SCHEDULING FOR SUPPLEMENTAL IRRIGATION IN MWALA, MACHAKOS DISTRICT.

BY

NGURE, KEZIAH NJERI
B.Sc. (Hons) Agricultural education and extension (Egerton University)

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DECLARATION

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of information have been acknowledged.

....
Keziah Njeri Ngure

15/08/03
Date

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

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Dr. F. N Gichuki

15/08/03
Date

DEDICATION

Dedicated to my parents, Mr. and Mrs. Ngure Burugu.

APPRECIATION

I would like to extend my acknowledgement to the following;

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ABBREVIATIONS AND ACRONYMS

ASAL	Arid and semi arid lands
CPK	Church of the province of Kenya
CWR	Crop water requirement
Eta	Actual evapotranspiration
Etc	Crop evapotranspiration
Eto	Reference crop evapotranspiration
E_{pan}	Pan evapotranspiration (mm / day)
Etm	Maximum evapotranspiration
Kc	Crop coefficient
K_p	Pan coefficient
Ky	Yield response factor
LAI	Leaf area index
Masl	metres above sea level
MOA	Ministry of Agriculture
PARCH	Prediction arable resource in hostile environment
Pe	Effective rainfall
Rz	Root depth
Sa.D	Allowable soil water depletion
SI	Supplemental irrigation
Wb	Stored water at the beginning of each pentad
We	Water balance
Ya	Actual Yield
Ym	Expected maximum yield

ABSTRACT

This study focuses on supplemental irrigation in Mwala area of Machakos District. The area is classified as Arid and Semi-Arid Land (ASAL) where rainfall is unreliable in both time and space. This has often led to crop failure that results to famine in the area.

Rainfall analysis was done to determine onset, cessation, length of the rainy season and occurrence of in-season drought spells. Early onset resulted to more seasons' rainfall. During the short rains, early onset dates of 4th October in the years 1984, 1994 and 1997 gave an average rainfall amount of 822mm while late onset dates of 8th November 1981, 18th November 1983 and 3rd November 1991 gave an average rainfall amount of 248. Early onset also resulted to more wet days as opposed to late onset. The short rains season was found to be more reliable for maize growing being more and better distributed over the growing season. The average amount for the short rains was 506 mm spread over 70 days for the short rains and 421 mm spread over 60 days for the long rains during the 19 years analyzed.

The in-season dry spells were found to occur in most seasons. Severity of the dry spells increased as the crop-growing season progressed. Dry spells occurring early in the growing season were an indication of a shortened rainy season. Examples are the long rains of 1983, 1984, 1987, 1992 and 1993. Dry spells occurring during flowering were considered hazardous as they resulted into high yield reduction and hence the need to store water for supplemental irrigation. There was a general shift of weather as the length of the rainy season got more with advance in years during the short rains.

The amount of water required for supplemental irrigation for all the seasons was carried out. Results showed uniformity in the amount of water required during the long rains but much variation during the short rains. The average amount required for the short rains was 152.8mm with a standard deviation of 77.3 while the average amount was 124.7 for the long rains with a standard deviation of 44.7. However better distribution of rainfall during the short rains is an indication supplemental irrigation could give better yields during the short rainy seasons.

Supplemental irrigation schedule to supply water to the crops during dry spells was carried out for the short rains of 1997. This was achieved through determining the moisture holding capacity of the soil, the actual crop evapotranspiration, the crop's root depth, and the level of allowable moisture depletion.

1.0 INTRODUCTION

About 80% of land in Kenya is classified as arid and semi arid lands (ASAL). Only 20% receive enough rainfall to sustain crop growth and this is not enough to support the ever-growing population in terms of food production. The country can broadly be categorized as 20% non-arid, 30% semi-arid and 50% arid (Ndambuki, 1996). Increasing population pressure in the non-arid areas has resulted in a forced migration of people to the semi-arid areas (Mugo and Njoroge, 1996). This has resulted into sub-divisions of existing land and continued cropping that has led to poor yields. A combined birth and immigration in recent years has led to population growth rate of about 8% per annum in Machakos District (Wafula, 1997). In arid and semi arid areas, farmers have to deal with the problem of little, uncertain and variable rainfall, and the effect it has on agricultural production namely; low yields and crop failure.

The population in the district was estimated as 915,000 according to the 1999 population and housing census (GOK, 2000). Majority of the people in Machakos District live in the rural areas (Mutiso, 1989). As population pressure increases, the district's medium potential, often called marginal and semi arid environments are being explored more for increased food production. Due to the adverse weather conditions, farmers achieve meager harvests out of holdings that have shrunk and lost productivity.

In semi arid areas rain falls irregularly, often as heavy storms and much of the water is lost as surface runoff. Little of the rainwater is available for crop growth (Ragab, 1996; Farmer, 1989; Onyango et al, 1989). Short dry spells during the rainy season are a common phenomenon. These in-season dry spells cause moisture stress to the growing crop resulting into reduced yields or total crop failure. Whenever rains fail or falter, there is evident suffering for both human beings and livestock as most farmers rely on rainfed agriculture (Onyango et al, 1989). These large fluctuations in seasonal rainfall have caused recurring famine to the people of Machakos district and other regions with similar weather patterns.

The poor rains have affected agriculture, the economy, social organizations and ultimately, sometimes tragically people of Machakos district. As a result farmers are often at risk of starvation and death due to food shortage and related problems like malnutrition. They are also unwilling to invest in modern technologies of crop production due to the high risks of crop failure (Wafula, 1995). In Mwala division of Machakos district some farmers often depend on relief food supplies, which are uncertain (Onyango et al, 1989).

Irrigation to supply the crop with water during drought periods is an obvious response but this is mainly constrained by water scarcity in semi-arid areas and the high cost of irrigation development. An alternative to conventional irrigation can be found in channeling of runoff from catchments, either directly to food crops or into storage structures e.g. tanks or earth dams where it can be retained for supplemental irrigation. The water stored can be used to synchronize irrigation with the critical growth stages of a crop. This might not guarantee a crop full water requirement but they are cheaper, easier to adopt, can benefit many people and can increase food production compared to rainfed production alone.

1.1 Problem Statement

Machakos district receives between 350-850 mm of rain per year with a mean of about 350 mm as short rains between October and December and a mean of about 450 mm as long rains between March and May (Wafula, 1995). For the long rains, 60% rainfall reliability varies from 50-540 mm while the short rains 60% rainfall reliability varies from 60-530 mm. The low annual rainfall and its low reliability are major constraints to expansion of agricultural production in the district (Onyango et al 1989). Annual evapotranspiration is high and, the available rainfall is inadequate to meet this high evaporative demand. Annual average precipitation for Mwala is 40-50% of the potential evapotranspiration (Eto). The average annual Eto is 1755mm (MOA, 1987).

The 300 mm rainfall is a critical threshold for maize grain production (Jaetzold and Schmidt, 1983). The Katumani composites need at least 250 mm of rainfall for a crop to mature and 350 mm for average yields (Onyango et al, 1989). Poor soils (moderate to low fertility) and unsuitable climate makes the smallholder rainfed agriculture difficult in more than 80% of the district (MOA 1994). Most soils in Machakos developed on basement system rocks- on the granitoid gneisses, which are quartz rich, the soils are sandy and very poor from a chemical standpoint.

Only one third of Machakos District receives rain amounting to 750 mm/annum and above. The rainfall in the district is characterized by strong seasonal concentration with a high temporal and spatial variation from year to year and season to season (Mutiso, 1989, Kenworthy and Glover, 1958). Between and within season distribution of rainfall is highly variable and crop failures are a common feature (Wafula, 1995). As a result, much of the rain ends up as runoff that significantly contributes to soil, water and nutrient losses. In-season drought periods are a common phenomenon in the district and have always resulted into reduced crop yields and crop failure.

Large scale irrigation is not feasible in the area due to surface water scarcity. Very few rivers in the district are permanent. The permanent rivers are Athi and Tana (Wafula, 1997). The upper reaches of Tana have been dammed for hydro-electric power generation, while the stream flow of the Athi river fluctuates with seasons. All the other rivers show intermittent flow, periods of flood being separated by periods of dryness. Most of them are insignificant, sand-choked channels carrying water for only short periods. Runoff harvesting for irrigation is not widely practiced due to high costs (Wafula, 1997).

Boreholes have not been successful owing to the abundance of impervious granitoid gneisses and massive biotite in the area (Mutiso, 1989). They also require high capital investment to develop. Most of the boreholes that are developed have inadequate discharges (Mutiso, 1989). Approximately 33% of the boreholes in the basement are dry implying that they have a yield of less than $1m^3$/hr. The average yield for a successful borehole is nearly 6 m^3/hr, but more than 69% of these boreholes have a yield range of 2-10 m^3/hr.

The available water has to meet domestic water needs first before any irrigation can be considered but is hardly enough for domestic purposes. There is therefore the need to use available water efficiently. Due to the nature of the rainfall, and high run-off losses some farmers have tapped run-off for supplemental irrigation. Others channel runoff from catchments and direct it to the growing crop. The limitation with this technique of channeling runoff directly to food crops is that, this extra water is available to the crop as long as there is runoff to harvest, hence it is no more reliable than the weather itself. An on going study by Baron (1998) aims at evaluating the effectiveness of rainwater harvesting, storage and utilization system for increasing maize yield and reducing production risks. This study compliments her study by addressing water utilization issues.

1.2 Objectives

The overall objective was to formulate an irrigation schedule for supplemental irrigation using harvested rainwater. The specific objectives were:

1. Analyze rainfall data to determine on-set of rains, cessation of rains and in crop drought occurrence periods when supplemental irrigation was required.
2. Determine crop water requirements, effective rainfall and irrigation requirements for maize crop.
3. Develop an irrigation schedule (how much water to apply and when to apply) for a maize crop.

2.0 LITERATURE REVIEW

2.1 Water Constraints to Food Production

2.1.1 Crop Production Risk

A large proportion of the ASAL is characterized by unreliable rainfall, high radiation and high evaporative demand, with soils generally of poor structural stability, low water holding capacity, and low fertility. Few farmers are able to control pests and diseases effectively or to apply optimal amounts of fertilizers. Crop production is predominantly conducted under rainfed conditions. Consequently there is a high risk of water deficit at various stages of growth. When water supply from the soil falls short of maximum evapotranspiration (Etm) the plants suffer water stress. The water deficit in the plant can develop to a point where crop growth and yield are affected.

In semi-arid areas, Etm is rarely met by rainwater throughout the growing season. The actual evapotranspiration always falls short of Etm (Doorenbos and Kassam, 1979). Potential yields are generally low in this zone and the high yield variability is strongly tied to climatic factors. Rainfall variability in both space and time results in seedling mortality, retarded development and reduced yield (Monteith and Virmani, 1991).

Early sowing often result into low germination rates due to light showers or wide spacing between rainfall events, but on the other hand if sowing is delayed, the land becomes too wet to till. Use of fertilizers does not always give anticipated yields due to poor rains. When fertilizers are used, unfavorable water conditions often reduce utilization efficiency, either due to drought or high rates of leaching. This has forced farmers to adopt low inputs.

2.1.2 Maize growing in Machakos

Maize is the most important cereal crop in the country (Reeves, 1996; Mugo and Njoroge, 1996). High weather variability in Kenya's semi-arid regions causes marginal rainfed maize yields most of the time (Wafula, 1995). In Machakos, maize is grown in small farm units averaging 4 ha, shared with other crops and livestock. The maize variety grown in Machakos is the Katumani composite (Njoroge et al, 1996).

Production is dependent on family labour, using ox- drawn plows and hand tools. There is little use of fertilizers (Mugo and Njoroge, 1996). Yields are low, averaging 0.5 t/ha due to drought, stem borers, weeds and lack of capital to purchase inputs.

The Katumani composite maize takes 100 days from emergence to physiological maturity in Katumani area of Machakos district (Njoroge et al, 1996), whereas it takes 50 days to start flowering (Ndambuki, 1996; Micheni, 2000). Within this zone drought stress begins soon after flowering and increases in intensity throughout the reproductive and grain filling stages.

2.1.3 Water Harvesting for Crop Production

The productivity of land and water in semi arid rainfed areas can still be greatly enhanced through water harvesting and supplemental irrigation. Water harvesting is the process of concentrating rainfall runoff from a large area for use in a smaller area. The harvested water is used for irrigation of crops, pastures and trees. Marginal lands with annual rainfall of 300 mm can still be cultivated if controlled but limited additional water is made available. In many instances, such an incremental water supply can be provided through appropriate water harvesting techniques (Oweis et al, 1999). There is high generation of runoff in marginal areas due to high rainfall intensities experienced over short duration and low infiltration rates predominant in the ASAL.

A water harvesting system consists of two subsystems, a cropped area and a catchment area. High runoff generation is important in the catchment area. On the other hand minimal runoff and more infiltration is desired in the cropped area.

Water harvesting for crop production has been reported in Kenya where rain water alone cannot meet the crop water requirements. In Katiorin and Baringo, micro and macro catchments were used for irrigating crops and pasture using receding flood water. They used the ratios of 2:1 and 1:1 between the catchments and the cropped area. The sorghum planted yielded 50 times more than that of control plot at Katiorin and Marigat for the 2:1 ratio. In a second experiment in Baringo designed to compare four runoff harvesting techniques with deep tillage alone, it was concluded all runoff harvesting techniques were superior to deep tillage alone. A third experiment demonstrated the same results (Wafula, 1997).

Burgess (1992) reports that at CPK plots in Isiolo, semi-circular bunds yielded 195 and 813 kg/ha of Katumani maize and Serena sorghum while conventional farming produced 6.3 and 25 kg respectively.

In Kitui the ASAL program set up plots in 1984 –1986 at Ukai, Waita, Zombe and Kyuso where maize, sorghum and bulrush millet were intercropped with legumes. The treatments consisted of external catchment, contour ridges, Fanya juu and control. Results obtained during the first season were not conclusive due to above average rains (Critchley, 1989). During the second and third seasons, runoff harvesting increased yield at varying magnitudes as reported by Wafula, 1997.

The Prediction Arable Resource in Hostile environment (PARCH) model predicts the growth of crops in response to meteorological conditions, soil factors, crop parameters and management factors. Simulations were carried out assuming runoff from catchments of 50%, 100%, 150%, 200%, 250%, and 300% of the cultivated area. Results obtained are reported in Wafula, 1997. Wafula, 1997, reports another runoff harvesting techniques that is in common use in dry areas in Kenya as Zai pitting.

2.2 Supplemental Irrigation

Crop production in semi arid areas is constrained by water scarcity that can be alleviated by supplemental irrigation. Supplemental irrigation is the application of a limited amount of water to crop when rainfall fails to provide sufficient water for plant growth to increase and stabilize yields. Supplemental irrigation is practiced in wetter parts of dry areas with rainfall of 300 – 600 mm annually (Oweis, 1997). One characteristic of supplemental irrigation in rainfed areas is that the amount and timing of supplemental irrigation are not meant to provide water stress-free conditions over the growing season. Supplemental irrigation is meant to provide enough water during the critical stages of crop growth to ensure optimal yield in terms of yield per unit of water (Oweis, 1997).

In Baringo district, Sandai location, a dam constructed across River Wesegess which is seasonal provides water for supplemental irrigation. The water is channeled to the nearby farms by canals (Wafula, 1997). In Machakos, water harvesting across seasonal drainage ways such as gullies and ephemeral streams are common. This water is used for supplemental irrigation employing a number of irrigation systems whose performance has not been evaluated. Several farmers in Masii location of Machakos district practice supplemental irrigation for horticulture crops.

2.2.1 Importance of Supplemental Irrigation

Supplemental irrigation has three effects:

- Yield improvement
- Stabilization of food production from year to year thus increasing reliability
- Providing condition suitable for economic use of higher technology inputs such as high yielding varieties, fertilizers and herbicides irrespective of seasonal rainfall.

Yield improvements through supplemental irrigation are widely reported in Oweis, 1997; perrier and Salkini, 1991; Tenkinel et al, 1992; Islam and Bhuiyan, 1991; Salkini and Ansell, 1992. Supplemental irrigation has increased incomes for few farmers in Machakos district. Water productivity (i.e. the ratio of economic yield of a crop and the total amount of water consumed) of rain and supplemental irrigation exceeds the water productivity of either component if applied alone according to Oweis et al, (1999).

2.2.2 Need for Supplemental Irrigation

Supplemental irrigation is used in areas where a crop can be grown by natural rainfall alone but additional water stabilises and improves yield. Supplemental irrigation also provides conditions suitable for using high yielding varieties, fertilizers, herbicides as well as more intensive cropping. The main objective is to ensure that a crop has an adequate supply of water in its root zone for the production of optimum yields. Different soil types hold different amounts of moisture. Of this, only part is available to the crop, water must be applied before this portion is wholly depleted.

Gikonyo (1992) states that yields of many crops tend to be near their maximum when root zone available moisture is not depleted by more than 40% of the maximum soil moisture deficit between irrigations. Timing of irrigation involves the computation of available moisture and the rate at which this moisture is depleted. Where tensiometers are being used it is time to irrigate when the reading is 400-500 cm soil water potential (Gikonyo, 1992).

2.3 Risks of Rainfed Agriculture in Machakos

Factors that influence crop growth in Machakos are rainfall, soil and temperature. Rainfall is low in amount and poor in distribution. The intraseasonal droughts result into moisture stress while the crops are not mature. Growth periods are accompanied by high temperatures which lead to loss of water through evaporation especially where low crop density are used.

2.3.1 Rainfall Data Analysis

Agro climatic analysis and modeling work has attempted to relate crop growth and yield to climate variables (Keating et al, 1992). Rainfall governs crop yields in the arid tropics and determines the choice of crops that can be grown. There is a relationship between crop yield and water supply which can be determined when crop water requirements and crop water deficits, on the one hand and maximum and actual crop yield on the other, can be quantified (Doorenbos and Kassam, 1979).

2.3.2 Evaluating Rainfall Onset

Onset of rains is a signal for the beginning of the planting season. It has been found to indicate whether adequate rainfall for crop establishment will be received or not. In semi arid eastern Kenya, farmers plant in response to what they perceive as the onset of the rainy season (Keating et al, 1992). In the ASAL defining an event to mark the start of the rain is not easy, due to the intermittent and patchy nature of tropical rainfall (Stern et al., 1981). Methods that have been used include the curvature method by Illesamni, 1972 and amount per decade by Stern et al, 1981.

Illesamni (1972), proposed the use of Pentad method to determine the onset, advance and retreat of rainfall in Nigeria. The method involves plotting the cumulative percentage of the mean annual rainfall that occurs at each 5 days interval. The onset is then taken as the first point of maximum curvature on the graph. The end of the rains is signaled by the point of maximum negative curvature, occurring after an accumulation of about 90% of the annual rainfall.

The method present difficulty in establishing the point of maximum curvature by visual observations. It is also not applicable for two season rainfall areas like Machakos. Illesamni (1972) quoted by Alusa (1974) put onset of rains as the pentad when mean five day rainfall consistently exceeds 1/73rd of the mean annual rainfall. The number of pentads in one year is 73.

Onset of the rains has also been based on the rainfall amount within a given number of days. Onset is proposed to occur during the first 10 days with rainfall of more than 25 mm, provided that rainfall in the next decade exceed half the potential evapotranspiration (Stern et al, 1981). In eastern Kenya onset of the long rains was deemed to occur when 40 mm of rains was recorded within an 8-day period with no more than one contiguous dry day. The onset rule for the short rains was similar but based on 30 mm instead of 40 mm (Wafula et al, 1992). The 30 mm rainfall amount per decade was also quoted in FAO (1979). Defining onset by use of rainfall amount within a given number of days ensure the crop has enough moisture to germinate and continue to thrive due to adequate moisture in the soil. (FAO, 1979).

2.3.3 Effects of onset date on rainfall

Wafula et al, (1992) and Onyango et al, (1989) reported that the date of season onset was negatively correlated with the amount of rainfall received in eastern Kenya semi arid areas mainly for the long rainy season. Early onset results to more season's rainfall. The start of the rains can therefore be a useful predictor of potential yield and can therefore be used to determine resource allocation.

