DECLARATION

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

SIGNATURE:-------Thome.-------DATE ----4.05.2005

Josephine N. Thome.

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

SIGNATURE:------------------------------- DATE:--4/5/05------------------

Eng. Reuben K. Muni

This thesis has been approved after examination by:

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Dr. Zablon I. Oonge.

DEDICATION

This thesis is dedicated to all the women in the world.

"You know the worth of water
when the well dries up"

ACKNOWLEDGEMENT

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LIST OF ABBREVIATIONS

Abbreviation	**Description**
ApproTEC	Appropriate Technologies for Enterprise Creation
ASAL	Arid and Semi-Arid Lands
ASAE	American Society of Agricultural Engineers
FAO	Food and Agricultural Organization of the United Nations
GoK	Government of Kenya
GHARP	Greater Horn of Africa Rainwater partnership
ICRISAT	International Crops Research Institute for the Semi Arid
ICID	International Center for Irrigation Development
IR	Irrigation Requirement
ITDG	Intermediate Technology Development Group
IWMI	Irrigation Water Management Institute
NGO	Non Governmental Organization.
NRM3	Natural Resources Modeling, Monitoring and Management Project.
PVC	Polyvinyl Chloride
RWH	Rainwater Harvesting
RWHS	Rainwater Harvesting Systems
RWCS	Rainwater Catchment Systems
SWIM	System wide Initiative on Water Management
UK	United Kingdom
UNESCO	United Nations Educational Scientific and Cultural Organization
USA	United States of America
WMO	World Meteorological Organization

ABSTRACT

An inventory of the existing runoff harvesting systems for crop production was carried out in Rugutu location of Laikipia district. An evaluation of rainwater storage system was also performed in two of the water pans. This was carried out using the water balance approach. It was realized that the major hindrance to the adoption of runoff storage water harvesting systems was the excessive water loss through evaporation and seepage. The evaporation losses ranged between 0.1 and $0.3m^3$/day while seepage losses ranged between 0.03 and $0.3m^3$/day which accounted for 30 to 50% of the total storage. Seepage water losses increased with an increase in water level. The water pans are neither lined nor covered with a roof and therefore most of the stored water is lost through seepage and evaporation.

The historical rainfall record is bounded to the right by zeros. Frequency analysis was carried out analytically using the mixed distribution to determine the design rainfall at different reliabilities. It would be misleading to design systems based on the means as it was observed that the mean rainfall values could only be expected at 30 to 40% reliability levels. The failure rate of a design based on the means would be high. The Markov model was used to determine the conditional and unconditional probabilities of wet and dry decades as well as the occurrences of different lengths of wet and dry spells.

The start of the growing season was on the 10th decade during the long rains and on the 29th decade during the short rains. The length of the growing period during the long and short rains was 80 days and 60 days respectively. Rainfall analysis shows that during the growing seasons, the probability of having a dry spell longer than 2 decades was higher than 50%. The dry spells are preceded by wet spells and runoff water harvesting for supplemental irrigation is then vital to avert the intra seasonal dry spells.

The construction of water pans was funded by NGOs operating in the area. They did not take into consideration the catchment size available or the size of farms to be irrigated when deciding on the storage sizes. This has led to the under design of the water pans. The water pans had capacities ranging from $30\text{-}40m^3$ while the catchment areas ranged from 4000 to $10000m^2$. Mass curve analysis was used to determine the catchment area and storage capacity at different irrigated areas and rainfall reliability. Design tables have consequently been developed and they will help farmers in selection of the proper storage system. A

farmer planning to practice supplemental irrigation on a 250m^2 kitchen garden with a crop planted at the onset of the long and short rains and at a reliability of 80% would require a water pan with 40.2m^3 and 50.3m^3 storage capacity and a runoff catchment area of 4290m^2 and 7499m^2 respectively. The choice of the design reliability level selected would depend on the individual farmers' financial status.

Soil moisture balance was carried out for different planting decades to determine when and how much water should be applied. The results have been presented in tabular form and will help a farmer when scheduling water applications. A crop planted at the onset of the long and short rains at rainfall reliability of 80% would require a total of 228mm and 232mm of supplemental irrigation water respectively. Water stored may not be enough to meet the full crop water requirement and deficit irrigation may be considered. In this case, crop water deficits should be avoided when the crop is at its sensitive growth stages. For cabbage crop this occurs during the head formation stage.

Farmers within the study area practice different methods of runoff conservation for crop production. They mainly practice in-situ water conservation while the adoption rate of the runoff storage systems is low. Out of the 11 homesteads visited, only 3 of the homesteads had operating water pans. There is however a great potential of improving the livelihood of people living in these area through runoff storage systems for crop production.

1 INTRODUCTION

1.1 Background

Kenya's arid and semi-arid lands (ASAL) cover about 80% of the total land area and hold over 50% of the livestock and 25% of its human population (GoK, 1986). In general, semi-arid areas are characterized by erratic rainfall with great annual variability, annual potential evapotranspiration exceeding the rainfall amounts, high amounts of runoff due to low infiltration and recurrent soil moisture deficits limiting crop production (Ben-Asher and Berliner, 1994; Perrier, 1988; Evenari *et al.,* 1971). Under these conditions, rainfed agriculture has failed to provide the minimum food requirements for the rapidly increasing population

The growing population is placing an ever-increasing burden on food supplies and agricultural technology to meet the increasing demands. This steady population growth has led to the migration of the rural population from high potential areas to dry lands in search of land (Barrow, 1987, Rapp and Hasteen-Dahlin, 1990). The dry lands in their present state support meager crop production.

Clearly the development of the ASAL represents the highest potential for further economic advancement in the region. The major concern is how to utilize the available water, which is the most limiting factor to economic activities. Although natural precipitation in an area may be inadequate to raise a crop, enough water can be collected from an area for ample crop yield. Marginal lands with annual rainfall as low as 300mm can be made productive if controlled and limited water is made available by rainwater harvesting (RWH) techniques (Flug, 1981). Currently, Kenya, among other developing countries is not able to acquire financial resources to enable bulk water transfers, construction of big dams and reservoirs for most of the ASAL. Simple and sustainable rainwater harvesting technologies could be the long awaited solution for improving rainfed agriculture and overall food security (Ngigi, 2003). Thus the way forward is in the development of small-scale RWH technologies by the communities and individuals who live within the ASAL.

Mere survival tactics have led many land users in the ASAL to improvise various indigenous RWH systems. These water harvesting methods are now receiving renewed interests and a number of water harvesting projects have been set up with the objective of combating the effects of intra seasonal drought. However few of the projects have succeeded in combining technical efficiency with low cost and acceptability to the local farmers (Reij *et al.*, 1988).

This has been partially attributed to the limited technical know-how and inappropriate approach with regard to the prevailing socio-economic conditions. Storage systems of the same size are constructed giving minimal considerations to the farmers water demand and the available catchment area. Therefore benefits can be realized through technical improvements of the existing water harvesting initiatives and technologies.

The harvested runoff can either be directly applied to an adjacent cropped area or is stored in some type of storage facility. The former option requires a good distribution of rainfall as well as a high soil moisture holding capacity. Experience has also shown that runoff onto cultivated strips is sometimes too great when the crop is at its early growth stage (Pacey and Cullis, 1986). The distribution of rainfall in ASAL areas is not very dependable. Therefore, there may occur crop failure even with concentration of rainfall through water harvesting if only the soil is used for storage (Cluff, 1981).

For rainwater harvesting to be successful there is need to combine in-situ water harvesting with efficient surface storage facilities for supplemental irrigation. Otherwise, moisture concentration would be limited to soils of high moisture holding capacity and for growing crops that are deep rooted and which possess a certain tolerance to drought.

Supplemental irrigation is the application of a limited amount of water to the crop when rainfall fails to provide sufficient water for plant growth. The storage systems could be on-water pans, rock catchments or tanks. The value of applying a small amount of water at a critical time to rainfed agriculture has been documented. Krantz (1979) as quoted by Cluff (1981) found in India that the addition of as little as 50mm of water, more than doubled the production from several crops including corn. It was also noted that with as little as 20mm of supplemental irrigation in a cropping cycle consisting of pearl millet, pigeon pea and cowpea, gross yields increased significantly (Vijayalakshmi *et al*, 1989). Therefore, the judicious application of small amounts of water to wet the root zone during stress period can lead to a significant increase in yields.

1.2 Objectives

The main objective of the research is to establish how rainwater harvesting potential in Rugutu Location of Central Laikipia can be exploited. The specific research objectives are:

1. To review the existing RWH technologies for crop production.
2. To perform a hydrological evaluation of storage rainwater harvesting system.
3. To formulate design criteria that enhances the selection of optimal design parameters for on-farm rainwater storage systems.
4. To present strategies for application of limited supplemental irrigation water.

1.3 Project Justification

The study area falls within the ASAL where limited availability of water is in most cases the major constraint to rainfed agriculture. The amount of rainfall received is not only insufficient to sustain a crop through to maturity but it is also unevenly distributed. There is a high risks of periods of below optimal cumulative soil water availability during the growing season (Rockstrom, 2000b).

The area was originally inhabited by the Maasai community and the main land use was livestock keeping. Migration of people from adjoining districts, mostly Nyeri and Muranga district has however led to land use change. The farmers brought with them their agricultural farming practices and are practicing both small scale farming and livestock keeping. The area receives low rainfall amounts and faces very high risk for annual droughts and intra-seasonal dry spells. This makes rainfed agriculture in the region a risky enterprise. This however has not deterred the migrant inhabitants from practicing rainfed agriculture.

Appropriate food policies and technological interventions will determine the prospects of increasing crop production in such situations. RWH has proved to be a viable technology for improving food production where rainfall is low and erratic in distribution (Oweis *et al.*, 1999; Oweis and Taimeh, 1996; Reij *et al.*, 1988 and Krantz, 1981). However, if RWH technology is to be taken seriously as a technique for improving food production in the ASAL, then, there is need for more research to provide design guidelines and essential technical data.

2 LITERATURE REVIEW

2.1 Rainwater Harvesting for Crop Production

Dryland farming describes systems where rainfall is often inadequate for crop production. In this system crop production critically depends on the amount of water available during the crop-growing season. Three major hydro-climatic hazards experienced in dryland farming are:

- Poor rainfall partitioning where only a fraction of rainfall is channeled to the root zone coupled with infield crop competition for soil water.
- The high risks of periods of below optimal cumulative soil water availability during growth seasons.
- The high risk of intermittent droughts or dry spells occurring during critical growth stages of crop (Rockstrom, 2000b).

RWH is one of the interventions, which would ensure an increase in amount of water available for plant growth. RWH is defined in its broadest form as the collection of runoff for its productive use (Siegert, 1994). It is one of the management practices by means of which water availability to plants can be increased. Other management practices include conserving stored soil water by minimizing evaporation from soil surface and transpiration by weeds and maximizing the use of available water through improved management practices and use of adapted crops varieties.

Some of the simplest RWHS can collect 20–35% of the precipitation for later beneficial uses while a more elaborate system can collect more than 90% (Frasier, 1981). RWH is an important option for improving the management of rainwater. An increase in the amount of water available to crops in the ASAL can lead to an improvement of the reliability of crop production (Reij *et al.*, 1988, and Critchley, 1989).

2.1.1 Classification of RWHS

Boers and Ben-Asher (1982) have classified rainwater harvesting into two groups:

a) Micro-catchment water harvesting (MCWH).

The runoff is collected from a contributing area over a flow distance of less than 100m and storing it for consumptive use in the root zone of an adjacent infiltration basin. Examples of MCWH are contour catchment water harvesting, desert strip farming, contour bench farming, and runoff based pitcher farming.

b) Runoff farming water harvesting (RFWH).

This is a method of collecting surface runoff from a catchment area, using channels, dams or diversion systems and storing it in a surface reservoir or in the root zone of a farmed area for direct use. In general, a water catchment system comprises a catchment area and a storage component. In a further classification system two major categories evolve:

- Short-term techniques that store water in the soil profile.
- Long-term storage techniques for supplemental irrigation.

Short–term storage systems includes insitu water conservation techniques--tie ridges and strips, tree micro-catchment (Negarim), semi-circular bunds, trapezoidal bunds, furrows, trash lines, terraces and pitting (Zai pits, Matengo pits). The long–term storage systems include in-situ, rock catchment, ground catchment–tanks, ponds, hafirs, sand dams and earth dams.

Storage systems offer the farmer a tool for water stress control where risks of crop failure are reduced though the investment costs and the need for technological know-how are high. This system, however, still depends on rainfall distribution as during drought years there is no runoff producing rainfall and very little can be done to bridge a dry spell occurring during any of the growth stages of a crop.

2.2 Rainwater Harvesting for Crop Production in Kenya

RWH for crop production is becoming more widespread in Kenya where numerous projects have sprung up all over the country. The first attempt at water harvesting in Kenya was done in Turkana by the Ministry of Agriculture and the Salvation Army (Pacey and Cullis, 1986; Reij *et. al.*, 1988). According to Rockstrom *et al.*, (1999), in Machakos district, Mwala location, earth dams for supplemental irrigation of maize have proved successful while in Kitui, rock catchment systems and "*Fanya juu*" terraces where soil is heaped onto the upper part of terrace are widely used for moisture conservation. Some farmers divert runoff from seasonal rivers and roads into cultivated areas (Mwangi, 1993). An attempt to evaluate water harvesting techniques was done by ASAL programme in 1984-1986 when trials for tie ridges, *"Fanya juu"* terraces and external catchment systems were conducted (Critchley, 1989).

