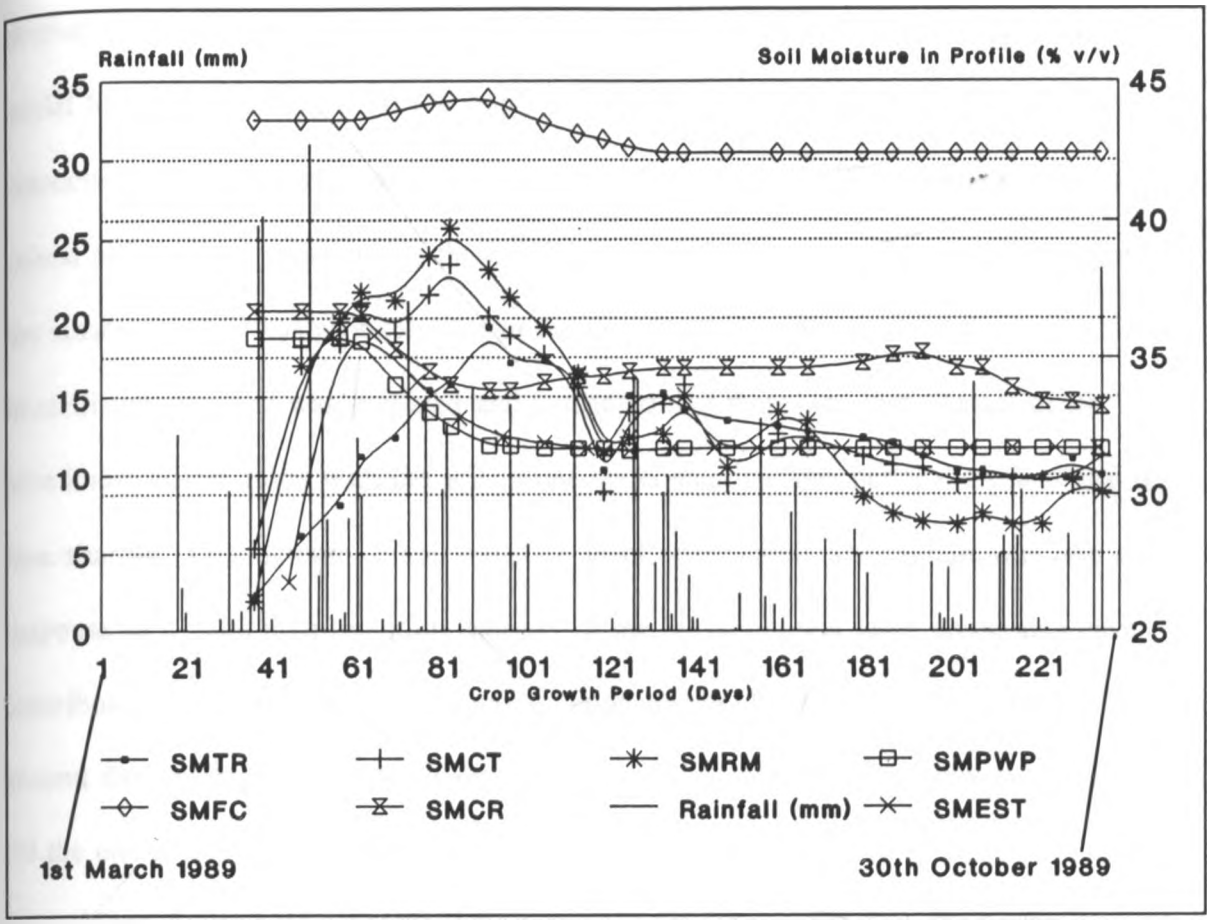

Fig. 14 Rainfall and soil moisture in profile during maize crop growth period (10th April 1989 to 30th October 1989) at Kalalu

Similarly the SMPWP was 35.7 percent from the 37th day till the 57th day. From then on it declined to 31.7 percent at the 97th day and remained at that level throughout the period in consideration.

SMCR nearly followed the same trend as SMPWP. The highest SMCR was 36.7 percent which occurred during the 37th day and 57th day. Thereafter there was a gradual decrease to a value of 33.8 percent at the 97th day. It slowly rose to a value of 34.6 percent at 133rd day at which point it remained constant till the 167th day. A small gradual increase followed till 35.2 percent at the 194th day. This was followed by another gradual

decrease to the lowest SMCR of 33.2 percent at the end of the crop growth period. The initial SMRM, SMCT and SMTR was 26.2 percent, 28.0 percent and 26.1 percent respectively. This moisture was far below both SMCR and SMPWP. Although it had rained before (38.6 mm) during the last 2 weeks, this did not affect the soil moisture and the reason for this was probably due to the fact that soil moisture was measured immediately the land was prepared and it seemed that there was less contact of the aluminium access tubes with the soil. After the contact became better the soil moisture rose sharply. The increase of soil moisture level immediately after tillage was also as a response to it. The high retention capacity of the 30-60 cm soil layer could also have contributed to the increase as the rooting depth increased. SMTR rose beyond SMPWP at around the 78th day till the 187th day i.e for about 110 days. After this period it was below till the end of the crop growth period.

SMCT was below SMPWP from the 37th day till the 57th day. Thereafter it remained higher till the 167th day i.e for about 110 days also.

SMRM was less than the SMPWP between the 37th day and the 48th day. It became higher all the way till the 167th day, a total of 120 days.

From the above it can be said that the initial response of SMTR to rainfall was the lowest. SMRM had the highest response and hence the duration of the moisture being higher than SMPWP was longest than other treatments. SMTR initial response was poor probably because the soil was made drier due to higher rates of evaporation. More soil surface was exposed and hence this gave rise to higher soil moisture depletion through evaporation. Nonetheless, later this method had a prolonged duration over which soil moisture was above SMPWP. This fact could be explained probably through the crop canopy which might have been less in the case of TR and hence soil moisture loss

through evapotranspiration was lower than in the other treatments or that TR was capable towards the end of retaining more water which infiltrated into the soil. The above might have also been caused by the fact that at this stage direct open evaporation was reduced by the crop canopy and that then the ridges in TR acted as traps for raindrops which slowly got the opportunity to enter into the soil.

Residue mulch had an overall longer duration of soil moisture being above SMPWP because its response to rainfall was immediate and this was probably because of reduced open evaporation during the time the ground was bare. The difference can thus be explained that way since there was no runoff as found out by Gicheru (1990).

SMRM was higher than the other treatments from the 57th day till around 113th day (i.e for about 57 days). Thereafter it fluctuated with the other treatments up and down in sympathy with high rainfall peaks till around 167th day after which its level became the lowest of the three treatments. This was probably due to higher soil moisture depletion rates as a result of having a better crop which was properly established from the initial crop growth stage because of more soil moisture conserved by residue mulch than the other two treatments during that period.

This trend was followed by CT. By opening the land through tillage, more rain was allowed to infiltrate and although there was open evaporation, it was not as in TR i.e. more water might have infiltrated than in TR.

SMTR was above SMCR between the 17th day and 113th day that is for about 35 days. SMCT was above SMCR between the 62nd day and 105th day that was about 42 days and lastly SMRM was above SMCR between 62nd day and 113th day which was about 50 days.

SMEST started with an initial value of 26.8 percent being the average value of the initial soil moisture for TR, CT and RM. It varied from 26.8 percent to a maximum of 35.8 percent v/v. From the initial value till the 55th day it was above SMPWP and remained so although very close to it till the end of the crop period. SMEST was above SMCR between the 80th day and 110th day i.e for about 30 days. The SMEST values were always below the actual measured soil moisture probably due to the reasons given hereunder and the fact that during the estimation process, the (new) AASM was made to assume the value of TASM each time the (new) AASM becomes more than TASM. The reason that the estimated SMEST was low could probably be attributed to suspected low values of TASM and hence the accuracy of SMFC and SMPWP as measured by Gicheru (1990). Martin Smith, (1992) gives the total available soil moisture for clay soils as 180 mm/m. Since Kalalu soils were predominantly clay (varying between 66-70%, see appendix 7) a value close to it was expected but the earlier research data a value of 107 mm/m was found. This was far way off the 180 mm/m. It is probable that either one or both SMFC and SMPWP soil moisture contents used were low. The field measurements of these values are normally tricky in the sense that one is never sure when exactly free drainage is complete or at what level crops will wither irreversibly. Because of that it was likely that during the instances that the (new) AASM assumed the value of TASM meaning the former was more than the latter should not have been the case.

In summary, the probable reasons for the low SMEST values were as follows:

a) The assumptions made might not be the case for Kalalu site. The land unit did not have deep homogeneous and adequately draining soil as the measured values of field capacity and permanent wilting point showed that they were not constant down the profile. Also complete lateral water flow could not be ruled out. One of

the of the conditions in which the program LUSA works well is that there should be no lateral movement of water.

b) There probably might have been errors in determining the permanent wilting point and field capacity since these values were extensively used in the method. The field determination of these values might have been done when the conditions were not favourable especially PWP since it is normally difficult to know when the soil is dry enough when crops wither irreversibly.

c) The time interval of ten days chosen for the estimation method was probably a long interval and was possible that soil moisture fluctuations occurring within the interval could not be registered. A shorter interval would have given more accurate results but considering that the resolution of some data used were approximations it was doubtful of the improvement on the accuracy of shortening the time interval. The approach depended heavily on accurate quantitative data on land and land-use for good results. If a computer program was developed and written and then used with accurate data of shorter intervals then the method could produce reasonable results.

4.3.3 Seasonal Available Soil Moisture, Long Rains Period (1989) at Kalalu

Figure 15 shows that the total available moisture varied from 7.9 mm at rooting depth of 10 cm to a maximum of 101 mm at maximum equivalent rooting depth of maize of 94.5 cm. These are the maximum available moisture which could have been held by the soil within the corresponding equivalent rooting depths. TASM acts as an upper limit for available moisture. During any time the actually available moisture would either be equal or less than TASM. The lower limit of the actually available moisture was zero.

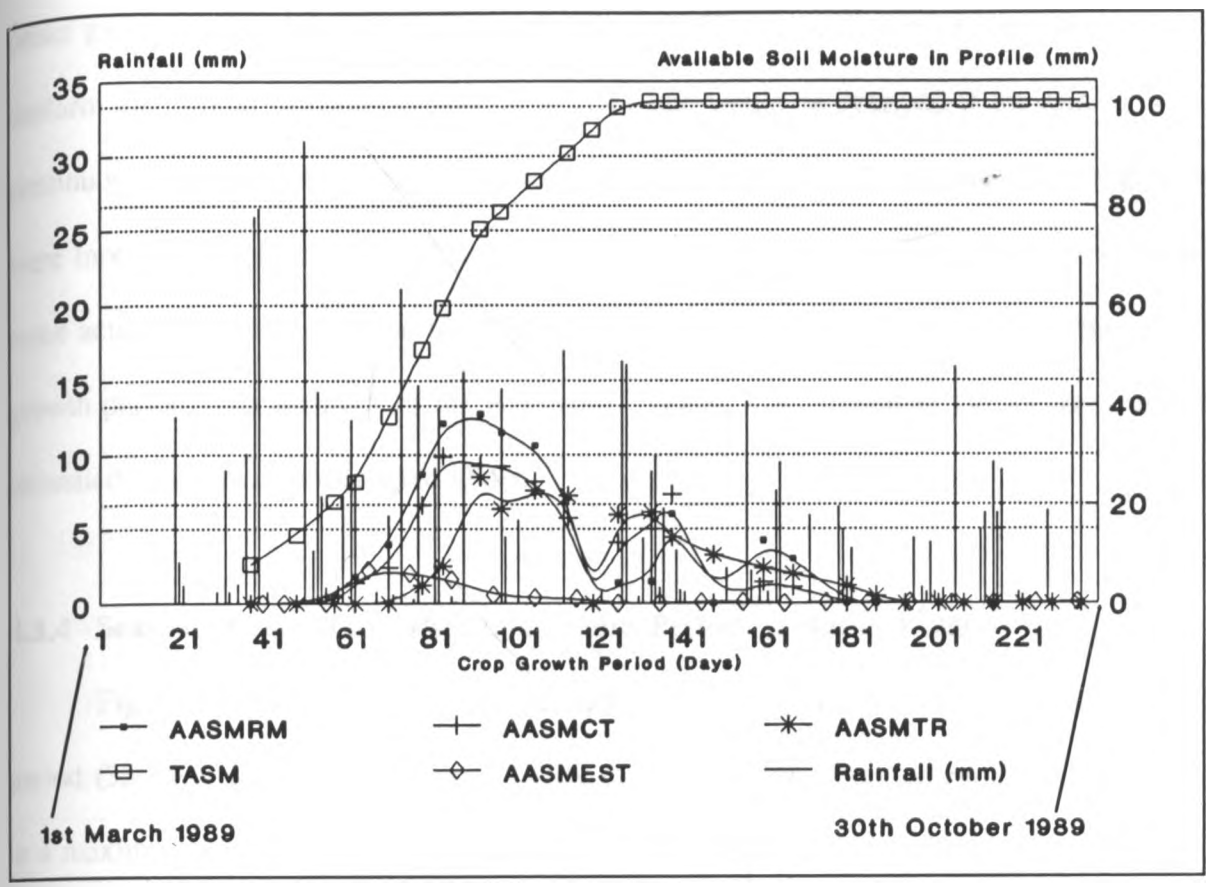

Fig. 15 Rainfall and the available soil moisture during maize crop growth period (10th april 1989 to 30th October 1989) at Kalalu

The actually available soil moisture variation during the crop growth period was found to be as follows:

AASMTR varied from 0 to 25.5 mm. There was actually available moisture in TR from the 78th day to 187th day i.e for about 110 days. Similarly AASMCT varied from 0 to 29.7 mm starting from 62nd day to around 167th day, about 105 days. AASMRM varied from 0 to 38.3 mm starting from 57th day till 167th day, about 110 days.

There were three visible peaks of actually available moisture. The first and the highest occurred around the 92nd day and this was followed by the second largest on around the 138th day. The last and smallest of the three came around the 160th day. These

peaks gave an indication of the rainfall distribution. The more they were the more uniform the rainfall distribution was. A straight line would be obtained if the rainfall was continuous and uniform in amount. In comparison to 1988 short rains, the 1989 long rains were more uniformly distributed. Lastly AASMEST varied from 0 to 6.8 mm. There was some actually available soil moisture, although small, in most days during the crop growth period. The accuracy of the AASMEST values was as good as the accuracy of the estimated soil moisture discussed above.

4.3.4 Seasonal Crop Water Use, Long Rains Period, (1989) at Kalalu

Figure 13 shows that the crop coefficient was 0.4 during the initial crop stage period (35 days) and thereafter rose steadily during the crop development stage (55 days) to a maximum value of 1.15 at the beginning of the middle stage of the crop development. It remained at this level for nearly the 65 days of middle stage and then it started declining within the late stage of crop development. It fell to around 0.7 at the end of the late stage when the crop was ready for harvesting.

A combination of reference evapotranspiration (ET_o) and the crop coefficient determined the maximum evapotranspiration rate of the crop. Figure 13 shows that ET_o values started from 3.6 mm/day and dropped to 3.5 mm/days at the 62nd day. It remained at that level till the 83rd day and then rose to 3.6 mm/day and remained constant till 119th day. Then it dropped and remained at 3.2 mm/day from 125th day until 180th day. It rose to 3.7 mm/day and remained at that level till the 208th day. From then till the end of crop growth period the value was 3.2 mm/day.

What this meant was that ET_o varied between 3.2 mm/day and 3.7 mm/day while crop coefficient (K_c) varied from 0.4 to 1.15. The variation of maize crop water

requirement was caused more by the variation of K_c values than the variation of ET_o. The higher the K_c value the higher the crop water requirement.

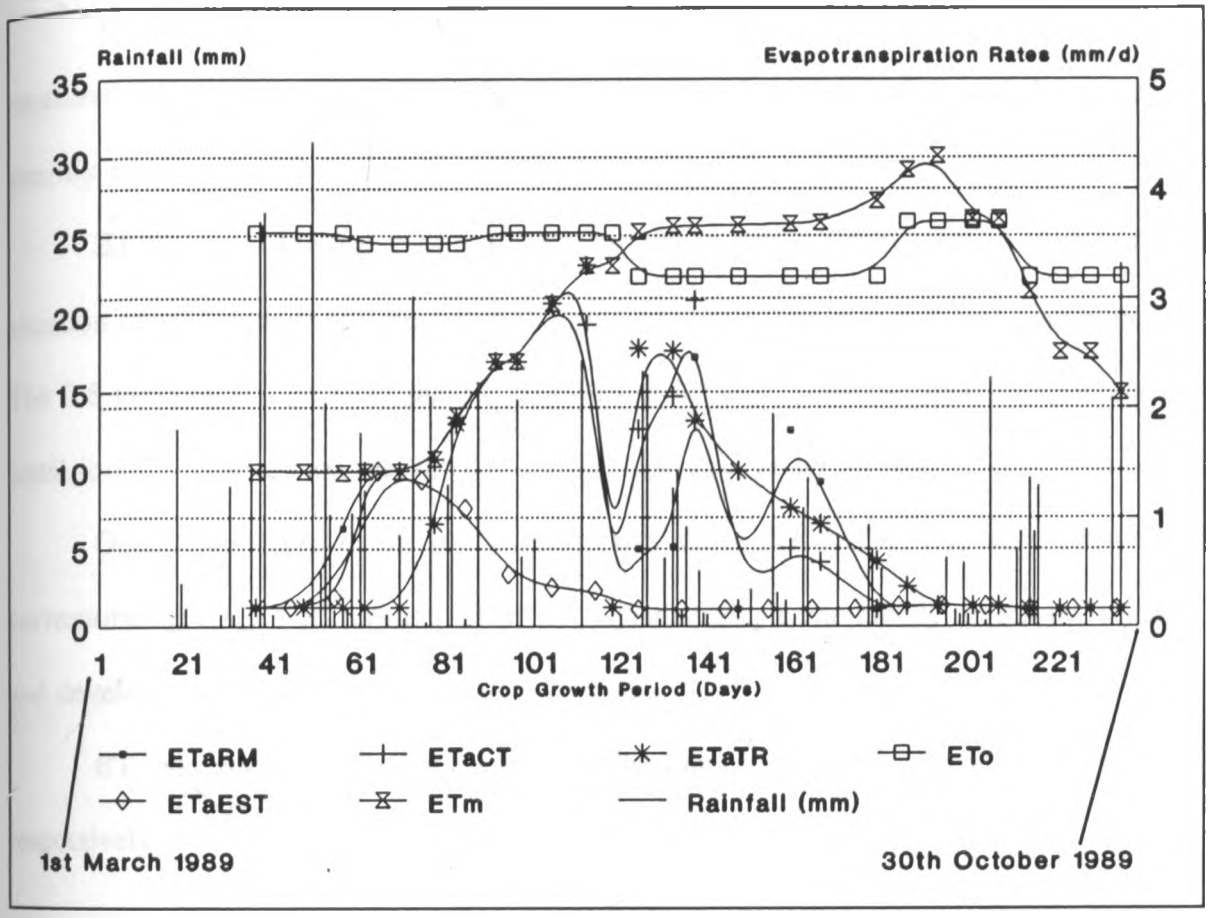

Fig. 16 Rainfall and the evapotranspiration rates during maize crop growth period (10th April 1989 to 30th October 1989) at Kalalu

Figure 16 shows that ET_m varied from 1.41 mm/day to a maximum of 4.30 mm/day. From the 37th day till the 70th day ET_m was nearly constant. After this it rose steadily till it by-passed the ET_o values at around 120th day. It remained greater till the 210th day. During this period the K_c values were higher than one. From this period ET_m dropped below ET_o till the end of crop growth period. From the shape of ET_m curve, it

showed that the crop water requirement for maize at Kalalu started from a low value of 1.41 mm/day at the start of the growth period and then rose steadily to a maximum of 4.30 mm/day at around the 200th day (around 16th of September 1989).

The actual evapotranspiration rates as calculated by use of LUSA method with measured soil moisture for the three treatments started from low values and then rose steadily just the same way the measured soil moisture rose.

ET_aTR had a low value of 0.18 mm/day which was arbitrarily set to represent a situation of no available soil moisture and thus any water loss was through evaporation. The 0.8 mm/day started from the 37th day till the 70th day (about 34 days). ET_aTR was equal to ET_m from around the 78th day till the 113th day, about 35 days.

Generally, wherever the soil moisture was above the SMCR, ET_a were equal to corresponding ET_m. The duration when ET_a equalled ET_m came mostly within the initial and development stages of the crop development.

ET_a was equal to ET_m for 35 days, 42 days and 50 days for TR, CT and RM respectively.

4.3.5 Summary of Seasonal Crop Water Use as Estimated by Various methods

Table 10 ET_m and ET_a (mm/crop growth stage) values during various crop growth stages (long rains, 1989) at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	LUSA with SMM			ASI			LUSA with SMEST
				RM	CT	TR	RM	CT	TR	
Init	35	50.2	45.9	6.3	23.7	27.3	50.2	50.2	50.2	25.4
Dev	55	149.6	149.5	112.9	111.2	107.9	122.5	118.1	117.9	30.8
Mid	65	249.1	173.1	80.5	61.4	64.1	121.7	119.5	126.5	10.9
Late	45	135.9	74.5	7.8	7.8	7.8	87.3	87.3	89.0	7.7
Total	200	584.7	443	207.5	204.1	207.1	381.7	375.1	383.0	74.8

4.3.6 Seasonal Crop Water Use Sufficiency Under Different Methods

Table 11 Water sufficiency (%) as estimated by various methods (long rains, 1989) at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	LUSA with SMM			ASI			LUSA with SMEST
				RM	CT	TR	RM	CT	TR	
Init	35	50.2	92	54	47	13	100	100	100	51
Dev	55	149.6	100	72	74	75	82	79	79	21
Mid	65	249.1	70	43	25	32	49	48	51	4
Late	45	135.9	55	6	6	6	64	64	65	6
Total	200	584.7	76	35	35	35	65	64	66	13

The ASI method gave monthly average estimates and therefore did not show particular variation within the months. It could be seen that the water used by the maize crop was nearly equal in all the treatments. From the analysis it was not possible to

priotize the three water conservation practices in terms of which method had the best impact on final yield.

The LUSA method with measured soil moisture above showed that RM was best during the initial crop growth stage followed by CT and lastly TR. During the development stage, the three treatments were nearly the same in terms of water conserved. This was probably because of crop cover which eliminated most of the water loss through evaporation. During the middle stage the order was RM (43%), TR (32%) and CT (25%). The water sufficiency was the same during the late stage of maize development. It was only 6% which meant that the plots had little or nil available water to the crop. The average water sufficiency was 35 percent for all the treatments.

The ET_a from the estimated soil moisture were dismally small apart from the initial stage. Generally the estimation method did not work well for reasons discussed elsewhere in this thesis.

It was clear that the water sufficiency was adequate for the first two crop growth stages. The lowest occurred during the late stage when moisture was not very critical. As explained under methodology on CROPWAT, the actual monthly rainfall was arbitrarily redistributed with two showers per decade and hence the above results showed an ideal situation where water sufficiency values gave an indication of the importance of proper water distribution using the actual rainfall within each decade for high crop yields.

In summary, the maximum water requirement of maize at Kalalu during the long rains of 1989 was 584.6 mm. As calculated using CROPWAT, the actual water used by the crop during this same period was 443.1 mm i.e. about 76 percent of maize crop water sufficiency was met.