According to Stewart and Faught (1984) the date of season onset is negatively correlated with the amount of rainfall received and the seasons duration is dependent mainly on date of onset (Fig 2.1 a and b). Stewart and Faught (1984) also classified onset into early and late onset. Early onset occurred before 18th March (calendar day 77) and 2nd November (calendar day 306) for long and short rains respectively. Seasons starting after these dates within the defined onset windows were said to be late (Fig 2.1 a and b).

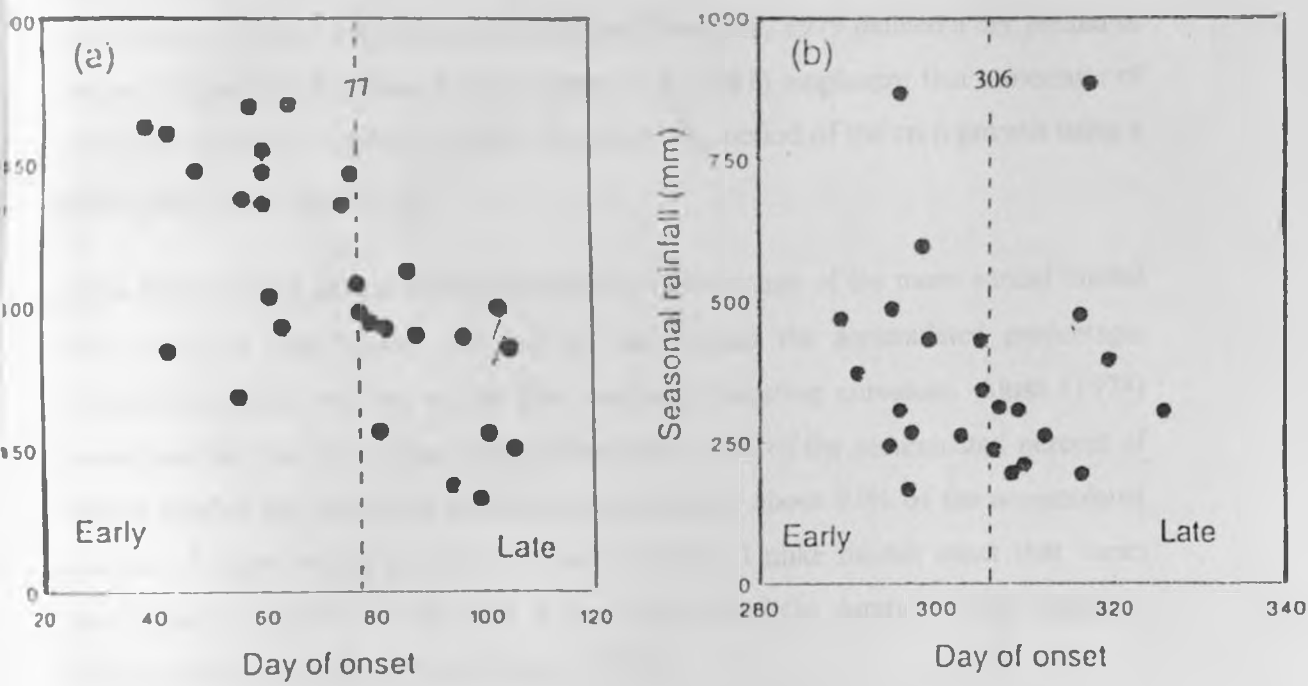


Fig 2.1. The relationship between total seasonal rainfall for (a) long rains and (b) short rains, and Julian date of rainy season onset for Katumani (lat. 1° 35'S;long. 37° 14'E; alt. 1601 m) for the period 1957-1988. Classification into early and late onset based on the criteria of Stewart and Faught (1984).

2.3.4 Cessation of Rains

The end of the rains marks the period when moisture availability to the crops reduces due to reduced rains. Annual crops can produce a crop if the rainy seasons' duration is as long as the crop growth duration. However, if the rainy seasons' duration is shorter than the crop growth duration, the crop continues to obtain moisture from soil reserves. As the soil moisture continue to be depleted, plants that have still not matured may start to suffer moisture stress that could result to poor yields or death of crops.

Cessation of rains is defined by Stern (Stern et al 1981) as the first occurrence of a 10-day dry spell after a specified date. The specified date being the date when rain has been known to cease over the years. Bille and Heemstra, 1979 defined a dry pentad as one with rainfall of less than 8.3mm. Stern et al. (1981) emphasize that a measure of soil water storage is needed to define the end of the period of the crop growth using a simple daily water balance.

Alusa (1974) using pentad rainfall obtained the percentage of the mean annual rainfall that occurs at each pentad. He derived and plotted the accumulated percentage. Cessation of rain was put as the first maximum negative curvature. Alusa (1974) found that the first rains (long rains) ceased after 67% of the accumulated percent of annual rainfall has fallen and short rains ceased after about 95% of the accumulated percent of mean annual rainfall had been recorded. Unlike rainfall onset that varies considerably, cessation of the rains is less variable and the duration of the season is not dependent on it (Stewart and Faught, 1984).

2.3.5 Length of the Rainy Season

Duration of the rain is taken as that period between onset and cessation (Stern et al,.1981). The length of the rainy season determines the type of crops to be planted and their productivity. The lengths of the growing seasons in semi-arid areas range between 70-90 days (FAO, 1979). Where the rainy season is shorter than the planted crop's growth duration, supplemental irrigation is necessary (Oweis et al, 1999).

2.3.6 In-Season Drought Occurrence

The occurrence of dry spells during the rainy season may impose unbearable moisture stress on crops at critical phonological stages. A dry spell is a period of dry day(s) between two successive rainy days. Crops suffer water stress when the soil moisture content in the root zone drops below a certain threshold level. In circumstances where rainfall resumes after a long dry spell, the growing crop may have suffered severe moisture stress to fully recover and give maximum yield or may have completely dried up. Njoroge et al, 1996, considered a period of 10 days to be the duration of a dry spell needed to start reducing the growth of the maize crop because of the effects of water deficits in semi-arid Eastern Kenya.

Droughts are natural phenomenon and cannot be prevented but there are possibilities of predicting them to provide the necessary information for early warning and preparedness (Sharma 1994). A drought is defined as a period during which rainfall is less than 50% of the long term mean. A month with less than 50 mm of rainfall is considered a dry month. The minimum amount of rainfall required for crop growth is 50 mm/month according to Bille and Heemstra, 1979. Sharma defined drought as a period of at least 15 consecutive days with none receiving 1 mm or more of rainfall. Studies have focused on rainfall amount received within the growing season but distribution of rainfall within the seasons is often more critical than total amount. Njoroge et al, 1996 classified maize growing zone in Kenya into six agro-climatic zones where Mwala division fell under dry transitional where severe drought are experienced during grain filling and early in the season. Maize production is seriously reduced by drought in at least 6 out of 10 years. Intra-seasonal drought is reported to occur both in the long and short rainy season (Mugo and Njoroge, 1996).

2.4 Yield Response to Water

When water supply does not meet crop water requirements, actual evapotranspiration (Eta) will fall below maximum evapotranspiration (Etm) (Richard et al, 1998; Smith, M 1992; Doorenbos and Kassam, 1979; Doorenbos and Pruit, 1977). Under this condition, water stress will develop in the plant which will adversely affect crop growth and ultimately crop yield. Crops are more sensitive to water deficit during emergence, flowering and early yield formation than they are during early (vegetative, after establishment) and late growth periods (ripening) (Doorenbos and Kassam, 1979; Doorenbos and Pruit, 1977).

Yield response to water deficit can vary among varieties of the same crop. In general high yielding varieties are also the most sensitive to water stress. Low yielding ones are less responsive, hence more suitable for rainfed crop production in areas that are prone to drought (Doorenbos and Kassam, 1979).

The response of crop yield to water supply is quantified through the yield response factor (Ky) which relates relative yield decrease (1-Ya/Ym) to relative evapotranspiration deficit (1-Eta/Etm) in the relationship;

$$(1-Ya/Ym) = Ky(1-Eta/Etm) \quad \text{...} \quad (2.1)$$

Where:

Ya = actual yield

Ym = Maximum yield

Ky = yield response factor

Eta = actual evapotranspiration

Etm = maximum evapotranspiration

Yield is inversely correlated to Ky. Doorenbos and Kassam (1979) report that the decrease in yield is quite high for maize when water deficits occurs. The most sensitive period is flowering especially if there was no prior water deficit. In Mwala area, a reported distinct dry period results into serious yield reduction of maize since it occurs at the stage of peak water requirements (MOA, 1987).

For maize production, supplemental irrigation should be programmed to meeting water deficits during flowering and yield formation whose Ky values are 1.5 and 0.5 respectively (Doorenbos and Kassam, 1979). Water stress during vegetative development reduces expansive growth of stems and leaves and results into reduced plant height, lower leaf area index (LAI) and reduced internode lengths (Rhoads and Bennett, 1990).

Water deficits during silking, tasselling and pollination are especially detrimental to yield and may result in the delay of silking, reduced silk elongation and inhibition of pollination. Stress imposed shortly before or after silking considerably reduces seed numbers. Stress imposed later during the grain-filling period may cause increased leaf senescence, a shorter duration of the seed-filling period, increased lodging and lower individual seed weight. Effect of stress during the grain filling period is a reduction in current photosynthate supply, which is critical for optimum seed filling.

2.4.1 Crop Water Requirements

Michael (1978) defines crop water requirement (CWR) as the quantity of water required by a crop over a given period of time for its normal growth under field conditions at a given place. Crop water requirements varies with different crops, atmospheric demand, size of fields, advection, soil water availability, salinity, method of irrigation and cultivation methods and practices.

2.4.1.1 Estimating Reference Crop Evapotranspiration

The reference crop evapotranspiration (Eto) 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. Eto is expressed in mm per day. There are several methods used for estimating Eto and they are clearly outlined in Doorenbos and Pruit (1977). The choice of the method to be used depends on the data available.

2.4.2. Calculating (Eto) Using the Pan Evaporation Method

Evaporation from an open water surface provides an index of the integrated effect of radiation, air temperature, air humidity and wind on evapotranspiration. Plants respond similarly to the same climatic conditions. Differences in the water surface produce significant differences in the water loss from an open water surface and the crop (Allen et al, 1998). Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature, humidity of air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance. Empirical coefficients (Kp) to relate pan evaporation (Epan) to Eto have been applied in the relation shown below (Doorenbos and Pruit, 1977 and Doorenbos and Kassam, 1979). Kp is influenced by pan dimensions, construction materials, wind run, vegetation surrounding pan and relative humidity level (Doorenbos and Pruit, 1977)

$$Eto = K_p . E_{pan} \quad (2.2)$$

where:

Eto = Reference crop evapotranspiration

E_{pan} = pan evaporation in mm/day and represents the mean daily value of period considered

K_p = pan coefficient

The pan method is simple and requires only the pan evaporation data (Heermann, 1985). In the absence of rain, the amount of water evaporated during a period in mm corresponds with the decrease in water depth in that period.

Several different types of pans exist. The colour, size, and position of the pan have a significant influence on the measured evaporation results. The pan coefficients are pan specific. In selecting the appropriate pan coefficient the pan type, ground cover, its surrounding, general wind and humidity conditions should be checked (Doorenbos and Pruit, 1977 and Doorenbos and Kassam, 1979).

2.4.3 Estimating Crop Water Requirement

Crop coefficient (Kc) relates reference crop evapotranspiration of a disease free crop grown in large fields under optimum soil water and fertility conditions and achieving full production potential under the given growing environment to crop evapotranspiration (Etc). The equation relating Etc with Kc and Eto is:

$$Etc = Kc*Eto \quad 2.3)$$

Where;

Etc = crop evapotranspiration.

Eto = reference crop evapotranspiration

Kc = crop coefficient

Factors affecting the value of Kc are mainly crop characteristics, rate of crop development, length of growing season and climatic conditions. According to

Doorenbos and Pruit (1977) crop growing season has been divided into 4 stages as shown in Table 2.1

Table 2.1: Crop growth stages. The growth stages are divided into initial, crop development, mid stage and late season.

stage	*start*	*End*	*Kc for maize*
Initial (1)	Germination	Crop cover up to 10 %	0.2 (20 days)
Crop development (2)	End of initial stage	Crop cover 70-80 %	0.4–1.1 (30 days)
Mid stage (3)	End of crop development	Start of maturing as indicated by discolouring of leaves	1.1 (30days)
Late season stage (4)	End of mid stage	Full maturity or harvest	1.1-0.6 (20 days)

For Mwala division, Kc and crop development stages were derived from Doorenbos and Pruit, 1977. Their results are as indicated in the table 2.2 below.

Table 2.2: Crop development stages (1-4) and Kc for Katumani composite in Mwala division. Source: MOA, 1987.

	Number of decades from seeding to physiological maturity.								
Decade	1	2	3	4	5	6	7	8	9
Stage	1	1	2	2	3	3	3	4	4
Kc	0.4	0.6	0.7	0.93	1.05	1.05	1.05	0.91	0.66

2.4 Irrigation Requirements

Irrigation requirement is that amount of water required by the crop but is not met by the local effective rainfall. It needs to be applied to the growing crop to facilitate proper crop growth.

2.5.1 Net and Gross Irrigation Requirement

Irrigation is never 100% efficient (Doorenbos and Pruit, 1977). Losses occur during conveyance and application of water. If waterproof pipes are used to convey the water, conveyance losses can be reduced to zero. Application losses result due to unequal and excessive depth of wetting, lack of proper water supply control, care taken by the irrigator and leaks in pipes (Sifuna, 1997). Due to these losses an efficiency factor is incorporated in computation of irrigation supply.

Net irrigation requirement is the difference between the field capacity and the soil moisture content in the root zone before starting irrigation (Michael, 1978). Gross irrigation requirement is net irrigation requirement plus losses in water application and other losses. It is given in the relationship;

$$\text{Gross irrigation requirement} = \frac{\text{Net irrigation requirement}}{\text{Field efficiency of system}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.4)$$

A method of calculating the net irrigation water requirement during a growing season was given by Heermann (1985) and Doorenbos and Pruit (1977) as

$$In = Etc - Pe - Gw - Ws \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.5)$$

Where;

In = net irrigation water requirement, mm/month

Etc = Evapotranspiration requirement, mm/month

Pe = Effective rainfall, mm/month

Gw = The water table contribution from a high water table

Ws = available stored soil water

Ground water contribution is negligible where the water table is deep.

2.5.2 *Effective Rainfall*

Effective rainfall is defined as that part of rainfall which is used effectively by the crop after rainfall losses due to surface runoff and deep percolation have been accounted for (Dastane, 1974). In Eastern Kenya, runoff has been observed from a rainfall event of as low as 7.8 mm (Wafula, 1997). Effective rainfall can be approximated using the following formulae by Gichuki, 1998.

$$Re = 0.8R - 25 \text{ if } R > 75 \text{ mm / month} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.6a)$$

$Re = 0.6R - 10$ if $17 < R < 75$ mm / month............................ .(2.6b)

$Re = 0$ for $R < 17$ mm / month.. (2.6c)

Where;

Re = Effective rainfall in mm for the month

R = Total monthly rainfall in mm

Evaluation of effective rainfall involves measuring rainfall, losses by surface run-off, percolation losses beyond the root zone and the moisture uptake by the crop for evaporation. Several other methods of calculating effective rainfall are outlined by Dastane (1974). In water balance calculations, carried out for the irrigation scheduling, the intake of rainwater into the soil is determined on a daily basis and rainfall losses due to deep percolation and surface runoff are estimated according to actual soil moisture content in the root zone. Total rainfall and not effective rainfall is therefore used for the water balance calculations and effective rainfall calculated over the total growing season (Smith, 1992).

Effective rainfall is high for soils of high water holding capacity. Soil and water conservation structures e.g. terraces, ridging and mulching increase effective rainfall by reducing runoff losses. For a runoff harvesting system, effective rainfall is increased by increasing the amount of water received by the crop area and reducing overflow losses. Runoff is increased by increasing the catchment area or by surface treatment.

2.5.2.1 Factors Influencing Effective Rainfall

Effective rainfall of a place is influenced by several factors, which include;

Rainfall characteristics: Greater quantities as well as intensities of rainfall normally reduce the effective fraction of rainfall, increasing runoff and lessening infiltration.

Meteorological parameters: These include temperature, radiation, relative humidity and wind velocity. An increase in temperature, radiation, wind velocity and a decrease in relative humidity enhance evaporation thus lowering effective rainfall.

Land characteristics: Water stays longer on flat and leveled land thus increasing effective rainfall. On sloping land there is rapid runoff and effective rainfall is reduced.

Soil characteristics: For maximum absorption of rain high infiltration rate and permeability are desired. Effective rainfall increases with increased water holding capacity in a soil. Amount of water held and retained by a soil depends upon its depth, texture, structure and organic matter content.

Soil water characteristics: These characteristics include depth of water received, turbidity, viscosity, temperature and nature of the dissolved salts.

Management practices: Management practices such as bunding, terracing, ploughing, ridging and mulching reduce runoff and increase effective rainfall.

Crop characteristics: Effective rainfall is directly proportional to the rate of water uptake by the plant. Factors that influence rate of water uptake are the degree of ground cover, rooting depth and stage of growth.

2.5.3 Irrigation Scheduling

Irrigation scheduling involves determining the time for water application and determining amount of water to apply. To do irrigation scheduling, allowable deficit at each growth stage must be known and the level of water already in the root zone. Irrigation is needed when the soil water content drops to a depletion rate of 50% of available water (Field capacity minus permanent wilting point in the root zone) according to Oweis et al. (1999). For maize it is necessary to satisfy 75-80% of the crop water requirements starting from the most sensitive stages to the less sensitive stages (Varlev and Popova, 1996). Varlev and Popova further reported that if 2/3 of required water was available, yield levels of 90-95% of maximum yield were attainable.

Maximum evapotranspiration (Etm) will be maintained until the fraction (p) of the available soil water, has been depleted (Doorenbos and Kassam, 1979). Beyond this depletion level actual evapotranpiration (Eta) becomes increasingly smaller than Etm until the next irrigation or heavy rain. When Eta is less than Etm, the magnitude of Eta will depend on the remaining available soil water and on Etm. The remaining available soil water is related to the crop group and Etm and to the total available soil water over the root depth as shown in the Table 2.3 below.

Table 2.3: Soil water depletion (p) for crop groups and maximum evapotranspiration (Etm) Water depletion capacity increases from group 1 to 4 Source: Doorenbos and Kassam, 1979.

Crop group	*Etm mm/day*								
	Etm=2	*Etm=3*	*Etm=4*	*Etm=5*	*Etm=6*	*Etm=7*	*Etm=8*	*Etm=9*	*Etm=10*
(1) Onion, pepper, potato	0.50	0.425	0.35	0.30	0.25	0.225	0.20	0.20	0.175
(2) Banana, cabbage, pea, grape, tomato	0.675	0.575	0.475	0.40	0.35	0.325	0.275	0.25	0.225
(3) Alfalfa, bean, wheat citrus, sunflower, .pineapple, groundnut, watermelon,	0.80	0.70	0.60	0.50	0.45	0.425	0.375	0.35	0.30
(4)Cotton, maize, olive, sunflower, sorghum, soybean, sugarbeet, sugarcane, tobacco	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.40

Irrigation scheduling requires the knowledge of the amount of water already present in the soil, the moisture retention capacity for the soil, crops grown and climate. Knowledge of crop root depths is also required in irrigation management as the absorptive capacity of water for a plant is determined by the distribution and depth of the root system (Schuurman and Goedewaagen, 1971). Determination of root depth requires two values namely rooting depth of initial stage representing the effective soil depth from which the small seedling extracts its water and the maximum rooting depth attained by the crop (Smith, 1992).