2.2.1 Rainwater harvesting in Laikipia district

The semi-arid highlands of Laikipia are located on the Western and Northwestern footslopes of Mt. Kenya. As in many other semi-arid areas in Kenya, the formerly European white highlands face increasing pressure as a result of population growth and migration from the densely populated high-potential area. Migrants have brought with them farming systems developed for high potential area but inappropriate for the area of their new settlement (Liniger, 1989). The limited water resources do not allow irrigation and research has been going on aimed at the promotion of rainwater harvesting technologies both for domestic and crop production (Liniger, 1989).

In an effort to solve the water crisis problem, the local people have worked mostly in self-help groups and sometimes with the assistance from donor agencies and local churches to construct water tanks and water pans on their farms. The Anglican Church of Kenya (ACK) Nakuru diocese, is involved in rainwater harvesting in Ng'arua division of the district where roof and ground water catchment are being promoted for supplying water for domestic use and agriculture.

Different types of storage tanks such as ferrocement, water jars and underground tanks are used. Individual farmers, through self help groups, assisted by the ACK diocese construct these tanks. The catholic diocese of Nyeri, ASAL Development and Semi-arid Lands Development Program (SARDEP) are other stakeholders who are involved in RWH activities in the district. The underground water tanks have been promoted for multi purpose uses. The tanks have storage capacity of $9m^3$-$100m^3$. The bottom is smeared with cement to avoid seepage and the tanks are covered with local materials to reduce evaporation losses.

At Katiorini, in Baringo, sorghum and bulrush millet yielded best in the micro-catchment system (Imbira, 1989). Micro and macro catchments were used for crops and for reseeding pastureland. The most commonly used harvesting structures are micro-catchments, semi-circular hoops and trapezoidal bunds.

2.3 Crop Water Requirement

To estimate the irrigation water required in agriculture, it is necessary to predict the crop water requirement during the different growth stages and various management practices. The methods available for the estimation of potential evapotranspiration are Blaney Criddle, radiation, Thornthwaite, Penman, and pan evaporation method. The choice of method depends on the type of climatic data available and on the accuracy required in determining the water needs. A relatively high correlation exists between the potential evapotranspiration and the pan evaporation from a properly located class A pan (Tanner, 1967; Doorenbos and Pruitt, 1977; Michael, 1978). The equations 2.1 are used to calculate crop evapotranspiration.

$$ETc = Kc * ETo \tag{2.1a}$$

$$ETo = Ks * Epan \tag{2.1b}$$

Where,

ETo = Potential crop evapotranspiration, mm/day

$Epan$ = Pan evaporation, mm/day

ETc = Crop evapotranspiration, mm/day

Kc = Crop coefficient

Ks = Pan coefficient

Procedures for selecting the appropriate *Kc* values take into account the crop characteristics, time of planting or sowing, crop development stages and general climatic conditions. Four stages of crop development can be identified namely initial stage, crop development stage, mid-season stage and the late season stage. According to Berger (1989), evapotranspiration is conservative in the sense that it varies much less than rainfall.

2.3.1 Irrigation requirement

The net irrigation requirement is the quantity of water to be applied by artificial means, exclusive of precipitation, carry over soil moisture, ground contribution or other gains in soil moisture that is required for crop production. In ASAL the groundwater contribution may be assumed equal to zero. The irrigation requirement is determined using Equation 2.2.

Knowing the irrigation efficiency of a system, gross irrigation requirement (GIR) can then be determined.

$$IR = ETc - \mathrm{Re} - W - Gc \qquad (2.2)$$

Where,

IR = Net irrigation requirement, mm

Re = Effective rainfall, mm

Gc =Groundwater contribution, mm

W = Available soil water over root depth, mm

2.3.2 Supplemental irrigation

Supplemental irrigation is the application of a limited amount of water to the crop when rainfall fails to provide sufficient water for plant growth with the aim of improving yields. It is a temporal intervention designed to augment natural evapotranspiration during the dry spells. Dry spells may be associated with late commencement of sowing rains, failure of the rains during the growing season or early cessation of the rains.

In areas where periods of severe water stress are common and often coincide with the most sensitive stages of growth then supplemental irrigation is carried out. When applied at the right time and amount it can make a crucial difference in the yield potential of crops (Oweis *et al.*, 1999). With supplemental irrigation, cropping intensity of production can be significantly increased and stabilized. The essential characteristics of supplemental irrigation are:

- Water is applied to rain-fed crops, which are normally produced without irrigation;
- It is applied only when rainfall is inadequate; and
- The amount and timing of supplemental irrigation are not meant to provide enough water stress-free conditions over the growing season but to provide enough water during the critical stages of crop growth to ensure optimal yields in terms of yield per unit of water (Oweis *et al*, 1999).

The use of supplemental irrigation requires selection of drought resistant crops. Strategies for supplemental irrigation include allocation of less water to the more drought resistant crops, irrigating crops only during the most critical growth stages or planting the crop so as to stagger the critical demand periods. To plan for supplemental irrigation, the farmers must know the moisture deficit that can be allowed at each of the growth stages. Appropriate water stress indicators should be used to determine when to irrigate and how much to apply. In general water stress in crops is likely to occur when 50% of the available water is depleted (Frere and Popov, 1979). However this value should be related to particular crops.

2.3.3 Irrigation schedules

This is the process of determining when to irrigate and how much to apply per irrigation. The schedules can be designed to fully or partially provide the irrigation requirement. Full irrigation involves providing the entire irrigation requirement and results in maximum production. Partially meeting the irrigation water or deficit irrigation reduces yields. When water supply is limiting then the crop selection, total acreage and total production are primarily determined by the extent to which the available water supply over the growing season can fully meet the water requirement of the crop.

In general, crops are more sensitive to water during emergence, flowering and early yield formation stages (Doorenbos and Kassam, 1979). Water management in this situation must, therefore take into consideration the optimal allocation of water over the crop growing period. Water allocation of the limited water should be directed towards meeting the water requirement during the crop's most sensitive growth stages.

everal techniques are used to determine when to irrigate. These include plant indicators, il indicators and soil moisture balance. Monitoring plants is the most direct method of termining when to irrigate. It is, however, necessary to relate plant parameters to soil ter content to determine the amount of irrigation (James, 1988). Soil indicators involve mation of soil water contents. Some of the soil indicators include the appearance and , and gravimetric sampling, use of tensiometers and porous blocks among others. In soil ture balancing, equations are used to determine the soil water content.

2.3.4 Soil moisture balance

The principles of moisture balance analysis on short time steps is normally seen as very complicated, due to the dynamic and complex process involved when water flows through saturated and unsaturated soils. However simple approaches have been used for the purpose of RWH planning (Rockstrom, 2000a). In order to access water needs to bridge or mitigate dry spells, a detailed water balance analysis has to be carried out. The soil moisture available at the end of a given time step is calculated from Equation 2.3.

$$W_t = W_{t-1} + \mathrm{Re}_t - ETc_t - DP_t \tag{2.3}$$

Where,

W_t and W_{t-1} =Available soil moisture at time t and t-1 respectively (mm)

ETc_t = Evapotranspiration at time t (mm)

Re_t = Effective rainfall at time t (mm)

DP_t = Deep percolation at time t (mm)

The accounting has to be carried out on a time step that actually captures the occurrence of dry spells. This time step should be ideally on a daily basis, but for practical purposes, not longer than 10 days (Rockstrom, 2000a). The following data is required when carrying out a water balance accounting for a given location.

- Rainfall data preferably on a daily basis;
- Estimates of effective rainfall;
- Soil water holding capacity and field capacity;
- Estimates of hydraulic conductivity for calculation of deep percolation losses; and
- Estimates of crop water requirement.

Deep percolation below the root zone occurs when the water content in the root zone exceeds the field water holding capacity of the soil (Rockstrom, 2000a). For the purpose of water balancing it is important to determine when deep percolation occurs and how much water is lost below the root zone. The percolation can be estimated by assuming that all water in excess of field capacity will percolate below the root zone. The field capacity hence gives the threshold of when the deep percolation occurs.

Effective rainfall is the portion of the total rainfall that assists in meeting the consumptive water use requirements of the growing crops (Avinash *et al.*, 1988). Dastane (1974) defines effective rainfall as the portion of the total seasonal annual rainfall, which is used directly and/or indirectly for crop production at the site where it falls without pumping.

The effective rainfall is a function of rainfall, slope, ground cover, usable soil depth, soil water holding capacity and antecedent soil moisture. The higher the soil moisture deficit, the higher the effective rainfall. All effective rainfall measurement and estimation methods are based on the representation and varying degrees of simplification of the hydrological cycle. The estimation methods include a fixed percentage of rainfall, and empirical formula.

According to Gichuki, (1996) the effective rainfall (Re) for the given monthly rainfall amount R is determined using the formulae:

$$\mathrm{Re} = 0.8R - 25 \qquad \text{If } R \geq 75 \text{ mm/month} \qquad (2.4a)$$

$$\mathrm{Re} = 0.6R - 10 \qquad \text{If } 17 < R < 75 \text{ mm/month} \qquad (2.4b)$$

$$\mathrm{Re} = 0 \qquad \text{If } R < 17 \text{ mm/month} \qquad (2.4c)$$

2.4 Soil Moisture Characteristics

The soil stores water needed by plants. The available soil moisture in a profile depends on soil depth, soil water storage capacity and the moisture extraction range of the crop (Doorenbos and Kassam, 1979). The soil depth of interest is the rooting zone of a crop as crops extract water from the effective root zone. The moisture removal over the rooting depth is 40%, 30%, 20% and 10% from the 1st, 2nd, 3rd and 4th quarter of the rooting depth respectively (Astatke *et al,* 1986). The soil moisture content in the upper soil layers is particularly variable mainly due to the variations in daily weather conditions especially rainfall.

2.4.1 Soil moisture retention

The water content at field capacity and the permanent wilting point define, respectively, the upper and lower limit of the soil moisture that is available to the plants. The values of field capacity and permanent wilting points can either be determined by field or laboratory methods. The pressure plate apparatus is the most common laboratory method. Undisturbed core samples are collected from the field. They are then pre-saturated and put in a pressure plate chamber where they are subjected to a stepped increase in desired suction pressures.

The water is drained out of the soil sample pores at the given pressure. Changes in sample weight are monitored at regular intervals and the suction pressure is changed when there is no more change in sample weight. As the suction increases, water in the finer pores will drain until eventually even the film of water held mostly at strong suctions is removed. The corresponding suction and water content values are plotted.

Neither field capacity nor permanent wilting point is a sharply defined quantity. Permanent wilting point for example is a function of crop and crop growth stage (James, 1988). A suction potential of 33 Kpa is used to define field capacity for most soils while permanent wilting point is the water held at suction potential of 1500Kpa.

The water between the field capacity and the wilting point is the available water (AW). Only the water held at the more moderate suctions can be taken up rapidly by the crops to sustain good growth. This part of the available water is called the readily available water (RAW). According to Nugteren (1970), plants easily abstract 40-60% of the available water while Smedema and Rycroft (1988) states that the RAW is often assumed to equal 2/3 of the AW. The following equation is used to compute the available water (James, 1988):

$$Aw = \frac{Drz(fc - pwp)}{100} \tag{2.5}$$

Where,

Aw = Available water, mm

fc = Field capacity in percent by volume

pwp = Permanent wilting point in percent by volume

Drz = Depth of the root zone, mm

2.4.2 Soil hydraulic conductivity

The rate of water movement into and through a soil profile is determined by the hydraulic conductivity (K_h). Water moves through the soil due to the presence of a hydraulic gradient. Hydraulic conductivity of a soil depends mainly on the geometry and distribution of water filled pores. K_h-value of a field soil may vary considerably across an area as well as in depth due to variations in soil texture and soil structure. The presence and characteristics of bio-pores (root channels, wormholes and other small conduits left by biological processes in the soil also greatly influences the hydraulic conductivity.

The hydraulic conductivity tests help to determine whether the soils within the water pan site can hold water satisfactorily. If the soils have a very high conductivity, water losses through seepage will be very high. According to Astatke *et al.* (1986), seepage water losses will be minimal in soils with conductivity of 0.01-0.001m/day. There are several methods of determining hydraulic conductivity. These include the laboratory method and the field measurements. The principle in all the measurement methods is that water is arranged to flow through the sample while the rate of flow and the corresponding head losses are recorded.

In the laboratory method, it is measured on undisturbed core samples taken from the field. The quality of the results depends very much on the quality of the samples which should be representative of the site under investigations. During measurements, the head may be kept constant (constant head method) or the head may decrease (falling head method). The hydraulic conductivity is then determined from the flow and head recorded using the Darcy's law.

The field measurements include the inverted auger hole method and the infiltrometer method. The inverted auger hole method is used for measurements of unsaturated hydraulic conductivity above the water table. The saturated K_h is then computed from the following equation (Smedema and Rycroft, 1988).

$$K_h = \frac{1.15r \log\left(h_o + \frac{r}{2}\right) - \log\left(h_t + \frac{r}{2}\right)}{2} \tag{2.6}$$

Where,

K_h = Saturated hydraulic conductivity (cm/hr)

r = Radius of auger hole (cm)

h_0 = Initial height of water(cm)

h_t = Final height of water (cm)

t = Time taken for the test (min)

2.5 Rainfall Analysis

The objective of the statistical analysis is to abstract the essential information from a set of data. Analysis of historical data covers a wide range of variety of subjects including probability distribution, frequency analysis, persistence and dry spell analysis. Proper characterization and interpretation of climatic variables is required in order to determine the appropriate technological and management interventions required to minimize crop production risk and enhance food security.