The ASI method calculation gave 384.1 mm (66%), 377.5 mm (65%) and 385.9 mm (66%) for RM, CT and TR treatments respectively. It was interesting to note that TR had the highest water used followed by RM and finally conventional tillage.

The LUSA method using measured soil moisture gave 203 mm (35%), 204 mm (35%) and 207.5 mm (36%) for RM, CT, and TR respectively. Similarly here TR had the highest followed by conventional tillage and finally residue mulch.

By use of LUSA and estimated soil moisture, the total water used was 76.7 mm which was about 13 percent of the total maize water requirement.

4.4 Estimated Yields For Maize and Beans

4.4.1 Estimated Actual Yields for Beans

Table 12 Crop yield ratios, (Y_a/Y_m) expressed as a percentage (%), short rains period, 1988 at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	(LUSA and SMM)			ASI			LUSA and SMEST
				RM	CT	TR	RM	CT	TR	
Initial	20	23.1	97	99	99	93	100	100	100	100
Dev	28	81.0	51	85	85	85	62	64	65	42
Mid	38	173.3	52	86	93	86	86	88	86	31
Late	19	76.3	87	92	96	89	97	99	95	83
Total	105	353.7	35	77	86	70	76	81	76	14

Table 12 gives the results for each crop stage and for the total average. CROPWAT results showed that the yield reduction in the development and middle stages was highest and this reduced drastically the average estimated total yield to 35 percent of

the maximum yield. LUSA with measured soil moisture showed that conventional tillage was least affected followed by residue mulch and then by tied ridging. The ASI method gave conventional tillage as least affected followed by both residue mulch and tied ridges.

4.4.2 Estimated Actual Yield for Maize

Table 13 Crop yield ratios, (Y_a/Y_m) expressed as a percentage (%), long rains period, 1989 at Kalalu.

Stage	No of Days	CWR (mm)	CROPWAT	LUSA with SMM			ASI			LUSA with SMEST
				RM	CT	TR	RM	CT	TR	
Initial	35	50.2	97	90	90	80	100	100	100	80
Dev	55	149.6	100	60	60	60	70	70	70	0
Mid	65	249.1	85	60	60	70	70	70	90	50
Late	45	135.9	91	80	80	80	90	90	90	80
Total	200	584.7	70	20	20	20	60	60	60	0

Total Ya/Ym was determined using Ky = 1.25

Table 13 gives crop yield ratios during the various crop growth stages as estimated by Doorenbos and Kassam (1979) Method. The actual evapotranspiration rates used were estimated by the various indicated methods during same period. The actual water used by the crop and its impacts on yield in terms of ratios of Y_a/Y_m (ASI method using measured soil moisture, Table 11) shows that during the initial stage it was 100 percent for all the three treatments. This was followed by the late crop stage in which the ratio was 90 percent and during the crop development stage it was 70 percent for all treatments.

TR had the highest ratio of 90 percent whereas the RM and CT had the same value of 70 percent during the middle stage. This meant that assuming all other factors were not limiting save for water then the final actual estimate of the yield for all the treatments would have been the same i.e.

Y_{me} = 8.9 tons/ha and therefore actual yield Y_a = 0.6 x 8.9 = 5.3 tons/ha.

The final yield ratio (as estimated by LUSA method with measured soil moisture) was 0.2. Therefore the actual yield estimate for maize under same conditions as above was:

Y_a = 0.2 x 8.9 tons/ha

= 1.8 tons/ha in all the treatments

Similarly the actual maize yield estimate (using LUSA method with estimated soil moisture) was zero:

Y_a = 0 (there was no yield since the crop was affected permanently by water stress and this occurred during the development stage).

The Y_a/Y_m estimate from CROPWAT Program was 0.7.

Therefore Y_a = 8.9 x 0.7 tons/ha = 6.2 tons/ha

From YES Program results (appendix 7) it showed that rainfall restriction had a yield index of 16% and if it was assumed that water was the only limiting factor then:

Y_a = 0.16 x 8.9 tons/ha = 1.42 tons/ha.

With some more extra limitations to maize crop yield (appendix 7) e.g. temperature for the 1st four months the index was 0.6 and therefore the combined index with rainfall is 0.096. Hence the actual, Y_a = 0.096 x 8.9 = 0.85 tons/ha.

The difference from 1.42 tons/ha to 0.85 tons/ha i.e. 0.57 tons/ha could be accounted for as a result of limitations of temperature, or combination of both temperature and rainfall during the 1st four months of the maize crop growth period.

Table 14 Measured and estimated crop yields (tons/ha) for short and long rains periods, 1988/89 at Kalalu.

Crop	Measured			LUSA with MSM			ASI			CROPWAT	YES
	RM	CT	TR	RM	CT	TR	RM	CT	TR		
Maize	1.08	0.85	0.83	1.78	1.78	1.78	5.34	5.34	5.34	6.23	.85
Beans	0.94	0.92	0.68	2.5	2.8	2.3	2.5	2.7	2.5	1.2	-

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Although the results by Dynamic Land Use Systems Analysis (LUSA) in estimating soil moisture did not correctly simulate soil moisture, nevertheless its use with the measured soil moisture showed clearly how the problem of quantifying soil water may be done. After the quantification it was possible to assess the water availability to maize and bean crops at Kalalu under rainfed cultivation.

This study has proven several things which would normally pass unnoticed were it not for the systematic analysis chosen.

It has been shown that the effectiveness of residue mulch as the best soil water conservation practice was not that it was capable of conserving more water than the other methods but it was as a result of retaining, initially, more water hence enabling the crop to establish itself from the start. This initial proper establishment of the crop increased the final yield of the crops under residue mulch.

Evidence shows that the tillage methods used created a positive soil moisture response and that the level at which this started depended on past rainfall amount and its distribution. For the 1988 short rains the initial soil moisture was higher than it was the case for 1989 long rains. This was unexpected indicating that there was more soil moisture during the short rains than that in the long rains and this could not be explained considering the rainfall amounts and distribution for the two seasons. Once tillage practices were established, the soil moisture increased proportionally to the previous and present amount of rainfall and distribution. Also the particular soil moisture conservation method had an impact on the increase of soil moisture. The three tillage practices were capable of conserving soil water even when the following period was dry.

There was a better rainfall distribution during the long rains than that of the short rains as was seen from the rainfall and the trends on available soil moisture graphs. The better the rainfall distribution the more the expected soil moisture and therefore final yield as was seen from the yield values for the maize and beans.

The variation and therefore impacts on yield due to water during the different growth stages of the crops depended on yield response factors which were different for various growth stages of crop development.

The final harvested yield depended on the impacts of water stress during shorter periods than that normally assumed for whole growth stage periods as was the case for maize which although the crop water used in all treatments was nearly the same but the actual yields were different as measured. The difference was probably due to moisture distribution within shorter periods than the whole growth stages.

Water was the main constraint to yield reduction in Kalalu although the real problem when it came to production was more of a combination of water and unsuitable temperature which caused a big yield reduction. The temperature impact on maize yield for the first four months only at Kalalu, was great as was seen from YES yield estimate. The measured yield for maize was close to that estimated by YES method.

The ASI method results overestimated actual evapotranspiration especially in 1989 long rains than the other methods. The monthly evapotranspiration averages did not reflect the real situation and therefore these values should be used with caution. They may be used only to give an indication of soil moisture trends.

The CROPWAT results showed an idealized situation of a redistributed rainfall. This therefore gave a standard for comparison and to emphasize the importance of rainfall distribution. None of the three methods showed a well distributed soil moisture due to

poor rainfall distribution and the inability of the tillage methods to conserve moisture for long durations without losses. Residue mulch was better initially but was overtaken by tied ridging towards the end.

Water sufficiency during the development and middle stages of crop development had more impact on yield than during the other growth stages. The initial stage was only important for crop establishment which when well established would enable the crop to better cope with short term water stress and also utilize any water given during subsequent growth stages.

CROPWAT Program would give reliable results when the rainfall distribution is good. At least each decade should have some rainfall otherwise it will give misleading results as was the case for the 1988 short rains where because of some decades not having rainfall it underestimated the crop water use. It also overestimated the 1989 long rains because it carried forward the rainfall during the first ten days of the month of April when the crop had not been planted.

5.2 Recommendations

There is need to do the impact analysis of water stress on yield for even shorter periods than for whole growth stages as was done in this study. In this way it will be made clearer to ascertain specific influences of water at each particular growth period of the crop. This will determine to what extent the crop suffers in terms of final yield during the absence of certain quantity of water.

A combination of the soil moisture conservation methods is recommended. For example from the analysis, residue mulch was found to be better initially in conserving more water than the other two methods and that tied ridging became better towards the

end of crop growth stages. A combination of the RM and TR would further improve water conservation than just a single method.

Further research work is recommended on the estimation of soil moisture by use of the LUSA method but with shorter intervals and accurately determined field data.

Also a recommendation is here given that this research should be continued for more years to come out with results which can be used to draw relationships of rainfall with soil moisture. These will later be used for prediction of yields given rainfall amount and distribution.

Still further work is recommended to update and validate the YES Program by expanding data base of crops and their requirements. After this then thorough testing should be done for several places and years to determine its application value as a yield estimation tool.

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APPENDICES

APPENDIX 1

Agrometeorological Data for Kalalu 1988 and 1989

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: OCT — YEAR: 1988

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 m Max	Min	Mean	Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
OCT	1	23.5	8.5	16.0	8.0	42	7.6	10.5	3.3	6.1	2330	6.5	6.0	0.0	5.0	5.6	4.2
OCT	2	23.5	9.0	16.3	8.0	65	11.9	6.5	3.3	5.9	1600	4.4	3.0	0.0	4.0	4.1	3.2
OCT	3	24.0	9.0	16.5	7.5	NA	NA	NA	4.6	8.8	1910	5.3	5.0	0.0	4.0	NA	NA
OCT	4	23.0	10.0	16.5	7.0	64	12.0	6.7	3.3	6.8	1460	4.1	2.5	0.0	3.5	3.8	3.0
OCT	5	21.0	10.5	15.8	9.5	72	12.9	4.9	2.7	5.3	1130	3.1	3.5	0.0	2.0	2.5	1.8
OCT	6	22.5	8.5	15.5	7.0	72	12.6	5.0	3.3	6.0	1760	4.9	4.0	0.0	3.5	4.3	3.2
OCT	7	21.5	7.5	14.5	6.5	73	11.9	4.5	2.9	4.5	1320	3.7	4.5	0.0	2.0	2.8	2.0
OCT	8	22.5	7.0	14.8	5.5	55	9.2	7.5	2.9	5.4	1760	4.9	6.0	0.0	2.5	3.8	2.8
OCT	9	23.5	6.5	15.0	4.0	42	7.1	9.9	4.5	9.2	2370	6.6	10.0	0.0	5.5	4.9	3.5
OCT	10	25.0	6.5	15.8	4.0	NA	NA	NA	4.7	8.8	2400	6.7	9.0	0.0	6.0	NA	NA
OCT	11	25.0	7.0	16.0	4.5	49	8.8	9.3	4.9	8.5	2120	5.9	8.0	0.0	4.5	4.9	3.6
OCT	12	23.5	8.5	16.0	5.5	72	13.0	5.1	5.0	8.2	1600	4.4	5.0	3.4	0.5	3.8	2.8
OCT	13	22.5	8.5	15.5	6.0	69	12.2	5.4	3.7	8.4	1510	4.2	6.0	16.0	2.0	3.2	2.3
OCT	14	21.5	9.0	15.3	7.5	87	15.0	2.3	3.0	4.5	2170	6.0	5.0	25.8	NA	5.1	3.8
OCT	15	22.0	8.5	15.3	6.5	62	10.6	6.6	2.5	5.1	2310	6.4	5.0	0.0	4.5	5.5	4.2
OCT	16	21.5	7.5	14.5	3.5	61	10.0	6.4	2.6	4.9	1700	4.7	5.0	0.0	2.5	3.8	2.8
OCT	17	23.5	4.5	14.0	3.0	46	7.3	8.6	3.4	4.3	2590	7.2	7.0	0.0	3.5	6.1	4.5
OCT	18	24.5	5.5	15.0	3.5	36	6.1	10.9	3.3	6.2	2310	6.4	11.5	0.0	6.5	4.1	2.8
OCT	19	24.5	6.5	15.5	4.5	49	8.5	9.0	4.2	6.8	2450	6.8	6.5	0.0	4.0	6.0	4.6
OCT	20	22.5	5.5	14.0	5.5	68	10.8	5.1	3.7	5.9	1910	5.3	4.0	0.6	5.5	4.7	3.6
OCT	21	22.0	6.0	14.0	5.5	66	10.6	5.4	3.3	5.1	2120	5.9	6.0	5.4	0.2	4.8	3.5
OCT	22	21.5	7.0	14.3	5.0	54	8.7	7.4	4.3	5.2	2070	5.8	8.0	0.0	3.5	4.3	3.1
OCT	23	24.0	7.0	15.5	5.0	60	10.5	7.0	5.5	10.2	2170	6.0	8.0	0.0	5.5	4.9	3.7
OCT	24	21.5	8.5	15.0	7.5	79	13.5	3.5	4.0	8.6	1740	4.8	2.5	1.9	5.6	4.4	3.4
OCT	25	19.0	9.0	14.0	8.0	77	12.2	3.7	2.6	5.1	1510	4.2	4.0	17.9	2.9	3.3	2.5
OCT	26	21.0	10.0	15.5	10.0	76	13.4	4.1	3.0	5.1	1460	4.1	2.5	6.1	2.3	3.6	2.8
OCT	27	21.5	7.5	14.5	6.5	66	10.9	5.5	3.5	6.7	1530	4.3	5.5	1.0	3.6	3.2	2.3
OCT	28	21.0	8.0	14.5	5.5	66	10.9	5.6	2.8	4.9	1320	3.7	2.5	0.0	4.0	3.3	2.5
OCT	29	20.0	10.0	15.0	6.0	82	14.0	3.0	2.5	4.4	1400	3.9	2.5	12.9	2.5	3.4	2.5
OCT	30	21.0	8.0	14.5	6.0	67	11.0	5.5	2.4	4.3	1770	4.9	4.5	7.6	0.5	4.0	3.0
OCT	31	NA	NA	NA	NA	NA	NA	NA	3.0	4.6	1320	3.7	4.0	0.0	4.0	NA	NA
AVER MONTH		22.5	7.8	15.1	6.1	63	10.8	6.3	3.5	6.3	1843	5.1	5.4	98.6	3.4	4.2	3.1
AVER 1 DEC		23.0	8.3	15.7	6.7	60	10.5	7.2	3.5	6.7	1804	5.0	5.4	0.0	3.8	4.2	3.1
AVER 2 DEC		23.1	7.1	15.1	5.0	60	10.2	6.9	3.6	6.3	2067	5.7	6.3	45.8	3.4	4.7	3.5
AVER 3 DEC		21.3	8.1	14.7	6.5	70	11.6	5.1	3.4	5.8	1674	4.6	4.5	52.8	3.1	3.8	2.8
MAX		25.0	10.5	NA	10.0	NA	NA	NA	5.5	10.2	2590	7.2	11.5	25.8	6.5	NA	NA
MIN		19.0	4.5	NA	3.0	NA	NA	NA	2.4	4.3	1130	3.1	2.5		0.0	NA	NA
NO OF DATA		30	30	31	30	31			31	31	31	31	31	11	31		

NA: not available — ERR: error
1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

*: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: NOV YEAR: 1988

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 m Max	Min	Mean	Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	B)	RAIN (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
NOV	1	22.0	7.5	14.8	4.5	72	12.0	4.7	2.6	3.0	1320	3.7	3.5		0.0	1.5	3.0	2.3
NOV	2	21.5	8.5	15.0	5.5	66	11.3	5.7	2.9	3.3	1810	5.0	4.0		0.0	3.5	4.3	3.3
NOV	3	22.5	10.0	16.3	7.5	72	13.3	5.1	3.6	3.5	2010	5.6	2.5		0.0	7.5	5.3	4.1
NOV	4	20.5	9.5	15.0	4.5	77	13.1	3.8	7.0	2.7	1340	5.1	4.0		1.5	5.5	4.5	3.4
NOV	5	19.5	8.5	14.0	6.5	56	8.9	7.0	2.7	3.2	1650	4.6	7.0		0.0	8.0	3.1	2.1
NOV	6	22.5	6.5	14.5	6.5	52	8.5	7.9	6.5	4.1	1650	4.6	8.0		0.0	4.5	3.5	2.6
NOV	7	21.5	6.0	13.8	6.0	69	10.8	4.9	5.5	10.2	1840	5.1	6.0		0.0	6.5	4.1	3.1
NOV	8	23.0	7.5	15.3	7.5	58	9.9	7.3	6.6	8.2	2260	6.3	6.0		0.0	2.0	5.7	4.4
NOV	9	20.0	13.0	16.5	13.0	66	12.3	6.4	5.1	6.3	1890	5.3	5.5		1.8	2.0	4.5	3.3
NOV	10	20.0	9.5	14.8	9.0	71	11.9	4.8	3.0	1.0	1460	4.1	2.0		4.0	2.0	3.7	2.8
NOV	11	20.0	9.5	14.8	9.5	89	14.9	1.8	2.3	4.0	1180	3.3	1.5		10.3	0.8	2.9	2.2
NOV	12	21.5	10.5	16.0	10.5	70	12.6	5.5	2.6	4.5	1890	5.3	4.0		0.0	4.5	4.6	3.5
NOV	13	21.5	6.5	14.0	4.5	73	11.6	4.3	2.8	4.7	1930	5.4	5.0		0.5	3.0	4.4	3.2
NOV	14	20.5	7.0	13.8	6.5	81	12.6	3.0	6.9	12.3	1890	5.3	3.0		1.4	2.4	4.8	3.7
NOV	15	21.5	6.5	14.0	5.0	57	9.0	6.9	6.1	8.8	1270	3.5	9.0		0.0	5.0	2.0	1.3
NOV	16	22.5	6.0	14.3	5.0	55	8.8	7.3	4.4	7.0	2060	5.7	6.0		0.0	6.0	4.8	3.6
NOV	17	17.5	5.5	11.5	5.5	74	10.0	3.5	1.2	1.0	2260	6.3	2.0		0.8	3.3	5.5	4.2
NOV	18	17.0	7.5	12.3	6.0	91	12.9	1.3	2.6	2.8	1580	4.4	0.5		13.8	3.8	4.0	3.1
NOV	19	17.5	6.5	12.0	5.5	86	12.0	2.0	0.7	1.4	1300	3.6	5.5		22.7	2.7	2.2	1.5
NOV	20	16.0	7.5	11.8	7.0	91	12.5	1.3	0.0	0.1	1180	3.3	3.5		19.0	NA	2.3	1.6
NOV	21	23.5	7.0	15.3	6.0	70	12.0	5.2	3.9	5.5	800	2.2	3.0		1.6	2.1	1.9	1.4
NOV	22	22.5	5.0	13.8	6.0	78	12.2	3.5	2.3	2.6	1400	3.9	2.5		0.5	1.0	3.4	2.6
NOV	23	23.0	7.0	15.0	6.5	60	10.1	6.8	4.7	7.0	1320	3.7	7.0		0.0	6.0	2.6	1.8
NOV	24	22.0	7.5	14.8	5.0	61	10.1	6.6	4.1	8.1	2070	5.8	8.0		0.0	4.0	4.3	3.1
NOV	25	21.5	7.0	14.3	4.5	57	9.2	7.0	4.5	8.5	2590	7.2	7.0		0.0	4.5	6.0	4.5
NOV	26	22.0	7.0	14.5	4.0	46	7.6	8.9	5.6	10.5	1790	5.0	10.5		0.0	5.0	3.1	2.1
NOV	27	21.5	6.5	14.0	6.0	52	8.2	7.7	6.8	12.7	2640	7.3	11.0		0.0	5.0	5.5	3.9
NOV	28	NA	NA	NA	NA	69	NA	NA	4.4	7.6	2170	6.0	3.0		0.0	4.0	NA	NA
NOV	29	NA	NA	NA	NA	48	NA	NA	1.7	2.7	1840	5.1	9.0		0.0	3.5	NA	NA
NOV	30	23.0	6.5	14.8	3.5	57	9.5	7.2	3.4	7.6	2310	6.4	8.5		0.0	4.5	4.9	3.5
AVER MONTH		19.6	7.1	13.3	5.9	67	10.3	5.0	3.9	5.5	1773	4.9	5.3		77.9	3.8	3.9	2.8
AVER 1 DEC		21.3	8.7	15.0	7.1	66	11.2	5.8	4.5	4.6	1773	4.9	4.9		7.3	4.3	4.2	3.1
AVER 2 DEC		19.6	7.3	13.4	6.5	77	11.7	3.6	3.0	4.7	1654	4.6	4.0		68.5	3.2	3.7	2.8
AVER 3 DEC		17.9	5.4	11.6	4.2	60	8.1	5.5	4.1	7.3	1893	5.3	7.0		2.1	4.0	3.7	2.7
MAX		23.5	13.0	NA	13.0	91	NA	NA	7.0	12.7	2640	7.3	11.0		22.7	8.0	NA	NA
MIN		0.0	0.0	NA	0.0	46	NA	NA	0.0	0.1	800	2.2	0.5			0.0	NA	NA
NO OF DATA		30	30	30	30	30			30	30	30	30	30		12	30		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