2.5.4 *Field Capacity*

Field capacity is the amount of water remaining in a well drained soil when velocity of downward flow from saturated soil has become minimal (Loveday, 1974). A saturated soil will reach field capacity after two to three days of free drainage (Rich, 1971). Field capacity depends on soil texture and structure. Soil structure has the major role of determining field capacity (Bear et al,. 1968). Water in excess of field capacity value quickly drains away and is not of much value to the crops (Taylor, 1972).

In the laboratory, field capacity is determined by use of pressure plate apparatus, where field capacity is taken to be the water held at a tension of 1/3 bar suction (Hillel, 1980). The field capacity is a constant for any given soil (Hillel, 1980). The available water for plant use is the difference between field capacity and permanent wilting point. It is low at less than 80 mm/m, moderate at 80-120 mm/m, high at 120-160 mm/m and very high at above 160 mm/m (MOA, 1978).

2.5.5 Permanent Wilting Point

Marshall (1959) defined permanent wilting point as the moisture level at which plants wilt and fail to regain their original cell turgidity even when placed in wet soil. At permanent wilting point the ease of release of water to plants is too small to counter-balance the transpiration losses. Below permanent wilting point water is considered unavailable to the growing crops (Doorenbos and Kassam, 1979).

Permanent wilting point is dependent on soil profile features and is determined by amount of water in soil at various depths. It involves any soil depth in which plant roots are growing (Taylor, 1972). In the laboratory permanent wilting point is determined by use of the pressure plate apparatus. Undisturbed saturated soil samples are subjected to a suction of 15 bars and the permanent wilting point is taken as the water held at this pressure (Hillel, 1980).

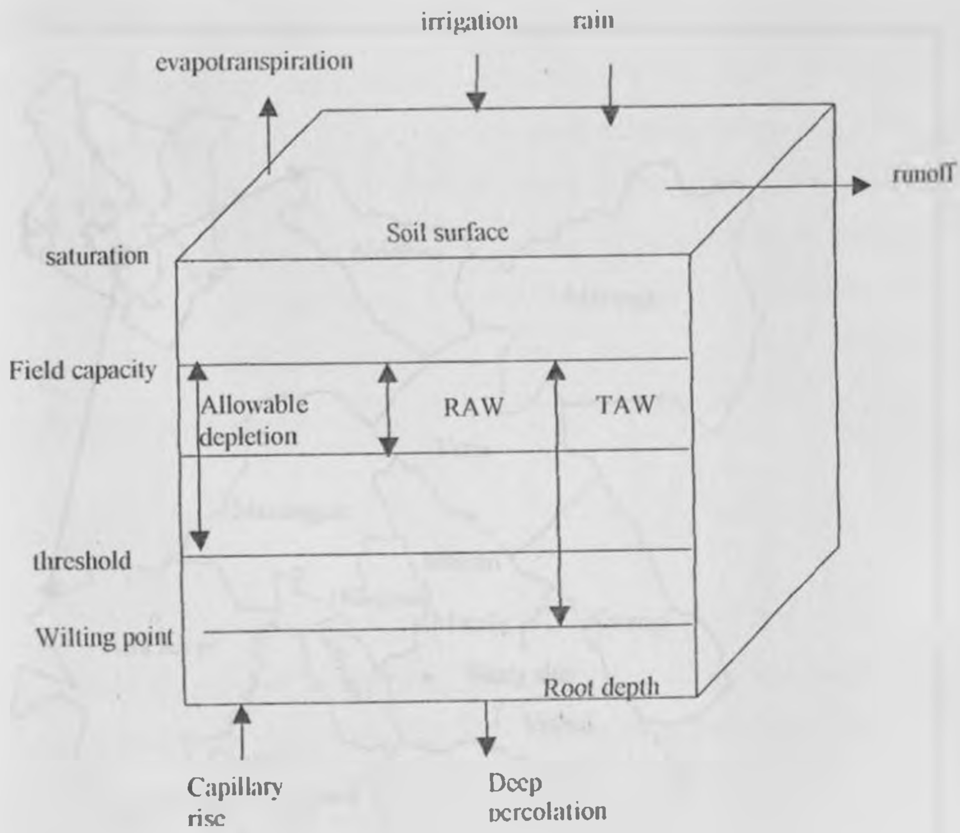
2.5.6 Soil Water Balance

A field water balance is an account of all quantities of water added to, subtracted from, and stored within a given volume of soil during a given period of time (Hillel, 1980). In any given volume of soil, the difference between the amount of water added (W_{in}) and amount of water withdrawn (W_{out}) during a certain period is equal to the change in water content (ΔW) during the same period.

$$\Delta W = W_{in} - W_{out} \qquad (2.7)$$

W_{in} is made up of rainfall, irrigation and upward capillary flow into the root zone while W_{out} is made up of runoff, downward drainage out of the root zone, evaporation and evapotranspiration (Hillel, 1980). A water balance quantifies the difference between the two as a change in the amount of the soil moisture stored (Stone, 1976;

Sifuna, 1997). The root zone is a continuous soil layer with an upper boundary at the soil surface and a lower boundary at a depth corresponding to the crop rooting depth (Fig 2.3). Water that is available for plant use is marked depletion. Water enters and leaves the root zone via these two boundaries but is also removed directly from the root zone via the water uptake by plant roots which is almost entirely discharged as transpiration (Driessen, 1986).



RAW = Readily available water; TAW = Total available water

Fig 2.3; Root zone water balance.

3.0 MATERIALS AND METHODS

3.1 Description Of Study Area

The study area is in Mwala village of Mwala division, Machakos district. It lies 40 KM North East of Machakos town at approximately 37^0 , 27 East and 1^0, 21 South. The study site is about 1Km to the West of Mwala town (Fig 3.1)

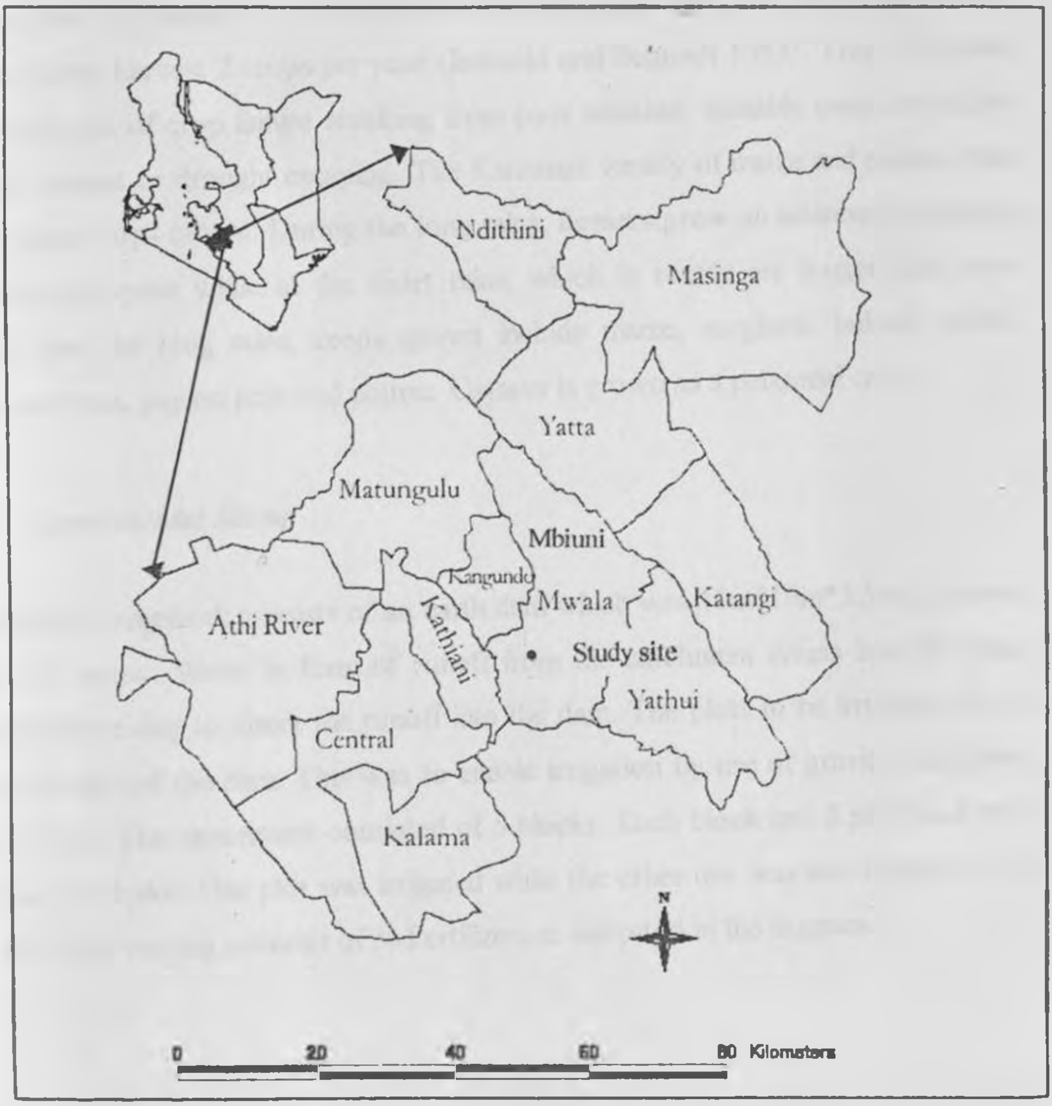


Fig. 3.1 The study area

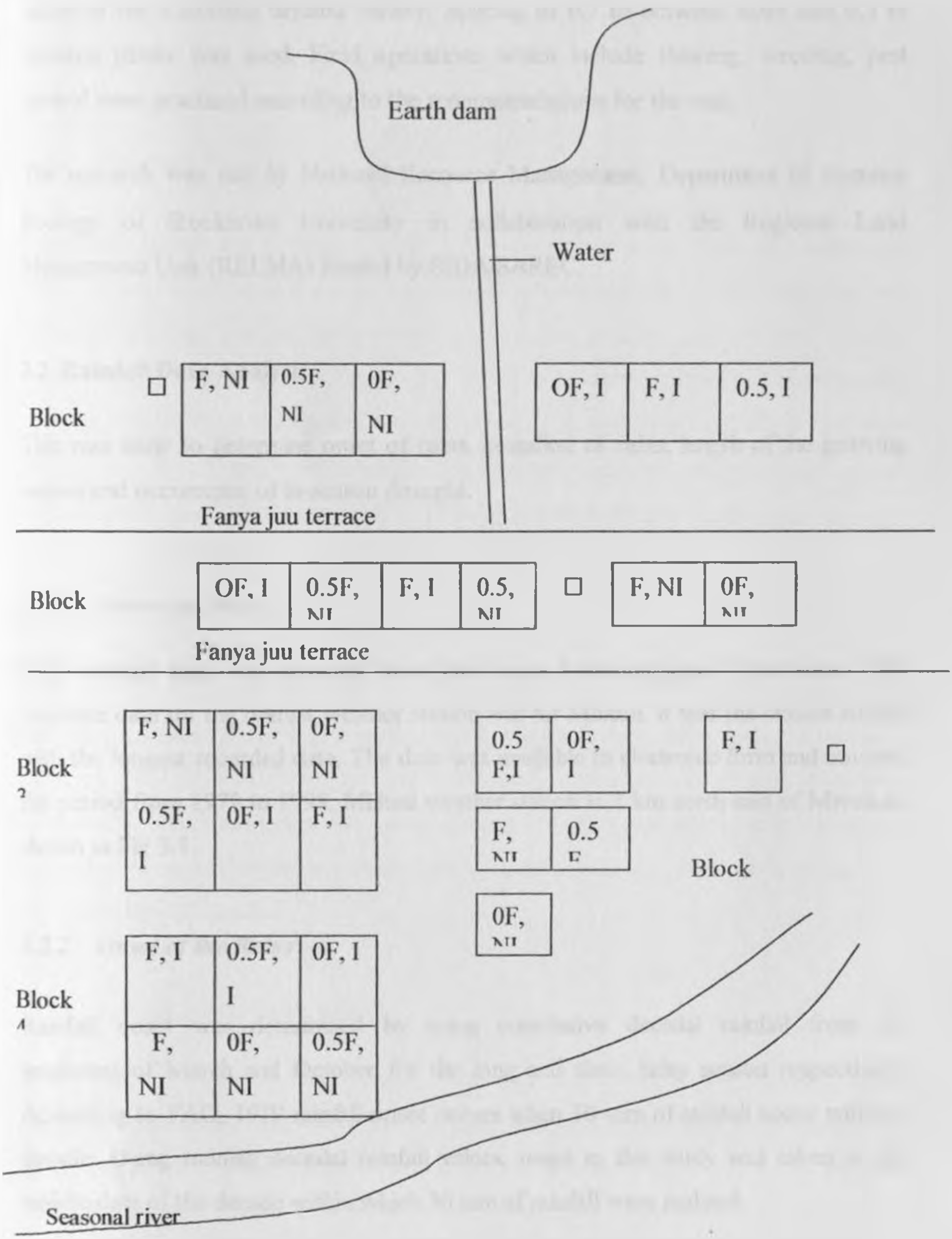
3.1.1 Characterization of study area

In Mwala soils are Orthic Acrisols. Soil fertility in the region is generally low. Crops are intercropped without any addition of mineral fertilizers. Some farmers use farmyard manure that is below the recommended rates because most of it is deposited on the pasture due to the common practice of free-range grazing. Organic matter content is low, not exceeding 1% (MOA, 1987). Moisture storage capacity is rated low (80-120 mm). Infiltration capacities are also low.

Farmers plant one annual crop during the first rains (long rains) and one in the second but they rarely harvest 2 crops per year (Jaetzold and Schmidt 1983). This is because of the high risk of crop failure resulting from poor weather. Suitable crops are either drought tolerant or drought escaping. The Katumani variety of maize and pigeon peas are the main crops grown. During the long rains, farmers grow an intercrop of maize, beans and cowpeas while in the short rains, which in reality are longer and more reliable than the long rains, crops grown include maize, sorghum, bulrush millet, beans, cowpeas, pigeon peas and cotton. Cassava is grown as a perennial crop.

3.1.2 Experimental Set-up

The project framework consists of an earth dam which was 10m*10m*3.5m as shown in fig 3.2 below. Water in form of runoff from the catchment drains into the dam. Channels were dug to direct the runoff into the dam. The plots to be irrigated are on the lower side of the dam. This was to enable irrigation by use of gravity. Each plot was 7m*7m. The experiment consisted of 5 blocks. Each block had 2 plots and each plot had 3 subplot. One plot was irrigated while the other one was non-irrigated. The sub-plots had varying amounts of N-Fertilizers as indicated in the diagram.



Key □: Profile pit, I : irrigated, NI : non-irrigated
F : full fertilizer, 0.5F : Half fertilizer, 0F : no fertilizer

Fig. 3.2; Experiment site.

Water was distributed by use of furrows between the plants. The crop grown was maize of the Katumani dryland variety. Spacing of 0.7 m between rows and 0.3 m between plants was used. Field operations which include thinning, weeding, pest control were practiced according to the recommendations for the area.

The research was run by National Resource Management, Department of Systems Ecology of Stockholm University in collaboration with the Regional Land Management Unit (RELMA) funded by SIDA/SAREC.

3.2 Rainfall Data Analysis

This was done to determine onset of rains, cessation of rains, length of the growing season and occurrence of in-season drought.

3.2.1 Source of Data

Daily rainfall data was acquired from the Kenya Meteorological Department. The available data for the nearest weather station was for Mbiuni. It was the closest station with the longest recorded data. The data was available in electronic form and covered the period from 1979 to 1998. Mbiuni weather station is 7 km north east of Mwala as shown in Fig 3.1.

3.2.2 Onset of the Rains

Rainfall onset was determined by using cumulative decadal rainfall from the beginning of March and October for the long and short rainy season respectively. According to FAO, 1979 rainfall onset occurs when 30 mm of rainfall occur within a decade. Using running decadal rainfall values, onset in this study was taken as the middle date of the decade within which 30 mm of rainfall were realized.

The onset of rain data was categorised into early, mid and late onset categories using the criteria developed by Stewart and Faught, 1984, where the onset window was divided into 3 sections. Onset window was taken as the period from the earliest onset to the latest onset. Early onset occurred during the first third, mid onset occurred during the second third while the remaining third after early and mid was classified as late onset. Onset dates were plotted against the rainfall amount for each season to show how onset influenced the rainfall amount.

3.2.3 Dry Spell Analysis

Dry spells within the growing season were determined using Bille and Heemstra, 1979 criteria where a dry pentad has rainfall of less than 8.3 mm. Dry and wet pentads within the growing season were marked. Wet and dry pentads for all pentads within the growing season were counted and their numbers indicated. This was done for long and short rainy seasons from 1979-1998. The probabilities of any pentad after onset being dry or wet were computed by obtaining the total number of dry or wet pentads after onset and dividing by 19, 19 being the total number of seasons.

3.2.4 Cessation of Rains

The criteria used was developed from Bille and Heemstra (1979) where a pentad with less than 8.3 mm rainfall was considered a dry pentad. For each season, 100 days of the crop growing season were marked from onset. One hundred days are the number of days the Katumani composite maize requires to reach maturity. Cessation pentad was taken as one after the last pentad with rainfall of more than 8.3 mm, within 100 days after rainfall onset.

3.2.5 Length of the Rainy Season

Length of the growing season was determined by obtaining the period in days between onset and cessation of the rainfall. This was determined by obtaining the difference between onset and cessation dates for each season for the period 1979 to 1998. Onset and cessation dates were as determined in sections 3.2.3 and 3.2.4 respectively.

The length of the growing season was then plotted against the onset date to determine whether there was any relationship between onset date and the length of the season.

3.3 Crop Water Requirements

3.3.1 Reference Crop Evapotranspiration

Pan evaporation data was used to work out reference crop evapotranspiration (Eto). Pan evaporation data for Katumani station was multiplied by a pan coefficient of 0.8 to obtain an estimate of Eto for Mbiuni (Doorenbos and Pruit 1977). This was done for the period 1979 to 1998. The relating equation is:

$$Eto = 0.8 * E_{pan} \quad (3.1)$$

Where:

Eto = reference crop evapotranspiration

E_{pan} = pan evaporation

0.8 = pan coefficient

3.3.2 Crop Coefficient

The length of maize growing season was divided into four stages namely initial (1). crop development (2). mid-season (3) and late season stage (4). The length of each stage was estimated and each stage crop coefficient established as outlined in Doorenbos and Pruit (1977) and given in Table 3.1 below.

Table 3.1: Katumani maize crop coefficient for the different growth stages.

Growth stage	*Length in days*	*Kc*
Initial (1)	20	0.4
Crop development (2)	30	0.4-1.1
Mid stage (3)	30	1.1
Late season (4)	20	1.1-0.6

The Kc values for crop development and late season growth stages were linearly interpolated between the indicated values.

To calculate crop water requirement, Eto data obtained from section 3.3.1 above and Kc data above were multiplied to obtain maximum crop evapotranspiration (Etm) using equation 2.3 given under section 2.4.3. It was assumed that planting took place on the first day of the decade of onset. The Etm values were determined for all the pentads of the growing season.

3.4 Irrigation Scheduling

Irrigation scheduling to determine how much water to apply and when was based on the field water balance and expressed in depth (mm) (Doorenbos and pruit, 1977).

Parameters used were maximum evapotranspiration (Etm), Root depth (Rz) in cm, effective rainfall (mm), water holding capacity of the soil (mm/m) and level of available soil water depletion (p). The root depth, water holding capacity of the soil and effective rainfall are discussed in section 3.4.1 to 3.4.3.

3.4.1 Root Depth

The root depth for maize was assumed to be at the planting depth of 10 cm on the first pentad. It developed linearly over a period of 10 pentads (the period it takes to flower) when it reached a maximum of 120 cm (Dastane, 1974). At 120cm the root development had reached maximum and the effective zone for water absorption remained there until harvesting (Appendix 6).