In the ASAL, there is spatial and temporal variability of seasonal rainfall totals and of distribution of rainfall within season. However, it is common to find the rainfall of a specific region described in terms of its long term average value and specific seasons totals described in terms of their departure from the average (Pain, 1992). As a result much agronomically useful information such as the wet and dry spells, beginning and end of rains is lost (Wanakwanyi, 1992). Designs based on average values are also likely to fail. Assessment of within season distribution of rainfall is often based on daily records (Wanakwanyi, 1992) summation of 10 day (Kiggundu, 1998, Mulengera and Ngobei, 1992) or 5 day totals (Narayana, 1979).

2.5.1 Design rainfall

The design rainfall is obtained from frequency analysis of the rainfall data. This is a procedure that estimates the probability of occurrence of a certain amount of rainfall. Return period of an event of given magnitude is the average recurrence interval between events equaling or exceeding the specified magnitude. The probability of occurrence of a certain amount of rainfall is the inverse of the return period. Depending on the return period of the design structure, the required design rainfall amount can be determined.

Frequency analysis by analytical method

The magnitude of a hydrologic event may be represented as the mean plus the departure of the variate from the mean (Chow *et al*, 1988; Haan, 1977). This is represented by the following equation;

$$X_T = \overline{X} + K_T S \tag{2.7}$$

Where,

X_T = Magnitude of the event having a return period T

K_T = Frequency factor

$\overline{X}$ = Mean value

S = Standard deviation

The frequency factor is a function of the return period and type of probability distribution used in the analysis. The calculation of the statistical parameters required in the frequency analysis is done for the proposed distribution by the method of moments.

The K_T relationships for several probability distributions have been described by Chow *et al*, (1988). The factors can either be calculated from equations or obtained from respective tables and the magnitude of expected event computed. If an analytical procedure is used, it is recommended that the data still be plotted to determine how well the data fits the assumed distribution.

2.5.2 Probability Distribution

The simplest and useful approach to evaluating rainfall data is by studying the probability of occurrence of rainfall (Finkel and Finkel, 1986b; Kottegoda, 1980, Haan, 1977). A probability distribution is a function representing the probability of occurrence of the random variable. By fitting a distribution to a certain set of data, a great deal of probabilistic information can be compactly summarized in the function and its associated parameters.

Distribution fitting can be accomplished by the method of moments or the method of maximum likelihood.

Probability distributions commonly used for hydrological variables are normal distribution, log-normal distribution, exponential distribution, gamma distribution, Weibull distribution and Poisson distribution (Chow *et al.*, 1988). Other distributions include the mixed distribution, pearson type III, log pearson type III and extreme value type I.

Normal distribution

The normal distribution is the most widely used and important probability distribution (Haan, 1977; Kottegoda, 1980). The main limitations of the normal distribution for describing hydrological variables is that it varies over a continuous range while most hydrological variables are nonnegative, and that it is symmetric about the mean, while hydrological data tends to be skewed (Haan, 1977). It gives a good fit in cases where the variables are unbounded above or below (Thom, 1966). The distribution is a two-parameter distribution whose probability density function is as follows.

$$F(x) = \frac{1}{\delta\sqrt{2\pi}} \exp\left[-\frac{(X-\mu)^2}{2\delta^2}\right] \qquad -\infty \le X \le \infty \qquad (2.8)$$

$$\mu = \overline{X},\ \delta = S_x$$

The probability distribution for monthly rainfall totals can be obtained by the normal distribution (Linsley *et al.*, 1992; Chow *et al.*, 1988). Sharma (1989) found that annual rainfall process in the Kenyan regions where mean rainfall exceeds 650mm obeys the normal distribution.

Log-normal distribution

If the random variable Y=log X is normally distributed, then X is said to be log-normally distributed. The log-normal distribution has advantage over the normal distribution because it is bounded (X>0) and the log transformation tends to reduce the positive skewness found in hydrological data (Chow *et al.*, 1988). The log-normal distribution is positively skewed with the skewness decreasing as the coefficient of variation decreases (Haan, 1977). The distribution has the same probability density function as the normal distribution with Y=log X.

Mixed distribution

Most hydrological variables are bounded to the left by zero. According to Nieuwolt (1977) as quoted by Berger (1989), the frequency distribution of rainfall in tropical areas is often positively skewed. A zero in a set of data that is being logarithmically transformed requires special handling. The solution could be to add a small constant to all the observations or to analyze the non-zeros and then adjust the relation to the full period of record. A more theoretically sound method is to use the mixed distribution (Doorenbos and Pruit, 1977; Haan, 1977; Thom, 1966).

The mixed distribution has a finite probability that X=0 and a continuous probability distribution for X>0. The probability density function of the mixed distribution is as follows (Haan, 1977).

$$F(X) = \sum_{i=1}^{m} \lambda_i p_i(X) \tag{2.9}$$

Where,

$F(X)$ = Probability density function of random variable X.

λ_i = Probability that random variable is from the probability distribution $p_i(X)$

$p_i(X)$ = Probability distribution of X given that X is in the ith distribution, i =1,2....m

2.5.3 Probability plotting

Probability plotting is a check that a distribution fits a set of hydrological data. Fitting a probability distribution to rainfall data can be done by either graphical or statistical method.

Graphical method

In graphical method the data is plotted on specially designed probability papers, or using a plotting scale that linearizes the distribution function (Chow *et al.*, 1988). The plotted data are then fitted with a straight line for interpolation, extrapolation or comparison purposes.

The probability distribution that fits the data adequately is the one that is adopted for the determination of the design parameters.

Alternatively, various transformations are tried to return the data to normality. Beran and Rodien (1985) suggest the use of the following transformation equations.

$$x_t = \left(\frac{X-1}{T}\right) \text{ for } T \neq 0 \qquad (2.10a)$$

$$x_t = \log_e X \text{ for } T = 0 \qquad (2.10b)$$

Where,

x_t =Transformed value

T = Transforming index.

The transforming index encompasses all power transforms. For example T=0.5 is proportional to square root and T=2 to square transform while T=0 is the logarithmic transform. The skewness values for trial T values can then be tried out and a T chosen which zeros the skewness (Beran and Rodien, 1985). The transformed data can also be plotted on normal probability paper and the T values that linearises the data is chosen.

Plotting positions refer to the probability value assigned to each piece of data to be plotted. Numerous methods have been proposed for the determination of the plotting positions (Chow *et al.*, 1988). Most plotting positions are represented in the following form:

$$P(X \geq x_m) = \frac{m-b}{n+1-2b} \qquad (2.11)$$

Where,

$P(X \geq x_m)$ = Probability of exceedance

x_m = Probability of exceedance of the largest m^{th} value

m = Rank

n = Total number of values and

b = Constant

The simplest plotting-position is expressed in the Weibull formula with the parameter b=0. Once the data series is identified, ranked and the plotting positions calculated, a graph of magnitude X verses probability of exceedance $(P(X \geq x_m)$ or probability of non exceedance $P(X \leq x_m)$ can be plotted to graphically fit the distribution.

Statistical methods

The methods used are the method of moments and method of maximum likelihood. In the method of moments different frequency curves are fitted by calculating as many moments of the sample as there are parameters to be evaluated (Kottegoda, 1980). The best estimates of a probability distribution are those for which the moments of the probability density function about the origin are equal to the corresponding moments of the sample data.

In the method of maximum likelihood, the best value of a parameter of a probability distribution is that value which maximizes the likelihood or joint probability of occurrence of the observed sample. The method of maximum likelihood is the most theoretically correct method of fitting probability distributions to data in the sense that it produces the most efficient parameter estimates (Chow *et al.*, 1988). In general, the method of moments is the easiest to apply and is more suitable for practical hydrological analysis (Chow *et al.*, 1988).

2.5.4 Analysis of wet and dry spell

The tendency of wet or dry spell to persist follows some kind of process known as the Markov process (Sharma, 1993a). The level of persistence may be negligible or may extend to one, two or several steps behind. The process that goes one step behind is called a lag 1 Markov process. The Markov chain model gives a basic probable representation for the spells distribution and goes further in making it possible to derive several other properties of rainfall occurrence patterns. The probabilities of rain occurrence displaying a first order Markov persistence can be written in the form of the following transitional matrix:

$$\begin{bmatrix} pp & 1-pp \\ 1-qq & qq \end{bmatrix} \tag{2.12a}$$

And when the process is purely random, the transitional matrix takes the form,

$$\begin{bmatrix} p & 1-p \\ 1-q & q \end{bmatrix} \qquad (2.12b)$$

Where,

pp = P(w/w), probability of any day being wet given that the previous day is wet.

qq = P(d/d), probability of any day being dry given that the previous day is dry.

p = P(w), the probability of any day being wet.

q = P(d),the probability of any day being dry.

The numerical values of p , pp , q and qq all lie between 0 and 1 and $p+q=1$

In design for supplemental irrigation it is important to know for how long the wet and the dry spells persist. The critical length of spells for the design of RWCS is the dry spell. It determines the required storage capacity. In the ASAL the critical dry spell for RWCS is dictated by the successive months without adequate rainfall to offset the water demand. In runoff agriculture the critical dry spell are obtained from the seasonal values at different reliability levels. The lengths of wet and dry spells are calculated from the Markov chain model.

2.6 Determination of the Growing Period

The growing period is the time when crop development is possible. The temperature and the amount of soil moisture available for plant use determine the length of this period. There are many definitions of onset and end of rains. According to Berger (1989) the start of the rainy phase is defined based on 15 days period. The rainfall within 5 consecutive days must be higher than 20mm. If another 20mm are received within the following 10 days, then the first day of the period marks the beginning of the rainy phase. He defines the end of rainy phase by the last day of a 10-day period without rainfall.

According to FAO (1978) the reliability of precipitation in terms of frequency and the amount of the rainfall increases considerably once the precipitation is equal to or exceeds half of the potential crop evapotranspiration (ETo). The growing period is defined as the period during a year when precipitation exceeds half the ETo, plus a period required to evapotranspire an assumed 100mm of water from excess precipitation stored in the soil profile (FAO, 1978). Thus for the normal growing period the start of the growing period and hence the start of rains is taken as the time when precipitation equals half ETo.

The end of the rains is similarily defined as the time when the precipitation falls below 0.5ETo in the post humid period. The end of the growing season however also depends on the soil moisture storage capacity. This is because the growing period for most crops continues even after the end of the rains maturing on moisture reserves stored in the soil profile. The number of days that the plant would take to deplete this soil moisture reserve is considered when determining the end of the rains.

2.7 RWHS Design for Crop Production

In planning and design of rainwater harvesting system for crop production the socio-economic factors, agronomic options and engineering alternatives should be considered. There is need to strike a balance between designing a system able to produce the total crop water requirement on a reliable basis as opposed to a cheaper system which recognizes the ability of the crops grown in semi-arid areas to perform adequately with sub-optimum moisture.

The ideal water harvesting system for plant production should be simple and based on small structures which require minimum labor or supervision while the construction technology should also be compatible with the skills of the community. The system should also exhibit versatility, simplicity and durability (Critchley, 1986).

Although rather sophisticated, computer programs have been developed to aid in rainwater harvesting system (RWHS) design, they only consider a few of the numerous factors involved and no procedure is available to provide optimum design (Muni, 1993). So the system is designed using compromise methods that consider a few factors, plus the experience and judgement of the designers. In many regions local rules of the thumb are used for designing the systems (UNEP, 1983; Finkel and Finkel, 1986b). The factors that control the performance of the system are:

- The amount and distribution of rainfall;
- The runoff coefficient of the collecting surface;
- The size of the catchment;
- The reservoir storage provided;
- The amount and distribution of the demand; and
- Evaporation and seepage losses.

2.8 Design of Runoff Storage Systems

The major design criteria for RWHS are the hydrologic and economic criteria. Before designing a project, it may be necessary to undertake a study of what priorities and socio-economic variables are necessary to increase the adoption rate of rainwater harvesting technique by farmers. It is necessary to compare design options using cost benefit analysis. However, the measure of benefits may be difficult and it may not be possible to measure all the benefits which can be expected to result from the project (UNEP, 1983).

The economic approach is to find the least cost solution to supply the estimated demand for water. An excessively large reservoir would represent a wasted economic resource and reservoir too small cannot meet the irrigation water demands and therefore proper sizing is important (Palmer *et al.*, 1982b). The storage size which optimizes economic returns will not necessarily be the one that has water when irrigation is required, therefore an economic analysis is required to determine the optimum storage size (Palmer *et al.*, 1982b).

Hydrologic design is the process of determining the impact of hydrological events on a water resource system and choosing values for the key variables of the system so that it will perform adequately. The hydrologic design scale is the range in magnitude of the design variables such as rainfall within which a value must be selected to determine the inflow to the system. The relationship between the inflows and the outflows of a storage reservoir is often assumed to be linear (Buras, 1972). However this assumption is seldom tenable and the design of optimal reservoir capacity must take into account the stochastic aspects of the inflows and outflows. According to Vujica (1966) methods of stochastic reservoir design include:

- The empirical method which consists of deriving properties of various storage variables by using mass curves of available historical flow series;
- Data generation or Monte Carlo simulation methods which solves stochastic problems by generating large samples of data; and
- The analytical method that consists of mathematical derivation of exact properties of variables involved in the analysis of storage problems.

There are three approaches commonly used to determine a hydrologic design value namely, empirical approach, risk analysis and hydro-economic analysis (Chow *et al.*, 1988). A proper design of storage system would involve:

- Hydrologic analysis including probability of occurrence of runoff, rainfall reliability and distribution;
- Hydraulic design to determine physical sizes of the tanks considering water demand, available catchment area, seepage and evaporation losses;
- Management of stored water in terms of timing, quantity, crop to be irrigated and selection of the irrigation system;
- Desired system reliability and efficiency and
- Economic viability of the system.