*: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION

LAIKIPIA RESEARCH PROGRAMME / Li

MONTH: DEC YEAR: 1988

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
DEC	1	20.5	8.5	14.5	4.5	57	9.3	7.1	7.6	11.1	2590	7.2	6.0	0.0	3.5	6.4	4.9
DEC	2	21.5	10.0	15.8	5.5	54	9.6	8.2	8.1	11.7	1790	5.0	10.0	0.0	5.0	3.4	2.3
DEC	3	19.5	10.5	15.0	4.5	53	9.1	7.9	11.1	12.1	2310	6.4	10.5	0.0	6.5	4.9	3.5
DEC	4	21.5	10.5	16.0	5.0	48	8.6	9.5	7.4	9.8	2380	6.6	12.0	0.0	5.0	4.5	3.1
DEC	5	21.0	12.0	16.5	5.0	46	8.5	10.2	6.9	9.6	2310	6.4	8.0	0.0	5.5	5.3	3.9
DEC	6	21.5	8.0	14.8	4.0	52	8.6	8.1	6.5	8.7	2170	6.0	7.0	0.0	5.0	5.1	3.8
DEC	7	22.5	7.5	15.0	3.5	52	8.8	8.2	5.0	9.0	2120	5.9	7.5	0.0	6.0	4.7	3.5
DEC	8	23.5	9.0	16.3	4.0	64	11.7	6.7	4.6	7.3	2360	6.6	5.5	0.0	3.0	5.9	4.5
DEC	9	23.5	7.0	15.3	4.5	54	9.3	7.9	7.1	4.8	1740	4.8	5.0	0.9	4.9	4.7	3.6
DEC	10	23.5	7.0	15.3	4.0	56	9.7	7.5	3.6	3.8	1480	4.1	8.0	0.7	6.2	2.7	1.8
DEC	11	21.5	6.5	14.0	4.5	62	9.9	6.0	3.8	4.4	1750	4.9	3.5	0.0	4.5	4.3	3.3
DEC	12	21.0	6.0	13.5	5.0	82	12.6	2.8	8.2	6.3	1330	3.7	5.0	0.0	5.5	2.9	2.1
DEC	13	20.5	5.0	12.8	3.0	44	6.4	8.3	7.5	13.9	1740	4.8	7.5	0.0	6.5	3.9	2.9
DEC	14	23.0	6.0	14.5	3.5	47	7.7	8.7	8.2	12.9	1970	5.5	10.5	0.0	7.5	4.2	3.0
DEC	15	22.5	6.5	14.5	4.0	50	8.2	8.3	6.5	13.1	2730	7.6	10.0	0.0	7.5	6.1	4.5
DEC	16	23.5	8.5	16.0	6.0	50	9.1	9.0	8.9	11.6	2290	6.4	10.0	0.0	6.5	5.2	3.9
DEC	17	22.5	11.5	17.0	8.0	60	11.5	7.8	9.3	15.0	2310	6.4	9.5	5.1	5.1	5.2	3.8
DEC	18	22.0	9.5	15.8	6.5	72	12.8	5.0	9.0	7.2	2400	6.7	10.0	5.1	4.6	5.1	3.7
DEC	19	22.0	11.5	16.8	9.5	57	10.9	8.1	7.8	13.3	2170	6.0	6.5	2.0	5.0	5.3	4.0
DEC	20	21.5	12.5	17.0	10.5	69	13.4	5.9	9.6	11.5	2490	6.9	8.0	8.9	2.4	6.0	4.5
DEC	21	21.0	10.5	15.8	9.5	75	13.3	4.5	10.8	5.9	2070	5.8	7.0	2.7	4.2	4.8	3.6
DEC	22	21.0	11.0	16.0	10.5	68	12.2	5.9	10.1	8.6	1790	5.0	7.0	0.0	5.0	4.1	3.0
DEC	23	20.0	9.0	14.5	8.5	71	11.7	4.8	12.2	13.9	1980	5.5	6.0	0.0	6.0	4.8	3.6
DEC	24	21.5	12.0	16.8	10.5	61	11.6	7.3	9.2	14.4	2220	6.2	6.0	8.1	1.1	5.7	4.3
DEC	25	19.0	11.0	15.0	6.0	73	12.4	4.6	7.8	6.2	1840	5.1	4.0	0.0	5.5	4.6	3.5
DEC	26	21.0	10.5	15.8	7.5	63	11.3	6.5	4.5	4.4	2340	6.5	3.0	0.0	4.5	6.2	4.8
DEC	27	23.0	8.0	15.5	6.0	58	10.1	7.4	5.2	10.1	1890	5.3	9.0	0.0	4.5	3.8	2.7
DEC	28	23.0	7.0	15.0	4.0	59	10.1	6.9	9.9	12.3	2690	7.5	9.0	0.0	6.0	6.6	5.0
DEC	29	22.0	12.5	17.3	11.0	65	12.7	6.9	10.0	12.6	2170	6.0	4.5	0.0	4.0	5.9	4.6
DEC	30	22.5	12.0	17.3	8.0	56	11.0	8.6	11.2	14.9	1600	4.4	8.0	0.0	7.0	3.7	2.7
DEC	31	22.5	12.5	17.5	5.5	49	9.7	10.2	7.0	12.9	2450	6.8	12.0	0.0	5.5	4.8	3.3
AVER MONTH		21.8	9.3	15.6	6.2	59	10.4	7.2	7.7	10.1	2112	5.9	7.6	33.5	5.1	4.8	3.6
AVER 1 DEC		21.9	9.0	15.4	4.5	53	9.3	8.1	6.8	8.8	2125	5.9	8.0	1.6	5.1	4.8	3.5
AVER 2 DEC		22.0	8.4	15.2	6.1	59	10.2	7.0	7.9	10.9	2118	5.9	8.1	21.1	5.5	4.8	3.5
AVER 3 DEC		21.5	10.5	16.0	7.9	63	11.5	6.6	8.9	10.6	2095	5.8	6.9	10.8	4.8	5.0	3.7
MAX		23.5	12.5	17.5	11.0	82	13.4	10.2	12.2	15.0	2730	7.6	12.0	8.9	7.5	6.6	5.0
MIN		19.0	5.0	12.8	3.0	44	6.4	2.8	3.6	3.8	1330	3.7	3.0		1.1	2.7	1.8
NO OF DATA		31	31	31	31	31			31	31	31	31	31	8	31		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch

B: Gunn Bellani (daily values)

1/ PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION LAIKIPIA RESEARCH PROGRAMME / LI

MONTH:JAN YEAR: 1988 (355)

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	B	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
JAN	1	23.5	10.5	17.0	3.5	51	9.8	9.5	7.3	8.7	2520	7.0	10.5		0.0	6.0	5.5	4.0
JAN	2	23.0	7.0	15.0	3.0	51	8.7	8.3	7.3	10.6	2590	7.2	9.5		0.0	11.0	6.0	4.4
JAN	3	24.0	7.5	15.8	3.5	49	8.7	9.1	7.0	12.0	2450	6.8	11.5		0.0	13.0	5.2	3.7
JAN	4	23.0	8.5	15.8	4.0	59	10.5	7.3	6.5	10.9	2780	7.7	5.0		0.6	8.0	7.4	5.7
JAN	5	24.0	12.5	18.3	11.0	57	11.9	9.0	6.3	9.7	2120	5.9	4.0		0.0	6.0	5.8	4.5
JAN	6	24.5	8.5	16.5	6.0	60	11.1	7.5	7.3	6.0	2120	5.9	8.0		0.0	13.0	5.1	3.8
JAN	7	24.5	8.0	16.3	5.5	52	9.6	8.8	6.7	8.3	2760	7.7	8.5		0.0	11.0	6.8	5.1
JAN	8	24.0	8.0	16.0	5.0	52	9.4	8.7	5.3	9.8	2690	7.5	7.0		0.0	9.0	6.7	5.1
JAN	9	24.5	8.5	16.5	6.0	41	7.7	11.0	7.8	11.8	2270	6.3	10.0		0.0	14.0	5.3	3.9
JAN	10	24.0	8.0	16.0	5.0	54	9.8	8.3	6.9	9.5	2400	6.7	7.5		0.0	8.0	6.0	4.5
JAN	11	24.0	10.5	17.3	6.5	51	9.9	9.7	8.2	10.6	2220	6.2	8.0		0.0	13.0	5.4	4.1
JAN	12	24.0	9.5	16.8	7.5	43	8.1	10.9	7.0	9.4	2400	6.7	12.0		0.0	15.0	4.8	3.4
JAN	13	24.0	9.5	16.8	7.0	46	8.7	10.3	8.2	11.5	2830	7.9	11.0		0.0	14.0	6.5	4.8
JAN	14	24.0	12.0	18.0	12.5	62	12.7	7.9	6.8	12.9	2360	6.6	10.0		1.5	14.0	5.2	3.7
JAN	15	24.5	9.0	16.8	7.5	54	10.3	8.7	6.0	10.9	2170	6.0	9.0		2.1	NA	4.9	3.5
JAN	16	23.5	9.5	16.5	7.5	82	15.3	3.4	4.2	6.1	2070	5.8	4.5		5.5	NA	5.1	3.9
JAN	17	23.0	10.0	16.5	10.5	49	9.2	9.5	3.8	5.8	1150	3.2	4.5		0.0	8.0	2.6	1.9
JAN	18	23.0	9.0	16.0	7.0	42	7.6	10.5	6.6	5.4	1650	4.6	6.0		36.8	NA	4.1	3.1
JAN	19	21.5	9.5	15.5	8.0	67	11.7	5.8	8.4	13.1	1890	5.3	8.0		0.0	6.0	4.1	2.9
JAN	20	22.0	10.0	16.0	8.0	58	10.6	7.5	5.6	6.8	1700	4.7	4.0		0.0	8.0	4.3	3.3
JAN	21	23.5	9.0	16.3	12.5	53	9.8	8.6	5.7	7.6	1740	4.8	7.0		0.0	10.0	4.0	2.9
JAN	22	22.0	10.5	16.3	7.5	77	14.1	4.3	5.3	6.5	2310	6.4	NA		9.6	NA	NA	NA
JAN	23	20.5	9.5	15.0	10.5	79	13.5	3.5	6.3	10.9	1460	4.1	9.0		0.0	11.0	2.4	1.5
JAN	24	19.0	11.0	15.0	8.5	77	13.1	3.9	8.2	7.7	2310	6.4	8.0		0.0	12.0	5.1	3.7
JAN	25	23.0	11.0	17.0	8.5	46	8.9	10.4	9.3	14.4	2500	6.9	11.5		0.0	15.0	5.3	3.8
JAN	26	22.0	9.5	15.8	7.0	39	6.9	10.9	8.2	13.6	2500	6.9	12.0		0.0	15.0	5.0	3.5
JAN	27	22.5	6.5	14.5	4.0	42	6.9	9.6	7.7	10.4	2590	7.2	11.5		0.0	11.0	5.5	4.0
JAN	28	23.0	7.5	15.3	5.5	47	8.5	8.8	7.1	12.7	2550	7.1	10.0		0.0	12.0	5.7	4.2
JAN	29	24.0	8.0	16.0	5.0	56	10.1	8.0	8.0	9.6	2450	6.8	11.0		0.0	11.0	5.4	3.9
JAN	30	22.0	7.0	14.5	4.5	54	8.9	7.5	7.7	13.8	2400	6.7	5.5		0.0	9.0	6.3	4.9
JAN	31	22.5	7.0	14.8	4.0	54	9.1	7.6	6.7	10.8	2070	5.8	11.5		0.0	12.0	3.9	2.6
AVER MONTH		23.1	9.1	16.1	6.8	55	10.0	8.2	6.9	9.9	2259	6.3	8.2		56.1	10.9	5.2	3.9
AVER 1 DEC		23.9	8.7	16.3	5.3	53	9.7	8.8	6.8	9.7	2470	6.9	8.2		0.6	9.9	6.0	4.5
AVER 2 DEC		23.4	9.9	16.6	8.2	55	10.4	8.4	6.5	9.3	2044	5.7	7.7		45.9	11.1	4.7	3.5
AVER 3 DEC		22.2	8.8	15.5	7.0	57	10.0	7.5	7.3	10.7	2262	6.3	8.8		9.6	11.8	5.0	3.7
MAX		24.5	12.5	18.3	12.5	82	15.3	11.0	9.3	14.4	2830	7.9	12.0		36.8	15.0	NA	NA
MIN		19.0	6.5	14.5	3.0	39	6.9	3.4	3.8	5.4	1150	3.2	0.0			6.0	NA	NA
NO OF DATA		31	31	31	31	31			31	31	31	31	31		6	27		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch

B: Gunn Bellani (daily values)

1: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH:FEB YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer 2 Max	Min	Mean	Surface 3 Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
FEB	1	24.5	6.5	15.5	3.5	45	7.9	9.6	7.1	12.2	2640	7.3	11.5	0.0	7.0	5.9	4.3
FEB	2	24.0	4.5	14.3	1.5	48	7.8	8.4	8.0	14.4	2880	8.0	10.0	0.0	5.5	7.0	5.3
FEB	3	24.0	5.5	14.8	3.5	50	9.7	7.0	7.4	14.5	2430	6.8	7.5	0.0	5.5	6.1	4.6
FEB	4	23.5	6.5	15.0	4.0	51	8.7	8.3	7.7	16.1	2170	6.0	8.0	0.0	6.5	5.3	4.0
FEB	5	21.0	7.5	14.3	5.5	68	10.9	5.2	4.4	8.3	2640	7.3	3.0	0.0	1.3	6.9	5.4
FEB	6	21.5	10.0	15.8	3.5	94	16.8	1.0	2.6	3.5	1270	3.5	3.0	15.8	0.2	2.9	2.1
FEB	7	22.5	9.0	15.8	7.5	81	14.4	3.4	3.5	6.6	1090	3.0	1.0	10.1	0.9	2.9	2.3
FEB	8	22.5	7.5	15.0	7.0	63	10.6	6.3	6.2	7.7	1230	3.4	5.0	16.1	3.5	2.9	2.1
FEB	9	23.5	9.0	16.3	7.0	51	9.3	9.1	8.7	10.9	1790	5.0	8.0	0.0	6.5	4.3	3.2
FEB	10	22.5	7.5	15.0	4.5	45	7.7	9.3	8.5	16.2	2730	7.6	10.0	0.0	6.0	6.4	4.7
FEB	11	21.5	7.5	14.5	3.5	42	7.0	9.5	10.4	13.8	2730	7.6	11.5	0.0	7.0	6.1	4.5
FEB	12	23.0	8.0	15.5	8.5	46	8.1	9.5	8.3	11.4	2790	7.8	7.0	0.0	6.5	7.3	5.7
FEB	13	24.0	6.0	15.0	3.0	45	7.6	9.3	10.0	12.6	2710	6.2	10.0	0.0	7.0	5.6	4.3
FEB	14	24.0	8.0	16.0	4.0	54	9.7	8.4	7.8	6.3	2590	7.2	10.0	0.0	7.5	6.0	4.5
FEB	15	24.0	8.0	16.0	4.0	61	11.1	7.0	7.7	13.0	2690	7.5	8.0	0.0	7.0	6.7	5.1
FEB	16	22.5	8.5	15.5	4.5	49	8.5	9.0	10.3	16.0	2170	6.0	11.0	0.0	7.5	4.7	3.4
FEB	17	22.5	7.0	14.8	4.5	40	6.7	10.0	11.4	18.6	2450	6.8	12.0	0.0	7.5	5.6	4.1
FEB	18	22.5	8.0	15.3	5.5	37	6.4	10.9	11.2	13.3	2420	6.7	11.5	0.0	9.0	5.5	4.1
FEB	19	23.3	12.0	17.8	10.5	42	8.4	11.8	10.3	13.5	2560	7.1	11.5	0.0	7.5	5.6	4.0
FEB	20	23.5	9.0	16.3	8.0	45	8.2	10.2	6.1	10.2	2580	7.2	8.0	0.0	6.5	6.2	4.7
FEB	21	23.5	7.5	15.5	3.5	61	10.8	6.8	6.5	12.2	2070	5.8	7.5	0.0	6.5	4.8	3.6
FEB	22	24.0	10.5	17.3	7.5	54	10.5	9.1	9.8	15.7	2260	6.3	9.0	0.0	7.5	5.5	4.1
FEB	23	24.0	9.0	16.5	7.0	33	6.2	12.5	12.8	16.2	2520	7.0	12.0	0.0	7.5	6.2	4.7
FEB	24	23.5	10.0	16.8	8.0	34	6.4	12.6	11.8	14.4	2590	7.2	11.0	0.0	8.5	6.3	4.7
FEB	25	24.5	11.5	18.0	5.0	33	6.8	13.8	11.1	15.6	2450	6.8	11.5	0.0	10.0	5.7	4.2
FEB	26	24.5	9.5	17.0	6.0	30	5.7	13.6	10.1	16.0	2550	7.1	12.0	0.0	9.0	5.9	4.3
FEB	27	25.0	10.0	17.5	5.5	31	6.2	13.7	9.4	14.7	2610	7.3	12.0	0.0	9.0	6.0	4.4
FEB	28	26.0	8.0	17.0	5.0	32	6.1	13.2	9.6	12.2	2590	7.2	12.0	0.0	10.0	6.4	4.8
FEB	29	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	NA	NA	NA
FEB	30	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.0	NA	NA	NA
AVER MONTH		23.4	8.3	15.8	5.4	49	8.8	9.1	7.9	12.7	NA	NA	9.1	42.0	6.6	NA	NA
AVER 1 DEC		23.0	7.4	15.2	4.8	60	10.4	6.8	6.4	11.0	2087	5.8	6.7	42.0	4.3	5.0	3.8
AVER 2 DEC		23.1	8.2	15.7	5.6	46	8.2	9.5	9.4	12.9	2522	7.0	10.1	0.0	7.3	5.9	4.4
AVER 3 DEC		24.4	9.5	16.9	5.9	38	7.4	11.8	8.1	14.6	NA	NA	10.9	0.0	8.5	NA	NA
MAX		26.0	12.0	NA	10.5	NA	NA	NA	12.8	18.6	NA	NA	12.0	16.1	10.0	NA	NA
MIN		21.0	4.5	NA	1.5	NA	NA	NA	0.0	3.5	NA	NA	1.0		0.2	NA	NA
NO OF DATA		28	28	30	28	30			30	28	30	30	28	3	28		

NA: not available ERR: error
1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

* PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: MAR YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
MAR	1	25.0	8.5	16.8	6.5	30	5.7	13.3	8.8	12.3	2830	7.9	11.5	0.0	10.5	6.8	5.1
MAR	2	27.0	6.5	16.8	0.5	31	5.9	13.0	6.8	8.2	2690	7.5	12.0	0.0	10.0	6.3	4.6
MAR	3	27.5	6.0	16.8	2.5	31	5.9	13.0	6.7	11.5	2930	8.1	10.5	0.0	10.0	7.5	5.7
MAR	4	25.5	6.5	16.0	3.5	44	8.0	10.1	6.8	12.7	2670	7.4	9.0	0.0	8.0	6.7	5.1
MAR	5	25.5	6.0	15.8	2.0	42	7.5	10.3	8.5	16.3	2190	6.1	11.5	0.0	8.5	5.1	3.8
MAR	6	27.5	7.5	17.5	2.5	46	9.1	10.8	6.7	12.8	2590	7.2	9.0	0.0	5.0	6.7	5.1
MAR	7	23.5	7.0	15.3	4.0	55	9.5	7.7	7.4	11.5	2450	6.8	6.5	0.0	4.0	6.3	4.9
MAR	8	25.5	7.5	16.5	4.0	47	8.8	9.9	8.5	16.4	2030	5.6	9.0	0.0	9.5	5.1	3.9
MAR	9	26.0	7.0	16.5	3.5	44	8.3	10.4	5.3	9.3	2220	6.2	11.0	0.0	5.0	4.6	3.3
MAR	10	25.5	8.0	16.8	6.0	57	10.8	8.2	5.5	7.8	2640	7.3	8.0	0.0	7.0	6.5	4.9
MAR	11	27.5	9.5	18.5	6.0	44	9.3	11.9	7.5	14.0	1700	4.7	11.0	0.0	6.5	3.7	2.6
MAR	12	26.5	8.5	17.5	5.0	64	12.7	7.2	5.9	11.6	1600	4.4	5.5	0.0	3.5	4.1	3.1
MAR	13	24.0	11.5	17.8	3.0	64	12.9	7.3	5.9	7.8	1740	4.8	7.0	0.0	5.0	3.9	2.9
MAR	14	27.0	8.5	17.8	5.5	45	9.0	11.2	6.3	11.6	2070	5.8	11.5	0.0	8.5	4.4	3.1
MAR	15	26.5	7.5	17.0	4.5	38	7.3	12.0	6.7	13.6	2560	7.1	10.0	0.0	8.0	6.3	4.7
MAR	16	26.5	7.0	16.8	4.5	41	7.7	11.3	5.2	5.8	2450	6.8	9.0	0.0	6.0	5.9	4.4
MAR	17	28.0	8.0	18.0	5.0	46	9.4	11.1	6.4	10.2	2400	6.7	10.0	0.0	6.5	5.9	4.4
MAR	18	25.0	9.0	17.0	7.5	49	9.5	9.8	4.9	8.8	2360	6.6	6.0	0.0	7.5	6.1	4.6
MAR	19	25.5	9.0	17.3	6.5	80	15.6	4.0	4.2	7.3	1930	5.4	6.0	12.6	2.5	4.6	3.4
MAR	20	26.0	12.0	19.0	9.5	69	15.1	6.8	3.7	6.9	1270	3.5	6.0	2.8	2.4	2.7	1.9
MAR	21	24.5	12.0	18.3	10.5	64	13.4	7.5	5.6	10.1	2070	5.8	6.0	1.2	5.2	5.2	3.9
MAR	22	24.0	9.5	16.8	8.5	55	10.5	8.5	5.3	9.3	2030	5.6	5.0	0.0	5.0	5.3	4.0
MAR	23	24.5	7.5	16.0	5.5	52	9.4	8.7	4.9	9.0	1980	5.5	8.0	0.0	4.5	4.4	3.2
MAR	24	23.5	7.5	15.5	6.0	64	11.2	6.4	2.6	4.1	2360	6.6	1.5	0.0	2.0	6.6	5.1
MAR	25	24.0	7.5	15.8	5.5	61	10.8	7.0	5.4	11.5	1510	4.2	8.0	0.0	3.5	3.1	2.2
MAR	26	25.0	8.0	16.5	5.5	47	8.7	10.0	6.9	14.1	2550	7.1	10.0	0.0	6.0	6.0	4.4
MAR	27	26.5	10.0	18.3	7.5	51	10.6	10.2	6.5	12.9	2450	6.8	8.0	0.0	4.5	6.3	4.7
MAR	28	26.0	9.5	17.8	6.5	46	9.4	10.9	6.1	9.6	2170	6.0	10.0	0.0	4.0	4.8	3.5
MAR	29	25.5	9.0	17.3	6.0	66	12.9	6.7	4.4	7.3	2360	6.6	8.0	0.8	4.5	5.5	4.1
MAR	30	26.0	10.0	18.0	7.0	54	11.1	9.4	5.5	9.0	1740	4.8	7.0	0.0	4.5	4.2	3.1
MAR	31	24.0	8.5	16.3	4.5	58	10.7	7.7	5.1	8.2	2310	6.4	4.5	0.0	3.5	6.1	4.7
AVER MONTH		25.6	8.4	17.0	5.3	51	9.9	9.4	6.0	10.4	2221	6.2	8.3	17.4	5.8	5.4	4.0
AVER 1 DEC		25.9	7.1	16.5	3.5	43	8.0	10.6	7.1	11.9	2524	7.0	9.8	0.0	7.8	6.2	4.7
AVER 2 DEC		26.3	9.1	17.7	5.7	54	10.8	9.3	5.7	9.8	2008	5.6	8.2	15.4	5.6	4.7	3.5
AVER 3 DEC		24.9	9.0	16.9	6.6	56	10.8	8.4	5.3	9.6	2139	5.9	6.9	2.0	4.3	5.2	3.9
MAX		28.0	12.0	19.0	10.5	80	15.6	13.3	8.8	16.4	2930	8.1	12.0	12.6	10.5	7.5	5.7
MIN		23.5	6.0	15.3	0.5	30	5.7	4.0	2.6	4.1	1270	3.5	1.5		2.0	2.7	1.9
NO OF DATA		31	31	31	31	31			31	31	31	31	31	4	31		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