3.4.2 Water Holding Capacity of the Soil

The method used was the Pressure Chamber method as outlined by Richard, (1949). A Profile pit was dug, and 2 core samples collected every 20 cm for block 2. The profile pit dug was as shown in fig 3.3 below.

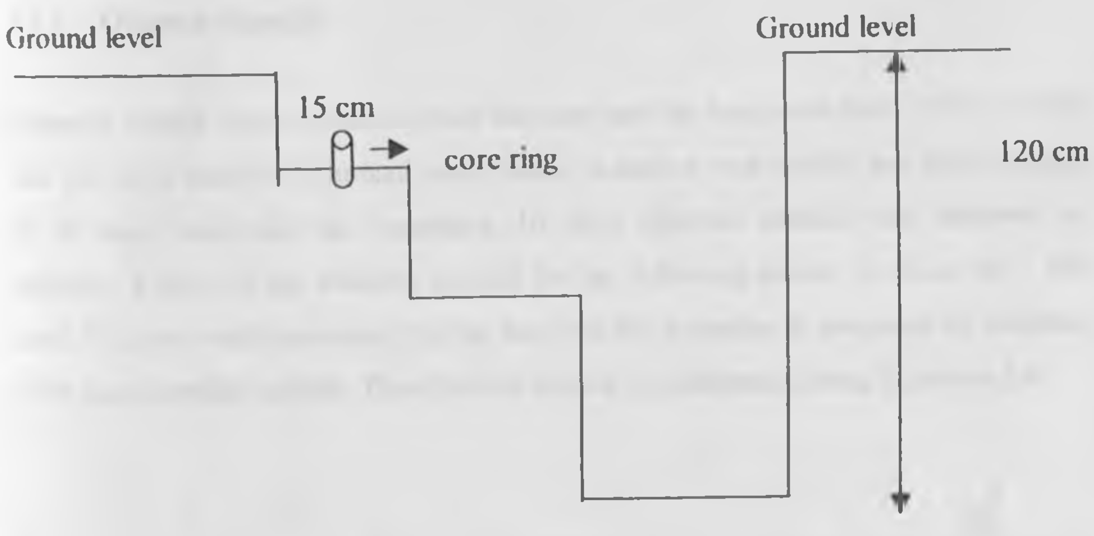


Fig 3.3: A profile pit showing how core samples were collected over the total rooting depth of 120 cm.

For block 1,3,4 and 5, the soils were first classified before samples were taken. Blocks 3,4 and 5 were fairly uniform and only one profile pit was dug to represent the 3 of them. Fig 3.2 shows where the 3 profile pits were dug. Each sample was covered with cheese cloth on one end and placed around a large tray that had water up to about half way to the top of the sample rings. The samples were left in the tray overnight to get saturated. The saturated samples were weighed and placed on a pre-soaked ceramic plate of 0.1 bars pressure. The plate was placed in pressure chamber and pressure adjusted to 0.1 bar. Samples reached an equilibrium weight after 4 days after which they were removed and weighed. The procedure was repeated with 15 bars ceramic plates and corresponding pressure of 15 bars at the pressure chamber.

Total available moisture was taken as the difference between the weight at pressure 0.1 bars (Field capacity) and 15 bars (permanent wilting point). The core samples were then oven dried and the mass determined. To convert available weight of moisture to depth of water (De), the following equation was used;

$$De = \text{Vol. Water } cm^3 / \text{Unit surface area (A) } cm^2 \;\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.2)$$

Where:

De = depth of water in the core ring in cm

$A = 25\ cm^2$

$1g = 1cm^3$

3.4.3 Effective Rainfall

Effective rainfall was estimated for all the short and the long rains from 1979 to 1998. The 100 days that the Katumani maize takes to mature was divided into three months of 30 days each and the remaining 10 days effective rainfall was obtained by obtaining a third of the effective rainfall for the following month, i.e from 90 – 100 days. This was made necessary by the fact that the formulae as proposed by Gichuki, 1998, uses monthly rainfall. The effective rainfall was estimated using Equation 2.6.

3.4.4 Irrigation Scheduling

Supplemental irrigation requirement was calculated for all the seasons by obtaining the difference between effective rainfall and Etc. To work out when and how much to apply, the growing season was divided into 1-30, 31-60, 61-90, 91-100 and the amount of water available from the rain or had to be met through supplemental irrigation determined.

- The Etc was calculated as in section 3.3.2
- Root depth for maize was assumed to be at 10 cm during the first pentad and was assumed to grow to a maximum of 120 cm after 10 pentads. The root depth for each pentad was linearly interpolated (section 3.4.1).
- The total rainfall for each period was obtained using Mbiuni station daily rainfall data. Rain water that was taken up by the crop was considered as the effective rainfall (section 3.4.3)
- The water holding capacity of the soil was determined by the pressure chamber method as given in section 3.4.2
- Level of allowable soil water depletion (p), was obtained from Table 3.2 below.

Table 3.2: Level of allowable soil water depletion (p) for maize in relation to maximum crop evapotranspiration.

Etm mm/da	2	3	4	5	6	7	8	9	10
p	0.875	0.80	0.70	0.60	0.55	0.50	0.45	0.425	0.4

Source: Doorenbos and Pruit, 1977, and Table 2.3 and 2.4.

Irrigation water was added when the available water dropped below the allowable soil moisture depletion. Available water for each pentad was not exactly equal to Wb for previous pentad during root development as additional root growth added onto the soil moisture available to the plant.

4.0 RESULTS AND DISCUSSION

4.1 Onset of Rains

Onset of the rains for the years 1979 to 1998 for Mbiuni station is shown in table 4.1. The 4th October was found to be the earliest date when the 30 mm of rain was received in a single decade for the short rains. It was 22nd February for the long rains.

Table 4.1: Onset of rains in Mwala from 1979 to 1998 for both the short and the long rains.

Year	*Short rains Onset date*	*Long rains Onset date*
1979	29/10/79	27/2/79
1980	19/10/80	13/3/80
1981	08/11/81	23/3/81
1982	09/10/82	12/4/82
1983	18/11/83	18/3/83
1984	04/10/84	18/3/84
1985	19/10/85	03/3/85
1986	19/10/86	28/3/86
1987	29/10/87	27/2/87
1988	29/10/88	13/3/88
1989	19/10/89	22/2/89
1990	19/10/90	18/3/90
1991	03/11/91	23/3/91
1992	24/10/92	07/4/92
1993	24/10/93	13/3/93
1994	04/10/94	22/2/94
1995	14/10/95	08/3/95
1996	29/10/96	28/3/96
1997	04/10/97	13/3/97

The beginning of the rainy season marks the period of planting crops in areas where rainfed agriculture is practiced. A threshold of 30 mm of rainfall in a single decade was noted for three years on date 4th October for short rains and twice on 22nd February for the long rains. These two dates were considered as the earliest dates when the seasons' rains are expected. Onset ranged from 4th October to 18th November for the short rains; a difference of 45 days and for the long rains onset ranged from 22nd February to 12th April; a difference of 50 days. Onset of rains within the first 15 days was considered as early onset. Mid-onset was within the following 15 days while late onset occurred during the remaining 15 days after mid-onset. A definition of early and late onset developed by Stewart and Faught (1984) does not give an indication of the period when onset is most likely to occur. This is because too many days have been categorized as early or late.

Most onset of the rains occurred at the middle of onset window which were 57.9% for the short rains and 47.4% for the long rains (Table 4.2 a and b). 15.8% and 21% of onsets occurred late for short and long rains respectively. During the short rains 84.2% of the onset occurred within the first 30 days of the onset period. The corresponding percentage for the long rains was 79%. This was an indication that most onsets will occur within the first 30 days of the onset period.

Table 4.2 a: Distribution of Mwala short rains onset from 1979 to 1998.

Category	*Date*	*Frequency*	*Percentage*
Early	04/10-19/10	5	26.3%
Mid	19/10-03/11	11	57.9%
Late	03/11-18/11	3	15.8%
Total	04/10-18/11	19	100.0%

Table 4.2 b: Distribution of Mwala long rains onset from 1979 to 1998.

Category	*Date*	*Frequency*	*Percentage*
Early	22/2-08/3	6	31.6%
Mid	08/3-23/3	9	47.4%
Late	23/3-12/4	4	21.1%
Total	22/2-12/4	19	100.1%

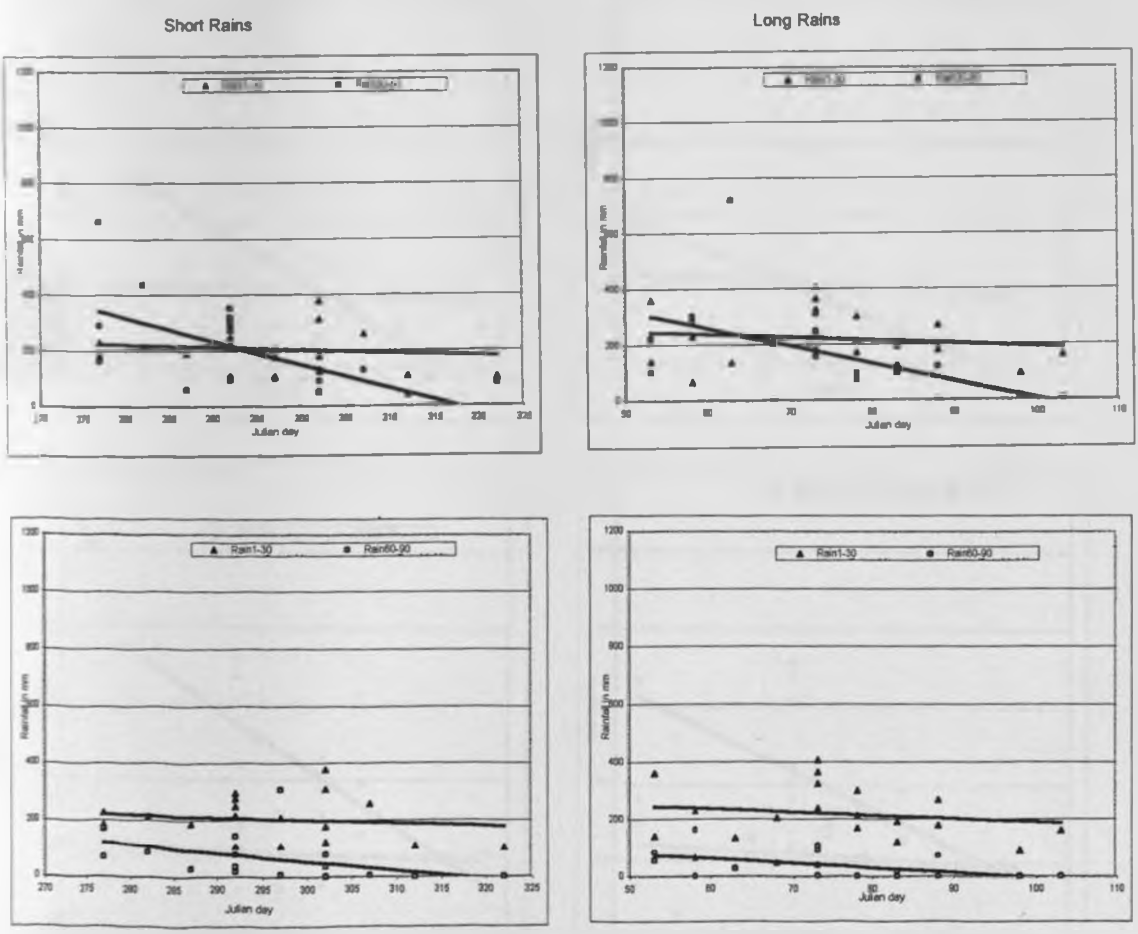
The 30 mm of rainfall in one decade that marked onset was followed by continuous rains which made crop development possible as is clear in Appendix 1.

4.1.1 Relationship between Onset Day and Rainfall Amount

The amount of rainfall received appeared to be influenced by the date of onset. Early onset resulted to more seasons' rainfall amount and vice versa. This means the rainfall amount was negatively correlated with onset date (Figs 4.1). The largest negative correlation was noted for rainfall amount falling 30-60 days after onset. This was followed by 60-90 days which showed less negative correlation than the 30-60 days. Then the 60-90 days after onset was less negatively correlated than 30-60 days and finally the 1-30 days after onset showed a small negative correlation with onset. The total rainfall amount for the 120 days after onset showed a strong negative correlation. The rainfall amount falling within 30-120 days showed to have more negative correlation than that for 1-120 days after onset.

This information is important particularly in planning for agriculture as it showed crop failure increases with increased lateness for onset. The type of crops grown, variety and level of inputs can be planned from a rainfall-onset point of view. Using a lot of inputs would be economically risky if the rains came late. This would be avoided by using less fertilizers and pesticides, and increasing the spacing between plants. This can be coupled by planting crops which are early maturing.

For the long rains the mean rainfall amount for 120 days after onset was 421.3 mm. Out of the total rainfall, 52% fell within 30 days after onset, 38.8 % was within 30-60 days after onset, 8.8% within 60-90 days and 0.3% within 90-120 days. The amount of rain received greatly decreased as the growing season progressed, with more than half of total seasons rainfall falling within the first 30 days as shown in Appendix 2.



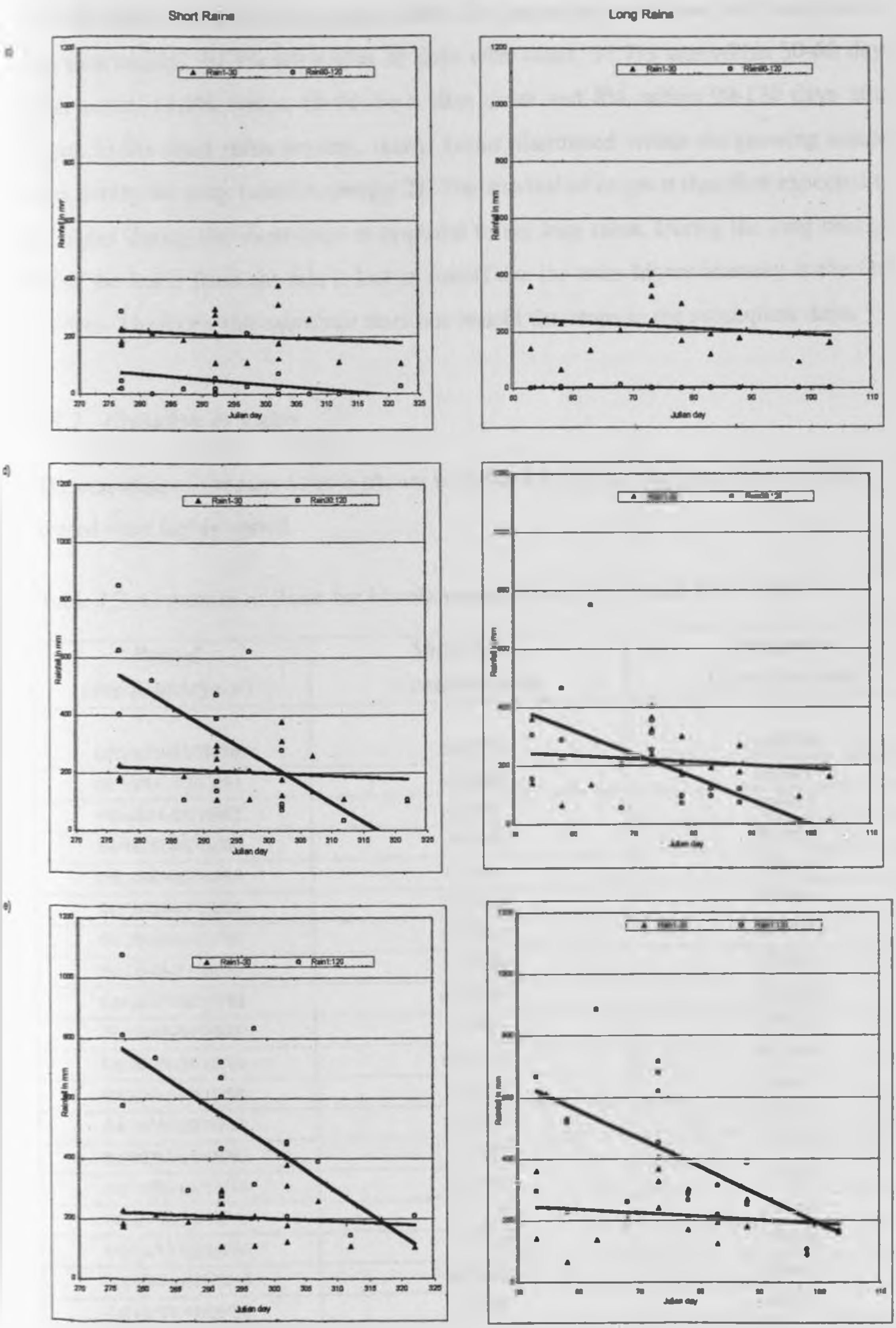


Fig 4.1: Relationship between rainfall amount and onset date for the periods 1-30 days, 30-60 days, 90-120 days, 30-120 days and 1-120 days.

For the short rains, the mean amount for 120 days after onset was 506.1mm. Out of the total rainfall, 40.7% fell within 30 days after onset, 37.7% was within 30-60 days after onset, 13.3% within 60-90 days after onset and 8% within 90-120 days after onset. In the short rainy seasons, rain is better distributed within the growing season than during the long rains (Appendix 2). The survival of crops is therefore expected to be higher during the short rains as opposed to the long rains. During the long rains, a lot of the water from the rain is lost as runoff due the rains higher intensity in the first 30 days. Therefore this rainwater does not benefit the crops in the subsequent days.

4.1.2 Cessation of Rains

The cessation of the rain dates is shown in Table 4.3 below. The dates when rainfall ceased were highly varied.

Table 4.3: Cessation of Rains for Mwala station during the period 1979-1998

Period (day/month/year)	*Short rains Cessation date*	*Long rains Cessation date*
04/10/79-03/10/80	28/12/79	22/5/80
04/10/80 -03/10/81	23/12/80	22/5/81
04/10/81-03/10/82	18/12/81	01/6/82
04/10/82-03/10/83	18/12/82	02/5/83
04/10/83-03/10/84	13/1/84	27/4/84
04/10/84-03/10/85	23/12/84	07/5/85
04/10/85-03/10/86	13/12/85	02/5/86
04/10/86-03/10/87	13/12/86	17/4/87
04/10/87-03/10/88	08/12/87	27/4/88
04/10/88-03/10/89	12/2/89	12/5/89
04/10/89-03/10/90	08/10/89	07/5/90
04/10/90-03/10/91	03/1/91	17/5/91
04/10/91-03/10/92	23/12/91	02/5/92
04/10/92-03/10/93	12/2/93	17/5/93
04/10/93-03/10/94	23/12/93	27/5/94
04/10/94-03/10/95	13/1/95	07/5/95
04/10/95-03/10/96	18/12/95	11/6/96
04/10/96-03/10/97	08/12/96	12/5/97
04/10/97-03/10/98	12/2/98	06/6/98

The cessation of rains marks the period of rainfall withdrawal. Annual crops that would not have matured by cessation are at risk of drying up due to increased moisture stress.

Annual crops should be ready for harvest by the time rainfall ceases as their only source of moisture is residual soil moisture. The residual soil moisture continuously gets depleted by the growing crops and once it is completely depleted the crops die. The day to mark when the rains come to an end in each season was difficult to isolate for Mbiuni station. This was because, often there were long dry spells in between the rainy season that were later followed by rains. A dry spell of even 15 days could not be taken to mark the cessation of the rains if the rains resumed thereafter. This was in dispute with Stern et al. (1981) as cessation was reported to occur if there was a 15 days dry spell after 90% of average annual rainfall has occurred. This would apply in areas where the wet season shows continuity but this was not the case in Mbiuni area.

The earliest cessation recorded was on 3rd December and the latest on 7th February for the short rains. This gives a range of 64 days. For the long rains the earliest cessation was on 17th April and the latest was on 6th June, a range of 50 days. This showed very wide variation that could make the growing season short or long. It follows that the growing crop could get caught up by the cessation of the rains before it matures and this increases the risk of crop failure. Stewart and Faught (1984) findings that the date of cessation of rains is less variable than that of the onset in semi-arid areas does not apply in the Mbiuni situation and probably other areas with similar weather patterns in Eastern province.