The maximum reservoir size can be determined as the reservoir size that will meet irrigation water demand at all times under period of study (Palmer *et al.*, 1982a). However, the optimal reservoir size may not necessarily be the maximum size since many factors other than water supply must be taken into consideration. These factors include the risk that the farmer is willing to accept that the reservoir does not meet irrigation water demand and the financial resources available.

2.8.1 Methods of storage capacity determination

The procedures for the determination of reservoir capacity can be classified into three, namely, the critical period technique, probability matrix methods and methods based on generated data (Mcmahon and Mein, 1978). In the critical period method, storage is associated with the severest drought sequence in the historical record. These include the

Mean Annual Value (MAV) and the Sequent Peak Algorithm (SPA) procedures. The MAV method uses a cumulative plotting of the net reservoir inflows for several years producing a mass curve.

The SPA method was designed for use with replicates of generated data. For a single sequence the method calculates the storage required to meet the worst drought in the period of record whereas for replicated sequences the storage is the average of the individual storage estimate. The method uses the historical data sequence directly and consequently the effects of seasonality, serial correlation and other flow parameters are taken into account (Mcmahon and Mein, 1978).

In probability matrix methods the storage capacity and the water demand are given and the task is to determine the probability of failure of the reservoir. Else the determination of the reservoir capacity and the water demand is determined by trial and error method.

Mass curve analysis

The storage mass curve analysis is widely used in the determination of reservoir storage capacity when the inflows and outflows are known (Klemes, 1987; Duranyildiz *et al.*, 1988). The difference between the cumulative inflows and the outflows are analyzed and the highest deficit taken as the required storage. The analysis would have to be carried out at given probabilities of occurrence of runoff. The capacity of the storage increases as the runoff probability level decreases.

Where surface water must be stored for irrigation purposes, a system for determining a reservoir water balance and for sizing reservoir must be employed. The proper sizing of the reservoir must start by considering the inflows and the outflows from the reservoir. Inflow into the storage system is the runoff generated from the catchment while the outflows include evaporation, seepage and irrigation water demand. The behavior of a reservoir system is represented by a mass balance equation as shown below.

$$V_{t+1} = (V_t + Q_t * Sa + Qp_t) - (Qi_t - E_t - Sp_t) \qquad (2.13)$$

Where,

V_{t+1} and V_t = Storage of the reservoir at time t+1 and t

Q_t = Runoff depth during period t

Sa = Collecting surface area

Qp_t = Direct precipitation during period t

Qi_t = Irrigation demand during period t

E_t = Evaporation during period t

Sp_t = Seepage losses during period t

Given that cumulative demand equals cumulative inflows over the given period, then using the mass curve analysis technique, the storage required for duration T is given by:

$$V_T = \sum_{t=1}^{T} (Qi_t + E_t + Sp_t - Q_t * Sa - Qp_t) \tag{2.14}$$

The mass curve analysis method could lead to serious under designs especially if the rainfall variability is high. This is because it assumes that the averages represent adequately the complete rainfall sequence and thereby ignore the annual variability of the rainfall which could have an adverse effect on the determined capacity (Ndiritu, 1992). In such cases it may be advisable to apply large factors of safety which again could lead to costly systems. According to Edward *et al.* (1983) the principal defects in mass curve analysis are:

- Analysis is based solely on a historical record, which may not include an adequate range of wet and dry spells.
- There is no means of assessing the risk of water shortage particularly if the run of the record is short.
- The optimum solutions are sensitive to the initial state of the storage system, which is normally assumed empty.

The mass curve analysis gives the minimum effective reservoir storage capacity required so that no water shortage occurs during the time period under consideration. Gidley (1986) as quoted by Duranyildiz (1988) proved that the mass curve analysis method gives the same value for the optimal capacity as the linear programming method.

The design of water harvesting tanks for supplemental irrigation is highly location specific and thus it is difficult to develop a general model that can be used for all areas. The number and range of variables involved is also very large and individual designs for every system would be laborious and there cannot be standard solution which will suit all conditions (Oweis *et al.*, 1999). Design procedures based on hydrological information should be laid out in the form of nomographs, slide rules or a small software package which could be run on a pocket calculator (Sharma, 1993b).

Other methods

Often simple formulas or procedures are adopted to compute the capacity depending on the demand and length of the dry spell (Ndiritu, 1992). An example is the use of the following equation:

$$\text{Capacity} = \text{Periodic demand} * \text{number of dry periods} \qquad (2.15)$$

Ndege (1992) recommended the following empirical formula:

$$C = 0.03D(T + 2) \qquad (2.16)$$

Where,

C = Reservoir capacity, m^3
D = Water demand, l/day
T = Longest dry spell in the month for average years.

According to Zimmerman (1966) as quoted by Palmer *et al.* (1982a) the storage capacity can be determined by superposition of average monthly potential evapotranspiration (PET) onto average monthly rainfall (R) forming a PET-R diagram. From this diagram, magnitudes and duration of long term average water deficiency and water surplus during the growing period can be determined. The deficit is the amount of water needed for irrigation. This method has its limitations as it results into an overestimation of the irrigation requirements and does not consider the inflows in storage determination.

Verma and Sharma (1990) found that the capacity of a reservoir increases as the probability level of design runoff decreases for all sizes of the catchment area. The volume of available water per unit of tank capacity also increases as this probability level increases for various sizes of the tank. They also observed that at higher probability levels the cost of the reservoir per unit volume was higher and vice versa at lower probability levels. The probability levels of assured runoff are selected at ten equal intervals and the corresponding value of assured runoff used for the design. The expected volume of stored water at the time of irrigation ($EVOL_r$) is given as:

$$EVOL_r = P_r V_{sr} + \sum_{i=r+10}^{100}(P_i V_{si}) \tag{2.17}$$

Where,

$P_i = 0.1$ for $i = r+10, r+20, \ldots, r+100$

V_{si} = Volume stored at probability, i

V_{sr} = Volume stored at probability, r

P_r = Probability level, r.

If a tank is designed at a lower probability level of assured runoff, it will have a larger capacity and lower chances of its being filled up to its full capacity. On the other hand a tank designed on the basis of a higher probability of the assured runoff will have a low storage capacity and higher chances of its being filled to full capacity.

2.8.2 Water losses in irrigation reservoirs

Evaporation losses from reservoirs are a continuous challenge in the design of storage reservoirs. The volume of water lost through evaporation depends directly on the evaporation rate and the reservoir surface area. In shallow reservoirs the overall water temperature will be higher than in a deep reservoir and thus evaporation from the surface area would take place at a slightly higher rate (Edward *et al.*, 1983). Surface evaporation losses can be calculated using the following equation,

$$Ve = Kp * Epan * Ae \tag{2.18}$$

Where,

Ve = Volume of water lost through evaporation, m^3

$Epan$ = Pan evaporation, m

Kp = Pan coefficient

Ae = Surface area exposed to evaporation, m^2

Substantial research has been carried out in an effort to reduce the water lost through evaporation (Arar, 1994; Cluff, 1981). Some of the methods used to reduce evaporation losses are:

- Mechanical covers (roofs, floating rafts and windbreaks);
- Surface area reduction by minimizing the surface area to storage volume and use of compartmented reservoirs;
- Reflective methods such as coloring the water, shading by suspended materials and floating reflective barriers; and
- Use of surface films (oils and long-chain fatty alcohols).

Floating hexagonal panels about $1m^2$ cast from expanded polystyrene have been successful inspite of their high cost. In an effort to reduce evaporation losses farmers in Mijjwala, Uganda have grown a tender lily weed to cover the water surface (Kiggundu, 1998). This, however, is not an efficient method as water lost through evapotranspiration of the weed would be higher than the amount lost through evaporation.

Seepage from a storage system will vary with the soils, the type of underlying rock, the time that water is held and the volume of water stored. Seepage losses are more difficult to determine than the evaporation water losses. This is because seepage rate cannot be determined by means of simple experiments like those used with evaporation measurements. Seepage losses can be taken to equal 5% of the storage volume (Schwab *et al*, 1981). Seepage losses can be computed from equations used for calculating losses from irrigation canals. The following equation is used.

$$q_s = \overline{C} A \sqrt{d} \tag{2.19}$$

Where,

q_s= Seepage loss, m^3/s

A= Inundated area, m^2

d= Depth of water, m

$\overline{C}$ = Numerical coefficient

When considering seepage, the amount lost is not as important as whether it is acceptable (Nelson, 1985). The acceptable amount of seepage loss will depend on individual projects. With proper design and site selection the losses can be largely controlled. Natural silting of water pans has been found to reduce seepage in large tanks. However this can not be encouraged as pond siltation also reduces storage capacity. Here below are some of the methods, which if incorporated in the design and construction stages would help reduce the water losses.

- Lining with concrete or rubble stones.
- Use of appropriate polythene linings.
- Selecting appropriate water pan location with sub soils having low permeability.
- Minimising the ratio of the wetted perimeter of the water pan through appropriate pan designs. Evaporation losses can be minimised by constructing deep rather than shallow pans.

The useful life of a reservoir is greatly reduced as a result of sedimentation. This is as a result of reduction in water yield due to a reduced storage volume. There are methods of controlling reservoir sedimentation. Non of these methods provides a complete mitigation (Mahmood, 1987). They include;

- Methods that aim at reducing sediment inflows. These include watershed management, retention of sediment in debris dam, and by passing the sediment;
- The use of hydraulics of flow to reduce the accumulation of load which has already entered the reservoir. This includes flushing operations and sediment sluicing; and
- The hydraulic dredging of existing sediment deposit.

2.8.3 Catchment area determination

Runoff is the proportion of rainfall that flows over the landscape from higher to lower elevations. Runoff will occur whenever the surface detention is full and rainfall rates exceed the soil infiltration rate. The success or failure of RWH depends to a great extent on the quantity of water that can be harvested from an area under given climatic conditions (Boers *et al*., 1986; Reij *et al.*, 1988; Pacey and Cullis, 1986; UNEP, 1983). The amount of runoff generated from the catchment depends upon the size of the catchment area, soil surface characteristics and the terrain among others. An optimal size of catchment will yield adequate water to satisfy the anticipated water demand (crop water requirement) and hence the storage capacity.

The main problem in designing a runoff irrigation scheme is the calculation of the catchment area for a given cultivation area. This is because the variation of runoff coefficients among others is a function of soil moisture conditions and the vegetation cover at the time of the rainfall event; both variables depending on the different climatological condition prevailing in the course of the rainy season. According to Tauer and Humborg (1992), of the various geomorphologic factors the size of the catchment has the most important effect on the determination of the water harvesting potential. Amerman and McGuinness (1968) as quoted by Sharma (1989), noted that because of reduced infiltration losses, the percentage runoff increases with decreasing catchment area.

The design of RWHS requires the determination of the optimal size of the catchment that would yield adequate water to meet the required demand. This would in turn dictate the capacity of the storage system and consequently the cost of the entire system. Optimal reservoir problems may be constrained or unconstrained. In the constrained problem, the size of the catchment area available for runoff production limits the reservoir volume while the unconstrained case assumes both unlimited catchment size and area available for irrigation.

In the past 20 to 30 years, researchers and farmers have attempted every conceivable method of waterproofing catchment areas and thus reducing the infiltration rate (Frasier, 1981). Catchment treatments include land clearing and smoothing, use of chemical treatments and additives to the soil, paraffin wax, gravel-covered sheeting, sheet metal, bitumen, concrete, sheet metal, artificial rubber and PVC (Maddocks, 1975).

Runoff efficiency for concrete and artificial rubber ranges from 60-95% while runoff efficiencies of 20-35% can be achieved with land smoothing and clearing (Frasier, 1981). Simple catchment modification involves the clearing of vegetation and rocks, smoothing, compaction of soils and cutting of small ditches on the slope to divert runoff water into the storage system. Cluff (1981) recommends the use of this type of treatment if the soil is easily compacted and sediment-laden water acceptable.

2.8.4 Rainfall runoff relationship

The catchment water yield depends on rainfall characteristics; amount and reliability and the catchment characteristics; vegetation type, soils, size, slope. The quantity of runoff generated from catchment depends on how much precipitation is lost on the catchment through depression storage, infiltration and evaporation. The problem of predicting surface runoff is very complicated. A lot of research work has been carried out on different methods of estimating the runoff generated from a given area.

The methods ranges from simplistic models relating runoff to catchment area and return period, to highly complex mathematical models which take into considerations a large number of catchment parameters, and are only solvable with the use of computers. The latter approach has its drawbacks as it requires a very good basic data bank, climatological, hydrological, geological and agricultural data that is often not available (Finkel and Finkel, 1986a). In these circumstances, the simple empirical rules of the thumb are used to give an estimate of the design runoff.

Runoff coefficient

The total runoff from a given catchment can be assumed to be equal to the volume of precipitation falling on the catchment reduced by a runoff coefficient (UNEP, 1983). This can be expressed mathematically as:

$$Q = C * P * A \tag{2.20}$$

Where,

Q = Total runoff volume
C = Runoff coefficient
P= Total precipitation on the catchment
A = Catchment area

The estimation of runoff from the semi-arid catchment is complicated due to the erratic distribution of the rainfall and the variability of the infiltration rate at different levels of soil moisture and surface conditions.

Curve number method

The SCS curve number method is widely applied in estimating runoff depth (Schwab *et al.* 1981). The method has been applied in India by Pathak *et al.* (1989) and in Sahel zone as reported by Tauer and Humborg, 1992. The amount of runoff generated by a given storm depth is given by Equation 2.21:

$$Q = \frac{(R - 0.2S)^2}{R + 0.8S} \tag{2.21}$$

Where,

Q = Daily runoff depth, mm

R = Daily rainfall, mm

S = Maximum potential between runoff and precipitation, mm

and S is given by:

$$S = \frac{25400}{CN} - 254 \tag{2.22}$$

Where,

CN = Curve Number for soil cover and moisture condition.