#: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: APR YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
APR	1	21.5	7.5	14.5	4.5	76	12.6	3.9	5.0	6.3	1740	4.8	4.0	9.0	2.9	4.2	3.2
APR	2	21.0	8.5	14.8	6.0	70	11.7	5.0	8.1	12.6	1980	5.5	7.0	0.8	3.9	4.4	3.3
APR	3	25.5	9.0	17.3	5.5	52	10.1	9.5	6.4	9.3	1890	5.3	6.0	0.0	5.5	5.0	3.8
APR	4	25.5	8.5	17.0	6.0	76	14.7	4.6	5.7	8.9	2070	5.8	6.0	1.3	3.3	5.1	3.8
APR	5	26.5	9.5	18.0	8.0	57	11.6	8.9	6.1	9.7	1740	4.8	6.5	0.0	6.5	4.4	3.3
APR	6	25.0	11.0	18.0	8.5	68	14.0	6.6	5.0	8.1	2480	6.9	3.5	10.1	2.5	6.9	5.3
APR	7	24.0	11.0	17.5	8.5	69	13.8	6.1	3.3	6.1	1420	3.9	3.0	0.0	2.5	3.6	2.8
APR	8	20.0	12.5	16.3	11.5	79	14.6	3.8	3.2	5.3	1600	4.4	5.5	25.9	1.0	3.5	2.5
APR	9	21.5	11.0	16.3	11.0	82	15.0	3.4	2.6	5.2	1230	3.4	3.0	26.5	0.3	2.9	2.1
APR	10	19.5	12.0	15.8	10.0	66	11.8	6.0	6.6	9.2	1270	3.5	8.0	0.0	6.0	2.2	1.4
APR	11	22.5	9.0	15.8	8.0	76	13.5	4.3	6.1	8.2	2270	6.3	4.0	0.4	2.5	5.9	4.5
APR	12	21.0	7.5	14.3	6.0	57	9.2	7.0	7.0	11.6	1060	2.9	10.0	0.0	6.0	1.2	0.6
APR	13	23.0	7.0	15.0	5.0	57	9.7	7.2	5.5	9.6	2360	6.6	6.5	0.0	3.5	5.7	4.3
APR	14	23.0	7.0	15.0	4.5	52	8.9	8.1	6.6	11.2	2400	6.7	11.0	0.0	5.0	5.0	3.5
APR	15	23.5	9.0	16.3	7.0	56	10.3	8.1	5.6	10.7	2390	6.6	8.0	0.0	4.5	5.6	4.1
APR	16	24.0	10.5	17.3	8.5	55	10.8	8.8	7.6	13.8	1700	4.7	8.0	0.0	5.5	3.8	2.8
APR	17	23.5	9.5	16.5	7.5	55	10.3	8.3	5.7	10.8	2140	5.9	7.0	0.0	4.0	5.1	3.8
APR	18	23.0	7.5	15.3	5.5	50	8.6	8.7	4.3	8.5	1890	5.3	10.0	0.0	6.0	3.4	2.3
APR	19	25.5	8.0	16.8	6.0	50	9.4	9.6	4.2	7.6	2260	6.3	7.5	0.0	4.0	5.3	4.0
APR	20	23.5	9.5	16.5	7.5	82	15.3	3.4	3.1	4.2	1840	5.1	6.0	31.0	0.7	4.1	3.0
APR	21	21.5	9.0	15.3	7.5	50	8.6	8.6	4.6	9.3	1090	3.0	11.0	0.0	5.5	0.8	0.2
APR	22	24.0	9.0	16.5	7.0	62	11.6	7.1	3.8	7.0	2550	7.1	7.5	3.6	3.2	6.0	4.4
APR	23	25.0	11.0	18.0	9.0	73	14.9	5.6	3.2	5.5	2340	6.5	7.5	14.3	3.6	5.4	4.0
APR	24	22.0	13.0	17.5	11.5	87	17.4	2.5	2.5	3.8	1600	4.4	1.5	7.2	0.8	4.3	3.3
APR	25	23.5	12.0	17.8	11.0	80	16.2	4.0	3.9	5.3	1280	3.6	NA	1.1	3.1	NA	NA
APR	26	23.0	11.0	17.0	10.0	77	14.9	4.4	3.6	5.9	1530	4.3	6.0	0.0	4.0	3.3	2.3
APR	27	24.0	11.0	17.5	9.5	76	15.2	4.7	3.4	4.4	1820	5.1	5.5	0.8	1.0	4.3	3.1
APR	28	23.5	12.0	17.8	9.5	78	15.8	4.4	2.9	5.6	1150	3.2	1.0	1.2	2.9	3.2	2.5
APR	29	20.0	8.5	14.3	12.0	82	13.3	2.9	4.3	9.0	1430	4.0	2.0	7.3	1.6	3.6	2.7
APR	30	23.0	11.5	17.3	9.5	59	11.6	8.0	5.3	9.3	1130	3.1	9.0	0.0	4.0	1.6	0.9
AVER MONTH		23.1	9.8	16.4	8.1	67	12.5	6.1	4.8	8.1	1788	5.0	6.1	140.5	3.5	4.1	3.0
AVER 1 DEC		23.0	10.1	16.5	8.0	70	13.0	5.7	5.2	8.1	1742	4.8	5.3	73.6	3.4	4.1	3.1
AVER 2 DEC		23.3	8.5	15.9	6.6	59	10.6	7.4	5.6	9.6	2031	5.6	7.8	31.4	4.2	4.5	3.3
AVER 3 DEC		23.0	10.8	16.9	9.7	73	13.9	5.3	3.7	6.5	1592	4.4	5.1	35.5	3.0	3.6	2.7
MAX		26.5	13.0	18.0	12.0	87	17.4	9.6	8.1	13.8	2550	7.1	11.0	31.0	6.5	NA	NA
MIN		19.5	7.0	14.3	4.5	50	8.6	2.5	2.5	3.8	1060	2.9	0.0		0.3	NA	NA
NO OF DATA		30	30	30	30	30			30	30	30	30	30	15	30		

NA: not available
1) AVER.=TOTAL

ERR: error

A: Robitsch
B: Gunn Bellani (daily values)

*: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION

LAIKIPIA RESEARCH PROGRAMME / LI

MONTH:MAY YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) *	POT. EVAPO TRANS. (mm) *
MAY	1	21.5	10.0	15.8	8.0	76	13.5	4.3	3.3	5.5	2220	6.2	NA	12.4	1.7	NA	NA
MAY	2	21.5	7.5	14.5	6.5	83	13.6	2.8	3.7	5.0	1430	4.0	NA	8.7	2.0	NA	NA
MAY	3	24.0	10.0	17.0	8.0	64	12.3	6.9	5.0	6.7	1600	4.4	9.0	0.0	4.5	3.0	2.0
MAY	4	23.5	8.0	15.8	7.0	54	9.6	8.2	5.6	5.3	2220	6.2	6.0	0.0	3.0	5.6	4.2
MAY	5	22.0	8.0	15.0	7.0	58	9.9	7.1	2.1	3.5	2310	6.4	7.5	0.0	4.5	4.9	3.5
MAY	6	24.0	8.5	16.3	7.5	65	12.0	6.4	6.4	7.7	2290	6.4	NA	0.0	6.0	NA	NA
MAY	7	23.0	9.5	16.3	8.0	52	9.5	8.7	4.0	6.7	3110	8.6	NA	0.8	2.5	NA	NA
MAY	8	23.0	8.5	15.8	7.0	55	9.7	8.1	6.0	13.0	1370	3.8	10.0	0.0	3.0	2.2	1.4
MAY	9	23.0	10.0	16.5	8.5	68	12.6	6.0	9.9	7.2	2260	6.3	9.5	0.0	7.0	5.1	3.7
MAY	10	24.0	11.0	17.5	9.5	57	11.3	8.6	5.3	6.5	1930	5.4	2.0	5.9	1.9	5.6	4.5
MAY	11	23.0	10.5	16.8	8.0	63	12.0	7.0	3.6	4.5	1720	4.8	6.0	0.6	4.1	3.8	2.8
MAY	12	23.0	9.5	16.3	8.5	61	11.2	7.2	4.9	8.5	1530	4.3	7.0	0.0	4.0	3.2	2.3
MAY	13	21.5	10.0	15.8	8.5	80	14.3	3.5	2.7	3.9	2170	6.0	6.0	22.1	0.5	4.9	3.6
MAY	14	21.0	8.5	14.8	7.5	76	12.8	4.0	2.7	4.3	2170	6.0	NA	0.0	2.0	NA	NA
MAY	15	21.5	10.5	16.0	10.0	74	13.4	4.7	3.2	5.1	1230	3.4	NA	0.0	2.0	NA	NA
MAY	16	21.0	9.0	15.0	8.0	78	13.2	3.7	3.4	5.1	1230	3.4	NA	0.3	2.0	NA	NA
MAY	17	23.0	7.5	15.3	6.0	82	14.1	3.1	3.3	4.5	1560	4.3	NA	14.7	3.2	NA	NA
MAY	18	23.0	8.5	15.8	6.5	62	11.1	6.7	4.2	7.9	2050	5.7	3.0	0.0	2.0	5.5	4.3
MAY	19	22.0	7.0	14.5	5.5	70	11.5	4.9	3.4	5.4	2220	6.2	7.0	0.0	2.5	4.9	3.6
MAY	20	22.0	7.5	14.8	6.5	64	10.6	6.1	3.9	7.6	1930	5.4	8.0	0.0	3.0	3.9	2.8
MAY	21	22.0	9.0	15.5	7.5	80	14.1	3.4	3.4	5.8	2000	5.6	6.5	9.1	3.0	4.4	3.2
MAY	22	23.5	8.0	15.8	7.0	78	13.8	4.0	4.4	8.0	1530	4.3	6.0	13.2	0.5	3.3	2.4
MAY	23	23.0	8.0	15.5	7.0	64	11.2	6.4	4.0	9.2	1520	4.2	6.0	0.0	4.0	3.3	2.4
MAY	24	23.0	8.0	15.5	7.5	64	11.2	6.4	3.4	5.1	1960	5.4	9.0	0.0	4.0	3.8	2.6
MAY	25	23.5	7.5	15.5	5.5	63	11.1	6.4	2.9	5.0	2060	5.7	8.5	0.5	2.5	4.2	2.9
MAY	26	23.5	7.5	15.5	5.5	65	11.4	6.1	2.9	5.7	2000	5.6	8.0	0.1	3.5	4.1	2.9
MAY	27	22.5	7.0	14.8	6.0	57	9.5	7.2	2.9	4.9	2120	5.9	7.5	0.0	3.0	4.5	3.2
MAY	28	22.5	7.5	15.0	6.5	63	10.7	6.3	3.3	5.2	2020	5.6	8.0	15.6	1.5	4.1	2.9
MAY	29	21.5	7.0	14.3	5.5	70	11.3	4.9	4.2	8.7	1980	5.5	7.5	0.0	4.5	4.1	2.9
MAY	30	23.0	8.0	15.5	5.5	65	11.4	6.1	4.3	8.1	1840	5.1	7.0	0.0	3.0	4.0	2.9
MAY	31	22.5	8.0	15.3	6.0	62	10.7	6.6	4.7	3.8	1840	5.1	12.0	0.0	3.5	2.9	1.8
AVER MONTH		22.6	8.5	15.6	7.1	67	11.8	5.8	4.1	6.2	1917	5.3	7.3	104.0	3.0	4.1	2.9
AVER 1 DEC		23.0	9.1	16.0	7.7	63	11.4	6.7	5.1	6.7	2074	5.8	7.3	27.8	3.6	4.7	3.4
AVER 2 DEC		22.1	8.9	15.5	7.5	71	12.4	5.1	3.5	5.7	1781	4.9	6.2	37.7	2.5	3.9	2.8
AVER 3 DEC		22.8	7.8	15.3	6.3	66	11.5	5.8	3.7	6.3	1897	5.3	7.8	38.5	3.0	3.9	2.8
MAX		24.0	11.0	17.5	10.0	83	14.3	8.9	9.9	13.0	3110	8.6	12.0	22.1	7.0	NA	NA
MIN		21.0	7.0	14.3	5.5	52	9.5	2.8	2.1	3.5	1230	3.4	2.0		0.5	NA	NA
NO OF DATA		31	31	31	31	31			31	31	31	31	23	13	31		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch

B: Gunn Bellani (daily values)

*: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: JUN YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm)	POT. EVAPO TRANS. (mm)
JUN	1	23.5	8.0	15.8	5.0	53	9.5	8.3	4.7	4.9	3020	8.4	11.5	0.0	3.5	6.4	4.6
JUN	2	23.5	7.0	15.3	5.0	50	8.6	8.6	5.4	8.4	2310	6.4	11.0	0.0	5.5	4.6	3.2
JUN	3	24.0	9.5	16.8	7.5	50	9.4	9.6	4.3	7.0	2500	6.9	8.5	0.0	7.0	5.7	4.1
JUN	4	24.0	7.5	15.8	6.0	51	9.1	8.7	4.2	8.1	2400	6.7	12.0	0.0	5.0	4.5	3.1
JUN	5	24.5	8.0	16.3	7.0	48	8.9	9.5	4.6	7.5	2770	7.7	9.5	0.0	6.0	6.3	4.6
JUN	6	24.0	7.5	15.8	5.5	75	13.4	4.4	3.3	6.4	2230	6.2	5.5	0.0	2.5	5.3	4.0
JUN	7	24.5	7.0	15.8	5.0	81	14.4	3.4	3.1	3.4	1720	4.8	6.0	14.5	3.0	3.8	2.7
JUN	8	22.5	6.5	14.5	5.0	64	10.5	6.0	3.7	2.6	1700	4.7	7.0	4.5	2.5	3.5	2.5
JUN	9	23.0	7.0	15.0	6.0	65	11.0	6.0	3.6	2.6	1890	5.3	7.5	0.0	3.5	3.9	2.8
JUN	10	23.0	7.0	15.0	5.5	60	10.2	6.7	3.4	5.0	1780	4.9	7.0	0.0	3.0	3.7	2.7
JUN	11	21.0	7.5	14.3	6.0	76	12.2	3.9	2.9	5.3	1840	5.1	5.0	5.6	2.0	4.1	3.0
JUN	12	23.0	9.0	16.0	7.0	65	11.8	6.3	2.7	5.1	1440	4.0	6.5	0.0	3.0	2.8	2.0
JUN	13	21.5	8.0	14.8	5.5	60	10.0	6.7	2.4	4.4	1880	5.2	6.0	0.0	3.0	4.0	2.9
JUN	14	22.5	8.5	15.5	6.5	52	9.2	8.4	3.8	7.5	1790	5.0	5.0	0.0	NA	4.3	3.2
JUN	15	22.0	7.5	14.8	5.5	62	10.4	6.3	3.3	4.9	2590	7.2	7.0	0.0	NA	5.9	4.4
JUN	16	22.0	8.0	15.0	6.0	60	10.1	6.8	3.2	4.3	2030	5.6	6.0	0.0	NA	4.6	3.4
JUN	17	21.5	9.5	15.5	6.0	64	11.2	6.4	3.0	6.3	1790	5.0	8.0	0.0	3.0	3.4	2.4
JUN	18	20.5	9.5	15.0	7.0	60	10.2	6.8	3.8	7.1	1900	5.3	8.0	0.0	3.0	3.7	2.6
JUN	19	22.5	7.5	15.0	5.5	63	10.7	6.3	3.3	5.2	1530	4.3	8.0	0.0	3.0	2.7	1.8
JUN	20	23.5	7.5	15.5	5.5	41	7.2	10.3	4.3	7.3	1810	5.0	10.0	0.0	4.5	3.2	2.2
JUN	21	24.0	6.0	15.0	5.0	40	6.8	10.2	4.4	5.1	2320	6.4	12.0	0.0	6.0	4.3	2.9
JUN	22	24.5	4.5	14.5	3.5	42	6.9	9.5	3.7	5.4	2430	6.8	10.0	17.0	4.5	5.0	3.6
JUN	23	23.0	4.0	13.5	4.5	56	8.6	6.8	3.3	3.5	2190	6.1	7.0	0.0	2.7	4.8	3.6
JUN	24	23.0	5.0	14.0	2.5	61	9.7	6.2	3.6	4.6	1770	4.9	7.5	0.0	3.5	3.6	2.6
JUN	25	25.0	5.0	15.0	1.5	55	9.4	7.6	3.2	4.3	2030	5.6	6.0	0.0	2.5	4.8	3.6
JUN	26	25.0	5.0	15.0	1.0	47	8.0	9.0	4.1	5.7	1790	5.0	10.0	0.0	5.5	3.4	2.3
JUN	27	24.0	5.5	14.8	2.5	48	8.0	8.7	4.1	6.9	2690	7.5	8.0	0.0	3.5	6.3	4.7
JUN	28	22.5	6.0	14.3	2.0	57	9.2	7.0	3.9	5.9	2220	6.2	8.0	0.0	4.0	4.7	3.4
JUN	29	23.0	6.5	14.8	2.5	53	8.8	7.9	4.9	8.1	1750	4.9	8.0	0.0	4.5	3.6	2.6
JUN	30	24.5	6.0	15.3	2.5	50	8.7	8.6	4.4	7.0	2070	5.8	10.0	0.0	4.0	4.1	2.9
AVER MONTH		23.2	7.0	15.1	4.9	57	9.7	7.4	3.8	5.7	2073	5.8	8.1	41.6	3.8	4.4	3.1
AVER 1 DEC		23.7	7.5	15.6	5.8	60	10.5	7.1	4.0	5.6	2232	6.2	8.6	19.0	4.2	4.8	3.5
AVER 2 DEC		22.0	8.3	15.1	6.1	60	10.3	6.8	3.3	5.7	1860	5.2	7.0	5.6	3.1	3.9	2.8
AVER 3 DEC		23.9	5.4	14.6	2.8	51	8.4	8.1	4.0	5.7	2126	5.9	8.7	17.0	4.1	4.5	3.2
MAX		25.0	9.5	16.8	7.5	81	14.4	10.3	5.4	8.4	3020	8.4	12.0	17.0	7.0	6.4	4.7
MIN		20.5	4.0	13.5	1.0	40	6.8	3.4	2.4	2.6	1440	4.0	5.0		2.0	2.7	1.8
NO OF DATA		30	30	30	30	30			30	30	30	30	30	4	27		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch

B: Gunn Bellani (daily values)

*: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH: JUL YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) *	POT. EVAPO TRANS. (mm) *
JUL	1	24.0	6.0	15.0	2.5	53	8.9	8.0	3.3	5.8	2500	6.9	7.0	0.0	2.5	5.8	4.4
JUL	2	24.5	6.0	15.3	2.5	57	9.9	7.4	3.9	5.6	2200	6.1	6.0	0.0	3.5	5.3	4.0
JUL	3	24.5	5.5	15.0	3.5	67	10.5	6.5	3.0	5.7	2400	6.7	8.0	0.0	4.5	5.3	3.9
JUL	4	24.0	7.0	15.5	4.0	58	10.2	7.3	4.9	4.9	1700	4.7	8.0	0.0	3.0	3.5	2.5
JUL	5	24.5	6.5	15.5	5.5	56	9.8	7.8	2.7	3.5	2120	5.9	7.0	0.0	4.5	4.7	3.4
JUL	6	22.5	7.0	14.8	5.0	70	11.6	5.1	3.8	6.3	1900	5.3	5.0	16.3	3.8	4.5	3.3
JUL	7	22.0	7.0	14.5	5.0	77	12.7	3.8	3.4	5.3	1630	4.5	6.0	16.1	1.6	3.4	2.4
JUL	8	23.0	6.5	14.8	4.5	63	10.5	6.2	3.3	6.0	1420	3.9	6.0	0.0	3.0	2.9	2.1
JUL	9	21.0	7.5	14.3	5.0	71	11.4	4.7	3.4	6.4	2310	6.4	7.0	0.0	2.0	5.0	3.7
JUL	10	22.5	7.0	14.8	4.5	67	11.1	5.6	3.6	5.9	1620	4.5	4.0	0.5	3.5	3.9	2.9
JUL	11	23.5	8.0	15.8	6.5	70	12.5	5.3	3.7	6.9	1560	4.3	7.0	4.4	2.9	3.2	2.2
JUL	12	24.5	8.5	16.5	7.0	64	12.0	6.7	4.0	5.4	2010	5.6	8.0	0.0	4.5	4.3	3.1
JUL	13	22.5	8.0	15.3	6.0	81	13.9	3.3	3.3	6.1	2190	6.1	8.0	8.9	2.9	4.6	3.3
JUL	14	22.0	8.0	15.0	7.0	75	12.7	4.3	2.7	3.9	2310	6.4	6.0	10.0	NA	5.3	3.9
JUL	15	22.0	8.5	15.3	6.5	72	12.5	4.8	2.7	3.1	2050	5.7	5.0	1.1	3.0	4.8	3.6
JUL	16	21.5	8.5	15.0	7.5	79	13.5	3.5	3.6	5.6	1770	4.9	4.5	6.4	2.4	4.1	3.0
JUL	17	21.5	10.5	16.0	9.5	74	13.3	4.8	3.5	5.6	1890	5.3	3.0	0.0	2.0	4.8	3.7
JUL	18	24.5	9.0	16.8	6.0	67	12.7	6.3	3.3	5.9	1360	3.8	7.5	0.0	3.5	2.5	1.7
JUL	19	24.0	8.5	16.3	7.5	78	14.4	4.0	7.6	4.7	1900	5.3	2.5	3.6	2.6	5.3	4.1
JUL	20	23.5	8.5	16.0	7.5	69	12.4	5.7	3.0	5.1	1560	4.3	6.0	0.9	2.4	3.3	2.4
JUL	21	21.5	10.5	16.0	9.5	60	10.9	7.2	3.3	5.9	1660	4.6	9.0	0.0	3.5	2.9	1.9
JUL	22	21.0	11.5	16.3	11.0	67	12.3	6.1	2.1	4.5	1840	5.1	5.0	0.0	3.0	4.2	3.1
JUL	23	20.0	8.0	14.0	5.5	65	10.3	5.6	2.2	4.9	1510	4.2	6.0	0.0	2.5	2.9	2.0
JUL	24	21.5	8.0	14.8	6.0	71	11.9	4.8	3.5	6.9	1180	3.3	6.0	0.0	3.0	2.2	1.5
JUL	25	22.0	8.5	15.3	6.5	57	9.9	7.4	2.7	5.7	2030	5.6	7.5	0.0	4.0	4.2	3.0
JUL	26	23.0	8.0	15.5	6.0	59	10.3	7.2	2.9	5.3	1950	5.4	10.0	0.0	4.0	3.5	2.3
JUL	27	23.0	7.0	15.0	3.5	55	9.3	7.6	3.2	5.3	1740	4.8	8.5	0.0	3.5	3.3	2.2
JUL	28	23.0	8.0	15.5	6.0	54	9.5	8.1	3.2	6.3	1740	4.8	6.0	0.0	3.5	3.9	2.8
JUL	29	20.5	8.0	14.3	6.5	61	9.9	6.3	2.7	5.1	1780	4.9	8.5	0.0	3.0	3.2	2.1
JUL	30	21.5	7.5	14.5	6.0	57	9.4	7.1	3.0	6.1	1790	5.0	7.0	0.0	3.5	3.6	2.6
JUL	31	NA	NA	NA	NA	NA	NA	NA	2.2	3.8	2120	5.9	6.5	0.2	3.7	NA	NA
AVER MONTH		22.6	7.9	15.3	6.0	66	11.3	5.9	3.3	5.4	1863	5.2	6.5	68.4	3.1	4.0	2.9
AVER 1 DEC		23.3	6.6	14.9	4.2	63	10.7	6.2	3.5	5.5	1780	5.5	6.4	32.9	3.2	4.4	3.3
AVER 2 DEC		23.0	8.6	15.8	7.1	73	13.0	4.8	3.7	5.2	1860	5.2	5.8	35.3	2.6	4.2	3.1
AVER 3 DEC		21.7	8.5	15.1	6.7	61	10.3	6.7	2.8	5.4	1758	4.9	7.3	0.2	3.4	3.5	2.4
MAX		24.5	11.5	NA	11.0	NA	NA	NA	7.6	6.9	2500	6.9	10.0	16.3	4.5	NA	NA
MIN		20.0	5.5	NA	2.5	NA	NA	NA	2.1	3.1	1180	3.3	2.5		0.0	NA	NA
NO OF DATA		30	30	31	30	31			31	31	31	31	31	11	31		

NA: not available ERR: error
1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