4.1.3 Length of the Growing Season

The wet period during which crop growth is possible varied from 40-108 for the short rains. For the long rains it was 20 to 95. The short rains were found to be longer than the long rains. The 19 years analyzed had a mean of 69.5 days of rain for the short rainy season and 60.3 days for the long rainy season. As a result, the probability of crop failure due to shortened rainy days is expected to be more for the long rains as compared to the short rains, although rainfall distribution also plays a significant role in ensuring proper crop growth. Crops that mature fast or are drought tolerant are the ones likely to reach maturity in most seasons. In the absence of intra-season dry spells, 70 days of rain are adequate for good maize yields (Doorenbos and Pruit, 1979). A rainy season of less than 70 days will subject the crop to moisture stress and consequently yield reduction whose severity will increase with decrease in the length of the growing season. For the short rains, rainfall duration of more than 70 days occurred in only 42% of the seasons. For the long rains, rainfall duration of more than 70 days occurred in 47% of the seasons. Njoroge et al (1996) reported there is severe yield reduction in Machakos in at least 6 out of 10 seasons. The 42% and 47% lengths of beyond 70 days during the short and the long rains respectively are close to the 40% findings by Njoroge et al (1996) when there is no severe yield reduction in Machakos.

The length of the growing season in Mbiuni area was less than 70 days in most of the seasons. The expected length of the growing season in semi-arid areas is 70 days. The results of the analysis are shown on table 4.4.

Table 4.4: Length of the growing seasons in Mwala for short and the long rains from 1979-98.

Period (day/month/year)	*Short rains*	*Long rains*
04/10/79-03/10/80	60	85
04/10/80 -03/10/81	65	70
04/10/81-03/10/82	40	70
04/10/82-03/10/83	70	20
04/10/83-03/10/84	53	40
04/10/84-03/10/85	80	50
04/10/85-03/10/86	55	60
04/10/86-03/10/87	55	20
04/10/87-03/10/88	40	60
04/10/88-03/10/89	103	60
04/10/89-03/10/90	78	75
04/10/90-03/10/91	73	80
04/10/91-03/10/92	50	40
04/10/92-03/10/93	108	40
04/10/93-03/10/94	60	75
04/10/94-03/10/95	98	75
04/10/95-03/10/96	65	95
04/10/96-03/10/97	40	45
04/10/97-03/10/98	128	85
Mean	69.5	60.3
std	24.7	21.7

During the short rains of 1997/98, there were above average rains that lasted for 128 days. This was an el-nino year whose rainfall total for 120 days after onset was 810.8mm and 679.3mm during the short and long rains respectively.

4.1.3.1 Relationship between Onset Date and Length of the Growing Season

The amount of rainfall received is of little help to crops if most of the rain is concentrated within few days. Rainfall that is well distributed over the growing season meets the crops water requirement throughout the crops growing season. The length of the growing season was longer for seasons when onset of rainfall came early as can be seen in Figures 4.2. This was more pronounced for the long rains. The date of rainfall onset has less influence on the length of the growing season for the short rainy season. The combination of more seasons' rainfall and longer lengths of the rainy season resulting from early onset of the rains is a good indicator of better crop yields. This would enable farmers to make decisions at planting based on rainfall onset date. Crops that take long to mature can be avoided if the onset of rains is late.

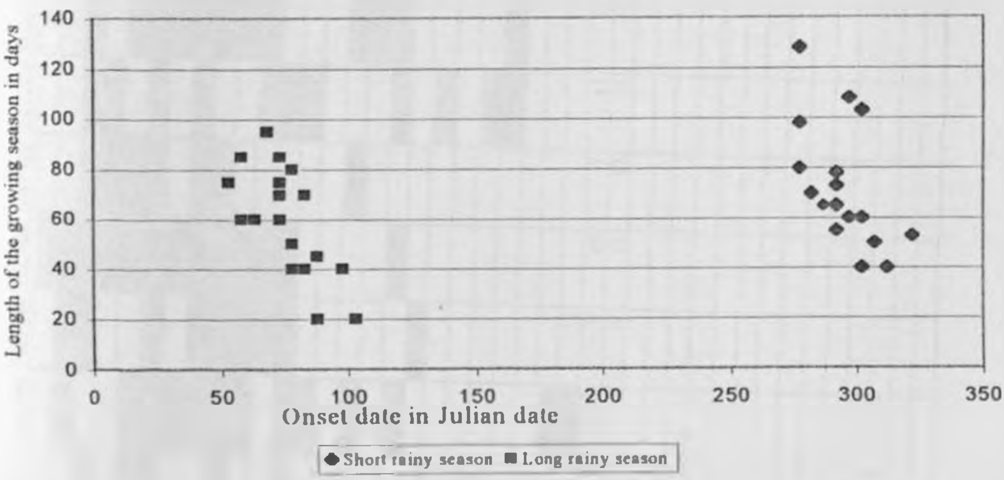


Fig 4.2; Relationship between onset date and length of the growing season.

4.1.4 Dry Spell Occurrence

The results are shown on Fig 4.3 a and b. The last 2 rows in the figures give the total number of dry and wet pentads during the 120 days of the growing season. The last 2 columns indicate the total number of wet and dry pentads for each season after onset for the 19 years analyzed.

	YEAR	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990	1990-1990	1991-199	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	TOTAL WET	DRY	% WET	% DRY
	PENTAD																							
	1																				9	10	47.4	526
	2																				18	1	94.7	5.3
	3																				12	7	63.2	36.8
	4																				13	6	68.4	31.6
	5																				14	5	73.3	26.3
	6																				12	7	63.2	36.8
	7																				16	3	84.2	15.8
	8																				13	6	68.4	31.6
	9																				9	10	47.4	52.6
	10																				11	8	57.9	42.1
	11																				11	8	57.9	42.1
	12																				9	10	47.4	52.6
	13																				6	13	31.6	68.4
	14																				6	13	31.6	68.4
	15																				4	15	21.1	78.9
	16																				7	12	36.8	63.2
	17																				4	15	21.1	78.9
	18																				3	16	15.8	84.2
	19																				3	16	15.8	84.2
	20																				6	13	31.6	68.4
	21																				4	15	21.1	78.9
	22																				2	17	10.5	89.5
	23																				3	16	15.8	84.2
	24																				2	17	10.5	89.5
TOTAL	WET	7	7	5	13	5	13	9	12	7	11	12	13	8	18	9	13	8	8	19	198		43.4	
	DRY	17	17	19	11	19	11	15	12	17	13	12	11	16	6	15	11	16	16	5		258		56.6

KEY

(shaded)	WET
(blank)	DRY

Fig 4.3 a; Short rains dry spell occurrence from onset to end of growing season at Mbiuni for the period 1979 to 1998.

	YEAR	1979-1980	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990	1990-1991	1991-1992	1992-1993	1993-1994	1994-1995	1995-1996	1996-1997	1997-1998	TOTAL WET	DRY	% WET	% DRY
	PENTAD																							
	1																				5	14	100	0
	2																				19	0	84.2	15.8
	3																				16	3	57.9	42.1
	4																				11	8	52.6	47.4
	5																				10	9	73.7	26.3
	6																				13	6	68.4	31.6
	7																				10	9	57.9	42.1
	8																				9	10	42.1	57.9
	9																				11	8	26.3	73.3
	10																				5	14	42.1	57.9
	11																				7	12	36.8	63.2
	12																				8	11	10.5	89.5
	13																				2	17	42.1	57.9
	14																				8	11	21.1	78.9
	15																				4	15	0	100
	16																				0	19	15.8	84.2
	17																				3	16	0	100
	18																				0	19	5.3	94.7
	19																				1	18	0	100
	20																				0	19	0	100
	21																				0	19	0	100
	22																				0	19	0	100
	23																				0	19	0	100
	24																				0	19	0	100
TOTAL	WET	11	11	6	3	4	10	10	4	11	8	13	7	3	4	9	8	7	5	8	142		31.1	
	DRY	13	13	18	21	20	14	14	20	13	16	11	17	21	20	15	16	17	19	16		314		68.9

KEY
WET
DRY

Fig 4.3 b; Long rains dry spell occurrence from onset to end of growing season at Mbiuni for the period 1979 to 1998.

Intra - seasonal dry spells cause moisture shortage that could result into yields being substantially depressed or complete death of plants. If the plants die there will be no harvest at all and this is partly the reason why there is persistent food shortages in the semi-arid areas of Kenya.

The results presented in tables 4.3a and 4.3b show a general increase in the number and length of dry spells with advance of the season during both the long and the short rains. During the long rains in Mbiuni, wet pentads during the first 25 days after planting were experienced 72.6% of the time. Dry pentads amounted to 27.4%. Planting was assumed to take place during the first pentad of the rainy season. The high percentage of wetness during the 6-30 days of the growing season was an indication of favourable moisture levels for crop growth that results into uniform crop establishment. The 27.4% dry pentads were mainly single dry pentads sandwiched between wet pentads.

During the long rains analyzed, there were 7 instances of 2 consecutive dry pentads and one instance of 4 consecutive dry pentads during 6-30 days after onset for the 19 years analyzed. Two consecutive dry pentads might require supplemental irrigation to save the crop from drying. Yield reduction at this stage is low owing to the low yield response factor of 0.4 (Doorenbos and Kassam, 1979; Allen et al, 1998.) at vegetative stage of growth. Any water available for supplemental irrigation needs to be sparingly used as it will definitely be required later in the growing season when dry spells are more pronounced. Some amount of water stress at the early stage of crop development help the crop to counter yield reduction during flowering stage of growth when water stress should be avoided (Doorenbos and Kassam, 1979.) Therefore supplemental irrigation at initial and vegetative stages needs to be done when it is absolutely necessary.

During 31-60 days of the long rains growing season, less than half of the pentads were wet. Increase in the length of dry spells was noted. In three seasons there were no wet pentads. These dry pentads were experienced in 1982-83, 1986-87 1991-92 and 1995-96. Also one wet pentad during 31-60 days was a sign the rainy season was about to end. This occurred twice in 1984 and 1993. About 60 days after planting coincided with the flowering stage whose yield response factor is highest at 1.5 for maize. The flowering stage was one when supplemental irrigation would have saved the crop in several seasons. These seasons would have been those that had rains continuing into the next stage of grain formation. This occurred in only 8 out of 19 seasons during the long rains.

Rainfall had ceased completely at 60 days in 9 seasons. In an additional 2 seasons, in 1987 and 1996 the rains received were not of much help as there was no rain during 31-60 days. In all these 9 and 2 cases above, the risk of crop failure was severe and supplemental irrigation using harvested rain water would not have saved the crop.

On average 7.47 pentads were wet during the long rains, a clear indication that supplemental irrigation using harvested rainwater would not save the maize crop from drying. This is attributed to the fact that areas requiring supplemental irrigation have water shortages and cannot meet huge irrigation water demands (Oweis et al, 1999). This huge water demands would have become necessary when the number of wet pentads were very few. This was so during the long rains of 1982-1983 and 1991-1992 which had only 3 wet pentads each and also long rains of 1983-1984, 1986-1987 and 1992-193 which had only 4 wet pentads each.

A weather shift was noted from 1990-1998 where the number of wet pentads remained persistently low and poorly distributed during the long rains. In this period no rainy season had more than 10 wet pentads while as before then, there were six seasons out of eleven with more than 10 pentads that were better distributed.

The short rains were slightly better. Generally there were more wet pentads. Each season had 10.4 wet pentads on average. During 1-30 days after onset, 3 seasons had 2 consecutive dry pentads which were the longest dry spells at this stage. There was at least a wet pentad during 31-60 days of the growing season for all the seasons. Prolonged intra-season droughts were noted to commence from pentad 12 after onset when the percentage dry pentad is persistently over 50%. A total of one or two wet pentads only during the 31-60 days was a sign of shortened rainy season and occurred in 5 seasons (26.3%). These were during the short rains of 1980-1981,1981-1982, 1983-1984, 1987-1988, 1996-1997 with 1981-82 and 1983-84 being particularly bad with only 5 wet pentads. Supplemental irrigation using harvested rainwater would not have helped the crop as the wet period was too short to have yielded enough runoff. Two seasons had 18 and 19 wet pentads and therefore did not require any additional moisture. These were experienced during the short rains of 1992-1993 and 1997-1998. The prolonged rains interfered with harvesting by causing sprouting and rotting of the already mature grains.

The short rains being slightly longer would be suitable for growing maize. Supplemental irrigation would have boosted the yield in 12 seasons (63%) as the rainfall received was slightly higher and rainfall distribution favourable. In general, an increase in the number of wet pentads was noted to develop over the years (Fig. 4.4), an indication the short rainy season is getting longer with advance in years.

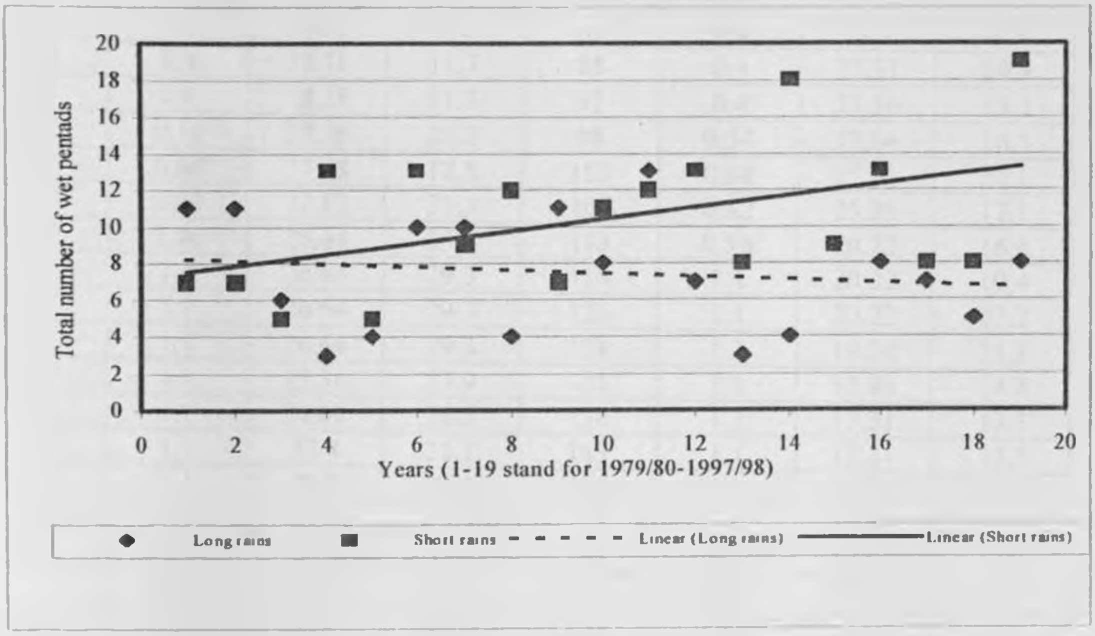


Fig 4.4: Total number of wet pentads for both long and short rains

4.2 Crop Water Requirement

4.2.1 Crop Coefficients

The results of maize crop coefficients are shown on Appendix 4. The Kc values for initial and mid seasons were extrapolated to obtain Kc values for crop development. The Kc values for mid and full maturity were extrapolated to obtain Kc values for late season. Crop coefficient values were lowest at 0.4 during initial stage and rose to a maximum of 1.1 at mid-season. The Kc values dropped to 0.6 at maturity. Crop water requirement is dependent on Kc values and a high Kc value results into high crop water requirement. This implies water requirement was low for initial and late season stages.

4.2.1 Reference Crop Evapotranspiration and Crop Water Requirements

The reference crop evapotranspiration (Eto) for each pentad is tabulated in Appendix 3. Eto and Etc for the 1997/98 short rains and long rains were as shown in Table 4.5.

Table 4.5: Eto and Etc data in mm/pentad for 1997-98 short and long rains respectively.

1996-1997 Short rains				*1997 - 1998 long rains*			
Date	*Kc*	*Eto*	*Etc*	*Date*	*Kc*	*Eto*	*Etc*
277				73			
282	0.4	23.60	9.4	78	0.4	21.3	8.5
287	0.4	24.32	9.7	83	0.4	21.3	8.5
292	0.4	28.16	11.3	88	0.4	27.31	10.9
297	0.4	28.16	11.3	93	0.4	33.36	13.3
302	0.54	28.16	15.2	98	0.54	30.64	16.5
307	0.68	27.68	18.8	103	0.68	27.93	15.1
312	0.82	27.12	22.3	108	0.82	25.21	17.1
317	0.96	26.64	25.6	113	0.96	20.22	16.6
322	1.1	26.64	29.3	118	1.1	20.22	19.4
327	1.1	26.64	29.3	123	1.1	20.22	22.2
332	1.1	26.64	29.3	128	1.1	19.34	21.3
337	1.1	25.36	27.9	133	1.1	13.46	14.8
342	1.1	24.08	26.5	138	1.1	12.31	13.5
347	1.1	22.8	25.1	143	1.1	12.31	13.5
352	1.1	22.8	25.1	148	1.1	17.03	18.7
357	1.1	22.8	25.1	153	1.1	12.31	13.5
362	0.975	22.8	22.2	158	0.975	12.04	13.2
3	0.850	28.72	24.4	163	0.85	7.05	6.9
8	0.725	28.72	20.8	168	0.725	6.78	5.8
13	0.6	28.72	17.3	173	0.6	6.78	4.9

The Eto values for Katumani station were moderate. Values of 12 to 14 mm/day (60-70 mm / pentad) are experienced in hot, areas with high temperatures, strong winds and low humidity. The low Eto values were attributed to moderate temperatures and high humidity experienced during the rainy season.

4.2.2 Water Holding Capacity

The amount of water available for plant use at each profile level is as shown in Table 4.7 and Appendix 5. There was no definite pattern in water distribution within the depths. The difference between the amount of water in volume contained by the core rings at permanent wilting point and field capacity was put in column 5 as available water in Table 4.7. The available water in mm per corresponding depth is presented in column 6 while column 7 gives the available water in mm per metre.

Table 4.6: Soils Water Holding capacity for blocks 1, 2, and 3,4 and 5 combined.

Block	*Depth (cm)*	*Field capacity (grammes)*	*Permanent wilting point (grammes)*	*Available water (grammes)*	*Available water mm/corresponding depth*	*Available water in mm/m*
1	0-20	32.945	22.725	10.22	20	80
	20-54	28.895	20.02	8.875	30	88
	54-120	29.065	18.95	10.115	67	102
2	0-20	37.925	22.395	15.525	31	155
	20-40	36.05	22.395	13.655	27	135
	40-60	35.95	21.08	14.87	30	150
	60-80	23.97	11.12	12.85	25	125
	80-100	32.355	15.725	16.63	33	165
	100-120	30.57	8.665	21.905	44	220
	120-140	30.305	23.475	6.83	14	70
3,4,5	0-20	32.86	21.575	11.91	24	120
	20-48	26.485	14.15	12.335	34	121
	48-90	30.62	18.765	11.855	50	119
	90-120	33.24	19.645	13.595	41	137

The amount of available water was lowest in block one at 80-102 mm/m. This was attributed to its higher elevation that resulted to soil erosion hence the low water holding capacity. The available water in blocks 3,4 and 5 was relatively uniform over the soil layers especially from 0 cm 90 cm depth (119-121 mm/m). This was because the three blocks were subject to sediment deposition and the soil layers were relatively similar. Proper crop growth can be enhanced by adding organic matter to the soil in form of organic manure and organic mulches, which can increase the moisture retention capacity of the soil.

The maize roots absorb moisture from the depth they have reached (Appendix 6). Younger crops would require more frequent irrigations as they have fewer roots for absorbing moisture from the soil. Due to variations in available moisture in the 3 blocks, block 2 was selected to determine the maximum available moisture for each root depth. This was because moisture held was determined in smaller intervals for block 2. The maximum amount of water held at each root depth was as shown in Appendix 6.