In ASALs, relatively small amounts of rainfall can generate runoff (Tauer and Humborg, 1992). The antecedent soil moisture and the rainfall intensity influence the threshhold rainfall level. According to Ball (1937) as quoted in Perrier (1988), a rainfall threshold value of at least 6mm and 10mm can be expected to produce runoff in a catchment under compacted soil surface and natural conditions, respectively.

The curve number ranges from 0-100. They can be obtained from Schwab *et al.* (1981). These values reflect the soil type, vegetation and the antecedent soil moisture status. The most reasonable runoff estimates are those based on a curve number that is dynamic throughout the season (Hawkins, 1978).

2.9 Irrigation Water Management

Farmers try to time their tillage operations and planting dates to match the crop growth stages and their evapotranspiration needs with existing soil water storage and the expected replenishing rainfall. When rainfall combined with the residual soil water storage cannot meet the crop water requirement, some supplemental irrigation becomes most profitable to the farmer (Rawitz and Hadas, 1994).

The amount of water stored in the reservoirs may not be enough to meet the full crop water demand and only minimal irrigation to wet the root zone can be provided to derive maximum benefits. This brings out the need for the development of proper water management procedures. When water availability is insufficient farmers would need to make decisions on when to irrigate and how much water to apply.

Decision rules for water use can be simple such as a rule based on the relationship between volume of water in the storage reservoir at the start of the time period and the water demand. Alternatively, they can be more complex incorporating the expectations as to the future demands and supply. Operation of a reservoir for supplemental irrigation aims at promotion of effective release of water for crop production and restriction of release as a precaution against drought. According to Oweis and Taimeh (1996), quoted by Oweis *et al.* (1999), these present the complexity and difficulty of operating a reservoir for supplemental irrigation. Farmers should time their supplementary irrigation schedule according to;

- The amount of water available;
- The time when irrigation water is available; and
- The critical stages of crop development.

With limited water supplies, the question arises whether a given amount of water can be utilized more efficiently by supplying a small area with the full requirement or by supplying a larger area with less than full requirement. The uncertainty of future rainfall and the economics of farming a larger area would affect the farmer's decision (Oweis *et al.*, 1999). Water consumption by crops varies during the growth season. The application of small amounts of water depending on the state of maturation of the crop may alleviate comparable levels of yield reduction (Oweis *et al.*, 1999).

Subsistence level of production is mainly practiced in the ASAL and the amount of water harvested is small. Water abstraction from the reservoirs is therefore mainly done using buckets. Other water lifting technologies include the use of small hand pumps like the "Money-Maker" pumps from ApproTEC. The small areas under irrigation and their nearness to the storage systems makes these systems applicable.

2.10 Shortcomings in the Present RWHS Technologies

For RWH to be reliable and economically viable, it should be based on appropriate design, operation and maintenance. Although rainwater harvesting techniques have been extensively used for along time and much written about the topics, there is little information available on water harvesting in Sub-Saharan Africa and whatever information there is has not been collected or analyzed systematically (Reij *et al.*, 1988).

There is little data available on design and almost nothing on water management and most systems are installed on the basis of local folklore (Bazza and Tayaa, 1994). In most cases there is no integrated study prior to the construction of the systems and hence the techniques applied are inappropriate and do not suit the environmental conditions.

The storage systems face water loss problems through evaporation and seepage. The seepage losses occur since the storage systems are not lined with any protective materials or roofed. In addition to the technical defect, water harvesting projects have rarely been monitored or evaluated to assess the degree and causes of success or failure. As a result, subsequent projects are planned in the same way with all the previous errors and without any benefit from past experiences.

3 METHODOLOGY

3.1 Description of Study Area

The study was carried out in Rugutu location, Central division, Laikipia District. The district is situated within the zone of transition from wetter to a drier regime. The annual rainfall ranges between 280-1100mm. The mean annual temperatures lie between 16^0c and 20^0c (Berger, 1989). The rainfall is bi-modal in nature with the long rains occurring from March to May and the short rains from October to November.

The Maasai community originally inhabited the area and the main land use was livestock keeping. Migration of people from adjoining districts, mostly Nyeri district has led to land use change into small scale farming. They mainly grow maize, beans, potatoes, onions, kales and cabbages. Much of the area is semi-arid and rainfall is a critical factor to the small scale farming. Figure 3.1 shows the map of Rugutu location in Laikipia district.

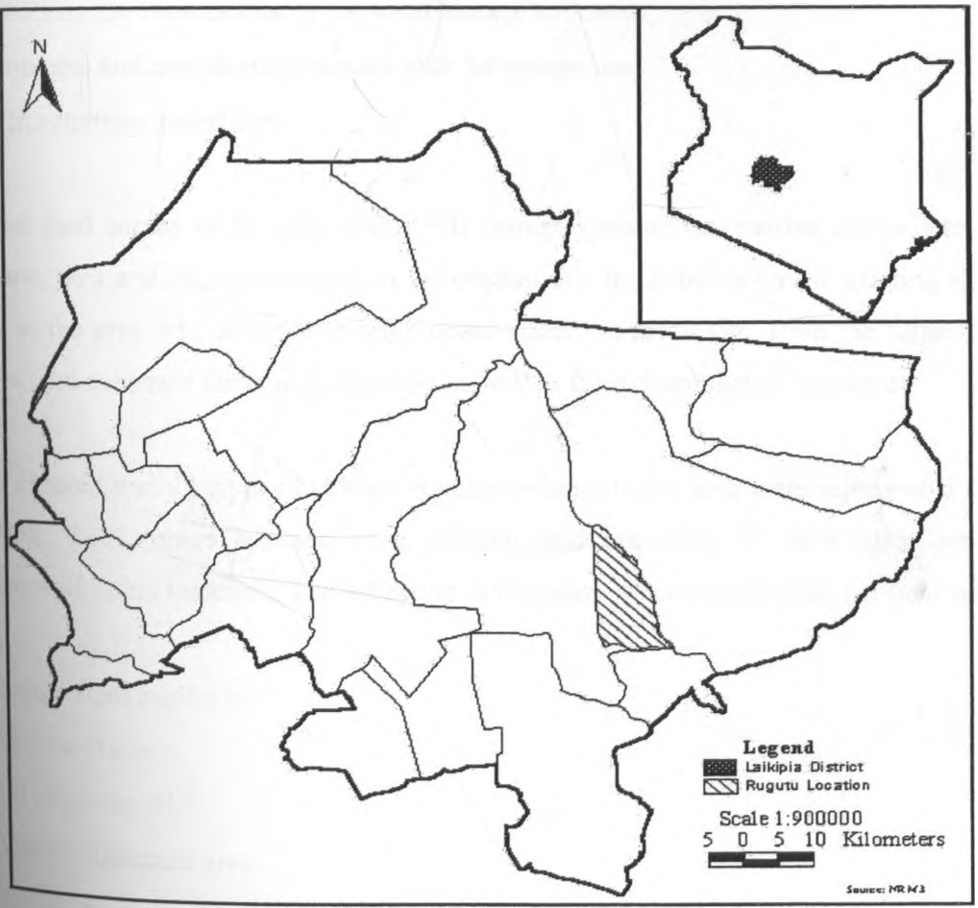

Figure 3.1: Rugutu location of Laikipia district

3.2 Data Collection

The climatic data collected included rainfall and pan evaporation data for Loldoto (De weck) farm meteorological station, which was the nearest station in the study area. The rainfall data for 48 years from 1951 to 1998 was obtained from Natural Resource Modeling, Monitoring and Management project (NRM3) while the evaporation data was obtained from the Kenya Meteorological Department headquarters.

A field survey was conducted to determine the existing technologies on RWHS for crop production. The selection of the respondents was done randomly within the location. The information gathered was mainly obtained through visual observations. This was further supplemented by interviewing the farm owners. The issues addressed in the field survey were:

- rainwater harvesting technologies in practice;
- details on the construction of the water storage structures;
- problems and benefits experienced with the system; and
- farm activities undertaken.

Detailed field survey of the sites with RWH storage systems was carried out to determine the slope, area and vegetation types in the catchments. Information on the existing storage ponds in the area was obtained through observations made on site, from the farmers and artisans who construct the storage facilities as well as from documented literature

It was ensured that all types of storage systems existing in the area were represented in the sampling. The storage systems were differentiated according to their size, and the seepage/wall lining materials. The following information was obtained from the field study:

- Storage sizes available;
- Catchment size;
- Soil characteristics;
- Type of catchment area;
- Procedures in design and construction of storage system;
- Water uses.

- Water shortages and
- Shortcomings in the designs.

Information collected on soils included the soil textures, soil moisture retention and hydraulic conductivity.

3.3 Soil Analysis

3.3.1 Texture analysis

The particle size distribution of the soil was determined by hydrometer method (IITA, 1979). The analysis involved initial destruction of the soil organic matter with hydrogen peroxide, dispersion with sodium hexametaphosphate and mechanical stirring, then analysis by hydrometer. This analysis gave the percentages of sand, silt and clay

3.3.2 Saturated hydraulic conductivity

An inverted auger hole method was used (Smedema and Rycroft, 1988). An auger hole was made into the soil. Water was then added to the hole and allowed to seep into the surrounding soil for an hour. The hole was then refilled with water to a known depth, and depth recorded. It was allowed to seep into the soil layer and with the help of a float, a measuring tape and a watch, the fall in the water level and the time taken was recorded. Using Equation 2.6 the saturated hydraulic conductivity was computed.

3.3.3 Soil moisture retention

The Pressure Chamber method (Klute and Dirksen, 1986) was used to determine the soil moisture characteristics in the 0 –1500kpa range. Profile pits were dug and core samples collected at given intervals. The soil horizons were used as a guideline when sampling from the profile. The depths used were between 0-10cm, 10-20cm, 20-40cm and 40-60cm. Each sample was fastened with gauze cloth on one end and placed in a water tray for saturation. The samples were left in the tray overnight. The weight of the saturated samples was taken and recorded. Plates for the respective suction pressure were pre-soaked.

The samples and the plates were then placed in pressure chamber and pressure adjusted accordingly. On reaching the equilibrium, the samples were weighed and the above procedure repeated at a different pressure level. This procedure was repeated for the entire suction pressure range and the respective pressure plates were used. After the 1500kpa equilibrium was reached, samples were oven dried and the final weight recorded.

The following equation was used to compute the soil water retention.

$$\theta = \left(\frac{W_t - W_{t(od)}}{W_{t(od)}} \right) \rho_b \qquad (3.1)$$

Where,

$\theta =$ Soil water retention (cm^3/cm^3)

ρ_b =Bulk density of the soil (g/cm^3)

$W_t =$ Weight of soil sample at given tension (g)

$W_{t(od)} =$ Weight of oven dried sample (g)

A layered soil profile was used to determine fc, pwp and Aw. The respective values were calculated from equations below.

$$Aw = \frac{Drz(fc - pwp)}{100} \qquad (3.2)$$

Where,

$Aw =$ Available water, mm

$fc =$ Field capacity in percent by volume

$pwp =$ Permanent wilting point in percent by volume

$Drz =$ Depth of the root zone, mm

The fc, pwp and Aw for the entire soil depth was then calculated by summation of the respective values at different soil depths.

The bulk density was determined by the core method. The core samples were placed in an oven at 105°c for 24 hours to dry. The bulk density was then calculated as:

$$\rho_b = \frac{W_d}{V_s} \tag{3.3}$$

Where,

ρ_b =Bulk density of the soil (g/cm^3)

W_d =Oven dry mass of soil (g)

V_s = Volume of the soil (cm^3)

3.4 Hydrological Evaluation of Runoff Storage Systems

During the data collection stage, the existing types and sizes of runoff water storage systems were identified. The area had 5 water pans 3 of which could not be used for the study because either access was denied or they had been abandoned. The major hydrological parameters in two of the water pans were quantified using a water balance approach. These parameters are as illustrated in Figure 3.2.