*: PENMAN Formula

MONTH:AUG YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) ‡	POT. EVAPO TRANS. (mm) ‡
AUG	1	22.5	5.5	14.0	5.0	82	13.1	2.9	2.3	3.2	1420	3.9	4.0	2.4	1.4	3.1	2.3
AUG	2	23.0	5.5	14.3	4.0	63	10.1	6.0	3.1	5.8	2030	5.6	5.5	0.0	3.5	4.7	3.5
AUG	3	23.5	6.5	15.0	4.5	53	8.9	8.0	4.0	6.2	1910	5.3	6.5	0.0	4.5	4.4	3.2
AUG	4	24.0	6.0	15.0	5.0	55	9.3	7.6	3.6	6.4	1630	4.5	4.0	0.0	3.5	4.1	3.2
AUG	5	20.5	8.5	14.5	7.5	75	12.3	4.2	3.3	5.9	1440	4.0	1.0	0.0	2.5	3.8	3.0
AUG	6	21.0	6.0	13.5	5.5	82	12.6	2.8	3.0	4.5	1560	4.3	6.0	13.6	2.6	3.1	2.2
AUG	7	27.0	6.5	16.8	4.5	63	12.0	7.0	2.9	5.3	2100	5.8	6.0	2.2	1.7	5.1	3.8
AUG	8	23.0	6.0	14.5	3.5	57	9.4	7.0	2.9	5.0	2070	5.8	5.0	0.0	2.5	4.9	3.7
AUG	9	23.0	6.5	14.8	4.5	65	10.8	5.9	3.8	5.0	1830	5.1	4.5	1.7	4.2	4.4	3.4
AUG	10	23.5	5.5	14.5	3.5	67	11.0	5.5	4.6	8.9	2030	5.6	4.0	0.0	3.0	5.2	4.0
AUG	11	23.0	5.5	14.3	3.0	53	8.6	7.6	3.9	4.3	2230	6.2	7.0	0.0	4.0	5.1	3.8
AUG	12	21.5	4.5	13.0	5.0	50	7.5	7.5	3.3	5.9	1740	4.8	4.5	0.0	4.5	4.1	3.1
AUG	13	24.0	5.0	14.5	4.5	75	12.3	4.2	3.2	5.8	1740	4.8	5.5	7.6	5.1	3.9	2.9
AUG	14	23.5	7.0	15.3	3.0	67	11.9	5.3	3.2	5.0	2010	5.6	5.0	9.5	3.0	4.8	3.6
AUG	15	23.0	7.0	15.0	4.5	57	10.1	6.7	3.2	6.0	1470	4.1	4.5	0.0	3.5	3.5	2.6
AUG	16	21.5	7.5	14.5	5.5	67	11.0	5.4	3.5	5.7	1740	4.8	4.0	0.0	3.0	4.2	3.1
AUG	17	21.5	6.5	14.0	3.5	62	9.8	6.1	3.0	4.4	2040	5.7	5.5	0.0	2.0	4.6	3.4
AUG	18	21.5	7.5	14.5	6.0	58	9.5	6.9	4.6	8.7	2010	5.6	6.0	0.0	3.0	4.6	3.4
AUG	19	23.5	5.5	14.5	3.0	54	8.8	7.6	3.2	5.8	2120	5.9	4.5	0.0	2.5	5.3	4.1
AUG	20	22.5	5.5	14.0	3.5	59	9.4	6.5	3.2	5.6	1930	5.4	6.0	0.0	3.5	4.3	3.2
AUG	21	23.5	6.0	14.8	3.0	74	12.4	4.3	3.2	2.6	1980	5.5	5.5	5.7	3.4	4.5	3.4
AUG	22	22.5	6.0	14.3	4.5	61	9.8	6.4	3.0	5.6	1820	5.1	5.5	0.0	2.5	4.1	3.0
AUG	23	22.5	6.0	14.3	4.0	57	9.2	7.0	3.6	6.2	1860	5.2	4.0	0.0	4.0	4.6	3.6
AUG	24	24.5	6.5	15.5	4.5	54	9.4	8.1	4.0	5.7	2120	5.9	4.0	0.0	4.5	5.6	4.4
AUG	25	24.0	6.0	15.0	3.5	52	8.8	8.1	4.1	5.5	2010	5.6	5.5	0.0	4.0	4.9	3.8
AUG	26	24.5	9.0	16.8	6.5	53	10.0	9.0	4.5	8.5	2050	5.7	5.5	0.0	5.0	5.2	3.9
AUG	27	24.0	8.5	16.3	5.5	51	9.4	9.0	4.3	4.5	1910	5.3	6.5	0.0	3.5	4.5	3.3
AUG	28	26.0	8.0	17.0	5.5	79	15.2	4.1	3.3	6.2	1700	4.7	4.5	6.5	3.0	4.1	3.1
AUG	29	23.5	8.0	15.8	6.0	ERR	ERR	ERR	3.6	6.9	1650	4.6	4.0	5.0	1.5	ERR	ERR
AUG	30	26.0	9.5	17.8	8.0	55	11.1	9.1	3.3	7.5	2310	6.4	5.5	0.0	4.5	5.9	4.5
AUG	31	25.5	8.5	17.0	7.5	52	10.0	9.3	4.3	6.7	1040	5.1	5.0	0.0	4.5	4.8	3.6
AVER MONTH		23.3	6.6	15.0	4.8	62	10.6	6.4	3.5	5.8	1881	5.2	5.0	54.4	3.4	4.5	3.4
AVER 1 DEC		23.1	6.3	14.7	4.8	66	11.0	5.6	3.3	5.6	1802	5.0	4.7	19.9	2.9	4.3	3.2
AVER 2 DEC		22.6	6.2	14.4	4.2	61	7.7	6.4	3.4	5.7	1705	5.3	3.3	17.1	3.4	4.4	3.3
AVER 3 DEC		24.2	7.5	15.8	5.3	61	10.9	7.0	3.7	6.0	1932	5.4	5.0	17.4	3.7	4.7	3.6
MAX		27.0	9.5	17.8	8.0	ERR	ERR	ERR	4.6	8.9	2310	6.4	7.0	13.6	5.1	ERR	ERR
MIN		20.5	4.5	13.0	3.0	ERR	ERR	ERR	2.3	2.6	1420	3.9	1.0		1.4	ERR	ERR
NO OF DATA		31	31	31	31	31			31	31	31	31	31	9	31		

NA: not available ERR: error
1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani
(daily values)

‡: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / Li

MONTH:SEP YEAR: 1989

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) ‡	POT. EVAPO TRANS. (mm) ‡
SEP	1	23.5	8.5	16.0	6.5	51	9.3	8.8	3.4	6.6	1740	4.8	5.5	3.7	1.7	4.0	3.0
SEP	2	24.0	11.0	17.5	10.0	59	11.7	8.2	3.2	5.8	1420	3.9	3.5	0.0	4.0	3.6	2.7
SEP	3	25.5	8.0	16.8	6.0	48	9.1	9.9	3.6	7.5	2170	6.0	7.0	0.0	5.0	5.1	3.8
SEP	4	25.5	7.0	16.3	3.5	42	7.7	10.7	4.1	7.6	2570	7.1	11.0	0.0	5.0	5.3	3.8
SEP	5	24.5	7.5	16.0	5.0	53	9.6	8.5	2.9	6.4	1570	4.4	4.0	0.0	5.5	3.9	3.0
SEP	6	24.5	9.5	17.0	7.5	65	12.5	6.0	4.0	7.6	1770	5.0	5.0	0.0	4.0	4.4	3.3
SEP	7	24.5	9.5	17.0	5.0	61	11.7	7.6	4.5	7.1	1680	4.7	4.0	0.0	4.0	4.4	3.4
SEP	8	24.0	6.5	15.3	4.5	52	9.0	8.3	3.3	6.2	1390	3.9	4.0	0.0	2.5	3.4	2.6
SEP	9	24.5	5.5	15.0	2.5	57	9.7	7.2	4.2	7.1	2070	5.8	4.5	0.0	3.5	5.4	4.1
SEP	10	23.5	6.0	14.8	3.5	49	8.2	8.5	4.5	8.7	2270	6.3	6.0	0.0	5.0	5.6	4.2
SEP	11	23.5	4.5	14.0	2.5	47	7.5	8.4	5.8	10.6	2500	6.9	7.0	0.0	6.5	6.2	4.8
SEP	12	26.5	5.0	15.8	2.5	47	8.4	7.4	4.9	8.6	2450	6.8	7.5	0.0	6.5	6.2	4.7
SEP	13	26.5	7.0	16.8	2.5	55	10.4	8.5	3.4	6.1	1840	5.1	6.5	0.0	4.0	4.3	3.2
SEP	14	27.0	5.5	16.3	3.0	49	7.0	9.4	4.1	7.3	2050	5.7	6.0	0.0	3.5	5.3	4.0
SEP	15	24.0	6.0	15.0	3.0	43	7.3	9.7	4.5	8.3	2360	6.6	7.0	0.0	4.0	5.7	4.3
SEP	16	23.0	6.0	14.5	2.0	65	10.6	5.8	3.8	6.8	2070	5.8	7.0	4.4	4.9	4.6	3.3
SEP	17	25.0	7.0	16.0	4.5	57	10.6	7.5	4.4	7.0	1570	4.4	4.0	0.0	4.0	4.1	3.2
SEP	18	24.0	8.5	16.3	5.5	64	11.0	6.6	4.1	6.8	1250	3.5	4.0	1.1	3.1	3.0	2.3
SEP	19	25.0	7.0	16.0	4.0	67	12.1	6.0	3.9	8.0	1640	4.6	4.5	0.0	3.3	4.1	3.1
SEP	20	24.0	9.0	16.5	7.0	73	13.6	5.0	4.9	9.3	1100	3.3	2.0	4.1	2.1	3.2	2.5
SEP	21	25.0	8.0	16.5	7.0	45	8.3	10.3	5.8	10.9	2640	7.3	11.5	0.0	5.5	5.7	4.1
SEP	22	26.0	8.0	17.0	5.0	44	8.4	10.9	5.4	10.6	2580	7.2	11.0	0.0	6.5	5.7	4.1
SEP	23	25.0	10.0	17.5	6.5	52	10.3	9.6	5.5	11.0	2080	8.0	8.5	1.0	7.0	7.0	5.3
SEP	24	25.0	11.0	18.0	8.5	47	9.7	10.9	6.0	10.8	2430	6.8	7.5	0.0	7.0	6.0	4.5
SEP	25	26.0	9.5	17.8	6.5	51	10.2	10.0	4.5	9.9	2060	5.7	7.0	0.4	4.9	5.0	3.7
SEP	26	23.0	7.5	15.3	10.0	67	11.5	5.8	2.7	5.1	1270	3.5	1.5	15.9	1.9	3.4	2.7
SEP	27	23.0	12.5	17.8	12.0	72	14.6	5.6	3.2	5.3	1460	4.1	3.5	0.0	2.5	3.6	2.7
SEP	28	24.0	7.0	15.5	5.0	60	10.5	7.0	3.2	5.9	1830	5.1	5.5	0.0	3.0	4.3	3.2
SEP	29	23.0	10.0	16.5	8.0	60	11.1	7.5	5.4	10.1	1870	5.3	2.0	0.1	4.1	5.4	4.3
SEP	30	25.5	9.5	17.5	7.5	52	10.3	9.6	4.0	8.6	1890	5.3	4.5	0.0	3.0	5.0	3.8
AVER MONTH		24.6	7.9	16.3	5.6	55	10.1	8.3	4.2	8.0	1950	5.4	5.8	31.5	4.3	4.8	3.6
AVER 1 DEC		24.4	7.9	16.2	5.4	51	9.8	8.4	3.8	7.3	1867	5.2	5.5	3.7	4.0	4.5	3.4
AVER 2 DEC		24.7	6.6	15.7	3.7	57	10.1	7.7	4.4	7.9	1891	5.3	5.6	10.4	4.2	4.7	3.5
AVER 3 DEC		24.6	9.3	16.9	7.6	55	10.5	8.7	4.6	8.8	2073	5.8	6.3	17.4	4.5	5.1	3.8
MAX		27.0	12.5	18.0	12.0	73	14.6	10.9	6.0	11.0	2800	8.0	11.5	15.9	7.0	7.0	5.3
MIN		23.0	4.5	14.0	2.0	42	7.3	5.0	2.7	5.1	1100	3.3	1.5		1.7	3.0	2.3
NO OF DATA		30	30	30	30	30			30	30	30	30	30	9	30		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

‡: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION

MONTH:OCT YEAR: 1987

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) ‡	POT. EVAPO TRANS. (mm) ‡
OCT	1	24.0	6.5	15.3	5.5	47	8.4	8.9	3.9	6.6	2010	5.6	7.0	0.0	5.5	4.6	3.4
OCT	2	23.5	7.0	15.3	4.0	70	12.1	5.2	3.4	5.5	1570	4.4	4.0	5.0	2.5	3.8	2.8
OCT	3	24.0	8.0	16.0	5.5	72	13.0	5.1	4.4	7.6	1500	4.4	4.0	6.1	3.1	3.9	3.0
OCT	4	25.0	8.0	16.5	5.5	56	10.5	8.2	5.3	9.9	2250	6.3	4.5	0.0	4.5	6.1	4.8
OCT	5	25.0	7.5	16.3	5.5	49	9.0	9.4	3.9	7.9	1780	4.9	4.5	9.5	2.0	4.6	3.6
OCT	6	23.0	12.0	17.5	12.0	84	16.7	3.3	2.9	3.2	1350	3.8	3.0	6.1	3.1	3.3	2.5
OCT	7	22.0	10.0	16.0	7.5	80	14.4	3.7	3.6	6.8	1320	3.7	3.5	9.0	1.5	3.1	2.3
OCT	8	23.0	13.0	18.0	7.5	64	13.1	7.5	3.1	5.6	1500	4.2	1.5	0.0	3.0	4.2	3.3
OCT	9	23.5	7.5	15.5	4.0	49	8.6	8.9	6.2	13.3	2300	6.6	6.5	0.0	5.0	6.0	4.6
OCT	10	23.5	8.5	16.0	6.5	57	10.7	7.4	5.1	10.2	2310	6.4	4.5	0.0	4.0	6.1	4.7
OCT	11	21.5	5.5	13.5	6.5	70	10.8	4.6	3.9	7.4	1250	3.5	1.5	0.0	2.0	3.3	2.6
OCT	12	24.0	8.5	16.3	5.5	62	11.5	6.9	4.2	8.4	1900	5.3	4.0	0.0	3.5	4.9	3.8
OCT	13	21.5	7.5	14.5	7.0	77	12.7	3.8	2.7	4.3	1160	3.2	0.5	0.2	2.2	3.1	2.5
OCT	14	22.5	7.5	15.0	6.5	58	9.8	7.2	3.5	6.4	1360	3.8	4.0	0.0	3.0	3.2	2.4
OCT	15	23.0	7.0	15.0	5.5	57	9.6	7.4	3.4	5.7	1770	4.9	2.5	0.0	3.0	4.8	3.7
OCT	16	22.0	8.0	15.0	6.5	57	7.7	7.2	3.0	6.3	1450	4.0	3.5	0.0	3.0	3.6	2.7
OCT	17	23.5	7.0	15.3	5.5	60	10.4	6.8	3.3	5.7	1620	4.5	4.0	0.0	2.0	4.0	3.0
OCT	18	23.5	8.0	15.8	6.5	80	14.2	3.6	2.9	5.3	1410	3.9	4.0	6.2	2.7	3.2	2.4
OCT	19	23.5	8.0	15.8	5.5	62	11.1	6.7	4.1	6.5	1680	4.7	4.5	0.0	3.0	4.1	3.1
OCT	20	24.5	9.0	16.8	6.5	54	10.3	8.7	3.7	5.8	2080	5.8	3.5	0.0	3.0	5.6	4.4
OCT	21	26.5	6.5	16.5	4.5	57	10.7	8.0	4.2	6.5	2000	5.8	5.0	0.0	3.0	5.5	4.2
OCT	22	25.0	7.5	16.3	4.5	37	6.8	11.6	4.3	7.8	2590	7.2	7.5	0.0	5.5	6.3	4.7
OCT	23	25.5	8.0	16.8	6.5	49	9.4	9.6	6.8	10.8	2200	6.1	5.0	0.0	5.5	6.2	4.9
OCT	24	23.5	9.0	16.3	7.5	69	12.8	5.6	4.7	8.2	1420	3.9	3.0	14.6	1.1	3.7	2.8
OCT	25	20.5	11.5	16.0	10.5	70	12.6	5.5	3.3	5.9	1030	2.9	1.0	0.0	3.0	2.8	2.2
OCT	26	18.5	7.5	13.0	8.5	73	10.9	4.0	2.1	3.9	1020	2.8	1.0	23.2	0.2	2.5	2.0
OCT	27	23.0	10.5	16.8	8.5	62	11.7	7.3	5.9	10.5	1840	5.1	4.5	0.0	3.5	4.7	3.6
OCT	28	20.5	13.5	17.0	10.5	74	14.3	5.0	5.0	8.7	1390	3.9	1.5	0.0	3.5	3.9	3.0
OCT	29	20.5	12.5	16.5	11.5	68	12.6	6.0	6.8	12.7	1830	5.1	2.0	0.7	5.2	5.2	4.0
OCT	30	19.5	10.5	15.0	8.5	71	12.0	5.0	3.8	7.4	820	2.3	NA	2.2	0.7	NA	NA
OCT	31	22.0	12.5	17.3	10.5	60	11.7	7.9	4.3	7.8	1740	4.8	NA	0.0	3.5	NA	NA
AVER MONTH		22.9	8.8	15.9	7.0	63	11.3	6.6	4.1	7.4	1667	4.6	3.6	82.8	3.1	4.2	3.2
AVER 1 DEC		23.7	8.8	16.2	6.4	63	11.6	6.8	4.2	7.9	1805	5.0	4.3	35.7	3.4	4.5	3.5
AVER 2 DEC		23.0	7.6	15.3	6.2	64	11.0	6.3	3.5	6.2	1568	4.4	3.2	6.4	2.7	4.0	3.1
AVER 3 DEC		22.3	10.0	16.1	8.3	63	11.4	6.8	4.6	8.2	1633	4.5	3.4	40.7	3.2	4.2	3.2
MAX		26.5	13.5	18.0	12.0	84	16.7	11.6	6.8	13.3	2590	7.2	7.5	23.2	5.5	NA	NA
MIN		18.5	5.5	13.0	4.0	37	6.8	3.3	2.1	3.9	820	2.3	0.5		0.2	NA	NA
NO OF DATA		31	31	31	31	31			31	31	31	31	27	11	31		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani
(daily values)

‡: PENMAN Formula

CLIMATIC SUMMARY : KALALU STATION — LAIKIPIA RESEARCH PROGRAMME / LI

MONTH:NOV YEAR: 1987

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) ‡	POT. EVAPO TRANS. (mm) ‡
NOV	1	23.5	7.5	15.5	5.5	54	9.5	8.1	5.6	11.5	1860	5.2	8.0	0.0	3.0	4.1	3.0
NOV	2	23.5	7.0	15.3	5.0	53	9.1	8.2	4.1	4.4	1560	4.3	5.5	3.4	3.4	3.6	2.7
NOV	3	25.0	9.0	17.0	7.0	56	10.7	8.6	4.8	9.5	2200	6.1	6.0	0.0	5.0	5.6	4.2
NOV	4	25.0	8.0	16.5	5.5	56	10.5	8.2	5.3	9.9	2250	6.3	4.5	0.0	4.5	6.1	4.8
NOV	5	25.0	7.5	16.3	5.5	47	9.0	9.4	3.9	7.7	1780	4.7	4.5	7.5	2.0	4.6	3.6
NOV	6	23.0	12.0	17.5	12.0	84	16.7	3.3	2.7	5.2	1350	3.8	3.0	6.1	3.1	3.3	2.5
NOV	7	22.0	10.0	16.0	7.5	80	14.4	3.7	3.6	6.8	1320	3.7	3.5	9.0	1.5	3.1	2.3
NOV	8	23.0	13.0	18.0	7.5	64	13.1	7.5	3.1	5.6	1500	4.2	1.5	0.0	3.0	4.2	3.3
NOV	9	23.5	7.5	15.5	4.0	59	10.4	7.1	7.5	14.4	2280	6.3	10.5	0.0	6.0	4.9	3.5
NOV	10	20.5	11.5	16.0	7.5	59	10.7	7.4	6.4	10.5	1290	3.6	4.0	[illegible]	2.5	3.2	2.4
NOV	11	16.5	11.5	14.0	6.5	83	13.2	2.8	3.3	5.5	920	2.6	5.0	[illegible]	13.2	1.5	1.0
NOV	12	22.5	9.5	16.0	8.0	81	14.7	3.4	4.4	7.6	1130	3.1	6.0	[illegible]	1.4	2.1	1.4
NOV	13	22.0	9.5	15.8	7.5	68	12.1	5.7	4.5	8.6	1750	5.4	7.0	[illegible]	4.0	4.2	3.1
NOV	14	21.5	10.5	16.0	9.0	65	11.8	6.3	8.2	11.6	1580	4.4	6.0	0.0	4.0	3.6	2.7
NOV	15	21.0	8.5	14.8	4.5	57	9.9	6.7	6.9	12.4	1760	5.4	10.0	0.0	4.5	3.7	2.5
NOV	16	21.0	7.5	14.3	6.0	79	12.7	3.5	8.7	12.1	1420	3.9	4.0	2.5	0.5	3.4	2.6
NOV	17	21.0	13.0	17.0	12.5	85	16.5	2.8	4.9	7.4	1380	3.8	5.0	28.4	0.2	3.0	2.2
NOV	18	20.0	12.5	16.3	11.5	77	14.6	3.8	3.4	3.6	1240	3.4	2.0	0.0	3.0	3.1	2.4
NOV	19	23.5	9.5	16.5	8.0	57	10.6	8.1	5.9	11.2	2560	7.1	11.0	0.0	5.5	5.4	3.8
NOV	20	23.0	9.5	16.3	7.5	77	14.1	4.3	4.6	6.9	1190	3.3	3.0	2.6	1.1	2.9	2.2
NOV	21	20.5	9.5	15.0	7.5	83	14.1	2.8	3.1	4.6	1090	3.0	4.0	2.4	1.4	2.2	1.6
NOV	22	20.5	9.5	15.0	8.5	82	14.0	3.0	3.8	4.5	1260	3.5	7.0	5.7	1.6	2.1	1.4
NOV	23	19.5	12.5	16.0	11.0	83	15.0	3.1	2.8	5.7	1030	2.9	6.0	21.4	0.9	1.7	1.1
NOV	24	20.5	11.5	16.0	11.0	84	15.3	2.8	3.4	5.1	1050	2.9	5.0	12.1	0.6	2.0	1.3
NOV	25	20.5	10.5	15.5	8.5	86	15.0	2.5	1.9	3.9	1200	3.3	5.0	3.4	0.9	2.3	1.6
NOV	26	19.0	11.5	15.3	9.0	79	13.7	3.6	3.3	4.2	1120	3.1	6.0	0.0	0.5	1.9	1.3
NOV	27	20.5	11.5	16.0	10.0	77	14.0	4.1	7.0	10.9	1970	5.5	4.0	0.0	4.0	5.0	3.8
NOV	28	20.5	11.5	16.0	10.5	62	11.2	6.9	10.2	13.3	2150	6.0	6.5	3.1	5.1	5.3	4.0
NOV	29	20.0	13.5	16.8	12.5	77	14.7	4.3	9.7	10.9	1780	5.5	6.0	0.0	4.0	4.8	3.6
NOV	30	20.5	12.5	16.5	10.5	77	14.3	4.4	9.1	12.1	1430	4.0	3.0	0.0	3.0	3.8	2.9
AVER MONTH		21.6	10.3	15.9	8.2	71	12.8	5.2	5.2	8.3	1567	4.4	5.4	~~643.7~~ 113	3.1	3.5	2.6
AVER 1 DEC		23.4	9.3	16.4	6.7	61	11.3	7.2	4.7	8.6	1737	4.8	5.1	29.0	3.4	4.2	3.2
AVER 2 DEC		21.2	10.2	15.7	8.1	73	13.0	4.7	5.5	8.7	1533	4.3	5.9	66.6	3.7	3.3	2.4
AVER 3 DEC		20.2	11.4	15.8	9.9	79	14.1	3.7	5.4	7.5	1428	4.0	5.3	48.3	2.2	3.1	2.2
MAX		25.0	13.5	18.0	12.5	86	16.7	9.4	10.2	14.4	2560	7.1	11.0	28.4	13.2	6.1	4.8
MIN		16.5	7.0	14.0	4.0	47	9.0	2.5	1.9	3.6	920	2.6	1.5		0.2	1.5	1.0
NO OF DATA		30	30	30	30	30			30	30	30	30	30	16	30		