4.3 Irrigation Scheduling

4.3.1. Effective rainfall

The difference between effective rainfall and crop evapotranspiration is the amount of water in millimeters that need to be met through supplemental irrigation. Supplemental irrigation for all the seasons analyzed is given in Table 4.7. The periods when supplemental irrigations should be applied are also given.

Effective rainfall was very low compared to the total rainfall as indicated in (Fig. 4.5). Reading from the figure, less than half the total rainfall amount went into losses. Most of the losses occurred early in the season when rainfall intensity was highest and decreased as the seasons advanced (Table 4.7). Poor soil cover, soil crusting, high rainfall intensities early in the season and poor rainfall distribution were responsible for the high losses. In the absence of water loss through surface runoff and deep percolation, the rainfall amount would be adequate to meet crop evapotranspiration for maize in most of the seasons in Machakos District.

During the short rains, crop evapotranspiration was fully met by effective rainfall during the first 30 days after onset for all the years (Table 4.7). In the following 30 days, only 37% of the seasons (7 seasons) had Etc being fully met by effective rainfall. The other seasons had some amount of effective rainfall that ranged between 11.5 to 133.3 mm. Between 60 to 90 days only one season had enough effective rainfall to fully meet Etc. In 7 seasons there was no effective rainfall at all between 60-90 days. In another 5 seasons, i.e. 1988/89, 1992/93, 1997/98 and 1991/92, effective rainfall amounted to more than 50% of maximum evapotranspiration. According to Oweis et al 1999, irrigation is needed when rainwater falls below 50 % of maximum crop evapotranspiration. It therefore follows that, during the 7 seasons when effective rainfall fully met Etc and the other 5 seasons when effective rainfall met 50% of Etc, it was possible for the crop to continue growing. This adds up to 70.6% of the seasons during the short rains. This period (30 – 60 days) coincide with the period maize is most sensitive to water deficit. Harvested rainwater stored from runoff during 1-30 days when a lot of runoff yield is high can be used to increase available moisture for the 5 seasons with more than 50% effective rainfall. The harvested water need to be used for the other 7 seasons when effective rainfall was below 50% of Etc during 30-60 days after onset.

Table 4 7 supplemental irrigation showing the amount of water required during the first second and third months after onset

		1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	1996/97	1997/98
Short rains																				
1 to 30	Etc	64 2	62 3	32 9	66 3	45 2	56 9	55 5	52 4	34 3	64 2	59 2	50 9	59 9	50 8	48 4	60 5	51.7	41 2	66
	Effective rainfall	64 2	62 3	32 9	66 3	45 2	56 9	55 5	52 4	34 3	64 2	59 2	50 9	59 9	50 8	48 4	60 5	51.7	41 2	66
	Supplemental irrigation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30 to 60	Etc	92 4	119 3	121 6	114 5	135 9	87 6	102 8	66 2	99 5	116 4	127 8	78 9	100 5	86 2	101 2	133.3	108 9	98 5	154 5
	Effective rainfall	19	57 9	11 5	114 5	39 7	87 6	49 6	66 2	19 7	80	127 8	78 9	76 8	55 9	101 2	133 3	26 2	46 7	105 1
	Supplemental irrigation	73 5	61.5	110	0	96 2	0	53 3	0	79 8	36 3	0	0	23.7	29 4	0	0	82 8	51.8	49 4
60 to 90	Etc	122 7	108 9	160 3	115 1	154	120 4	142 2	110 7	137 8	137 3	108 8	113 1	126 9	131 3	97 4	111 5	87 2	91 9	146
	Effective rainfall	0	8 3	0	43 7	0	31 7	37 6	11.8	11 7	36 6	91 6	1 3	0	131 3	0	110 4	0	0	114 6
	Supplemental irrigation	122 7	100 6	160 3	71 4	154	88 7	104 7	99	126 2	100.6	17 2	111 8	126 9	0	97.4	1.2	87.2	91 9	31 4
	Effective rainfall 1-90	83 2	128 5	44 4	224 5	84 9	176 2	142 6	130 4	65 7	180 9	278 7	131 1	136 6	238	149 6	304 2	77 9	87 9	285 7
90 to 100	Etc	26 4	25	26 6	35 1	38 1	18 4	25	27 9	22	31 6	31 5	31.5	39 3	31 5	34 5	29 2	27 9	22 8	38 1
	Effective rainfall	1 4	0	0	0	1 9	5 6	0	0	0	10 7	0 6	7 4	0	31 5	2	0 4	0	0	38 1
	Supplemental irrigation	25	25	26 6	35 1	36 3	12 7	25	27 9	22	20 8	30 9	24 1	39.3	0	32 5	28 7	27 9	22 8	0
	Total suppl Irr.	84 6	128 5	44 4	224 5	86 8	181 9	142 6	130 4	65.7	191 6	279 3	138 6	136 6	269 5	151 6	304 6	77 9	87 9	323 8
Long rains																				
1 to 30	Etc	72 4	58 2	60 6	45 4	77 1	48 6	67	57	48 2	63 8	40 2	60 1	60 6	46 7	46 2	71.7	70 7	50 6	68 6
	Effective rainfall	28	58 2	60 6	45 4	77 1	48 6	67	57	48 2	63 8	40 2	60 1	60 6	46 7	46 2	71.7	70 7	50 6	68 6
	Supplemental irrigation	44 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30 to 60	Etc	117 4	89 7	73 5	67 2	107 4	111 6	88 1	97 2	110 5	109 4	104 4	114 9	86	91 4	106	118 8	74 2	113 1	111 5
	Effective rainfall	111.4	89 7	56	0	32 7	50 4	88 1	0	110 5	109 4	104 4	52	51 6	0	106	55 2	0	69 9	111 5
	Supplemental irrigation			17 5	67 2	74 7	61 3	0	97 2	0	0	0	63	34 4	91 4	0	63 6	74 2	43 3	0
60 to 90	Etc	82 7	93 8	80 9	76 8	120	103 5	108 6	75 9	96 8	77 7	131 8	71 7	91 9	60	73 6	70.1	84	75 4	77 1
	Effective rainfall	82 7	51 7	0 7	0	0	0	5 4	33 9	0	0	42 8	0	0	0	12 4	22 8	16 5	0	60 9
	Supplemental irrigation	0	42.1	80 2	76 8	120	103 5	103 3	42	96 8	77 7	89	71.7	91 9	60	61.2	47 3	67 5	75 4	16 2
	Effective rainfall 1-90	228 1	199 7	117.3	45 4	109 8	99	160 5	90 9	158 7	173 2	187 4	112 1	112 2	46 7	164 5	149 6	87 3	120 5	241
90 to 100	Etc	15 9	23 5	14 7	14 8	9	14 7	24 9	18 1	16 1	14 7	28 8	11 6	14 7	18	20 4	16 3	17 5	11	9
	Effective rainfall	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Supplemental irrigation	15 9	23 5	14.7	14 8	9	14 7	24 9	18 1	16 1	14 7	28 8	11 6	14 7	18	20 4	16 3	17 5	11	9
	Total effective rainfall	228 1	199 7	117 3	45 4	109 8	99	160 5	90 9	158 7	173 2	187 4	112 1	112 2	46 7	164 5	149 6	87 3	120 5	241
	Total suppl Irr	60 3	65 6	112 4	158 8	203 7	179 5	128 2	157.3	113	92 4	117 8	146 2	140 9	169 4	81 6	127 3	159 2	129 7	25 1

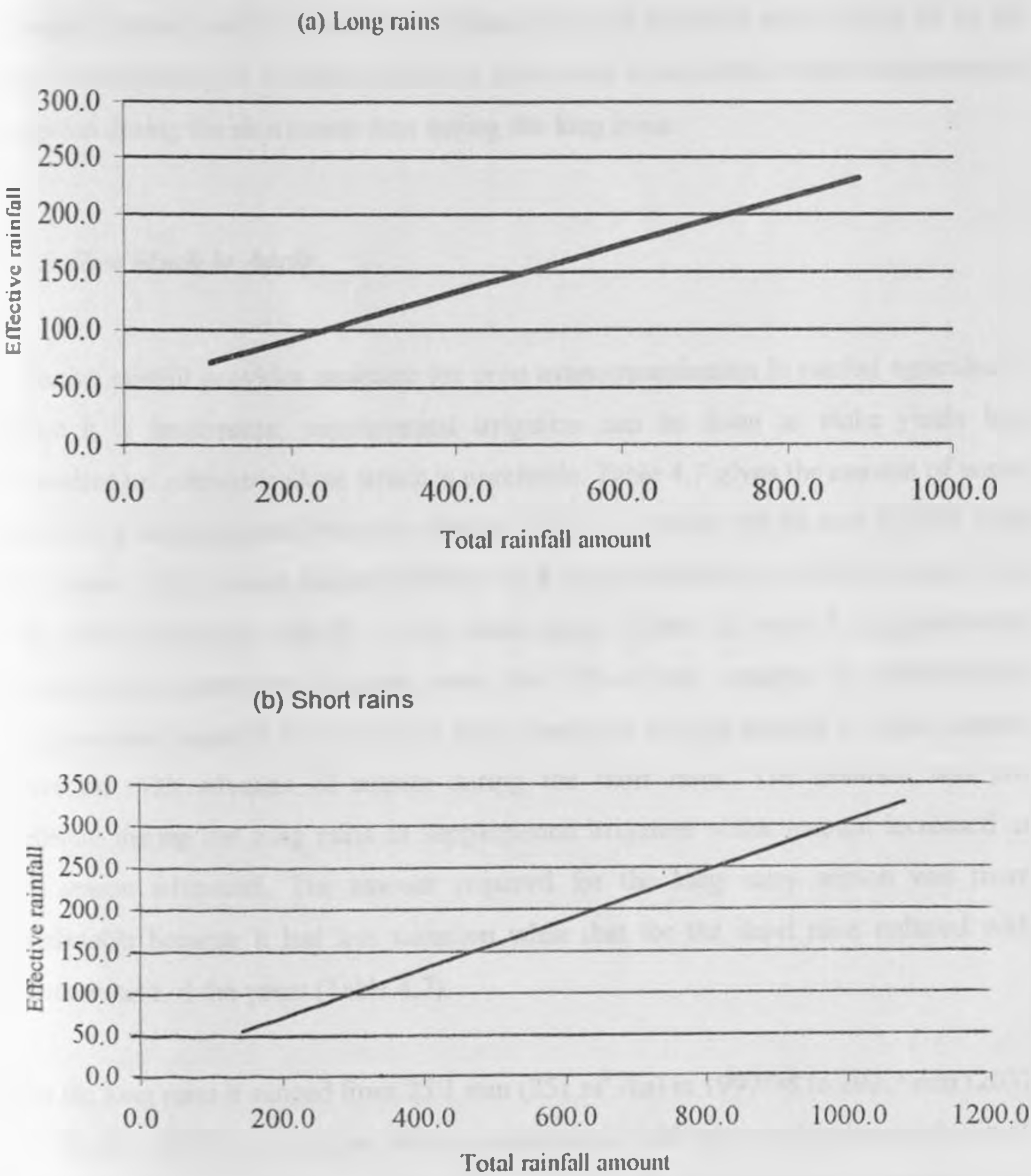


Fig 4.5 Relationship between total rainfall amount and effective rainfall for both the long rains (a) and the short rains (b).

During the long rains, there was enough effective rainfall to fully meet Etc for 18 out of 19 seasons (95%) during the first 30 days after onset. Between 30 to 60 days, 4 seasons had no effective rainfall and 9 had none between 60 to 90 days. Two out of the 4 seasons with no effective rainfall between 30 to 60 days (1982/83, 1992/93) had no effective rainfall between 60 to 90 days. Two seasons (1987/88, 1988/89) that had enough effective rainfall to meet Etc during 30 to 60 days had none during 60 to 90 days. Consequently, it would be easier to meet crop water needs though supplemental irrigation during the short rains than during the long rains.

4.3.2 How Much to Apply

Effective rainfall provides moisture for crop evapotranspiration in rainfed agriculture. When it is inadequate, supplemental irrigation can be done to make yields less dependent on rainwater alone which is unreliable. Table 4.7 gives the amount of water needed for supplemental irrigation during the 1-30, 30-60, 60-90 and 90-100 days after onset. The amount ranged between 29.4 mm (294 m3/ha) in 1992/93 and 296.9 mm (2969 m3/ha) in 1981/82 for the short rains. 200mm of water for supplemental irrigation can guarantee adequate water for 79% of the seasons. No supplemental irrigation was required between 1-30 days after onset but the amount of water needed increased with advance of season during the short rains. The situation was not different during the long rains as supplemental irrigation water amount increased as the season advanced. The amount required for the long rainy season was more predictable because it had less variation while that for the short rains reduced with advancement of the years (Table 4.7).

For the long rains it ranged from 25.1 mm (251 m^3 /ha) in 1997/98 to 203.7 mm (2037 m^3 /ha) in 1883/84. From the table, a maximum of 200 mm can be planned for in all the long rain seasons. An amount of 150 mm during the long rains can guarantee good yields in over 70% of the seasons. The results compare well with Fig. 4.2 and Appendix 2, where seasons with early onset showed rainfall amount to be more, have longer lengths of rainy days and therefore required less supplemental irrigation water.

In the semi-arid regions, water to be used for supplemental irrigation may be lacking and it is not always possible to refill the soil to field capacity. Under such circumstances a suitable percentage of water required to bring the soil to field capacity can be added. This percentage of water can be based on water availability and rainfall expectations. If a lot of water is available, then supplemental irrigation can be done to refill the soil to field capacity. This is made necessary by the fact that, the lengths of the intra-seasonal droughts are unknown and rainfall may come soon after irrigation. If that happens, water, which is in limited supply and could have been used for another supplemental irrigation will have been wasted. Resumption of rainfall after an intraseasonal drought episode is expected to occur and it could be soon especially early in the rainy season. However the situation is expected to change with an increase in the length of the droughts as the rainy season progresses.

4.3.3 When to Apply

Supplemental irrigation is needed during dry spells that occur during the crops growing season. The lengths of the dry spells were short during emergence and vegetative stage but became long as the crop growing season progressed. The dry spells were longer during flowering period which also coincided with the period when the maize crop is most sensitive to water deficits. To ensure the crop produces grain, supplemental irrigation need to be planned for at least during 30-100 days after planting. Figure 4.3 shows there was adequate rainfall to support crop growth during the first month after planting and therefore irrigation water will probably not be required between 1-30 days after onset. The water needs to be refilled to field capacity when the soil water available drops to critical depth as indicated in Table 4.8. This critical depth of water is indicated in column 6 of Table 4.8. The water balance in the soil should not be allowed to drop beyond the figures given in Table 4.8 column 6 for the corresponding pentads as this could result to severe yield reduction.

The critical depth of water is low early in the season when the root depth is low. This is because the available water can only be available from the short depth of soil covered by the roots. It rises to a maximum of 76 mm when the root depth reaches a maximum of 120 cm during the 11th pentad after planting.

During the short rains of 1997 - 98, soil deficit was reached during Julian date 347. Supplemental irrigation was done during the previous pentad of 342 to ensure the maize crop did not severely reduce yield. An amount of water similar to the deficit of 75.8 mm was required to bring the soil moisture to field capacity. In column 10, water balance calculations were repeated considering the additional water that was added as supplemental irrigation.

Table 4.8: Irrigation scheduling for the experimental site in Mwala

1. Julian date	*2. ETC*	*3. Effective rainfall*	*4. Fc (mm)*	*5. P*	*6. (1-p)Fc (mm)*	*7. 3-2*	*8. Cumm.7 (wb 1)*	*9. S.I*	*10. wb 2*
282	9.4	11	16	0.875	2	1.6	1.6		
282	9.7	11	32	0.875	4	1.3	2.9		
292	11.3	11	47	0.875	6	-0.3	2.6		
297	11.3	11	63	0.80	13	-0.3	2.3		
302	15.2	11	80	0.80	16	-4.2	-1.9		
307	18.8	11	94	0.70	28	-7.8	-9.7		
312	22.3	17.5	108	0.70	33	-4.8	14.5		
317	25.6	17.5	125	0.60	50	-8.1	-22.6		
322	29.3	17.5	143	0.60	57	-11.8	-34.4		
327	29.3	17.5	166	0.55	75	-11.8	-46.2		
332	29.3	17.5	190	0.55	86	-11.8	-58.0		
337	27.9	17.5	190	0.55	76	-10.4	-68.4		
342	26.5	19.1	190	0.60	76	-7.4	-75.8	75.8	0.0
347	25.1	19.1	190	0.60	76	-6.0	**-81.8**		-6.0
352	25.1	19.1	190	0.60	76	-6.0	-87.8		-12.0
357	25.1	19.1	190	0.60	76	-6.0	-93.8		-18.0
362	22.2	19.1	190	0.60	76	-3.1	-96.9		-21.1
3	24.4	19.1	190	0.60	76	-5.3	-102.2		-26.4
8	20.8	19.1	190	0.60	76	-1.7	-103.9		-28.1
13	17.3	19.1	190	0.60	76	1.8	-102.1		-26.3

Key

Column 1 Julian date after rainfall onset

Column 2 Etc

Column 3 Effective rainfall

Column 4 Field capacity within root depth reached by the roots

Column 5 Lowest allowable soil moisture depletion

Column 6 Depth of water within the achieved root depth that is critical and cannot be exceeded without resulting into severe yield reduction

Column 7 Difference between rainfall amount and Etc

Column 8 Water balance without supplemental irrigation. Water deficit was experienced during Julian date 347.

Column 9 Supplemental irrigation

Column 10 Water balance done considering the supplemental irrigation

During the short rains of 1997, only one supplemental irrigation was required. However, this may not be the case during other seasons as rainfall varies from season to season. Each season water balance need to be treated individually and water added to soil before the lowest depletion level (column 6) is reached.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Early onset of rainfall result into more rainfall that is better distributed than late onset rains. Careful identification of the onset could be a useful tool to maximum utilization of rainwater and resource allocation such as fertilizers, pesticides and crop type to be planted.

The rainy seasons are generally too short for growing maize. If maize for grain production is to be done, planning for supplemental irrigation is needed in all the seasons, not only to provide moisture during intra-season dry spells but also to lengthen the season as well in some of the seasons. During the short rains, water for irrigation amounting to 200 mm should be planned for. This amount should guarantee yield for about 80% of the seasons. During the long rains, 150 mm water should provide adequate water in at least 70% of the seasons.

Irrigation would require high levels of investment as rainwater harvesting alone would not provide enough water for supplemental irrigation. This is because rainfall is sometimes too little to yield much runoff and the rainy season too short to be compensated by runoff. All possible water sources need to be explored for the purposes of supplemental irrigation. These sources include seasonal rivers, shallow wells, dams, and tanks among others. It would be necessary to consider growing drought resistant or drought escaping crops such as pigeon peas, cowpeas, sweet potatoes, sorghum, cassava and millet in some of the land reserved for food production to diversify production.

The short rains are more suitable for growing maize than the long rains as rainfall received is more and better distributed. Maize production can be enhanced in most seasons of the short rainy season through supplemental irrigation that would ensure grain harvest in most of the seasons. Supplemental irrigation would reduce the uncertainty brought about by poor rains during the short rains. The long rains are more poorly distributed than the short rains and may require more events of supplemental irrigation. However, the amounts of water needed over the years are less varied and therefore more predictable than the short rains.

Farming methods should aim at retaining as much moisture in the soil as possible. Practices like mulching, early planting and deep ploughing should be carried out to enable the soil absorb and retain most of moisture.

5.2 Recommendations

In view of the findings of this study, supplemental irrigation should be encouraged during the short and long rains to enhance maize grain production. Some of the seasons are too short and rainfall amount too little to support maize growing even in situation where supplemental irrigation using harvested rainwater is applied. Other crops that are drought tolerant or drought escaping should be planted alongside maize to provide food during such seasons.