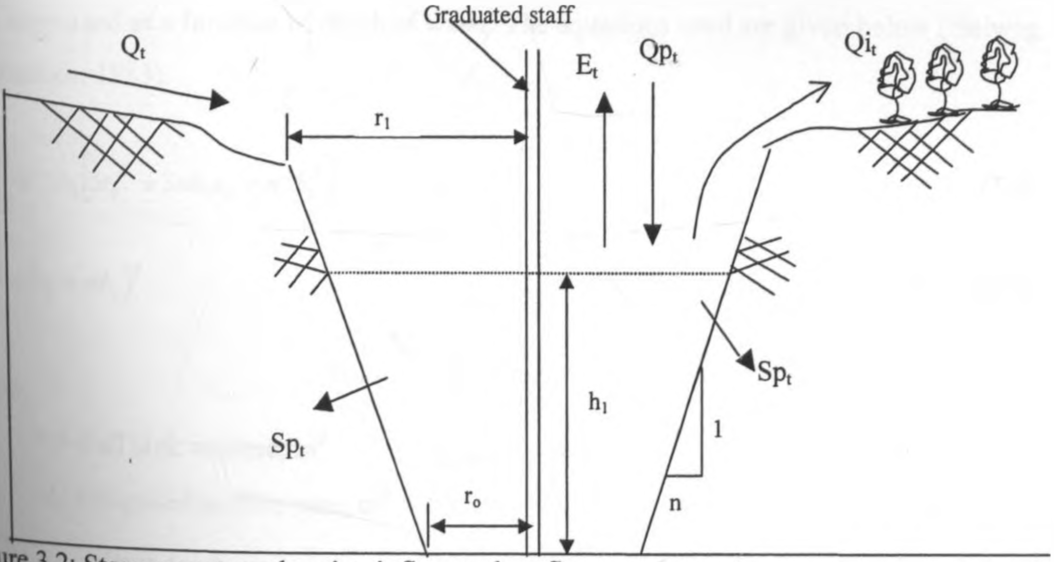

Figure 3.2: Storage system showing inflow and outflow components

Two sites were selected for the study. A water balance method of inflows-outflow analysis was employed in the reservoir evaluation exercise. Through water balance of the unlined farm reservoirs, the amount of runoff inflow into water pan (Q_t), seepage loss (SP_t) and evaporation loss (E_t) were estimated. Evaporation water loss was computed from Equation 2.18 while seepage water loss was computed from Equation 2.13. The amount of direct

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Where,

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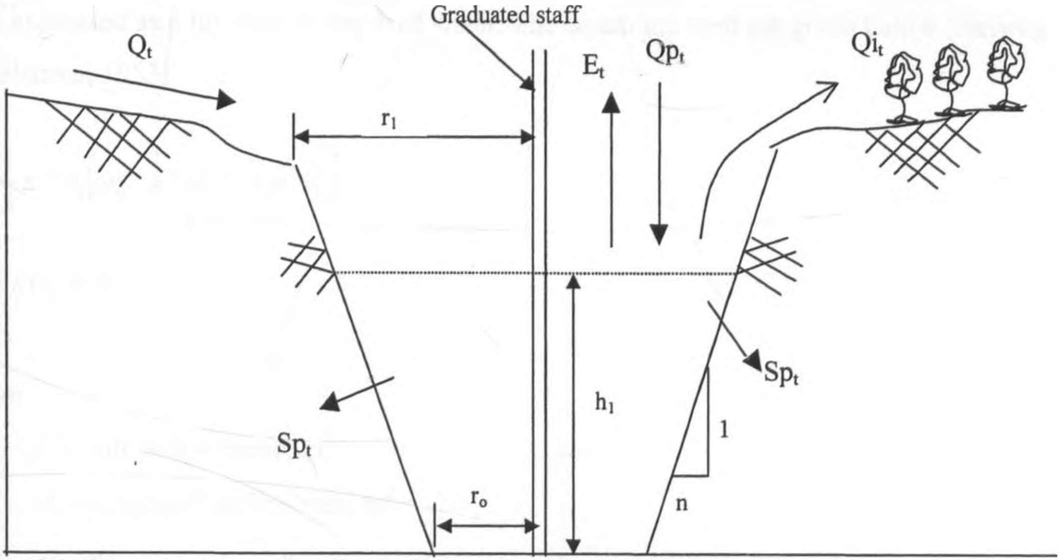

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Using graduated staff gauge installed at center of each water pan, water depths (h_l) were recorded on a daily basis and changes in storage calculated. They were then converted into volumetric values using the respective depth-volume graphs developed below. On rainy days water level was recorded immediately before the rains and after the rains. The rain gauge from a weather station about 6 Km from the research site was used for the daily rainfall records. Depth-water loss graphs for the respective water pan were developed.

3.4.1 Relationship between depth, volume and exposed surface area

The water pans have the shape of a truncated cone. The dimensions varied from one water pan to another. The general cross-sectional sketch of the pans is as illustrated in Figure 3.2. Through application of solid geometry the volume and exposed surface area of the water pan were expressed as a function of depth of water. The equations used are given below (Helweg and Sharma, 1983).

$$V = \frac{1}{3}\pi * h_1\left[3r_0^{\ 2} + 3nh_1r_0 + n^2h_1^2\right] \tag{3.4}$$

$$A_e = \pi\left(r_0 + nh_1\right)^2 \tag{3.5}$$

Where,

V = Full tank volume, m^3

A_e = Exposed surface area, m^2

h_1 = Water depth, m

n = Side slope^{-1}

r_0 = Bottom radius of tank, m

Using the above equations and the respective tank parameters the depth-volume, depth-exposed area graphs and their regression equations were obtained. From these graphs, the change in volume and hence volumetric inflow and water losses were calculated.

3.5 Rainfall Analysis

Rainfall analysis was done for a 48 year rainfall record. The daily rainfall data was summed up into 10 days to obtain decade rainfall. Due to the presence of decades with no rainfall, the mixed distribution was used to obtain the design rainfall at different probabilities. The non-zero values of the data record were found to fit best to a log-normal distribution. The analytical method of frequency analysis was used to determine the rainfall amount expected at different probabilities of exceedance (Haan, 1977).

The probability of exceedance was taken as the reliability level. The probability that a given value was not zero, K, was determined by counting the number of non zero values and dividing by the total number of values. Knowing the probability of exceedance and hence the return period, probability of a non zero value was determined from Equations 3.6 below

$$P(X) = 1 - K + KP_x^*(x) \tag{3.6a}$$

$$P_x^*(x) = \frac{\left(1 - \frac{1}{T}\right) - 1 + K}{K} \tag{3.6b}$$

Where,

$P(x)$=Cumulative probability distribution of all X $\Pr ob(X \le x / X \ge 0)$

$P_x^*(X) =$ Cumulative probability distribution of non-zero values of X .

K= Probability that X is not zero.

T= Return period

Using the standard normal table in Appendix 10, the frequency factors for the respective probabilities were determined. Equation 2.7 was then used with the mean and standard deviation of the log transformed variables to determine the magnitude of the event at the respective probability of exceedance.

The log-normal statistical parameters were computed using equations suggested by Kottegoda (1980) and Haan (1977). The equations are as given below.

The decade mean rainfall is computed from;

$$\mu = \exp(\mu_y + \frac{\delta_y}{2}) \tag{3.7a}$$

And the variance is given by;

$$\delta^2 = \mu^2 \left[\exp\left(\delta_y{}^2\right) - 1\right] \tag{3.7b}$$

Where,

δ = Standard deviation of decade rainfall, mm

μ = Mean of the actual data, mm

δ_y = Standard deviation of log transformed data

μ_y = Mean of log-transformed data, mm

The coefficient of skewness is given by;

$$C_s = 3C_v + C_v{}^3 \tag{3.7c}$$

Where,

C_v = Coefficient of variation

C_s = Coefficient of skewness

and the coefficient of variation is given by;

$$C_v = \sqrt{\exp\left((\delta_y^2) - 1\right)} \tag{3.7d}$$

3.5.1 Occurrence of wet and dry spells

Estimations of the occurrence of the dry spells within a growing season are essential in planning of supplemental irrigation. The Markov chain model was employed to determine the probability of occurrence of the wet and dry decades as recommended by Sharma, (1993a) A decade was considered wet when the total amount of rainfall equaled or exceeded a given threshold limit and vice versa for the dry period.

The threshold amount of rainfall was chosen as the minimum crop evapotranspiration at different crop growth stages of cabbage crop. The number of occasions that the decade rainfall amount exceeded or equaled this threshold rainfall amount was calculated. The unconditional probability of a decade being dry or wet was calculated from equations below.

$$p(w) = \frac{n}{N} * 100 \qquad (3.8a)$$

and,

$$p(d) = 100 - p(w) \qquad (3.8b)$$

The conditional probability of any decade being wet or dry given that the previous decade was wet is given by:

$$p(w/w) = \frac{n'}{n} * 100 \qquad (3.9a)$$

and,

$$p(d/w) = 100 - p(d/d) \qquad (3.9b)$$

The conditional probability of any decade being wet or dry given that the previous decade was dry were obtained as follows:

$$p(d/d) = \frac{n''}{N-n} * 100 \qquad (3.9c)$$

and,

$$p(w/d) = 100 - p(w/w) \qquad (3.9d)$$

Where,

n'' =Number of dry series of 2 decades

n' =Number of rainy series of 2 decades

n =Total number of rainy decades

N =Total number of decades

3.5.2 Length of dry and wet spells

According to Kottegoda (1980), the probabilities of wet and dry runs within a given population can be calculated from the Markov chain model. The probabilities of wet and dry spells of length j were obtained from the following equations.

$$P(L_w \le j) = 1 - pp^{j-1} \text{ or } P(L_w > j) = pp^{j-1} \tag{3.10a}$$

$$P(L_d \le j) = 1 - qq^{j-1} \text{or } P(L_d > j) = qq^{j-1} \tag{3.10b}$$

Where,

L_w = Length of wet spell, decades

L_d = Length of dry spell, decade

j = Number of decades (j=1,2,3..)

The occurrences were then plotted against the decade for different spell length. From the data, it was possible to determine the occurrence and distribution of intra-seasonal dry spells.

3.5.3 Determination of duration, onset and cessation of the rains

Activities like land preparation and when to plant are best planned if the farmer knows when the rains are likely to start and end of the rains. The onset, cessation and duration of the rainy periods are determined on the basis of decade records.

FAO, (1978) recommends that for a normal growing period or humid period, the beginning of the growing period which also marks the start of the rains be taken as the time when precipitation equaled 0.5 ETo while the end of the rains is the time when precipitation equaled 0.5ETo in the post humid period. The soil moisture reserve is considered when determining the end of the growing period.

Based on the available water calculated for the soils within the study area and the rate of crop evapotranspiration the time taken to deplete the available water was determined. This duration was added to time when the rains end to determine the end of growing season. The results were also supplemented by those obtained from rainfall analysis on the occurrence of wet and dry spells.

3.6 Crop Water Requirement.

The daily potential evapotranspiration was estimated from evaporation data from a class A pan obtained from Kenya Meteorology Department Headquarters. The daily record was then summed into decade values. Using Equations 2.1 ETo and ETc were determined. A pan coefficient value of 0.8 was used to convert the pan A data into ETo. This was carried out for an early maturing cabbage crop with a 90 day growing duration. The growth duration was divided into 4 stages. The crop coefficients at different growth stages are shown in Table 3.1.

Table 3.1: Growth duration and crop coefficient

Growth stage	Establishment	Vegetative	Yield formation	Ripening
Growth duration (Days)	20	30	20	20
Crop coefficient (Kc)	0.45	0.75	1.03	0.95

3.6.1 Supplemental irrigation requirement

A simple water balance approach to soil moisture balance was adopted

During the moisture accounting process it was assumed that;

- The ground water contribution is zero.
- Planting was done after some rain has fallen. Therefore initial soil moisture reserve in planting decade was taken to be equal to readily available water.

- The maximum rooting depth of most vegetable crops is 60cm. A maximum rooting depth of 60cm was adopted and applied through out the growing season.
- Deep percolation below root zone occurred when the soil moisture exceeded the soil field capacity.
- Drip irrigation is used and hence an irrigation efficiency of 0.9.

The decade supplemental irrigation water requirement for a cabbage crop was determined using Equations 2.2. The procedure was carried out on a decade time step with the start of the first time step corresponding to the planting decade. For each time step the soil moisture balance was undertaken using the following equations

$$Def_t = ETc_t - \mathrm{Re}_t \qquad \mathrm{Re}_t \le ETc_t \qquad (3.11a)$$

$$Sup_t = \mathrm{Re}_t - ETc_t \qquad \mathrm{Re}_t \ge ETc_t \qquad (3.11b)$$

In cases where rainfall was inadequate to meet crop water requirement, $Def_t > 0$, then soil moisture was withdrawn from the root zone storage accrued during the previous time steps. The procedure followed was;

If, $Def_t < W_{t-1}$

Then, $SIR_t = 0$

Else, moisture stored in soil cannot meet the crop water requirement and supplemental irrigation is applied. The amount applied is calculated from equation below.

$$SIR_t = ETc_t - \mathrm{Re}_t - W_{t-1}$$

Where there is surplus water, the soil moisture reserve was replenished hence increasing the amount of soil moisture available for use in the next decade. This was carried out as follows;

If, $Sup_t > 0$,

Then, $W_t = W_{t-1} + Sup_t$

The influence of soil field capacity and deep percolation was also considered as follows;

If $W_t > AW_{\max}$

Then $W_t = AW_{\max}$

And, the excess moisture lost to deep percolation is calculated as follows;

$$Sup_{dp} = Sup_t - AW_{\max}$$

Else there is no moisture lost to deep percolation and $Sup_{dp} = 0$.

Where,

ETc_t = Crop water requirement in decade t, mm.

Def_t = Deficit crop water requirement in decade t, mm.

SIR_t = Supplemental irrigation requirement in decade t, mm

Sup_t = Surplus water in decade t, mm

Sup_{dp} = Surplus water lost to deep percolation, mm

$AW_{\max}$ = Maximum available water (Field capacity), mm

Re_t = Effective rainfall in decade t, mm.

W_t and W_{t-1} = Available soil moisture in decade t and t-1 respectively, mm

This analysis was carried out using Microsoft Excel spreadsheet. Monthly rainfall amount was determined by summing the rainfall amount from 3 decades. Then the monthly effective rainfall was determined using Equations 2.4. This was then converted to decade effective rainfall using the following equation.

$$\mathrm{Re}_t,\mathrm{mm} = \frac{\text{Decade rainfall amount, mm}}{\text{Monthly rainfall amount, mm}} * \text{Monthly effective rainfall, mm} \qquad 3.12$$

The seasonal irrigation requirement was obtained by summation of the decade irrigation requirements within the season.

3.7 Reservoir Design

The required storage size was determined from the mass curve analysis as expressed by Equation 2.14. The Mass curve analysis was used with a decade time step. The starting decade was taken as the decade preceding a decade with the lowest reservoir volume, which corresponds with the end of dry spell. Decade 7 was used as the starting decade in the mass curve analysis.

The outflows were computed by assuming a given irrigated area and hence irrigation water demand and accounting for seepage and evaporation losses from the reservoir. The unlined and unroofed water pans lose a lot of water through seepage and evaporation. The designed water pan was therefore assumed to be lined and roofed and hence seepage and evaporation losses were taken to be zero.