NA: not available ERR: error

1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani (daily values)

‡: PENMAN Formula

MONTH:DEC YEAR: 1987

Altitude: 2020 m a.s.l.
Latitude: 0.05 N
Longitude: 37.10 E

MONTH	DATE	TEMPERATURE (Celsius) Thermometer : 2 Max	Min	Mean	3 Surface Min	REL. HUM. (%) Mean	AIR VAPOR PRESS. (mb)	AIR SAT. PRESS. (mb)	WIND SPEED (km/h) Mean	Day	GLOBAL RADIATION A (or B) (J/cm2)	(kWh/m2)	SUNS. HOURS A (hrs)	RAIN 1) (mm)	PAN EVAP. (mm)	POT. EVAP. (mm) ‡	POT. EVAPO TRANS. (mm) ‡
DEC	1	20.5	12.5	16.5	10.5	67	12.5	6.2	11.7	11.2	1320	3.7	5.5	0.0	5.0	3.2	2.4
DEC	2	20.5	13.5	17.0	11.5	74	14.3	5.0	11.1	15.5	1810	5.0	5.0	0.2	5.7	4.7	3,5
DEC	3	20.5	13.0	16.8	10.5	67	13.1	5.7	8.9	16.1	2080	5.8	6.0	0.0	5.5	5.1	3.9
DEC	4	20.5	8.5	14.5	6.5	82	13.4	3.0	9.0	12.8	1060	5.2	6.0	0.0	5.5	4.2	3.1
DEC	5	22.0	12.5	17.3	11.5	59	11.6	8.0	7.6	15.0	2270	6.3	8.0	0.0	5.0	5.3	3.9
DEC	6	22.5	9.5	16.0	7.5	71	12.7	5.2	6.4	13.6	2090	5.8	6.5	0.0	6.0	4.7	3.6
DEC	7	22.0	9.5	15.8	7.0	83	14.8	3.0	5.2	7.6	1560	4.3	3.0	0.9	4.4	3.9	2.9
DEC	8	20.5	8.5	14.5	6.0	80	13.2	3.3	5.1	10.1	1800	5.0	6.5	11.3	0.8	3.8	2.7
DEC	9	20.5	10.5	15.5	9.5	80	14.0	3.6	5.0	9.2	1440	4.0	5.0	0.0	3.0	3.1	2.3
DEC	10	20.5	8.5	14.5	6.5	67	11.4	5.0	9.7	15.3	1780	4.9	6.0	0.0	3.5	4.1	3.1
DEC	11	20.0	10.5	15.3	8.5	74	12.7	4.5	8.7	14.4	1840	5.1	7.0	0.0	5.0	4.0	2.9
DEC	12	20.5	10.5	15.5	8.0	75	13.1	4.4	9.3	11.0	1650	4.6	6.5	0.5	4.0	3.6	2.7
DEC	13	21.0	12.5	16.8	11.5	68	13.0	6.0	8.6	13.7	2020	5.6	5.0	0.0	4.5	5.2	3.9
DEC	14	22.0	7.5	14.8	6.0	46	7.7	9.0	8.5	14.7	2400	6.9	12.0	0.0	6.5	5.1	3.6
DEC	15	22.5	6.5	14.5	6.0	54	8.9	7.6	6.0	11.2	2120	5.9	7.5	0.0	4.5	4.9	3.6
DEC	16	21.0	7.0	14.0	5.0	61	9.8	6.2	9.2	11.2	2150	6.0	8.0	0.0	6.5	4.7	3.7
DEC	17	22.5	9.5	16.0	7.5	58	10.5	7.6	10.0	11.2	2360	6.6	8.0	0.0	5.5	5.8	4.3
DEC	18	21.5	8.5	15.0	6.0	55	9.3	7.7	10.8	17.5	2430	6.8	9.0	0.0	6.0	5.7	4.3
DEC	19	21.5	6.5	14.0	4.5	66	10.5	5.4	12.1	15.6	2380	6.6	10.0	0.0	5.0	5.4	4.0
DEC	20	20.5	13.5	17.0	12.5	65	12.5	6.8	7.5	12.9	1750	4.9	4.5	0.0	4.0	4.5	3.4
DEC	21	23.0	9.0	16.0	6.0	53	9.7	8.4	8.3	11.7	2470	6.9	10.0	0.0	6.5	5.6	4.1
DEC	22	23.5	9.5	16.5	8.0	64	12.0	6.7	6.8	10.5	1830	5.1	5.0	0.0	4.5	4.7	3.6
DEC	23	22.5	8.0	15.3	5.5	63	10.7	6.3	6.7	10.3	1600	4.4	2.5	0.0	3.5	4.5	3.6
DEC	24	23.5	11.0	17.3	8.5	72	14.1	5.5	6.2	10.3	1860	5.2	4.0	0.0	6.0	4.8	3.7
DEC	25	22.5	9.5	16.0	9.0	68	12.3	5.8	6.3	9.8	1810	5.0	6.5	0.0	5.0	4.1	3.0
DEC	26	23.5	9.5	16.5	10.5	57	10.6	8.1	5.2	8.4	1740	4.8	7.0	3.5	4.5	3.7	2.8
DEC	27	23.5	11.5	17.5	9.5	73	14.6	5.3	4.7	8.0	1470	4.1	3.5	0.6	5.1	3.7	2.8
DEC	28	21.5	7.5	14.5	5.5	53	8.7	7.8	6.1	7.7	2140	5.9	4.5	0.5	3.0	5.5	4.3
DEC	29	23.5	9.5	16.5	7.0	52	9.7	9.0	7.4	11.1	2290	6.4	6.0	0.0	3.0	6.0	4.6
DEC	30	23.5	11.5	17.5	8.5	61	12.1	7.8	10.5	11.4	2190	6.1	4.5	8.1	7.1	6.1	4.8
DEC	31	21.5	13.5	17.5	13.0	83	16.6	3.3	5.4	8.6	1530	4.3	2.5	2.0	3.5	4.0	3.1
AVER MONTH		21.8	10.0	15.9	8.2	66	11.9	6.0	7.7	11.9	1939	5.4	6.2	27.6	4.8	4.6	3.4
AVER 1 DEC		21.0	10.7	15.8	8.7	73	13.1	4.8	8.0	12.6	1800	5.0	5.8	12.4	4.4	4.2	3.1
AVER 2 DEC		21.3	9.3	15.3	7.6	62	10.7	6.5	9.1	13.3	2118	5.9	7.8	0.5	5.2	4.8	3.6
AVER 3 DEC		22.7	10.0	16.5	8.3	64	11.9	6.8	6.7	9.8	1703	5.3	5.1	14.7	4.7	4.8	3.6
MAX		23.5	13.5	17.5	13.0	83	16.6	9.0	12.1	17.5	2400	6.9	12.0	11.3	7.1	6.1	4.8
MIN		20.0	6.5	14.0	4.5	46	7.7	3.0	4.7	7.6	1320	3.7	2.5		0.8	3.1	2.3
NO OF DATA		31	31	31	31	31			31	31	31	31	31	9	31		

NA: not available ERR: error
1) AVER.=TOTAL

A: Robitsch
B: Gunn Bellani
(daily values)

‡: PENMAN Formula

APPENDIX 2

Sample Calculation for Soil Moisture Estimation by Use of LUSA Method

Kalalu (Long Rains 1989) Second Decade of April

1) Crop grown was Hybrid 614 and planted on 10th April 1989 Gicheru, 1990.

2) Initial soil moisture at germination was estimated as the average of the initial soil moisture measurements of the three treatments i.e.

SMPSinit = (26.1 + 26.2 + 28.0) / 3 = 26.8 percent (cm^3 cm^{-3}) and the actually available moisture (AASM) is:

AASM = (SMPSinit. - smpwp) * RD

RD = RDinit = 10 cm

AASM = (.268 - .357) x 10 = -0.89 cm

According to the calculation there was no available water. This might mean the soil moisture level must have been higher during the germination period and the end of the period it was reduced below permanent wiltig point or alternatively there might have been some measurement mistake either in SMPWP or SMPSinit. Nonetheless assuming that the above soil moisture level was at end of germination i.e SMPSinit = 26.8 % and that it remained constant during the first decade of the crop growth period then to get the soil moisture at the end of the decade the following calculation are done:

3) ETm = 1.42 mm/day (see CropWat printout).

4) Depletion level, p = 0.87 (see procedure above)

5) SMFC = 43.6 % v/v.

6) Precipitation during the previous decade (PREC) = 73.6 mm.

7) RD = 10 cm + (0.7 x 135 cm - 10 cm) x L/ EMS

Segment interval, Dt used was 9 days, Duration upto start of mid-season, EMS = 90

days and L = 10 days at end of the first 10 days (decade).

Therefore RD = 19.4 cm.

8) Calculation of critical soil moisture, SMCR:

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = (1 - 0.87)(43.6 - 35.7) + 35.7 = 36.7 %

SMPSI < SMPWP => ETa = 0.05ETo = 0.05 * 3.6 = 0.18 mm/d

9) (New), AASM = (SMPSI - SMPWP) * RD + PREC. * DT - ETa *DT = 0 + 73.6 - 1.8 = 71.8 mm

10) TASM = (SMFC - SMPWP) * RD = (43.6 - 35.7) * 1.94 = 15.3 mm

11) AASM > TASM => AASM = TASM = 15.3 mm

12) (New) SMPSI = AASM / RD + SMPWP = 15.3 / 194 + 35.7 = 35.8 % and is valid for the next decade.

Second Interval (3rd Decade of April).

SMPSI = 35.8 %, SMPWP = 35.7 %, ETm = 1.41 mm/d, p = 0.87,

SMFC = 43.6 %, PREC. = 31.4 mm and RD = 28.8 cm

SMCR = 0.13 (43.6 - 35.7) + 35.7 = 36.7 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo

= (35.8 - 35.7)(1.41 - 0.18) / (36.7 - 35.7) + 0.18 = 0.3 mm/d

(New) AASM = (35.8 - 35.7) * 2.88 + 31.4 - 3 = 28.8 mm

TASM = (43.6 - 35.7) * 2.88 = 22.7

AASM > TASM => AASM = TASM = 22.7

(New) SMPSI = (22.7 / 288) + 35.7 = 35.8 % which is valid for the next interval.

Third Interval (First Decade of May):

SMPSI = 35.8 %, SMPWP = 34 %, SMFC = 43.9 %, PREC. = 35.5 mm/dec.,

ETm = 1.42 mm/d, p = 0.87 and RD = 382 mm

SMCR = 35.3 %

SMPSI > SMCR => ETa = ETm = 1.42 mm/d

(New) AASM = ((35.8 - 34) * 3.82 + 35.5 - 14.2) = 28.0 mm

TASM = 37.8 mm

AASM < TASM => AASM = 28.0 mm

(New) SMPSI = (28.0 / 382) + 34 = 34.1 %

Fourth Interval (Second Decade of May)

SMPSI = 34.1 %, SMPWP = 32.8 %, SMFC = 44.2 %, ETm = 1.53 mm/d,

PREC. = 27.8 mm/dec., p = 0.87, RD = 476 mm

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.13 (44.2 - 32.8) + 32.8 = 34.3 %

SMPSI > SMPWP =>

ETa = (34.1 - 32.8) (1.53 - 0.18) / (34.3 - 32.8) + 0.18 = 1.4 mm/d

(New) AASM = (34.1 - 32.8) * 4.76 + 27.8 - 14 = 20.0 mm

TASM = 54.3 mm

(New) SMPSI = 20.0 / 476 + 32.8 = 32.8 % and is valid for the next interval.

Fifth Interval (Third Decade of May).

SMPSI = 32.8 %, SMPWP = 32.0 %, SMFC = 44.4 %, ETm = 1.91 mm/d,

PREC. = 37.7 mm/dec., p = 0.87, RD = 569 mm

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.13 (44.4 - 32.0) + 32.0 = 33.6 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (32.8 - 32.0) (1.91 - 0.18) / (33.6 - 32.0) + 0.18 = 1.05mm/d

(New) AASM = (34.1 - 32.8) * 5.69 + 37.7 - 10.5 = 34.6 mm

TASM = 70.6 mm

New (SMPSI) = 34.6 / 569 + 32.8 = 32.9 % and is valid for the next interval.

Sixth Interval (First Decade of June).

SMPSI = 32.9 %, SMPWP = 31.8 %, SMFC = 43.9 %, ETm = 2.42 mm/d,

PREC. = 38.5 mm/dec., p = 0.84, RD = 663.3 mm, ETo = 3.6 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.16 (43.9 - 31.8) + 31.8 = 33.7 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (32.9 - 31.8) (2.42 - 0.18) / (33.7 - 31.8) + 0.18 = 1.48 mm/d

(New) AASM = (32.9 - 31.8) * 6.633 + 38.5 - 14.8 = 30.99 mm

TASM = 80.25 mm

New (SMPSI) = 30.99 / 663.3 + 31.8 = 31.8 % and is valid for the next interval.

Seventh Interval (Second Decade of June).

SMPSI = 31.8 %, SMPWP = 31.7 %, SMFC = 43.3 %, ETm = 2.95 mm/d,

PREC. = 19.0 mm/dec., p = 0.80, RD = 757 mm, ETo = 3.6 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.2 (43.3 - 31.7) + 31.7 = 34.02 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (31.8 - 31.7) (2.95 - 0.18) / (34.02 - 31.7) + 0.18 = 0.3 mm/d

(New) AASM = (31.8 - 31.7) * 7.57 + 19.0 - 3 = 16.76 mm

TASM = 87.8 mm

New (SMPSI) = 16.76 / 757 + 31.7 = 31.72 % and is valid for the next interval.

Eighth Interval (Third Decade of June).

SMPSI = 31.72 %, SMPWP = 31.59 %, SMFC = 42.87 %, ETm = 3.30 mm/d,

PREC. = 5.6 mm/dec., p = 0.77, RD = 851.1 mm, ETo = 3.6 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.23 (42.87 - 31.59) + 31.59 = 34.18 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (31.72 - 31.59) (3.3 - 0.18) / (34.18 - 31.59) + 0.18 = 0.33 mm/d

(New) AASM = (31.72 - 31.59) * 8.511 + 5.6 - 3.3 = 3.4 mm

TASM = 96.0 mm

New (SMPSI) = 3.4 / 851.1 + 31.59 = 31.59 % and is valid for the next interval.

Nineth Interval (First Decade of July).

SMPSI = 31.59 %, SMPWP = 31.66 %, SMFC = 42.35 %, ETm = 3.61 mm/d,

PREC. = 17.0 mm/dec., p = 0.74, RD = 945 mm, ETo = 3.2 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.26 (42.35 - 31.66) + 31.66 = 34.44 %

SMPSI < SMPWP =>

ETa = 0.05*ETo = 0.16 mm/d

(New) AASM = (31.59 - 31.66) * 9.45 + 17.0 - 1.6 = 15.4 mm

TASM = 101.02 mm

New (SMPSI) = 15.4 / 945 + 31.66 = 31.68 % and is valid for the next interval.

Tenth Interval (Second Decade of July).

SMPSI = 31.68 %, SMPWP = 31.66 %, SMFC = 42.35 %, ETm = 3.66 mm/d,

PREC. = 32.9 mm/dec., p = 0.73, RD = 945 mm, ETo = 3.2 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.27 (42.35 - 31.66) + 31.66 = 34.55 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (31.68 - 31.66) (3.66 - 0.16) / (34.55 - 31.66) + 0.16 = 0.18 mm/d

(New) AASM = (31.68 - 31.66) * 9.45 + 32.9 - 1.8 = 31.29 mm

TASM = 101.02 mm

New (SMPSI) = 31.29 / 945 + 31.66 = 31.69 % and is valid for the next interval.

Eleventh Interval (Third Decade of July).

SMPSI = 31.69 %, SMPWP = 31.66 %, SMFC = 42.35 %, ETm = 3.67 mm/d,

PREC. = 35.3 mm/dec., p = 0.73, RD = 945 mm, ETo = 3.2 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.27 (42.35 - 31.66) + 31.66 = 34.55 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (31.69 - 31.66) (3.67 - 0.16) / (34.55 - 31.66) + 0.16 = 0.20 mm/d

(New) AASM = (31.69 - 31.66) * 9.45 + 35.3 - 2.0 = 33.58 mm

TASM = 101.02 mm

New (SMPSI) = 33.58 / 945 + 31.66 = 31.69 % and is valid for the next interval.

Twelveth Interval (First Decade of August).

SMPSI = 31.69 %, SMPWP = 31.66 %, SMFC = 42.35 %, ETm = 3.68 mm/d.

PREC. = 0.2 mm/dec., p = 0.73, RD = 945 mm, ETo = 3.2 mm/d

SMCR = (1 - p)(SMFC - SMPWP) + SMPWP

SMCR = 0.27 (42.35 - 31.66) + 31.66 = 34.55 %

SMPSI > SMPWP =>

ETa = (SMPSI - SMPWP)(ETm - 0.05*ETo) / (SMCR - SMPWP) + 0.05*ETo i.e.

ETa = (31.69 - 31.66) (3.68 - 0.16) / (34.55 - 31.66) + 0.16 = 0.2 mm/d

(New) AASM = (31.69 - 31.66) * 9.45 + 0.2 - 2 = - 1.5 mm

TASM = 101.02 mm

New (SMPSI) = 0 / 945 + 31.66 = 31.66 % and is valid for the next interval.

NB The calculation was similarly carried out for the rest of the maize growth period and also for the beans during the short rains of 1988 (see results in Appendix 8)

APPENDIX 3

(a) Calculation of Monthly Actual Evapotranspiration for Beans (ASI Method), Short Rains Period, (1988) at Kalalu

First a table of required data was prepared and then by use of the following equation the ASI values calculated. These then were used with tables in appendix 8 to estimate the monthly actual evapotranspiration.

$$ASI = \frac{Peff + Wb - [(1 - p)\ Sa.RD]}{ETm} \quad (mm/month)$$

Mon.	Days	RD (mm)	P (mm)	Peff (mm)	WbRM (mm)	WbCT (mm)	WbTR (mm)	SMLD p	Sa.RD (mm)
Nov.	20	414	74.6	74.6	1.4	1.6	1.4	0.8	45.5
Dec.	30	875	33.5	33.5	22.9	25.1	25.5	0.8	96.3
Jan.	30	875	56.1	56.1	60.3	60.3	63.6	0.6	96.3
Feb.	25	875	42.0	42.0	34.1	41.1	31.5	0.5	96.3

P_{eff} = 100 % P
Sa = 110 mm/m

Mon.	ETm mm/mon.	ETm mm/d	ASIRM	ASICT	ASITR	(1-p) Sa.D (mm)	ETaRM mm/d	ETaCT mm/d	ETaTR mm/d
Nov.	23.1	1.155	2.90	2.90	2.90	9.1	1.16	1.16	1.16
Dec.	89.1	2.97	0.42	0.44	0.44	19.3	1.9	1.96	1.97
Jan.	137.5	4.58	0.71	0.71	0.73	19.3	3.90	3.90	3.99
Feb.	104.1	4.16	0.55	0.61	0.52	193	3.35	3.92	3.07

Mon.	Days	ETaRM	ETaCT	ETaTR
Nov	20	23.2	23.2	23.2
Dec	30	57	58.8	59.1
Jan	30	117	117	119.7
Feb	25	83.75	98	76.75
Total	105	280.95	297	278.75

(b) Calculation of Actual Evapotranspiration (ASI Method), Long Rains Period, (1989) at Kalalu

Calculation results.

Mon.	Days	RD mm	SMLD p	WbRM mm	WbCT mm	WbTR mm	Peff
Apr.	20	287.8	0.87	0	0	0	64.02
May	30	569.4	0.87	5.4	4.2	0	100.88
Jun.	30	851.1	0.80	38.3	27.9	25.5	40.35
Jul.	30	945	0.73	4.2	12.3	17.9	66.35
Aug.	30	945	0.72	12.7	4.3	7.2	52.77
Sep.	30	945	0.70	0	0	3.5	30.56
Oct.	30	945	0.83	0	0	0	80.32

Effective Rainfall taken as 97% of total rainfall (see CropWat printout)

Table of Available Soil Moisture Index (ASI) results

ASIRM	ASICT	ASITR	ETm mm/mon.	(1-p)Sa.D mm	Sa.D mm
2.12	2.12	2.12	28.3	4.0	30.76
2.02	2.0	1.91	48.6	7.91	60.87
0.7	0.58	0.55	86.7	18.20	90.98
0.40	0.47	0.52	109.4	27.28	101.02
0.33	0.26	0.28	112.6	28.29	101.02
0.002	0.002	0.03	122	30.31	101.02
0.82	0.82	0.82	77.1	17.17	101.02

mon - month

Table showing Actual Evapotranspiration Results as Calculated by ASI Method

Mon.	ETaRM mm/d	ETaCT mm/d	ETaTR mm/d	ETm mm/d	ETaRM mm/mon.	ETaCT mm/mon.	ETaTR mm/mon.
Apr.	1.415	1.415	1.415	1.415	28.3	28.3	28.3
May	1.62	1.62	1.62	1.62	48.6	48.6	48.6
Jun.	2.52	2.29	2.23	2.89	75.6	68.7	66.9
Jul.	2.26	2.51	2.67	3.65	67.8	75.3	80.1
Aug.	2.07	1.83	1.90	3.75	62.1	54.9	57.0
Sep.	0.96	0.96	1.07	4.07	28.8	28.8	32.1
Oct.	2.43	2.43	2.43	2.57	72.9	72.9	72.9
				Total	384.1	377.5	385.9

APPENDIX 4

Monthly Rainfall Distribution

Monthly and annual Rainfall variation for Kalalu.

YR.	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1986	11.1	3.9	35.2	302.7	90.4	135.1	49.2	69.2	93.8	24.5	19.5	55.3
1987	25.8	0	9.5	46.6	130.5	100.7	36.8	56.2	0	17.5	87.7	8
1988	9	0	52.3	214.6	73.9	38.4	93.6	52.7	98.6	98.6	77.9	33.5
1989	56.1	42	17.4	140.5	104	41.6	68.4	54.4	31.5	82.8	113	27.6
1990	15.8	64.5	234	133.4	46.4	19.5	36	77.6	45.2	85.8	155	59.4
1991	6.7	2.4	82.7	71.7	96	28.5	59.3	63.9				
AV.	20.8	18.8	71.9	151.6	90.2	60.6	57.2	62.3	53.8	61.8	90.6	36.8

Mean Annual Rainfall (mm), Kalalu Farm, Laikipia (Based on 54 years data)

Source Gicheru, 1990.