More resources should be used if the rainfall onset is early. These include more fertilizers, high quality seeds and pesticides. This is because early onset results to more seasons rainfall that is better distributed.

Supplemental irrigation should be sparingly done during the initial and vegetative stages of growth in maize as the yield reduction due to water stress is low. Water stress during flowering stage of maize should be avoided by practicing supplemental irrigation using available water sources during the initial and vegetative stage. Water sources in Asal e.g seasonal rivers, wells and rainwater harvesting structures contain adequate water during the rainy season that should be utilized during the rainy season to do supplemental irrigation..

Other water management practices like use of organic manure, mulching, deep ploughing and terracing can be practiced alongside supplemental irrigation. Such an integrated approach could reduce the number of supplemental irrigation events and the amount of water needed each season.

An amount equivalent to 150 mm depth of water for supplemental irrigation should be planned for during the long rains to ensure maize harvest in 70% of the seasons. An amount of water corresponding to 200 mm depth should be planned for to ensure maize yield is achieved during about 80% of the seasons of the short rains.

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7.0 APPENDICES

Appendix 1 Pentad Rainfall in mm

DayofYear	PentadeMi	1979/80	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	19
277	4-Oct	0 0	0 0	0 0	0 0	0 0	44 0	0 0	0 0	
282	9-Oct	0 0	0 0	12.5	18 9	0 0	0 0	16 5	0 0	
287	14-Oct	0 0	0 0	0 0	17 3	0 0	0 0	0 0	0 0	
292	19-Oct	0 7	0 0	3 5	39 9	0 0	104 0	24 8	10 1	
297	24-Oct	21 0	66 5	5 5	14 5	0 0	10 4	44 5	45 1	
302	29-Oct	3.7	0 0	18 0	122 1	0 0	15 3	0 0	30 7	
307	3-Nov	244 5	103 2	0 0	0 0	2 1	100 8	4 6	29 9	
312	8-Nov	108 0	88 3	10 0	42 2	3 1	87 0	27 1	83 1	
317	13-Nov	22 8	37 7	44 1	68 9	11 9	26 0	6 7	17 4	
322	18-Nov	1 0	59 1	14 9	12 3	0 0	0 0	10 6	52 8	
327	23-Nov	0 0	35 8	7 9	148 8	32 5	57 0	11 0	76 2	
332	28-Nov	0 0	0 0	0 0	64 6	0 0	19 1	35 1	83 2	
337	3-Dec	0 0	0 7	31 2	98 9	56 4	0 0	21.3	110 8	
342	8-Dec	0 0	0 0	0 0	32 7	14 3	48 2	15 2	24 8	
347	13-Dec	8 8	8 0	30 7	53 2	0 0	0.0	0 0	5 0	
352	18-Dec	22 7	26 7	0 0	0 0	0 0	17.3	0 0	0 0	
357	23-Dec	16 8	0 0	0 0	0 0	30 2	4 0	0 0	0 0	
362	28-Dec	0.0	0 0	5 2	0 0	0 0	0 0	0 0	0 0	
3	3-Jan	0 0	3 8	0 0	0 0	0 0	0 0	0 0	35 0	
8	8-Jan	0 0	0 0	0.0	0 0	50 7	0 0	78 2	0 0	
13	13-Jan	0 0	0 0	0 0	0 0	0 0	0.0	0.0	1 3	
18	18-Jan	0 0	0 0	0 0	0 0	0 0	0 0	0.0	0 0	
23	23-Jan	0 0	0 0	0 0	0 0	0 0	17 5	0 0	0 0	
28	28-Jan	8 6	0.0	0 0	0 0	0 0	27 4	0 0	0 0	
33	2-Feb	2 5	0 3	0 0	0 0	0 0	62 8	0 0	0 0	
38	7-Feb	0 0	0 0	0 0	0 0	0 0	50 5	0 0	0 0	
43	12-Feb	0 0	4 8	0 0	53 9	0 0	1.5	0 0	0 0	
48	17-Feb	12 5	0 0	0 0	17 2	0 0	3 5	0 0	0 0	
53	22-Feb	0 0	0 0	0 0	12 8	0 0	0 0	0.0	0 0	
58	27-Feb	28 3	0 0	0 0	0 0	0 0	0 0	0 0	0 0	
63	3-Mar	35 1	0 0	0 0	0 0	0 0	0 0	4 3	0 0	
68	8-Mar	0 0	0 0	0.0	0 0	0 0	0 0	55 0	0 0	
73	13-Mar	0 0	4 1	0 0	0 0	26 0	0 0	32 6	8 5	
78	18-Mar	0.0	44 5	0 0	17 3	0 0	27.0	13 4	0 0	
83	23-Mar	0 0	131.5	0 0	0.0	99 6	60 0	0 0	0 0	
88	28-Mar	33 3	48 4	85 8	0 0	3 4	42 4	29 8	0.0	
93	2-Apr	15.5	53 5	41.0	0 0	2 7	12.3	54 2	70 0	
98	7-Apr	87 5	82.7	3 3	0.0	13 3	73 2	443 0	64 0	
103	12-Apr	13 7	10 3	0 0	5 9	94 5	84 5	21 0	38 0	
108	17-Apr	93 0	0 0	62 0	45 5	0 0	15 1	0.0	6 1	
113	22-Apr	59 2	0 0	0 0	76 3	64 7	33 5	21 0	0 0	
118	27-Apr	0 0	32 7	80 6	30 1	6 5	25 0	179 5	0 0	
123	2-May	63 1	17 7	10 4	0 0	0 0	20 6	0 7	0 0	
128	7-May	87.3	98 1	3 5	2 8	0 0	0 0	8 0	0 0	
133	12-May	2 2	76 3	2.3	3 9	0 0	0 0	0 0	0 0	
138	17-May	11.1	19 6	4 5	0 7	0 0	0 0	6.9	0 0	

87/88	1988/89	1989/90	1990/91	1991/92	1992/93	1993/94	1994/95	1995/96	1996/97	1997/98
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	10.9	0.0	0.0	0.0	0.0	97.5	0.0	0.0	39.4
0.0	0.0	0.0	4.5	21.4	0.0	0.0	58.0	3.5	0.0	24.6
0.0	12.5	3.2	18.1	7.6	0.0	0.0	45.0	69.8	0.0	0.0
0.0	7.1	81.7	72.0	0.0	28.1	2.0	0.0	74.4	0.0	22.5
0.0	0.0	6.4	8.0	0.0	130.8	58.4	27.0	0.0	29.6	98.4
72.5	107.4	17.2	48.1	10.0	12.8	5.3	161.0	0.0	18.8	54.0
13.0	25.3	76.1	19.9	54.0	5.8	16.8	368.6	41.8	107.6	6.3
17.5	5.3	64.7	110.3	43.5	16.3	1.3	26.9	19.6	73.8	0.0
20.0	39.9	194.0	15.1	84.7	15.1	24.4	0.0	0.0	45.6	0.0
0.0	0.0	34.1	0.0	66.6	12.0	63.8	28.1	0.0	34.6	16.0
26.0	15.2	30.6	149.4	0.0	6.1	52.7	77.5	23.4	65.3	86.3
21.0	6.5	47.6	55.7	39.6	14.8	12.3	131.7	0.0	24.3	57.7
0.0	0.0	0.0	57.1	23.9	29.0	32.9	0.0	17.3	0.0	10.7
0.0	18.6	0.0	41.8	0.0	39.2	2.5	0.0	23.2	0.0	14.1
2.5	61.0	0.0	0.0	63.7	0.0	8.7	17.5	4.7	0.0	30.0
0.0	30.0	17.6	0.0	0.0	17.7	7.9	20.0	0.0	0.0	30.0
0.0	0.0	111.9	18.9	0.0	32.4	0.0	0.0	0.0	0.0	32.0
31.3	4.7	16.3	0.0	5.3	54.3	0.0	0.0	1.1	2.8	38.7
4.8	0.0	0.0	0.0	0.0	8.9	0.0	13.8	0.0	0.0	129.8
0.0	42.7	0.0	0.0	0.0	107.1	0.0	0.0	0.0	0.0	32.3
0.0	2.7	0.0	0.0	0.0	88.6	0.0	0.0	15.4	0.0	23.0
0.0	27.0	5.4	19.1	0.0	20.0	0.0	0.0	0.0	0.0	50.0
0.0	0.0	9.9	34.8	0.0	55.3	0.0	5.0	0.0	0.0	15.0
0.0	39.2	0.0	0.0	0.0	6.1	0.0	0.0	1.5	0.0	0.0
0.0	31.1	4.5	0.0	0.0	131.9	6.7	127.7	0.0	0.0	102.9
0.0	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0
0.0	0.0	17.8	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28.0	0.0	38.7	0.0	0.0	0.0	0.0	84.3	0.0	0.0	0.0
21.0	0.0	82.3	0.0	0.0	0.0	0.0	45.1	1.5	0.0	0.0
33.6	8.4	48.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0
63.5	1.6	176.7	20.7	3.5	11.4	18.8	0.0	42.4	0.0	0.0
54.2	51.3	14.3	0.0	0.0	5.5	120.4	10.8	13.8	14.5	135.6
29.4	33.8	13.2	96.0	13.8	0.0	35.3	14.9	111.9	0.0	0.0
10.4	108.1	54.9	48.0	17.9	0.0	0.0	6.0	22.6	0.0	50.0
36.5	133.2	94.3	13.7	78.7	17.7	1.8	3.6	11.2	154.0	60.6
34.5	77.0	31.7	0.0	1.5	0.0	63.0	50.3	0.0	58.3	79.0
0.0	0.0	27.8	11.5	0.0	36.8	13.3	0.0	0.0	0.0	0.0
90.2	2.1	0.0	52.1	10.1	43.1	87.2	25.4	0.0	54.9	0.0
111.3	243.3	20.9	0.0	35.2	0.0	61.4	7.5	0.0	0.0	25.0
0.0	6.5	16.8	29.0	58.3	13.5	7.6	25.5	0.0	30.2	0.0
0.0	27.5	47.1	4.8	0.0	0.0	5.7	16.4	0.0	0.0	120.8
0.0	28.8	0.0	0.0	2.3	0.0	0.0	1.4	8.0	81.6	100.9
0.0	2.9	0.0	10.3	0.0	12.4	0.0	0.0	32.6	6.8	0.0
0.0	0.0	0.0	0.0	0.0	0.0	15.8	3.8	3.6	0.0	0.0

143	22-May	0.0	0.0	3.5	0.0	0.0	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	21.5	0.0	0.0	0.0	7.1
148	27-May	0.0	0.0	14.3	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
153	1-Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	60.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.3
158	6-Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6	0.0	0.0
163	11-Jun	0.0	0.0	0.0	0.0	0.0	0.0	3.1	0.0	8.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
168	16-Jun	0.0	1.8	0.0	0.0	0.0	0.0	1.3	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
173	21-Jun	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
178	26-Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
183	1-Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
188	6-Jul	0.0	0.0	0.0	0.0	0.0	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
193	11-Jul	0.0	0.0	1.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
198	16-Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
203	21-Jul	0.0	0.5	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
208	26-Jul	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
213	31-Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
218	5-Aug	6.5	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
223	10-Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
228	15-Aug	7.5	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	0.0	0.0
233	20-Aug	0.0	0.0	0.0	12.5	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
238	25-Aug	0.0	3.5	0.0	0.0	0.0	0.0	1.7	0.0	0.0	13.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
243	30-Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
248	4-Sep	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
253	9-Sep	0.0	0.0	12.2	0.0	0.0	0.0	0.0	0.0	18.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
258	14-Sep	0.0	14.3	0.0	0.0	0.0	0.0	0.5	0.0	9.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
263	19-Sep	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
268	24-Sep	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
273	29-Sep	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 2 Rainfall Amount Distribution within the Growing Season

Short Rains									
OnsetDay	302	292	312	282	322	277	292	292	302
Rain1-30	378	295 7	108 05	212 7	103 2	173 65	107 7	216 3	123
Rain30-60	48 3	103 58	35 9	435 7	80 9	289 9	93 2	352 8	49 5
Rain60-90	0	30 5	0	85 9	0	69 5	78 2	36 3	36 1
Rain90-120	23 6	5 05	0	0	28	44 9	0	0	0
Rain30 120	71 9	139 1	35 9	521 6	106 9	404 3	171 4	389 1	85 6
Rain1 120	449 9	434 8	144 0	734 3	210 1	578 0	279 1	605 4	208 6
LongRains									
OnsetDay	58	73	83	103	78	78	63	88	58
Rain1-30	63 4	364 7	192 1	160 55	213 46	299 4	135 1	178 1	229 7
Rain30-60	302 2	156 7	101 3	4 6	71 2	94 2	718 7	0	282 9
Rain60-90	163 7	95 9	17 8	0	0	0	25 6	73 1	0
Rain90-120	0 0	1 8	1 6	0	0	0	6 5	0	6 1
Rain30 120	465 9	254 4	120 7	4 6	71 2	94 2	750 8	73 1	289 0
Rain1 120	529 3	619 1	312 8	165 2	284 7	393 6	885 9	251 2	518 7

302	292	292	307	297	297	277	287	302	277
177 9	249 3	276 4	258 8	208 9	108 2	227 5	189 5	310	184 9
131 3	306 3	319 1	127 2	101 1	172 9	662 1	60.3	89 6	162 6
77 06	145 8	18 9	5 3	309	7 9	169 2	29	2 8	174 5
70 3	19 8	53 9	0	213 3	26 7	18 8	16.9	0	288 8
278 7	471 9	391 9	132 5	623 4	207 5	850 1	106.2	92 4	625 9
456 6	721 2	668 3	391 3	832 3	315 7	1077 6	295 7	402 4	810 8

73	53	78	83	98	73	53	68	88	73
405	360	169 2	122	93 4	239 3	140 2	204 9	267.2	325 2
308 2	221 9	96 2	95 8	12 4	175 2	100 2	0	118 6	246 7
2 9	84 8	0	0	0	37 3	54 62	44 2	0	107 4
0	0	0	0	0	0	0	11 6	0	0
311 1	306 7	96 2	95 8	12 4	212 5	154 8	55 8	118 6	354 1
716 1	666 7	265 4	217 8	105 8	451.8	295.0	260 7	385 8	679.3