The decade water inflows from the catchment were computed from Equations 2.20. From the average catchment description, the runoff coefficient was selected. To determine the exposed surface area and hence direct rainfall inflow volume into the water pan, runoff inflows into the water pan was calculated. Based on this inflow volume, tentative water pan dimensions were determined for the bottom radius, side slope and water depth. The exposed surface area and hence direct rainfall inflow into the water pan was calculated from equation 3.5. A curve of cumulated inflows and outflows against decade was plotted and storage capacity determined.

The catchment area and storage capacity were obtained by iterative solutions keeping the irrigated area constant. The optimum catchment area at a given reliability level was obtained by varying the catchment area. The iteration ended when the smallest difference between the cumulative inflows and the outflows was obtained and the corresponding catchment area and storage capacity recorded.

The difference between the cumulated inflows and outflows were analyzed from the mass curve and the highest difference recorded as the optimal storage capacity. The inflows were varied for different rainfall reliability levels and a predetermined runoff coefficient value. This facilitated the design of RWHS at various reliability levels.

3.8 Water Management Practices

Using the soil moisture accounting procedures, strategies for irrigation water management were derived. This helps in determination of time and amount of irrigation water applied. The assumption made was that the soil moisture was replenished with an amount equal to water deficit in the respective decade. The irrigation requirements were determined for cabbage crop with growth duration of 90 days.

Due to the limited water supply, deficit irrigation can be practiced. When water deficit occurs during a particular part of the total growing period of a crop, the yield response to the deficit can vary greatly depending on how sensitive the crop is at that period.

4 RESULTS AND DISCUSSIONS

4.1 Rainfall Characteristics

Data from a private meteorological station, Loldoto (De weck) in Laikipia was used. The analysis was carried out for a rainfall record of 48 years (1951-1998). The daily rainfall values were transformed into 10 day values (decade). The decade amounts and the annual totals are given in Appendix 1. Data analysis involved determination of rainfall distribution by means of statistical parameters ie. Mean, standard deviation, coefficient of variation and skewness. The statistical parameters are shown in Table 4.1.

Table 4.1: Rainfall statistical parameters (48 years)

Decade	Mean (mm)	Standard Deviation	Coefficient of Variation (Cv) %	Coefficient of skewness (Cs)
1	8.5	26.6	72.1	2.5
2	5.3	28.6	122.8	5.5
3	4.8	20.6	107.4	4.5
4	9.7	26.8	86.5	3.2
5	5.5	30.7	127.6	5.9
6	3.7	22.4	87.4	3.3
7	9.1	25.6	99.2	4.0
8	8.5	15.1	84.7	3.2
9	17.8	26.5	108.6	4.5
10	26.9	37.1	103.7	4.2
11	38.2	33.4	76.6	2.8
12	49.2	48.6	90.5	3.5
13	38.5	30.1	71.6	2.5
14	30.6	28.4	85.1	3.2
15	19.6	20.5	91.3	3.5
16	26.0	39.6	114.1	4.9
17	17.6	24.2	89.2	3.4
18	19.8	30.8	123.1	5.6
19	13.6	17.8	81.8	3.0
20	19.2	28.7	106.1	4.4
21	22.5	22.4	89.2	3.4
22	22.5	36.4	121.7	5.5
23	25.5	45.4	137.1	6.7
24	23.7	29.0	99.5	4.0
25	18.4	22.5	91.8	3.5
26	11.9	22.2	97.2	3.8
27	10.9	19.8	109.6	4.6
28	13.8	15.8	85.8	3.2
29	20.2	22.1	88.9	3.4
30	25.7	21.1	70.2	2.5
31	27.4	25.0	85.5	3.2
32	19.3	20.1	86.5	3.2
33	16.9	24.3	108.3	4.5
34	13.9	23.2	107.8	4.5
35	4.9	9.0	90.0	3.4
36	6.0	20.2	118.7	5.2

The standard deviation ranges from 48.6mm to 9.0mm with the highest value occurring in decade 12 and the lowest in decade 35. The coefficient of variation ranges from 137.7% to 70.2% with the extremes occurring in decades 23 and 30 respectively. The record is positively skewed. Decade 30 has the lowest skewness and variability coefficients and therefore is assumed to be the decade with most uniform rainfall.

The mean decade rainfall distribution is characterized by 4 cycles. They are marked by dry decades, long rains decades, continental rains decades and short rains decades. These occur in decade 1 to 8, 9 to 16, 17 to 25 and 26 to 36 respectively. The decade rainfall distribution is shown in Figure 4.1

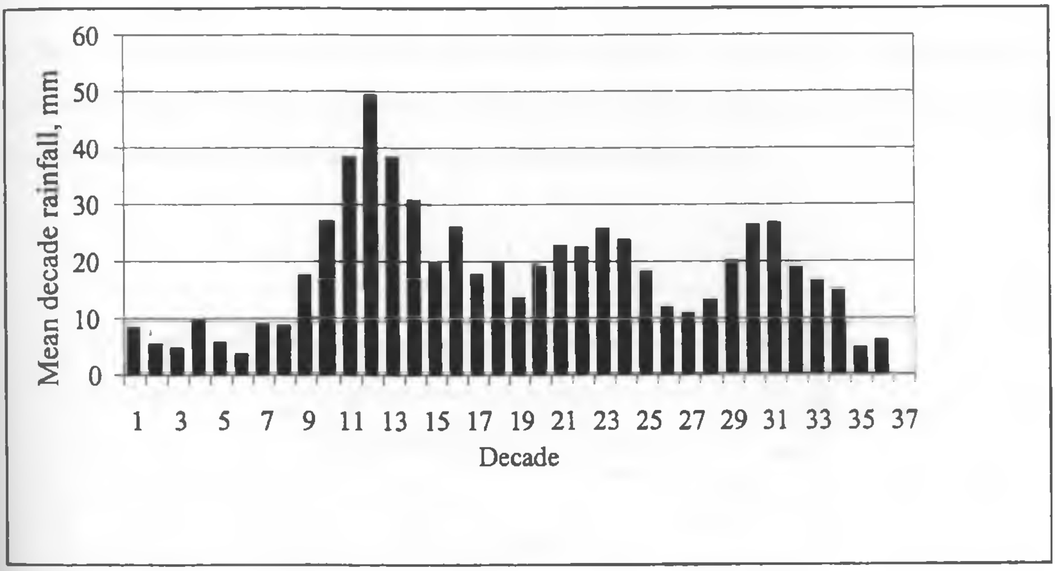

Figure 4.1: Mean decade rainfall distribution

From the analysis it was evident that the frequency distribution could not be described as normally distributed. The skewness ranges from 6.7 to 2.5. The high positive skewness is due to the occurrence of only a small number of very large rainfall amounts. The rainfall record is bounded to the right by zero values and hence the wide range between the extremes. These extreme values have a significant effect on the calculated arithmetic mean. The mixed distribution w here the non-zero values were analyzed separately was used to determine the design rainfall values. The non zero decade values of the data were found to plot well on a log-normal probability paper as shown in Appendix 2.

4.2 Determination of Growing Period, Onset and Cessation of Rains

Farmers have learnt that the start of the rains may not as well be the beginning of the growing period. Early planting can lead to a successful crop yield while late planting reduces the risks of early crop failures. However, the yields may reduce with late planting. Studies carried out in Machakos district by Stewart and Hash (1982) showed that the date of onset of the rains is correlated with the total seasonal rainfall expectation. Early onsets resulted to a higher seasonal rainfall amount while late onsets resulted into lower seasonal rainfall totals. The question then arises on when should farmers plant so as to take the maximum advantage of the growing period.

The start of the growing period must be defined with full knowledge of critical stages of crop growth when water shortages can cause serious yield reductions or total crop failure. Figure 4.2 below shows how the growing season was determined.

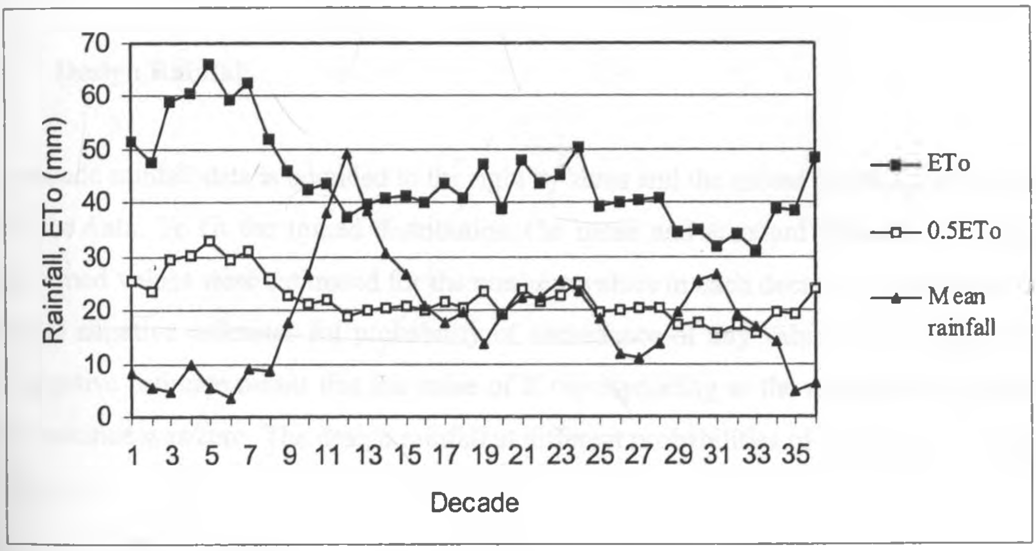

Figure 4.2: Determination of the growing period

The beginning of the growing period during the long rains occurs in the 10th decade while during the short rains it occurs in the 29th decade when rainfall is equal to half the potential evapotranspiration. The start of the short rains was, however, more difficult to determine. Due to the short lengths of the growing period, a delayed start would lead to the crop reaching the water sensitive stages when moisture is limiting. Therefore, the start of the short rains was taken as decade 29. Decades 17 to 25 marks the "continental" rains. To determine the end of the growing period, the soil moisture storage was also considered. This is because the growing period for most crops continues even after the end of the rains maturing on moisture reserves stored in the soil profile. The end of the rains during the short and long rains occurs in decades 16 and 33 respectively. The average available water at the root zone depth was 60 mm. It was hence assumed that the crop would take 1 decade to deplete the available soil moisture reserve at a crop evapotranspiration rate of 5.6mm/day. This was added to the duration of the rainy period to determine the end of the growing period.

The end of the growing seasons was therefore 17th decade and 34th decade respectively. The length of the growing period for the long and short rains was found to be 80days and 60days respectively. The growing seasons are short which is characteristic of the rainfall regimes in the ASALs. Berger (1989) in his study in Laikipia observed that the growing period ranges from 40-50 days. Supplemental irrigation is carried out so farmers can extend the season to conform to the growing period of most crops as well as for dry spell mitigation.

4.3 Design Rainfall

The decade rainfall data is bounded to the right by zeros and the mixed distribution was used to fit the data. To fit the mixed distribution, the mean and standard deviation of the log transformed values were estimated for the non zero values in each decade. It was possible to generate negative estimates for probability of exceedance of any value X in Equation 3.6. The negative estimate meant that the value of X corresponding to the respective probability of exceedance was zero. The design rainfall at different probabilities of occurrence is shown in Table 4.2.

At the lower reliabilities, the expected rainfall event is high. These high rainfall events are hardly experienced within the historical data. It is therefore not advisable to design at the low reliability levels. Although the size and hence cost of construction of a storage designed at these reliabilities would be low, the system failure rate would be high. A system designed at higher reliability levels would have lower failure rate. The decision on the design level would greatly depend on the farmers' financial capability as it will have a direct implication on the cost of constructing the system. The mean rainfall is expected within the 30-40% reliability level and a design based on the mean rainfall would have a high failure rate.