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
AV.	15.2	18.6	33.6	102.5	117.4	57.9	69.1	71.1	52.1	64.1	80.2	29.6

APPENDIX 5

(a) Calculation of Maximum Yield of Maize, Long Rains Period, (1989) at Kalalu.

Y_{me} for maize at Kalalu - Laikipia

Given: Maize with optimum plant density; Location 0.05°N; altitude 2020 m; total growing period = 200 days from 10th April to 1st November; cH = 0.45

$$R_s = (0.25 + \frac{0.50n}{N}) R_a$$

R_s = actual measured incoming shortwave radiation in cal/cm²/day

n = Actual measured incoming sunshine duration in hrs/day.

N = Maximum possible sunshine duration in hrs/day.

R_a = Extra-terrestrial radiation in mm/day.

Mth.	DAYS	RH%	MEAN T. (°C)	ET_m mm/d	n	(Tb in app. 8) R_a mm/d	RSe cal/cm²/d (Tb app.8)	y_o	y_e
APR	20	67	16.4	1.42	6.5	15.3	364	228	426
MAY	30	67	15.6	1.62	7.3	14.4	349	221	417
JUN.	30	57	15.1	2.89	8.1	13.9	337	216	410
JUL.	30	66	15.3	3.65	6.5	14.1	343	218	413
AUG	30	62	15.0	3.75	5.0	14.8	357	225	422
SEP.	30	55	16.3	4.07	5.8	15.3	368	230	429
OCT	30	63	15.9	2.57	3.6	15.4	365	228	427
MEAN		62.4	15.6	2.85	6.1	14.7	355	224	420

Calculation

	MON.	TB (app. 8)	MEAN mbar
y_o	224	e_a	17.7
y_e	420	e_d	11.06
R_m	355	e_a-e_d	6.6
F	0.48	CT	0.37
Y_e	326		
ET_m	2.85		

From table in appendix 8:

$$R_a = 14.7 \quad mm/day$$

$$R_s = (0.25 + 0.50 \times \frac{6.1}{12}) \times 14.7 = 7.4 \quad mm/d$$

$$F = \frac{(R_{se} - 0.5R_s)}{0.8R_{se}}$$

$$R_{se} = 355 \quad cal/cm^2/d$$

$$R_s = 7.4 \times 59 = 437 \quad cal/cm^2/d$$

$$F = \frac{(355 - 0.5 \times 437)}{0.8 \times 355} = 0.48$$

$$y_0 = 224, \quad y_c = 420$$

$$Y_0 = F.y_0 + (1-F)\,y_c$$

$$= 0.48 \times 224 + (1 - 0.48) \times 420 = 326$$

$$e_d\ mean = e_a \times \frac{RH}{100} = 17.7 \times \frac{62.4}{100} = 11.06$$

$$Y_{me} = 1.9 \times 0.45 \times 0.37 \times 200 \times 326 \times \frac{2.85}{6.6} \quad Kg/ha/period$$

$$Y_{me} = 8.9 \quad tons/ha \quad or \quad 8907 \quad Kg/ha/period$$

Y_{me} = 8.9 tons/ha/period:

The above yield was assumed equal to the constraint-free yield.

(b) Estimation of Potential Yield (Y_{mp}) for Beans, Short Rains Period, (1988) at Kalalu.

This was done by use of Agro- Ecological Zone Method as follows:-

Given: Beans; location 0.05°N; total growing period (G) 105 days from 10/11/1988 to 25/2/1989; LAI is 5; Average incoming shortwave radiation (R_s) over growing period 507.5 cal/cm²/day; Average mean temperature 15.4°C.

(i) R_a Calculation (from table in appendix 8)

Month	Nov.	Dec.	Jan.	Feb.
R_a mm/d	15.1	14.8	15.0	15.5
Days	20	30	30	25
Total	302	444	450	387.5

Therefore average R_a = 15.08 mm/d

N = 12.0 hrs

Average n calculation

Mon.	Nov.	Dec.	Jan.	Feb.	Grand Total
n	5.3	7.6	8.2	9.1	
Days	20	30	30	25	105
Total	106	228	246	227.5	807.5

n = 7.69 hrs

$$R_s = (0.25 + 0.5\frac{n}{N})R_a$$

∴ R_s = 8.6 mm/d = 507.5 cal/cm₂/d

R_{se} Calculation (table in appendix 8)

Month	Nov.	Dec.	Jan.	Feb.	Grand Total
R_{se}	349.8	336.8	342.8	359.9	
Days	20	30	30	25	105
Total	6996	10104	10284	8996.5	36380.5

∴ R_{se} = 346.5 cal/cm₂/d

Mean Daily Temperature

Month	Nov.	Dec.	Jan.	Feb.	Grand Total
Mean °C	13.3	15.6	16.1	15.8	
Duration	20	30	30	25	105
Total	266	468	483	395	1612

Mean temperature = 15.4°C

(From table in appendix 8)

Mean Rate y_m in Kg/ha/hr = 20

y_c and y_o are as follows

Month	Nov.	Dec.	Jan.	Feb.	Grand Total
y_c	417.8	409.8	412.8	423.9	
y_o	221.9	215.9	218.9	225.9	
Duration (D)	20	30	30	25	105
y_c * D	8356	12294	12384	10597	43631
y_o * D	4438	6477	6567	5648	23130

y_o = 220.3 kg/ha/day

y_c = 415.5 kg/ha/day

$$F = \frac{(R_{se} - 0.5R_s)}{0.8R_{se}}$$

F = 0.33

$$Y_o = F(0.8 + 0.01y_m)y_o + (1-F)(0.5 + 0.025y_m)y_c \quad kg/ha/day$$

$\therefore Y_o$ = 351 kg/ha/day

From various tables as given by Doorenbos and Kassam, 1979 the following corrections were applied as follows:

cL = 0.5, cN = 0.6, cH = 0.3

Y_{mp} = cL * cN * cH* G * Y_o

= 3.3 tons/ha

APPENDIX 6

CROPWAT Program Printout

CROPWAT :

Reference Evapotranspiration ETo according Penman-Monteith

Country : KENYA — Meteo Station : KALALU (1989 yr)
Altitude : 2020 meter — Coordinates : 0.05 N.L. 37.10 E.L

Month	MaxTemp °C	MinTemp °C	Humid. %	Wind km/day	Sunshine hours	Sol.Radia MJ/m²/day	ETo-PenMon mm/day
January	23.1	9.1	55	166	8.2	21.4	4.3
February	23.4	8.3	49	190	9.1	23.5	4.9
March	25.6	8.4	51	144	8.3	22.6	4.7
April	23.1	9.8	67	115	6.1	18.5	3.6
May	22.6	8.5	67	98	7.3	19.2	3.5
June	23.2	7.0	57	106	8.1	19.6	3.6
July	22.6	7.9	66	79	6.5	17.7	3.2
August	23.3	6.6	62	84	5.0	16.4	3.2
September	24.6	7.9	55	101	5.8	18.3	3.7
October	22.9	8.8	63	98	3.6	14.9	3.2
November	21.6	10.3	71	125	5.4	17.2	3.3
December	21.8	10.0	66	190	6.2	18.1	3.7
YEAR	23.2	8.6	61	125	6.6	18.9	1370

CROPWAT :

Climate file : kl89rn — Climate Station : KALALU

	ETO (mm/day)	Rainfall (mm/month)	Eff. Rain (mm/month)
January	4.3	56.1	54.4
February	4.9	42.0	40.7
March	4.7	17.4	16.9
April	3.6	140.5	136.3
May	3.5	104.0	100.9
June	3.6	41.6	40.4
July	3.2	68.4	66.3
August	3.2	54.4	52.8
September	3.7	31.5	30.6
October	3.2	82.8	80.3
November	3.3	113.0	109.6
December	3.7	27.6	26.8
YEAR Total	1369.4	779.3	755.9 mm

Effective Rainfall: 97 %

CROPWAT :

Crop data : MAIZE — Crop file : kal-mz

Growth Stage		Init	Devel	Mid	Late	Total
Length Stage	[days]	35	55	65	45	200
Crop Coefficient	[coeff.]	0.40	->	1.15	0.60	
Rooting Depth	[meter]	0.30	->	1.20	1.20	
Depletion level	[fract.]	0.87	->	0.74	0.86	
Yield-response F.	[coeff.]	0.40	1.50	0.50	0.20	1.25

CROPWAT :

IRRIGATION SCHEDULING MAIZE 10 April

Climate Station : KALALU
Crop : MAIZE
Soil : FERRIC ACRISOL

Climate File : kl89rn
Planting date : 10 April
Available Soilmoist : 107 mm/m.
Initial Soilmoist : 0 mm/m.

Irrigation Options selected :
Timing : No Irrigations, only Rainfall.

No. Irr.	Int days	Date	Stage -	Deplet %	TX %	ETA %	NetGift mm	Deficit mm	Loss mm	Gr.Gift mm	Flow L/s/ha
1	11	21 Apr	A	22	100	73	54.8	9.5	0.0	54.8	0.58
2	10	1 May	A	15	100	100	48.1	8.2	0.0	48.1	0.56
3	10	11 May	A	11	100	100	41.4	7.0	0.0	41.4	0.48
4	10	21 May	B	9	100	100	33.0	6.5	1.6	34.7	0.40
5	10	1 Jun	B	9	100	100	18.0	8.2	9.8	27.7	0.32
6	10	11 Jun	B	14	100	100	18.8	14.1	0.0	18.8	0.22
7	10	21 Jun	B	31	100	100	10.9	33.0	0.0	10.9	0.13
8	10	1 Jul	B	43	100	100	14.8	51.5	0.0	14.8	0.17
9	10	11 Jul	C	53	100	100	20.2	67.4	0.0	20.2	0.23
10	10	21 Jul	C	62	100	100	24.8	79.2	0.0	24.8	0.29
11	10	1 Aug	C	73	100	100	22.6	93.3	0.0	22.6	0.26
12	10	11 Aug	C	83	73	92	20.4	106.7	0.0	20.4	0.24
13	10	21 Aug	C	88	54	65	18.1	112.6	0.0	18.1	0.21
14	10	1 Sep	C	91	41	49	15.6	116.3	0.0	15.6	0.18
15	10	11 Sep	C	94	28	36	11.0	120.1	0.0	11.0	0.13
16	10	21 Sep	D	96	20	24	7.5	123.0	0.0	7.5	0.09
17	10	1 Oct	D	94	32	32	14.2	120.4	0.0	14.2	0.16
18	10	11 Oct	D	90	59	56	21.6	115.5	0.0	21.6	0.25
19	10	21 Oct	D	84	100	86	28.6	108.2	0.0	28.6	0.33
END	10	1 Nov	D	74	100	99					

Total Gross Irrigation	0.0 mm	Total Rainfall	487.4 mm
Total Net Irrigation	0.0 mm	Effective Rain	476.0 mm
Total Irrigation Losses	0.0 mm	Total Rain Loss	11.4 mm
Moist Deficit at harvest	95.5 mm		
Net Supply + Soilretention	95.5 mm		
Actual Wateruse by crop	443.1 mm	Actual Irr.Req	-32.9 mm
Potential Wateruse by crop	584.6 mm		
Efficiency Irr. Schedule	100.0 %	Efficiency Rain	97.7 %
Deficiency Irr. Schedule	24.2 %		

YIELD REDUCTIONS Stage	A	B	C	D	Season	
Reductions in ETC	8.5	0.0	30.5	45.2	24.2	%
Yield Response factor	0.40	1.50	0.50	0.20	1.25	
Reductions in Yield	3.4	0.0	15.2	9.0	30.3	%
Cumulative Yield reduct.	3.4	3.4	18.1	25.5		%

Crop Evapotranspiration and Irrigation Requirements

Climate File : kl89rn
Crop : MAIZE

Climate Station: KALALU
Planting date : 10 April

Month	Dec	Stage	Coeff Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IRReq. mm/day	IRReq. mm/dec
Apr	2	init	0.40	1.42	14.2	52.4	0.00	0.0
Apr	3	init	0.40	1.41	14.1	46.2	0.00	0.0
May	1	init	0.40	1.42	14.2	39.9	0.00	0.0
May	2	in/de	0.43	1.53	15.3	33.6	0.00	0.0
May	3	deve	0.54	1.91	19.1	26.9	0.00	0.0
Jun	1	deve	0.67	2.42	24.2	18.2	0.60	6.0
Jun	2	deve	0.81	2.95	29.5	10.5	1.90	19.0
Jun	3	deve	0.95	3.30	33.0	14.3	1.86	18.6
Jul	1	deve	1.08	3.61	36.1	19.6	1.65	16.5
Jul	2	mid	1.15	3.66	36.6	24.1	1.25	12.5
Jul	3	mid	1.15	3.67	36.7	21.9	1.47	14.7
Aug	1	mid	1.15	3.68	36.8	19.8	1.70	17.0
Aug	2	mid	1.15	3.69	36.9	17.6	1.93	19.3
Aug	3	mid	1.15	3.89	38.9	15.1	2.38	23.8
Sep	1	mid	1.15	4.17	41.7	10.7	3.11	31.1
Sep	2	mi/lt	1.12	4.30	43.0	7.2	3.58	35.8
Sep	3	late	1.03	3.73	37.3	13.7	2.36	23.6
Oct	1	late	0.91	3.06	30.6	20.9	0.97	9.7
Oct	2	late	0.78	2.51	25.1	27.8	0.00	0.0
Oct	3	late	0.66	2.14	21.4	30.7	0.00	0.0
TOTAL					584.6	471.0		247.7

CROPWAT :

Reference Evapotranspiration ETo according Penman-Monteith

Country : KENYA — Meteo Station : KALALU (1988 yr)
Altitude : 2020 meter — Coordinates : 0.05 N.L. 37.10 E.L

Month	MaxTemp °C	MinTemp °C	Humid. %	Wind km/day	Sunshine hours	Sol.Radia MJ/m²/day	ETo-PenMon mm/day
January	26.0	10.2	54	190	6.6	19.0	4.6
February	23.0	10.5	71	120	4.8	16.8	3.5
March	22.9	8.5	64	110	8.0	22.1	4.1
April	23.0	7.2	66	96	7.7	21.0	3.8
May	21.6	8.2	71	77	5.2	16.2	3.0
June	21.9	7.5	68	67	5.3	15.7	2.8
July	22.6	8.0	67	77	5.1	15.7	2.9
August	22.5	7.8	63	84	5.4	17.0	3.2
September	19.6	7.1	67	94	5.3	17.5	3.2
October	21.8	9.3	59	190	7.6	21.2	4.2
November	23.1	9.1	55	166	8.2	21.5	4.3
December	23.4	8.3	49	190	9.1	22.4	4.7
YEAR	22.6	8.5	63	122	6.5	18.8	1351

CROPWAT :

Climate file : kl88rnmd — Climate Station : KALALU

	ETO (mm/day)	Rainfall (mm/month)	Eff. Rain (mm/month)
January	4.6	52.3	52.3
February	3.5	214.6	214.6
March	4.1	73.9	73.9
April	3.8	47.9	47.9
May	3.0	93.6	93.6
June	2.8	52.7	52.7
July	2.9	95.1	95.1
August	3.2	98.6	98.6
September	3.2	77.9	77.9
October	4.2	33.5	33.5
November	4.3	56.1	56.1
December	4.7	42.0	42.0
YEAR Total	1350.9	938.2	938.2 mm

Effective Rainfall: 100 %

CROPWAT :

Crop Evapotranspiration and Irrigation Requirements

Climate File : kl88rnmd — Climate Station: KALALU
Crop : BEANS — Planting date : 10 September

Month	Dec	Stage	Coeff Kc	ETcrop mm/day	ETcrop mm/dec	Eff.Rain mm/dec	IRReq. mm/day	IRReq. mm/dec
Sep	2	init	0.35	1.09	10.9	26.0	0.00	0.0
Sep	3	init	0.35	1.22	12.2	21.0	0.00	0.0
Oct	1	deve	0.47	1.84	18.4	14.8	0.36	3.6
Oct	2	deve	0.72	3.04	30.4	9.2	2.13	21.3
Oct	3	de/mi	0.95	4.03	40.3	12.3	2.80	28.0
Nov	1	mid	1.05	4.51	45.1	16.2	2.89	28.9
Nov	2	mid	1.05	4.56	45.6	19.7	2.59	25.9
Nov	3	mid	1.05	4.68	46.8	17.8	2.90	29.0
Dec	1	mi/lt	1.01	4.63	46.3	15.2	3.11	31.1
Dec	2	late	0.88	4.15	41.5	13.0	2.85	28.5
Dec	3	late	0.70	3.26	16.3	7.2	1.81	9.0
TOTAL					353.8	172.4		205.3

Crop data : BEANS — Crop file : kal-88bn

Growth Stage		Init	Devel	Mid	Late	Total
Length Stage	[days]	20	28	38	19	105
Crop Coefficient	[coeff.]	0.35	->	1.05	0.70	
Rooting Depth	[meter]	0.10	->	1.20	1.20	
Depletion level	[fract.]	0.80	->	0.54	0.60	
Yield-response F.	[coeff.]	0.20	1.10	0.75	0.20	1.15

CROPWAT :

IRRIGATION SCHEDULING BEANS 10 September

Climate Station : KALALU
Crop : BEANS
Soil : FERRIC LUVISOL

Climate File : kl88rnmd
Planting date : 10 September
Available Soilmoist : 107 mm/m.
Initial Soilmoist : 1.07 mm/m.

Irrigation Options selected :
Timing : No Irrigations, only Rainfall.

No. Irr.	Int days	Date	Stage	Deplet %	TX %	ETA %	NetGift mm	Deficit mm	Loss mm	Gr.Gift mm	Flow L/s/ha
1	11	21 Sep	A	55	100	73	26.0	20.8	0.0	26.0	0.27
2	10	1 Oct	B	60	100	100	21.0	37.4	0.0	21.0	0.24
3	10	11 Oct	B	77	87	98	14.8	66.6	0.0	14.8	0.17
4	10	21 Oct	B	88	33	50	9.2	98.0	0.0	9.2	0.11
5	10	1 Nov	C	88	29	30	12.3	112.7	0.0	12.3	0.14
6	10	11 Nov	C	87	32	32	16.2	111.1	0.0	16.2	0.19
7	10	21 Nov	C	84	37	37	19.7	108.4	0.0	19.7	0.23
8	10	1 Dec	C	85	36	39	17.8	108.6	0.0	17.8	0.21
9	10	11 Dec	D	86	34	37	15.2	110.2	0.0	15.2	0.18
10	10	21 Dec	D	87	34	36	13.0	111.7	0.0	13.0	0.15
END	5	26 Dec	D	85	40	36					

Total Gross Irrigation	0.0 mm	Total Rainfall	172.4 mm
Total Net Irrigation	0.0 mm	Effective Rain	172.4 mm
Total Irrigation Losses	0.0 mm	Total Rain Loss	0.0 mm
Moist Deficit at harvest	109.1 mm		
Net Supply + Soilretention	109.1 mm		
Actual Wateruse by crop	154.4 mm	Actual Irr.Req	-18.0 mm
Potential Wateruse by crop	353.8 mm		
Efficiency Irr. Schedule	100.0 %	Efficiency Rain	100.0 %
Deficiency Irr. Schedule	56.3 %		

YIELD REDUCTIONS Stage	A	B	C	D	Season	
Reductions in ETC	14.0	44.4	64.3	63.7	56.3	%
Yield Response factor	0.20	1.10	0.75	0.20	1.15	
Reductions in Yield	2.8	48.9	48.2	12.7	64.8	%
Cumulative Yield reduct.	2.8	50.3	74.3	77.6		%

APPENDIX 7

YES Program Printout

Station = KALALU Latitude = 0° 5'N
Altitude = 2020m Longitude = 37° 6'E

Koppen Climatic Type = B

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Minimum Temp	C	9.1	8.3	8.4	9.8	8.5	7.0	7.9	6.6	7.9	8.8	10.3	10.0	8.5
Maximum Temp	C	23.1	23.4	25.6	23.1	22.6	23.2	22.6	23.3	24.6	22.9	21.6	21.8	23.2
Average Temp	C	16.1	15.8	17.0	16.4	15.6	15.1	15.3	15.0	16.3	15.9	15.9	15.9	15.9
Night Temp	C	15.3	15.0	16.1	15.7	14.8	14.2	14.5	14.1	15.4	15.1	15.3	15.3	15.1
Day Temp	C	18.6	18.5	20.1	18.8	18.1	18.0	17.9	18.0	19.3	18.4	17.9	18.0	18.5
Precipitation	mm	56	42	17	141	104	42	68	54	32	83	113	28	780
No. of Rain Days		6	3	4	15	13	4	11	9	9	11	13	9	107
Penman PET	mm	133	137	146	108	109	108	99	99	111	99	99	111	1359
Rel. Humidity	%	55	49	51	67	67	57	66	62	56	63	71	66	61
Vapour Pressure		10.0	8.8	9.8	12.4	11.8	9.7	11.4	10.5	10.1	11.3	12.8	11.9	10.9
Windspeed		1.9	2.2	1.7	1.3	1.1	1.2	0.9	1.0	1.2	1.1	1.4	2.2	1.4
Sunshine	%	68	76	69	51	61	68	54	42	48	30	45	52	55
Sunshine	h	8.2	9.2	8.3	6.2	7.4	8.2	6.5	5.1	5.8	3.6	5.4	6.3	6.7
Radiation	MJ/day	21.4	23.5	22.6	18.5	19.2	19.6	17.7	16.4	18.3	14.9	17.2	18.1	227.4

Slope in %..... = 2
Flood Risk..... = F0
Drainage Class..... = 7
Flood Plain or Recent Alluvial Terrace.. = Y
Surface Stoniness (Y/N)..... = N
CEC Meq/100g Clay at 50 cm depth..... = 46.9
Organic Carbon in top 20cm (o/oo)..... = 1.22

	0- 25	25- 50	50- 75	75-100	100-125	125-150
Clay content %	66	66	70	70	69	0
Silt content %	23	16	14	16	18	0
Texture/Struct.	C60+	C60+	C60+	C60+	C60+	--
Sand Type						
Base Saturat. %	93	75	39	41	43	0
Elect.Cond. dS/m	0.3	0.2	0.2	0.1	0.1	0.0
Structure:	Struct	Struct	Struct	Struct	Massiv	
Rock Gravel %	0	0	0	0	0	0
Quartz Gravel %	0	0	0	0	0	0
Laterit Gravel %	0	0	0	0	0	0
Stones 7.5-25 %	0	0	0	0	0	0
Boulders >25cm %	0	0	0	0	0	0

Code	Description	Type	Mon	Root
CASS	Cassava	A	12	90
COTT	Cotton	A	6	100
COWP	Cowpea	A	4	100
CPEA	Chickpea	A	4	80
GROU	Groundnuts	A	4	75
MAIZ	Maize	A	7	120
MILL	Millet	A	3	100
RICE	Paddy Rice	A	4	100
RICR	Rice - Rainfed	A	4	100
SAFF	Safflower	A	4	100
SESA	Sesam	A	3	100
SORG	Sorghum	A	4	90
SPOT	Sweet Potatoes	A	6	100
SUGA	Sugar Cane	A	12	100
SUNF	Sunflower	A	5	100