Appendix 3 Pentad Potential Crop Evapotranspiration

[illegible]	Pentade date	Eto 1979/80	Eto 1980/81	Eto 1981/82	Eto 1982/83	Eto 1983/84	Eto 1984/85	Eto 1985/86	Eto 1986/87	Eto 1987/88	Eto 1988/89	Eto 1989/90	Eto 1990/91
277	4-Oct	26 7851	26 7851	22 9177	26 7851	18 21847	22 50178	14 35108	18 21847	18 63439	26 7851	18 21847	18 63439
282	9-Oct	27 46922	27 46922	19 73444	27 46922	23 18591	23 18591	15 45112	23 18591	23 60183	27 46922	19 31852	15 45112
287	14-Oct	24 28595	24 28595	20 41856	28 15334	28 15334	24 28595	20 41856	28 15334	20 41856	28 15334	24 28595	20 41856
292	19-Oct	24 28595	24 28595	24 28595	24 28595	24 28595	24 28595	24 28595	28 15334	24 28595	24 28595	20 41856	20 41856
297	24-Oct	24 28595	24 28595	28 15334	24 28595	24 28595	20 41856	28 15334	24 28595	20 41856	20 41856	24 28595	20 41856
302	29-Oct	24 28595	24 28595	28 15334	24 28595	20 41856	20 41856	24 28595	20 41856	20 41856	20 41856	20 41856	20 41856
307	3-Nov	23 77565	23 77565	21 38897	27 64305	23 77565	19 90826	17 52158	13 65419	13 65419	23 77565	23 77565	17 52158
312	8 Nov	23 26535	23 26535	14 62459	27 13275	17 01128	17 01128	17 01128	17 01128	10 7572	27 13275	23 26535	20 87867
317	13-Nov	26 62245	26 62245	14 11429	20 36837	20 36837	14 11429	20 36837	20 36837	7 86022	26 62245	26 62245	20 36837
322	18-Nov	26 62245	26 62245	14 11429	14 11429	14 11429	7 86022	26 62245	20 36837	14 11429	26 62245	26 62245	20 36837
327	23-Nov	26 62245	26 62245	14 11429	14 11429	20 36837	14 11429	20 36837	14 11429	14 11429	26 62245	26 62245	14 11429
332	28-Nov	26 62245	26 62245	7 86022	20 36837	20 36837	20 36837	14 11429	7 86022	20 36837	26 62245	26 62245	7 86022
337	3-Dec	21 46742	21 46742	12 82855	25 3367	21 46742	21 46742	12 82855	8 95927	15 21335	25 3367	21 46742	12 82855
342	8-Dec	16 31239	16 31239	17 79688	20 18168	16 31239	16 31239	17 79688	10 05832	20 18168	20 18168	20 18168	13 9276
347	13-Dec	11 15737	11 15737	22 76521	18 89593	15 02665	15 02665	18 89593	11 15737	15 02665	18 89593	15 02665	15 02665
352	18-Dec	11 15737	11 15737	22 76521	15 02665	18 89593	18 89593	18 89593	15 02665	18 89593	15 02665	15 02665	15 02665
357	23-Dec	15 02665	15 02665	18 89593	15 02665	18 89593	22 76521	18 89593	15 02665	15 02665	18 89593	11 15737	15 02665
362	28-Dec	18 89593	18 89593	15 02665	15 02665	18 89593	22 76521	18 89593	15 02665	15 02665	18 89593	15 02665	18 89593
3	3-Jan	28 75213	13 8698	28 75213	28 75213	28 75213	13 8698	28 75213	28 75213	13 8698	13 8698	13 3698	13 3698
8	8-Jan	13 8698	28 75213	28 75213	28 75213	28 75213	13 8698	28 75213	13 8698	28 75213	28 75213	28 75213	28 75213
13	13-Jan	18 83058	18 83058	28 75213	23 79135	23 79135	13 8698	23 79135	18 83058	23 79135	23 79135	23 79135	18 83058
18	18-Jan	18 83058	18 83058	28 75213	18 83058	23 79135	13 8698	18 83058	18 83058	28 75213	23 79135	23 79135	23 79135
23	23-Jan	18 83058	18 83058	23 79135	13 8698	23 79135	18 83058	18 83058	23 79135	23 79135	23 79135	23 79135	23 79135
28	28-Jan	18 83058	23 79135	23 79135	18 83058	28 75213	23 79135	18 83058	28 75213	18 83058	23 79135	23 79135	23 79135
33	2-Feb	21 29957	31 22112	18 8838	26 26034	23 84458	31 22112	26 26034	31 22112	13 92303	23 84458	23 84458	26 26034
38	7-Feb	21 35279	26 31357	18 93703	33 6901	26 31357	33 6901	21 35279	33 6901	21 35279	26 31357	26 31357	21 35279
43	12-Feb	21 40602	28 78255	21 40602	28 78255	21 40602	28 78255	21 40602	28 78255	28 78255	21 40602	28 78255	21 40602
48	17-Feb	14 02948	21 40602	28 78255	21 40602	28 78255	28 78255	21 40602	28 78255	28 78255	28 78255	28 78255	14 02948
53	22-Feb	14 02948	28 78255	36 15909	21 40602	28 78255	21 40602	28 78255	21 40602	21 40602	21 40602	21 40602	14 02948
58	27-Feb	21 40602	28 78255	28 78255	21 40602	28 78255	21 40602	28 78255	21 40602	14 02948	28 78255	14 02948	21 40602
63	3-Mar	27 84963	29 18036	21 80382	21 80382	27 84963	20 47309	21 80382	14 42729	20 47309	21 80382	14 42729	27 84963
68	8-Mar	34 29325	28 24744	20 8709	14 82509	26 91671	20 8709	20 8709	20 8709	20 8709	28 24744	14 82509	28 24744
73	13-Mar	33 36032	27 31452	27 31452	15 2229	33 36032	21 26871	27 31452	27 31452	21 26871	21 26871	15 2229	27 31452
78	18-Mar	27 31452	33 36032	33 36032	15 2229	33 36032	15 2229	33 36032	33 36032	15 2229	27 31452	15 2229	21 26871
83	23-Mar	27 31452	27 31452	33 36032	21 26871	33 36032	15 2229	27 31452	27 31452	21 26871	21 26871	15 2229	21 26871
88	28-Mar	27 31452	21 26871	27 31452	27 31452	33 36032	21 26871	27 31452	27 31452	27 31452	27 31452	15 2229	21 26871
93	2 Apr	25 65094	13 55932	19 60513	30 6446	30 6446	19 60513	19 60513	24 5988	30 6446	24 5988	13 55932	24 5988
98	7 Apr	22 93522	16 88941	16 88941	22 93522	27 92889	22 93522	17 94155	22 93522	22 93522	27 92889	16 88941	27 92889
103	12 Apr	15 22583	15 22583	20 2195	20 2195	25 21317	20 2195	10 23217	20 2195	15 22583	25 21317	20 2195	25 21317
108	17 Apr	20 2195	15 22583	25 21317	15 22583	25 21317	25 21317	10 23217	20 2195	10 23217	25 21317	25 21317	20 2195
113	22 Apr	15 22583	15 22583	25 21317	20 2195	20 2195	25 21317	15 22583	20 2195	15 22583	25 21317	25 21317	20 2195
118	27 Apr	15 22583	15 22583	20 2195	20 2195	15 22583	25 21317	20 2195	20 2195	15 22583	20 2195	25 21317	20 2195
123	2 May	14 07035	19 06402	14 34513	19 3388	14 07035	19 3388	19 3388	19 06402	14 34513	14 34513	19 3388	24 05768
128	7 May	13 18965	13 18965	8 470764	13 46443	17 90853	13 46443	18 18331	22 9022	13 18965	8 470764	18 18331	18 18331
133	12 May	12 30895	12 30895	7 590063	7 590063	21 74671	12 30895	12 30895	17 02783	17 02783	12 30895	17 02783	17 02783
138	17 May	12 30895	12 30895	7 590063	7 590063	21 74671	17 02783	17 02783	12 30895	17 02783	17 02783	21 74671	12 30895
143	22 May	12 30895	17 02783	7 590063	12 30895	21 74671	21 74671	17 02783	12 30895	17 02783	17 02783	21 74671	17 02783
148	27-May	12 30895	17 02783	12 30895	12 30895	21 74671	17 02783	21 74671	12 30895	12 30895	12 30895	21 74671	12 30895
153	1-Jun	11 6233	16 34219	12 03966	16 34219	21 06107	16 34219	21 06107	12 03966	12 03966	7 32078	16 75854	12 03966
158	6-Jun	15 65655	15 65655	16 0729	11 35402	16 0729	11 35402	16 0729	11 35402	11 35402	7 051496	11 77038	7 051496
163	11-Jun	15 38726	19 68979	15 38726	15 38726	11 08474	15 38726	15 38726	11 08474	11 08474	11 08474	6 782213	6 782213
168	16-Jun	15 38726	15 38726	15 38726	15 38726	6 782213	11 08474	15 38726	15 38726	11 08474	11 08474	11 08474	6 782213
173	21 Jun	11 08474	11 08474	11 08474	15 38726	6 782213	11 08474	15 38726	11 08474	11 08474	11 08474	15 38726	11 08474
178	26-Jun	15 38726	11 08474	11 08474	11 08474	6 782213	11 08474	15 38726	15 38726	15 38726	11 08474	15 38726	11 08474
183	1-Jul	11 63679	14 37766	11 63679	7 334269	7 334269	11 63679	14 37766	11 63679	18 68018	14 37766	14 37766	14 37766
188	6-Jul	14 92971	17 67058	14 92971	7 886324	7 886324	14 92971	14 92971	14 92971	17 67058	17 67058	13 36805	13 36805
193	11-Jul	13 92011	13 92011	11 17924	11 17924	8 43838	13 92011	11 17924	11 17924	16 66097	16 66097	16 66097	16 66097
198	16-Jul	13 92011	13 92011	13 92011	11 17924	11 17924	16 66097	11 17924	11 17924	16 66097	13 92011	13 92011	16 66097
203	21-Jul	11 17924	13 92011	11 17924	11 17924	11 17924	13 92011	13 92011	11 17924	16 66097	11 17924	11 17924	16 66097
208	26-Jul	11 17924	13 92011	13 92011	8 43838	13 92011	13 92011	16 66097	11 17924	16 66097	11 17924	8 43838	13 92011
213	31 Jul	13 92011	11 17924	11 17924	8 43838	13 92011	13 92011	13 92011	11 17924	13 92011	13 92011	11 17924	11 17924
218	5-Aug	17 92813	12 4464	15 18726	12 4464	17 92813	17 92813	11 09575	8 354883	11 09575	13 83661	11 09575	12 4464
223	10-Aug	15 10377	12 3629	12 3629	12 3629	15 10377	15 10377	8 271386	8 271386	12 3629	11 01225	11 01225	16 45442
228	15-Aug	16 37092	16 37092	16 37092	12 2794	12 2794	12 2794	8 187888	8 187888	16 37092	8 187888	12 2794	20 46243
233	20-Aug	12 2794	16 37092	12 2794	8 187888	8 187888	8 187888	8 187888	12 2794	20 46243	12 2794	16 37092	20 46243
238	25-Aug	16 37092	20 46243	12 2794	8 187888	8 187888	12 2794	8 187888	12 2794	20 46243	12 2794	20 46243	16 37092
243	30 Aug	12 2794	16 37092	8 187888	8 187888	8 187888	12 2794	12 2794	12 2794	16 37092	16 37092	16 37092	12 2794
248	4-Sep	18 25043	18 25043	9 875602	14 15892	9 875602	13 96712	18 25043	14 15892	13 96712	13 96712	13 96712	9 875602
253	9-Sep	15 84663	20 12994	11 56331	15 84663	15 84663	15 84663	24 22146	15 84663	11 56331	15 65483	15 84663	11 56331
258	14-Sep	17 53434	21 81766	13 25103	17 53434	17 53434	21 81766	26 10097	17 53434	17 53434	17 53434	17 53434	17 53434
263	19 Sep	13 25103	21 81766	17 53434	17 53434	21 81766	26 10097	26 10097	17 53434	21 81766	21 81766	17 53434	17 53434
268	24-Sep	17 53434	21 81766	21 81766	17 53434	21 81766	21 81766	21 81766	17 53434	26 10097	21 81766	17 53434	21 81766
273	29-Sep	21 81766	26 10097	26 10097	17 53434	21 81766	17 53434	17 53434	21 81766	26 10097	17 53434	17 53434	17 53434

Appendix 3 cont.

[illegible]	[illegible] date	Eto 1991/92	Eto 1992/93	Eto 1993/94	Eto 1994/95	Eto 1995/96	Eto 1996/97	Eto 1997/98
277	4-Oct	18 63439	22 50178	22 50178	22 50178	22 9177	18 21847	22 9177
282	9-Oct	15 45112	27 46922	23 18591	19 31852	19 73444	19 31852	23 60183
287	14-Oct	16 55117	28 15334	24 28595	24 28595	20.41856	20 41856	24 28595
292	19-Oct	16 55117	24 28595	20 41856	24 28595	24 28595	16 55117	28 15334
297	24-Oct	20 41856	24 28595	16 55117	28 15334	28.15334	16 55117	28 15334
302	29-Oct	24 28595	20 41856	20 41856	24 28595	24 28595	16 55117	28 15334
307	3 Nov	27 64305	17 52158	23 77565	17 52158	17 52158	13 69419	27 64305
312	8-Nov	27 13275	17 01128	20 87867	17 01128	10 7572	10 7572	27 13275
317	13-Nov	26 62245	20 36837	20 36837	20 36837	14 11429	14 11429	26 62245
322	18-Nov	20 36837	20 36837	14 11429	26 62245	14 11429	20 36837	26 62245
327	23-Nov	20 36837	14 11429	20 36837	26 62245	20 36837	20 36837	26 62245
332	28-Nov	20 36837	7 86022	14 11429	26 62245	20 36837	20 36837	26 62245
337	3-Dec	21 46742	12 82855	15 21335	21 46742	21 46742	19 08263	25 3367
342	8-Dec	16 31239	13 9276	13 9276	20.18168	20 18168	20 18168	24 05096
347	13-Dec	15 02665	18 89593	18 89593	18 89593	15 02665	15 02665	22 76521
352	18-Dec	15 02665	18 89593	22 76521	18 89593	15 02665	15 02665	22 76521
357	23-Dec	18 89593	22 76521	18 89593	15 02665	11 15737	15 02665	22 76521
362	28-Dec	18 89593	18 89593	15 02665	11 15737	15 02665	18 89593	22 76521
3	3-Jan	28 75213	13 8698	13 8698	28 75213	13 8698	13 8698	28 75213
8	8-Jan	13 8698	28 75213	13 8698	13 8698	13 8698	13 8698	28 75213
13	13-Jan	18 83058	18 83058	13 8698	23 79135	18 83058	13 8698	28 75213
18	18-Jan	18 83058	23 79135	18 83058	18 83058	23 79135	13 8698	28 75213
23	23-Jan	18 83058	23 79135	23 79135	23 79135	28 75213	13 8698	28 75213
28	28-Jan	23 79135	23 79135	28 75213	18 83058	23 79135	13 8698	28 75213
33	2-Feb	26 26034	26 26034	31 22112	18 8838	18 8838	21 29957	31 22112
38	7-Feb	33 6901	21 35279	26 31357	13 97625	21 35279	21 35279	26 31357
43	12-Feb	28 78255	21 40602	21 40602	21 40602	21 40602	28 78255	21 40602
48	17 Feb	28 78255	14 02948	21 40602	21 40602	28 78255	28 78255	14 02948
53	22 Feb	28 78255	14 02948	28 78255	28 78255	21 40602	28 78255	14 02948
58	27-Feb	28 78255	21 40602	36 15909	28 78255	21 40602	28 78255	21 40602
63	3-Mar	21 80382	21 80382	29 18036	29 18036	20 47309	21 80382	27 84963
68	8 Mar	14 82509	22 20163	22 20163	28 24744	26 91671	22 20163	28 24744
73	13-Mar	21 26871	21 26871	15 2229	27 31452	33 36032	15 2229	21 26871
78	18 Mar	27 31452	21 26871	15 2229	27 31452	27 31452	15 2229	21 26871
83	23-Mar	33 36032	27 31452	21 26871	21 26871	27 31452	15 2229	27 31452
88	28-Mar	27 31452	21 26871	21 26871	15 2229	27 31452	21 26871	33 36032
93	2-Apr	19 60513	19 60513	19 60513	18 55299	25 65094	19 60513	30 6446
98	7 Apr	16 88941	16 88941	16 88941	21 38308	17 94155	22 93522	27 92889
103	12-Apr	20 2195	20 2195	20 2195	25 21317	10 23217	15 22583	25 21317
108	17 Apr	25 21317	25 21317	25 21317	20 2195	10 23217	20 2195	20 2195
113	22 Apr	20 2195	20 2195	25 21317	15 22583	10 23217	20 2195	20 2195
118	27-Apr	20 2195	15 22583	20 2195	10 23217	15 22583	20 2195	20 2195
123	2 May	14 34513	14 07035	14 34513	9 351465	14 34513	19 08402	19 3388
128	7-May	13 46443	17 90853	8 470764	8 470764	13 46443	17 90853	13 46443
133	12-May	12 30895	21 74671	12 30895	12 30895	12 30895	21 74671	12 30895
138	17 May	12 30895	17 02783	12 30895	12 30895	17 02783	21 74671	12 30895
143	22-May	17 02783	12 30895	12 30895	12 30895	17 02783	17 02783	17 02783
148	27 May	12 30895	12 30895	7 590063	12 30895	12 30895	12 30895	12 30895
153	1-Jun	16 34219	16 34219	11 6233	12 03966	7 32078	7 32078	12 03966
158	6-Jun	15 65655	16 0729	15 65655	16 0729	11 35402	11 35402	7 051496
163	11 Jun	15 38726	11 08474	15 38726	15 38726	15 38726	15 38726	6 782213
168	16 Jun	11 08474	6 782213	15 38726	19 68979	19 68979	15 38726	6 782213
173	21-Jun	11 08474	6 782213	15 38726	19 68979	15 38726	11 08474	11 08474
178	26-Jun	11 08474	6 782213	19 68979	19 68979	11 08474	6 782213	15 38726
183	1 Jul	11 63679	10 07513	18 68018	18 68018	10 07513	10 07513	15 93932
188	6-Jul	7 886324	13 36805	14 92971	17 67058	13 36805	13 36805	14 92971
193	11-Jul	8 43838	13 92011	13 92011	16 66097	16 66097	16 66097	11 17924
198	16-Jul	11 17924	11 17924	11 17924	16 66097	13 92011	13 92011	13 92011
203	21 Jul	11 17924	11 17924	13 92011	13 92011	11 17924	11 17924	13 92011
208	26-Jul	13 92011	11 17924	13 92011	11 17924	8 43838	8 43838	16 66097
213	31-Jul	11 17924	11 17924	16 66097	8 43838	8 43838	8 43838	13 92011
218	5-Aug	11 09575	8 354883	13 83661	8 354883	8 354883	12 4464	11 09575
223	10-Aug	8 271386	8 271386	11 01225	8 271386	8 271386	12 3629	12 3629
228	15-Aug	12 2794	8 187888	8 187888	8 187888	8 187888	16 37092	16 37092
233	20-Aug	16 37092	8 187888	8 187888	8 187888	12 2794	12 2794	16 37092
238	25-Aug	20 46243	8 187888	12 2794	12 2794	12 2794	16 37092	12 2794
243	30 Aug	20 46243	8 187808	16 37092	16 37092	16 37092	16 37092	12 2794
248	4-Sep	22 34195	14 15892	22 34195	18 05863	18 25043	22 34195	13 96712
253	9-Sep	19 93814	20 12994	24 22146	19 93814	24 22146	19 93814	19 93814
258	14 Sep	17 53434	21 81766	21 81766	17 53434	21 81766	21 81766	21 81766
263	19-Sep	13 25103	17 53434	21 81766	17 53434	17 53434	21 81766	26 10097
268	24-Sep	13 25103	17 53434	21 81766	17 53434	13 25103	26 10097	21 81766
273	29-Sep	17 53434	17 53434	21 81766	21 81766	13 25103	26 10097	17 53434

Appendix 4: Maize Crop Coefficient for initial (1), development (2), mid (3) and late seasons (4) growth stages.

Pentad	Growth stage	Kc
1	1	0.4
2	1	0.4
3	1	0.4
4	1	0.4
5	2	0.4
6	2	0.54
7	2	0.68
8	2	0.82
9	2	0.96
10	2	1.1
11	3	1.1
12	3	1.1
13	3	1.1
14	3	1.1
15	3	1.1
16	3	1.1
17	4	0.975
18	4	0.850
19	4	0.725
20	4	0.6

Appendix 5 Soil Moisture Retention data

Weight in grams of undisturbed soil samples at the given pressure

BLOCK 1

Sample number / Horizon	Depth	saturation	0 1 bar	0 3 bar	0 5 bar	0 7 bar
AP (a)	0-20	302 86	298 21	297 61	294 55	293 69
(b)		298 17	293 06	292 3	289 02	287 83
Bt (a)	20-54	299.51	293 24	292 63	289 94	288.5
(b)		300 34	294 35	293.86	291.79	290.37
Bc1&Bc2(a)	54-120	301 45	295 14	294 53	291 19	290 22
(b)		305 29	297 65	297 15	293 22	292 43

BK 2

SAMPLE NUMBER		depth	Saturation	0 1bar	0 3bar	0 5bar	0 7bar
P1	a		269.26	260 75	257 77	255 25	253 89
	b		273.04	267 85	263 41	261.56	259.6
P2	a	20-35	279 43	266 8	260.98	259.79	258 96
	b		286 95	277 4	273 15	272.59	269 71
P3	a	35-50	279 41	266 34	259 56	258 99	257 48
	b		279.18	270 22	263 1	262 05	261 38
P4	a	50-65	292.21	283.38	278 42	277.21	276 11
	b		304 71	294 85	290 36	288 94	287 55
P5	a	65-80	280 6	269 4	261 46	260.08	258 39
	b		300 09	291 35	284 26	282.96	282 72
P6	a	80-95	290 68	278 8	272.88	271 8	270 83
	b		297 48	287 68	281.12	280 58	279 48
P7	a	95-110	287 75	275 4	268 6	267 71	266 8
	b		287.02	275 56	270 02	269 19	268 36

BLOCK 3

Sample number / Horizon	Depth	saturation	0 1 bar	0.3 bar	0 5 bar	0 7 bar
AP (a)	0-20	286 34	280 26	279 55	274 63	273 09
(b)		285.72	279 13	278 45	274 53	273 45
Au1$Au2(a)	20-48	298 52	292 6	291 62	288 44	285 64
(b)		291 86	287 31	286 61	281 95	280 13
Ab1 (a)	48-90	314 35	309 07	308 36	306 57	303 84
(b)		308 29	298 41	297 43	292 57	290 5
Ab2 (a)	90-120	301 29	297 65	297 3	293.13	290 47
(b)		299 81	295 87	294 83	291 66	289 78

.0 bar	3 0 bar	5 0 bar	7 0 bar	10 0 bar	13 0 bar	15.0 bar
293 11	291 94	291 15	290 4	289 86	289 42	288 84
287 14	286 08	285.21	284 51	283 64	282 93	281.99
287 92	286 56	285 69	284 9	284 64	284 53	284 03
289 62	288 64	288 66	287 98	287 31	286 72	285.81
289 41	288 31	287 62	286 71	285 75	285.35	284 87
291 54	290 45	289.76	289 16	288.52	288 19	287.69

bar	3bar	5bar	7bar	10bar	13bar	15bar
252 97	252.22	248.71	247 6	246.24	245	244.77
258 54	257 8	255 47	254 44	253 68	253.22	252 78
258.37	257 63	253 74	252 9	252.59	252 57	252 55
268 79	267 91	265 56	265 08	264 76	264 51	264 34
256 98	256 04	252 74	252 58	252 65	252 44	252 36
260 94	260 05	256 29	255 67	255.15	254 76	254 46
275 4	274 38	271 32	270 77	270.52	270 37	270 29
286 88	286 02	282 72	283 08	282 64	282 51	282 24
257 97	256 85	253 66	253.17	252 88	252 76	252.76
281 3	279 88	276 21	275 48	275.01	274 8	274.73
270	268 64	264.85	264 33	260 49	260 29	260.24
278 85	278	274 46	274 12	262 68	262 51	262 43
266 12	265 01	261 52	260 92	264 05	263 93	263.91
267 6	266 68	263 64	263 06	273 62	273 47	273 39

0 bar	3 0 bar	5 0 bar	7 0 bar	10 0 bar	13 0 bar	15.0 bar
272.69	271 05	270 31	269 47	268 8	268 37	267 76
272 38	271 14	270 24	270 11	269 17	268 55	267 81
284 8	283 82	283 32	282 92	282.52	281.9	280 4
279 28	277 51	276.86	276 11	275 77	275 37	274 84
303 09	301 98	285 54	284 86	284 12	283 7	283 42
289 68	287 96	301.14	300.5	299.98	299 53	298 93
288 89	287 03	286 9	286 14	285 7	285 27	284 84
288 8	287 22	286 16	285 22	284 17	283 57	282 91

Appendix 6: Maximum amount of water held for each corresponding maize root depth.

Pentad	*Root Depth (cm)*	*Maximum amount of water held (mm/corresponding root depth)*
1	10	16
2	21	32
3	32	47
4	43	63
5	54	80
6	65	94
7	76	108
8	87	125
9	98	143
10	109	166
11	120	190
12	120	190
13	120	190
14	120	190
15	120	190
16	120	190
17	120	190
18	120	190
19	120	190
20	120	190
22	120	190