Variab	fm	to	Operator	=	Lev1	Lev2	Lev3	Lev4	Lev5
MAIZ = Maize									
TmpMin	1	4	Average	>	16	12	9	7	0
TmpMin	1	4	Average	<	18	24	28	30	35
TmpAvg	1	4	Average	>	22	18	16	14	7
TmpAvg	1	4	Average	<	25	30	35	40	47
Rainmm	1	1	Total	>	53	40	13	0	0
Rainmm	1	1	Total	<	200	275	400	475	600
Rainmm	2	2	Total	>	73	68	57	40	18
Rainmm	2	2	Total	<	200	275	400	475	600
Rainmm	3	3	Total	>	123	115	99	74	20
Rainmm	3	3	Total	<	200	275	400	475	600
Rainmm	4	4	Total	>	138	110	55	0	0
Rainmm	4	4	Total	<	200	275	400	475	600
Rainmm	5	5	Total	>	147	118	59	0	0
Rainmm	5	5	Total	<	200	275	400	475	600
Rainmm	6	6	Total	>	139	83	0	0	0
Rainmm	6	6	Total	<	200	275	400	475	600
Rainmm	7	7	Total	>	58	29	0	0	0
Rainmm	7	7	Total	<	200	275	400	475	600
RelHum	4	4	Average	<	60	65	70	85	100

Planting Month April

Variable		fm	to	x	=	Limit	Value	Index
Minimum Temp	C	1	4	A	>	16	8.3	60
Minimum Temp	C	1	4	A	<	18	8.3	100
Average Temp	C	1	4	A	>	22	15.6	64
Average Temp	C	1	4	A	<	25	15.6	100
Temperature								60
Precipitation	mm	1	1	T	>	53	141	100
Precipitation	mm	1	1	T	<	200	141	100
Precipitation	mm	2	2	T	>	73	104	100
Precipitation	mm	2	2	T	<	200	104	100
Precipitation	mm	3	3	T	>	123	42	16
Precipitation	mm	3	3	T	<	200	42	100
Precipitation	mm	4	4	T	>	138	68	75
Precipitation	mm	4	4	T	<	200	68	100
Precipitation	mm	5	5	T	>	147	54	67
Precipitation	mm	5	5	T	<	200	54	100
Precipitation	mm	6	6	T	>	139	32	78
Precipitation	mm	6	6	T	<	200	32	100
Precipitation	mm	7	7	T	>	58	83	100
Precipitation	mm	7	7	T	<	200	83	100
Precipitation								16
Rel. Humidity	%	4	4	A	<	60	66.0	86
Humidity								86
CLIMATE INDEX								8
Rock Gravel	%				<	150	0.0	100
Quartz Gravel	%				<	160	0.0	100
Laterit Gravel	%				<	170	0.0	100
Stones 7.5-25	%				<	180	0.0	100
Boulders >25cm	%				<	200	0.0	100
SOIL INDEX								100
TOTAL INDEX								8

Appendix 8

Assorted Tables Used in the Calculations Within the Thesis Report

Measured Soil Moisture, Available Soil Moisture and Actual Evapotranspiration per Treatment During the Short Rains of 1988 at Kalalu

DATE	RD	SMFC	SMPWP	TASM	ETo	ETm	SMDL	SMRM	SMCT	SMTR	AASMRM	AASMCT	AASMTR	SMCR	ETa RM	ETa CT	ETa TR
	cm	%v/v	%v/v	mm	mm/d	mm/d	p	% v/v	% v/v	% v/v	mm	mm	mm	% v/v	mm/d	mm/d	mm/d
15/11	8.5	43.6	35.7	6.7	3.2	1.09	0.8	37.3	37.6	37.3	1.4	1.6	1.4	37.3	1.09	1.09	1.09
19/11	16.7	43.6	35.7	13.2	3.2	1.09	0.8	37.4	37.5	37.1	2.8	3.0	2.3	37.3	1.09	1.09	0.16
26/11	28.3	43.6	35.7	22.4	3.2	1.22	0.8	40.1	40.4	40.1	12.5	13.3	12.5	37.3	1.22	1.22	1.22
02/12	38.1	43.9	34.0	37.7	4.2	1.84	0.8	40.0	40.6	40.7	22.9	25.1	25.5	36.0	1.84	1.84	1.84
09/12	49.6	44.2	32.6	57.5	4.2	1.84	0.8	39.7	40.5	40.5	35.2	39.2	39.2	34.9	1.84	1.84	1.84
17/12	62.8	44.2	31.8	77.9	4.2	3.04	0.7	39.9	40.7	40.7	50.9	55.9	55.9	35.5	3.04	3.04	3.04
24/12	74.3	43.4	31.7	86.9	4.2	4.03	0.6	39.3	39.7	40.2	56.5	59.4	63.2	36.4	4.03	4.03	4.03
29/12	82.6	43.0	31.7	93.3	4.2	4.04	0.6	39.0	39.0	39.4	60.3	60.3	63.6	36.2	4.04	4.04	4.04
07/01	87.5	42.8	31.6	98.0	4.3	4.51	0.5	37.9	37.8	37.3	55.1	54.2	49.9	37.2	4.51	4.51	4.51
20/01	87.5	42.8	31.6	98.0	4.3	4.56	0.5	36.1	36.7	35.7	39.4	44.6	35.9	37.2	3.71	4.17	3.40
26/01	87.5	42.8	31.6	98.0	4.3	4.68	0.5	35.5	36.3	35.2	34.1	41.1	31.5	37.2	3.32	3.96	3.09
04/02	87.5	42.8	31.6	98.0	4.7	4.63	0.5	34.3	35.2	33.9	23.6	31.5	20.1	37.2	2.35	3.06	2.04
16/02	87.5	42.8	31.6	98.0	4.7	4.15	0.6	34.4	35.2	33.3	24.5	31.5	14.9	36.1	2.68	3.38	1.72
23/02	87.5	42.8	31.6	98.0	4.7	3.26	0.7	33.0	34.8	32.4	12.2	28.0	7.0	35.0	1.50	3.12	0.96
02/03	87.5	42.8	31.6	98.0				32.3	34.2	31.6	6.1	22.8	0.0				
09/03	87.5	42.8	31.6	98.0				32.0	33.8	31.8	3.5	19.2	1.7				
16/03	87.5	42.8	31.6	98.0				32.1	33.6	32.0	4.4	17.5	3.5				
31/03	87.5	42.8	31.6	98.0				31.9	31.1	31.9	2.6	0.0	2.6				

Estimated Soil Moisture and Actual Evapotranspiration during the Short Rains of 1988, Kalalu, Kenya

DATE	DEC.	Days	RD cm	SMDL p	SMFC %v/v	SMPWP %v/v	PREC. mm	TASM mm	ETo mm/d	ETm mm/d	NEWAASM mm	SMCR %v/v	SMEST %v/v	ETa mm/d	AASMEST mm
10/11			8.5		43.6	35.7		6.7	3.2		1.4				1.4
20/11	2	11	26.6	0.8	43.6	35.7	3.3	21.0	3.2	1.09	21	37.3	37.4	1.09	4.5
30/11	3	10	43.1	0.8	44.1	33.3	72.5	46.5	3.2	1.22	46.5	35.5	36.5	1.22	13.7
10/12	1	10	59.5	0.8	44.4	31.8	2.1	75.0	4.2	1.84	13.3	34.3	36.8	1.84	29.6
20/12	2	10	76.0	0.7	43.3	31.7	1.6	88.2	4.2	3.04	0.0	35.2	33.5	1.69	13.9
30/12	3	10	87.5	0.6	42.8	31.6	21.1	98.0	4.2	4.03	19.0	36.1	31.8	0.38	1.7
10/01	1	10	87.5	0.5	42.8	31.6	10.8	98.0	4.3	4.51	9.0	37.2	31.9	0.46	2.8
20/01	2	10	87.5	0.5	42.8	31.6	0.6	98.0	4.3	4.56	0.0	37.2	31.7	0.29	0.9
30/01	3	10	87.5	0.5	42.8	31.6	45.9	98.0	4.3	4.68	43.8	37.2	31.6	0.22	0.0
10/02	1	10	87.5	0.5	42.8	31.6	9.6	98.0	4.7	4.63	7.7	37.2	32.1	0.63	4.4
20/02	2	10	87.5	0.6	42.8	31.6	42.0	98.0	4.7	4.15	39.7	36.1	31.7	0.31	0.8
25/02	3	5	87.5	0.7	42.8	31.6	0.0	98.0	4.7	3.26	0.0	35.0	32.1	0.64	4.0

Estimated Soil Moisture, Available Moisture and Actual Evapotranspiration during the Long Rains of 1989 at Kalalu

Days	Decade	ETm	SMDL	RD	SMEST	SMPWP	SMFC	PREC	SMCR	TASM	NEWAASM	ETo	ETaEST	AASMEST
		mm/d	p	mm	%v/v	%v/v	%v/v	mm	%v/v	mm	mm	mm/d	mm/d	mm
				100							0			
45	2	1.42	0.87	193.9	26.8	35.7	43.6	73.6	36.7	15.3	15.3	3.6	0.18	0.0
55	3	1.41	0.87	287.8	35.8	35.7	43.6	31.4	36.7	22.7	22.7	3.6	0.27	0.2
65	1	1.42	0.87	381.7	35.8	34.0	43.9	35.5	35.3	37.8	28.9	3.5	1.42	6.8
75	2	1.53	0.87	475.6	34.1	32.8	44.2	27.8	34.3	54.2	20.5	3.5	1.34	6.1
85	3	1.91	0.87	569.4	32.8	32.0	44.4	37.7	33.6	70.6	31.7	3.5	1.08	4.8
95	1	2.42	0.84	663.3	32.1	31.8	43.9	38.5	33.7	80.3	35.4	3.6	0.48	1.7
105	2	2.95	0.80	757.2	31.9	31.7	43.3	19.0	34.0	87.8	16.6	3.6	0.36	1.2
115	3	3.30	0.77	851.1	31.7	31.6	42.9	5.6	34.2	96.2	3.3	3.6	0.33	1.0
125	1	3.61	0.74	945.0	31.6	31.7	42.4	17.0	34.5	101.1	14.5	3.2	0.16	0.0
135	2	3.66	0.73	945.0	31.7	31.7	42.4	32.9	34.6	101.1	31.4	3.2	0.16	0.1
145	3	3.67	0.73	945.0	31.7	31.7	42.4	35.3	34.6	101.1	34.0	3.2	0.16	0.3
155	1	3.68	0.73	945.0	31.7	31.7	42.4	0.2	34.6	101.1	0.0	3.2	0.16	0.3
165	2	3.69	0.73	945.0	31.7	31.7	42.4	19.9	34.6	101.1	18.3	3.2	0.16	0.0
175	3	3.89	0.71	945.0	31.7	31.7	42.4	17.1	34.8	101.1	15.7	3.2	0.16	0.2
185	1	4.17	0.68	945.0	31.7	31.7	42.4	17.4	35.1	101.1	15.7	3.7	0.19	0.2
195	2	4.30	0.67	945.0	31.7	31.7	42.4	3.7	35.2	101.1	2.0	3.7	0.19	0.2
205	3	3.73	0.73	945.0	31.7	31.7	42.4	10.4	34.6	101.1	8.6	3.7	0.19	0.0
215	1	3.06	0.79	945.0	31.7	31.7	42.4	17.4	33.9	101.1	15.9	3.2	0.16	0.1
225	2	2.51	0.84	945.0	31.7	31.7	42.4	35.7	33.4	101.1	34.3	3.2	0.16	0.2
235	3	2.14	0.86	945.0	31.7	31.7	42.4	6.4	33.2	101.1	5.1	3.2	0.16	0.3

Measured Soil Moisture, Available Moisture, Optimum and Actual Evapotranspiration Rates per Treatment during the Long Rains of 1989 at Kalalu

DATE	RD	SMFC	SMPWP	TASM	SMTR	SMCT	SMRM	SMDL	AASMTR	AASMCT	AASMR	SMCR	ETo	ETm	ETaTR	ETaCT	ETaRM
	cm	%v/v	%v/v	mm	%v/v	%v/v	%v/v	p	mm	mm	mm	%v/v	mm/d	mm/d	mm/d	mm/d	mm/d
07/04	10.0	43.6	35.7	7.9	26.2	28.0	26.1	0.87	0.0	0.0	0.0	36.7	3.6	1.42	0.18	0.18	0.18
18/04	17.5	43.6	35.7	13.8	28.5	35.4	34.7	0.87	0.0	0.0	0.0	36.7	3.6	1.42	0.18	0.18	0.18
27/04	26.0	43.6	35.7	20.5	29.6	35.5	36.3	0.87	0.0	0.0	1.6	36.7	3.6	1.41	0.18	0.18	0.90
02/05	30.6	43.6	35.6	24.5	31.4	37.0	37.4	0.87	0.0	4.2	5.4	36.6	3.5	1.42	0.18	1.42	1.42
10/05	38.2	43.9	34.0	37.8	32.1	35.9	37.1	0.87	0.0	7.3	11.9	35.3	3.5	1.42	0.18	1.42	1.42
18/05	45.7	44.2	33.0	51.2	33.8	37.3	38.7	0.87	3.7	19.8	26.1	34.5	3.5	1.53	0.94	1.53	1.53
23/05	50.4	44.3	32.5	59.5	34.0	38.4	39.7	0.87	7.5	29.7	36.4	34.0	3.5	1.91	1.85	1.91	1.91
02/06	59.8	44.4	31.8	75.3	36.1	36.5	38.2	0.84	25.5	27.9	38.3	33.8	3.6	2.42	2.42	2.42	2.42
07/06	64.5	44.0	31.8	78.7	34.8	35.8	37.2	0.84	19.0	25.7	34.5	33.8	3.6	2.42	2.42	2.42	2.42
15/06	72.0	43.5	31.7	85.0	34.9	35.1	36.1	0.80	22.8	24.6	31.9	34.1	3.6	2.95	2.95	2.95	2.95
23/06	79.5	43.1	31.7	90.6	34.4	33.9	34.4	0.77	21.8	17.3	21.3	34.3	3.6	3.30	3.30	2.76	3.30
29/06	85.1	42.9	31.7	95.3	30.9	30.1	31.6	0.77	0.0	0.0	0.0	34.3	3.6	3.30	0.18	0.18	0.18
05/07	90.7	42.6	31.6	99.8	33.6	33.0	32.1	0.74	17.9	12.3	4.2	34.5	3.2	3.61	2.54	1.80	0.71
13/07	94.5	42.4	31.7	101.1	33.7	33.3	32.2	0.73	18.4	15.1	4.4	34.6	3.2	3.66	2.52	2.10	0.73
18/07	94.5	42.4	31.7	101.1	33.1	34.0	33.6	0.73	13.4	22.0	18.0	34.6	3.2	3.66	1.88	2.98	2.46
28/07	94.5	42.4	31.7	101.1	32.7	30.4	31.0	0.73	9.8	0.0	0.0	34.6	3.2	3.67	1.42	0.16	0.16
10/08	94.5	42.4	31.7	101.1	32.5	32.2	33.0	0.73	7.2	4.3	12.7	34.6	3.2	3.68	1.09	0.72	1.79
17/08	94.5	42.4	31.7	101.1	32.3	32.1	32.7	0.73	6.0	3.3	9.0	34.6	3.2	3.69	0.94	0.59	1.32
31/08	94.5	42.4	31.7	101.1	32.1	31.4	29.9	0.71	3.5	0.0	0.0	34.8	3.2	3.89	0.60	0.16	0.16
07/09	94.5	42.4	31.7	101.1	31.9	31.1	29.3	0.68	1.5	0.0	0.0	35.1	3.7	4.17	0.37	0.19	0.19
14/09	94.5	42.4	31.7	101.1	31.4	31.0	29.0	0.67	0.0	0.0	0.0	35.2	3.7	4.30	0.19	0.19	0.19
22/09	94.5	42.4	31.7	101.1	30.9	30.4	28.9	0.73	0.0	0.0	0.0	34.6	3.7	3.73	0.19	0.19	0.19
28/09	94.5	42.4	31.7	101.1	30.9	30.6	29.3	0.73	0.0	0.0	0.0	34.6	3.7	3.73	0.19	0.19	0.19
05/10	94.5	42.4	31.7	101.1	30.6	30.6	28.9	0.79	0.0	0.0	0.0	33.9	3.2	3.06	0.16	0.16	0.16
12/10	94.5	42.4	31.7	101.1	30.6	30.5	28.9	0.84	0.0	0.0	0.0	33.4	3.2	2.51	0.16	0.16	0.16
19/10	94.5	42.4	31.7	101.1	31.3	30.6	30.5	0.84	0.0	0.0	0.0	33.4	3.2	2.51	0.16	0.16	0.16
26/10	94.5	42.4	31.7	101.1	30.7	31.4	30.1	0.86	0.0	0.0	0.0	33.2	3.2	2.14	0.16	0.16	0.16
02/11	94.5	42.4	31.7	101.1	30.8	31.9	30.9										
09/11	94.5	42.4	31.7	101.1	30.5	32.2	30.8										

Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Latitudes / Southern Latitudes	Jan / July	Feb / Aug	Mar / Sept	Apr / Oct	May / Nov	June / Dec	July / Jan	Aug / Feb	Sept / Mar	Oct / Apr	Nov / May	Dec / June
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Effect of Temperature f(T) on Longwave Radiation (Rnl)

T°C	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
f(T) = σT_k^4	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
f(n/N) = 0.1 + 0.9n/N	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C 1/

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6	22.0

Temperature °C	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7*	37.8*	40.1*	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

1/ Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data. (Example: Tdewpoint is 18°C; ed is 20.6 mbar)

Extra-terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere												Lat	Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40°	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Maximum Active Incoming Shortwave Radiation (Rse in cal/cm²/day) and Gross Dry Matter Production on Overcast (yo) and Clear Days (yc) (in kg/ha/day) for a Standard Crop (De Wit, 1965)

North / South		Jan / July	Feb / Aug	Mar / Sept	Apr / Oct	May / Nov	June / Dec	July / Jan	Aug / Feb	Sept / Mar	Oct / Apr	Nov / May	Dec / June
0°	Rse	343	360	369	364	349	337	343	357	368	365	349	337
	yc	413	424	429	426	417	410	413	422	429	427	418	410
	yo	219	226	230	228	221	216	218	225	230	228	222	216
10°	Rse	299	332	359	375	377	374	375	377	369	345	311	291
	yc	376	401	422	437	440	440	440	439	431	411	385	370
	yo	197	212	225	234	236	235	236	235	230	218	203	193
20°	Rse	249	293	337	375	394	400	399	386	357	313	264	238
	yc	334	371	407	439	460	468	465	451	425	387	348	325
	yo	170	193	215	235	246	250	249	242	226	203	178	164
30°	Rse	191	245	303	363	400	417	411	384	333	270	210	179
	yc	281	333	385	437	471	489	483	456	412	356	299	269
	yo	137	168	200	232	251	261	258	243	216	182	148	130
40°	Rse	131	190	260	339	396	422	413	369	298	220	151	118
	yc	219	283	353	427	480	506	497	455	390	314	241	204
	yo	99	137	178	223	253	268	263	239	200	155	112	91

Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Latitudes / Southern Latitudes	Jan / July	Feb / Aug	Mar / Sept	Apr / Oct	May / Nov	June / Dec	July / Jan	Aug / Feb	Sept / Mar	Oct / Apr	Nov / May	Dec / June
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0

Effect of Temperature f(T) on Longwave Radiation (Rnl)

T°C	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36
$f(T) = \delta Tk^4$	11.0	11.4	11.7	12.0	12.4	12.7	13.1	13.5	13.8	14.2	14.6	15.0	15.4	15.9	16.3*	16.7	17.2	17.7	18.1

Effect of Vapour Pressure f(ed) on Longwave Radiation (Rnl)

ed mbar	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
$f(ed) = 0.34 - 0.044\sqrt{ed}$	0.23	.22	.20	.19	.18	.16	.15	.14	.13*	.12	.12	.11	.10	.09	.08	.08	.07	.06

Effect of the Ratio Actual and Maximum Bright Sunshine Hours f(n/N) on Longwave Radiation (Rnl)

n/N	0	.05	.1	.15	.2	.25	.3	.35	.4	.45	.5	.55	.6	.65	.7	.75	.8	.85	.9	.95	1.0
$f(n/N) = 0.1 + 0.9n/N$	0.10	.15	.19	.24	.28	.33	.37	.42	.46	.51	.55	.60	.64	.69	.73	.78	.82*	.87	.91	.96	1.0

Saturation Vapour Pressure (ea) in mbar as Function of Mean Air Temperature (T) in °C [1]

Temperature °C	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
ea mbar	6.1	6.6	7.1	7.6	8.1	8.7	9.3	10.0	10.7	11.5	12.3	13.1	14.0	15.0	16.1	17.0	18.2	19.4	20.6	22.0

Temperature °C	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ea mbar	23.4	24.9	26.4	28.1	29.8	31.7	33.6	35.7*	37.8*	40.1*	42.4	44.9	47.6	50.3	53.2	56.2	59.4	62.8	66.3	69.9

[1] Also actual vapour pressure (ed) can be obtained from this table using available Tdewpoint data. (Example: Tdewpoint is 18°C; ed is 20.6 mbar)

Extra-terrestrial Radiation (Ra) expressed in equivalent evaporation in mm/day

Northern Hemisphere												Lat	Southern Hemisphere											
Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40°	17.9	15.7	12.5	9.2	6.6	5.3	5.9	7.9	11.0	14.2	16.9	18.3
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1	38	17.9	15.8	12.8	9.6	7.1	5.8	6.3	8.3	11.4	14.4	17.0	18.3
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36	17.9	16.0	13.2	10.1	7.5	6.3	6.8	8.8	11.7	14.6	17.0	18.2
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34	17.8	16.1	13.5	10.5	8.0	6.8	7.2	9.2	12.0	14.9	17.1	18.2
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32	17.8	16.2	13.8	10.9	8.5	7.3	7.7	9.6	12.4	15.1	17.2	18.1
8.8	10.7	13.1	15.2	16.5	17.0	16.8*	15.7	13.9	11.6	9.5	8.3	30	17.8	16.4	14.0	11.3	8.9	7.8	8.1	10.1	12.7	15.3	17.3	18.1
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28	17.7	16.4	14.3	11.6	9.3	8.2	8.6	10.4	13.0	15.4	17.2	17.9
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26	17.6	16.4	14.4	12.0	9.7	8.7	9.1	10.9	13.2	15.5	17.2	17.8
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24	17.5	16.5	14.6	12.3	10.2	9.1	9.5	11.2	13.4	15.6	17.1	17.7
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22	17.4	16.5	14.8	12.6	10.6	9.6	10.0	11.6	13.7	15.7	17.0	17.5
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20	17.3	16.5	15.0	13.0	11.0	10.0	10.4	12.0	13.9	15.8	17.0	17.4
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18	17.1	16.5	15.1	13.2	11.4	10.4	10.8	12.3	14.1	15.8	16.8	17.1
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16	16.9	16.4	15.2	13.5	11.7	10.8	11.2	12.6	14.3	15.8	16.7	16.8
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14	16.7	16.4	15.3	13.7	12.1	11.2	11.6	12.9	14.5	15.8	16.5	16.6
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12	16.6	16.3	15.4	14.0	12.5	11.6	12.0	13.2	14.7	15.8	16.4	16.5
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10	16.4	16.3	15.5	14.2	12.8	12.0	12.4	13.5	14.8	15.9	16.2	16.2
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8	16.1	16.1	15.5	14.4	13.1	12.4	12.7	13.7	14.9	15.8	16.0	16.0
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6	15.8	16.0	15.6	14.7	13.4	12.8	13.1	14.0	15.0	15.7	15.8	15.7
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4	15.5	15.8	15.6	14.9	13.8	13.2	13.4	14.3	15.1	15.6	15.5	15.4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2	15.3	15.7	15.7	15.1	14.1	13.5	13.7	14.5	15.2	15.5	15.3	15.1
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8