Table 4.2: Design rainfall

Decade	Decade mean, mm	Design rainfall, mm at different probabilities of exceedance								
		10	20	30	40	50	60	70	80	90
1	8.5	33.2	14.3	0	0	0	0	0	0	0
2	5.3	17.1	4.9	0	0	0	0	0	0	0
3	4.8	16.3	6.2	0	0	0	0	0	0	0
4	9.7	33.2	17.9	0	0	0	0	0	0	0
5	5.5	17.3	4.8	0	0	0	0	0	0	0
6	3.7	13.9	0.0	0	0	0	0	0	0	0
7	9.1	29.5	16.0	7.8	0	0	0	0	0	0
8	8.5	24.6	15.8	10.7	6.6	0	0	0	0	0
9	17.8	44.1	31.9	24.6	19.1	15.0	11.7	8.9	0	0
10	26.9	64.2	42.3	30.9	23.2	17.2	12.1	6.9	0	0
11	38.2	78.5	57.4	45.6	37.3	30.7	24.9	19.6	13.7	0
12	49.2	103.1	72.6	56.2	45.0	36.4	29.3	23.1	16.5	7.9
13	38.5	75.3	56.3	45.5	37.8	31.7	26.5	21.7	16.4	8.9
14	30.6	63.1	45.2	35.4	28.7	23.4	19.0	15.2	11.0	5.4
15	19.6	42.3	29.6	22.7	18.0	14.4	11.4	8.6	5.7	0.0
16	26.0	63.0	40.4	28.8	21.2	15.4	10.6	5.8	0	0
17	17.5	44.1	29.9	21.7	16.1	12.3	6.6	0	0	0
18	19.8	21.7	6.9	2.9	1.3	0.6	0.3	0.1	0	0
19	13.6	34.4	23.6	17.5	13.1	9.2	4.8	0	0	0
20	19.2	47.2	30.6	22.0	16.1	11.6	7.6	2.6	0	0
21	22.5	47.6	33.6	26.0	20.8	16.8	13.4	10.4	7.3	0
22	22.4	54.8	34.4	24.2	17.5	12.6	8.5	4.5	0	0
23	25.5	62.2	37.8	26.0	18.5	13.2	8.9	5.0	0	0
24	23.7	54.0	36.5	27.2	21.0	16.2	12.2	8.4	3.4	0
25	18.4	43.1	29.4	22.0	16.9	12.9	9.4	5.6	0	0
26	11.9	33.3	20.8	14.0	16.4	9.0	3.9	0.0	0	0
27	10.9	28.9	18.0	12.3	8.4	5.3	1.4	0.0	0	0
28	13.8	31.8	22.2	16.8	13.1	10.1	7.5	4.6	0	0
29	20.2	45.0	31.4	24.0	18.8	14.8	11.4	8.1	3.6	0
30	25.7	52.3	39.0	31.4	25.9	21.5	17.6	13.8	9.4	0
31	27.4	55.8	40.1	31.4	25.4	20.8	17.0	13.6	10.2	6.1
32	19.3	42.2	29.8	22.9	18.2	14.5	11.4	8.3	4.7	0
33	16.9	40.6	26.4	19.1	14.2	10.4	7.3	4.1	0	0
34	13.9	35.8	22.9	15.9	11.2	8.2	4.0	0.0	0	0
35	4.8	13.8	8.7	5.8	3.5	0	0	0	0	0
36	6.0	18.8	9.4	4.2	0	0	0	0	0	0
Total	665.3	1526	987.1	695.6	533.4	404.4	298.5	198.8	101.8	28.3

To evaluate the risks of insufficient rainfall on crop management, the probability of occurrence of different amounts of rainfall on different decades were determined. The analysis has been carried out at 14mm and 45 mm rainfall amount. This is equivalent to minimum and the highest decade crop water required by a crop planted in decades 10 and 29 as shown in Appendix 4. The results are shown in Figure 4.3.

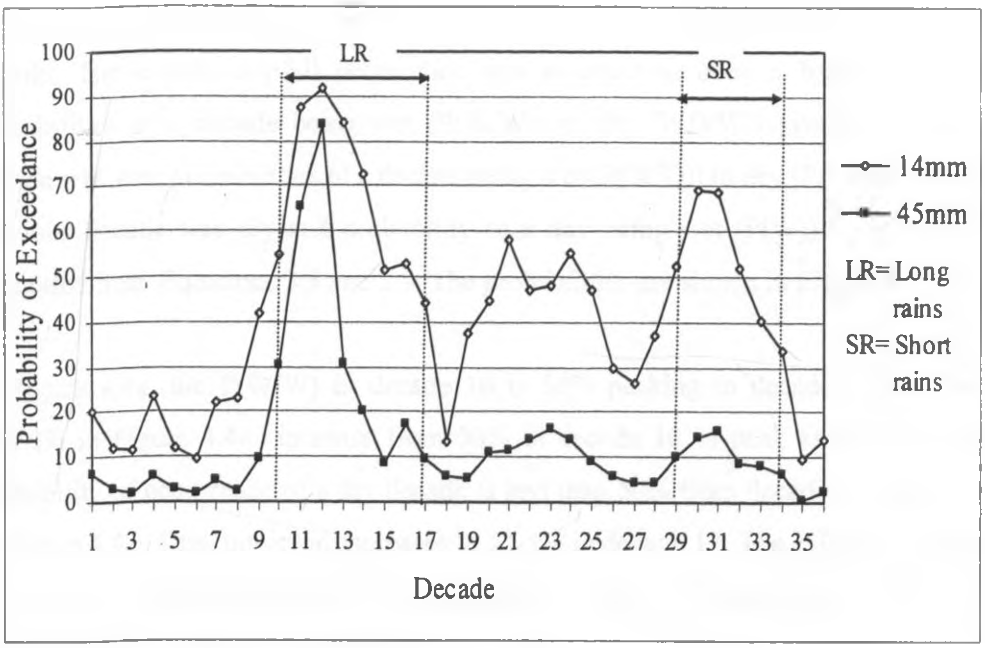

Figure 4.3: Probability of occurrence of different amounts of rainfall

The analysis indicates that at 50% rainfall occurrence, the dependable rainfall (>14mm) is limited only to decades 10 to 16, decades 21, 24 and decades 29 to 32. This implies that the planting decade can be chosen on the 10th and 29th decade. The "continental" rainfall is represented by decades 21 and 24. The "continental" rains are showers experienced between the end of the long rains and the start of the short rains Depending on the growth duration of the crop selected, supplemental irrigation should however be considered.

The probability of occurrence of rainfall greater than 45mm, which is the highest decade crop water requirement, is less than 30% in all the decades except in decades 10 to 13 while it is only higher than 50% in decades 11 and 12. This means that a crop is likely to suffer water stress during any other decade. Therefore, there is need for greater emphasis on the conservation of rainfall for crop production.

4.4 Wet and Dry Spells Analysis

The minimum decade crop water required by a cabbage crop was found to be 14mm as shown in Appendix 4. This value was adopted as the rainfall threshold value for a wet decade. The decade rainfall occurrence was assumed to obey a Markov process. The probabilities of a decade being wet (P(W/W)) or dry (P(D/W)) given that the previous decade was wet, probabilities of a decade being wet (P(W/D)) or dry (P(D/D)) given that the previous decade was dry and probability of a day being wet (P(W)) or dry (P(D)) were computed from Equations 3.8 and 3.9. The probabilities are shown in Figure 4.4.

In Figure 4.4a, the P(W/W) in decade 10 is 56% peaking in decade 13 at 82.4%. The P(W/D) in Figure 4.4c increase from 50% in decade 10 to peak at 80% in decade 11. Probability of occurrence of a dry decade is less than 50% from decades 10 to 15 as shown in Figure 4.4b. This, however, increases to 55.3% in decade 17. The P(D/D) in decade 10 is at 50% and it falls sharply to 20% in decade 11. The 10th decade marks the start of the growing season during the long rains.

The P(W/W) in Figure 4.4a increases sharply from 16% in decade 29 to peak at 69% in decade 30. For P(D/W) in Figure 4.4c the occurrence falls sharply from 84.2% in decade 29 to 31% in decade 30. The occurrence, thereafter, decreases to 35% in decade 32 only to rise to 47% in decade 35. Within this duration, only in 2 decades (30 and 31) is the P(W/W) and P(W/D) higher than 50%.

It is also worth noting that the P(D/W) is much higher than P(D/W) in most of the decades. The exception occurs in the initial stages of the growing season i.e. decades 10 to 14, 30 and 31 where the P(W/D) is higher than P(D/W). This shows that rainfall towards the end of the growing seasons is highly undependable for rainfed agriculture. As the P(D) is equal to 1-P(W), the probability of occurrence of wet decade shows the same variation as that of P(D) but in the reverse order.

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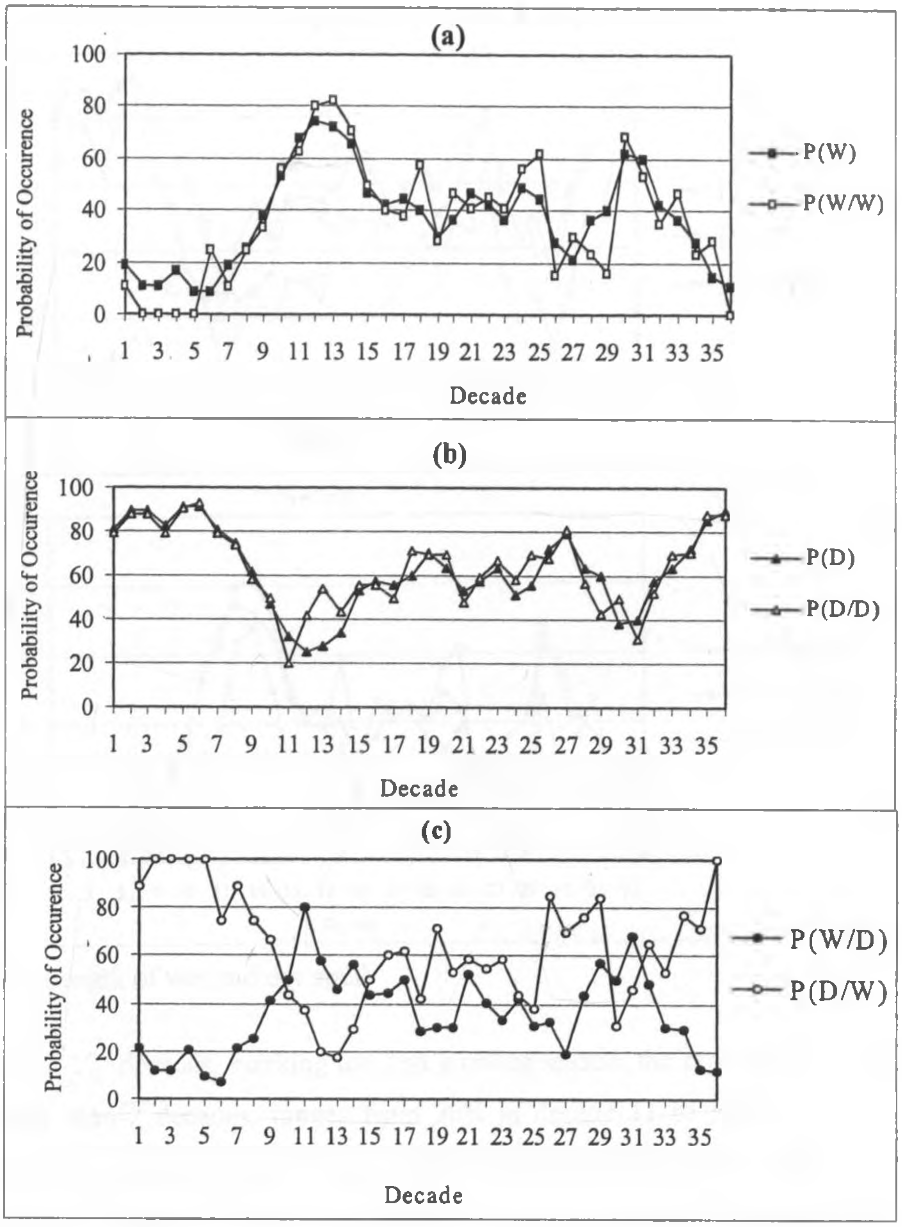


Figure 4.4: Relationship between the conditional and unconditional probabilities

4.4.1 Length of wet and dry spells

The hydro-climatic focus in the ASALs is the occurrence of inter-seasonal dry spells. These dry spells can cause complete crop failure especially in rainfed agriculture. There is need to know for how long the persistence of wet and dry days lasts. The length of the wet (L_w) and dry spells (L_d) for any number of decades (j) were calculated from Equation 3.10. The results are shown in the Figure 4.5.

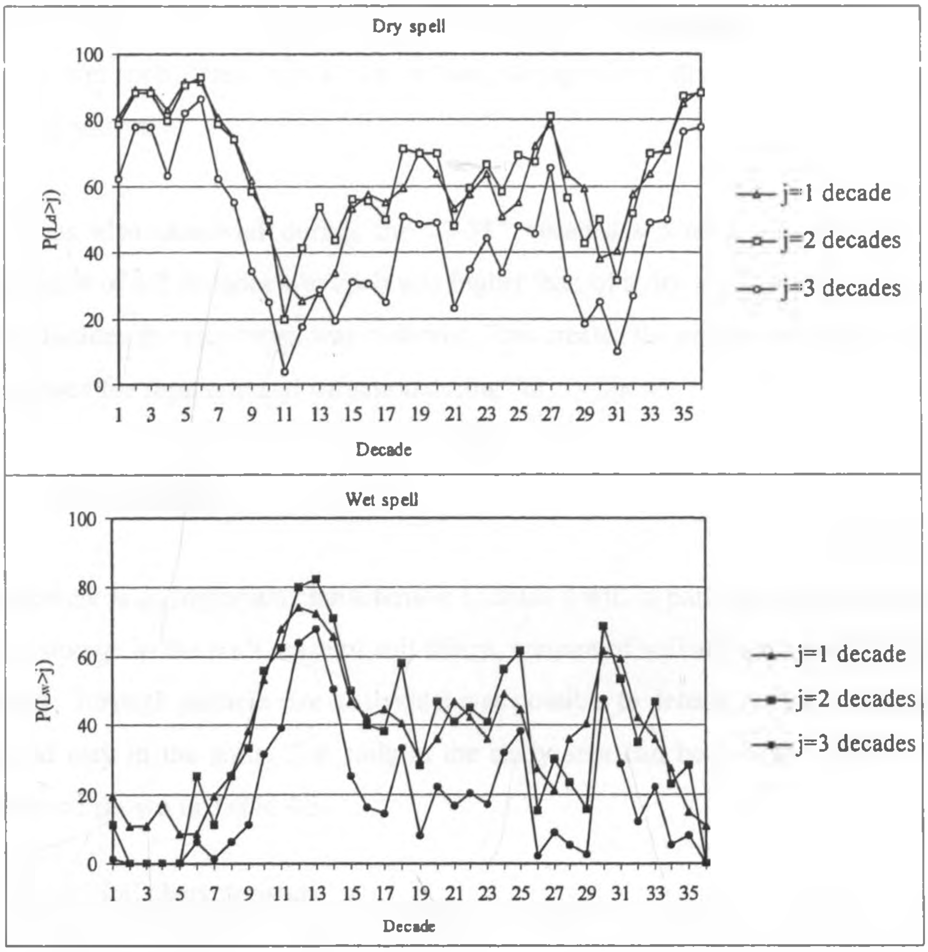
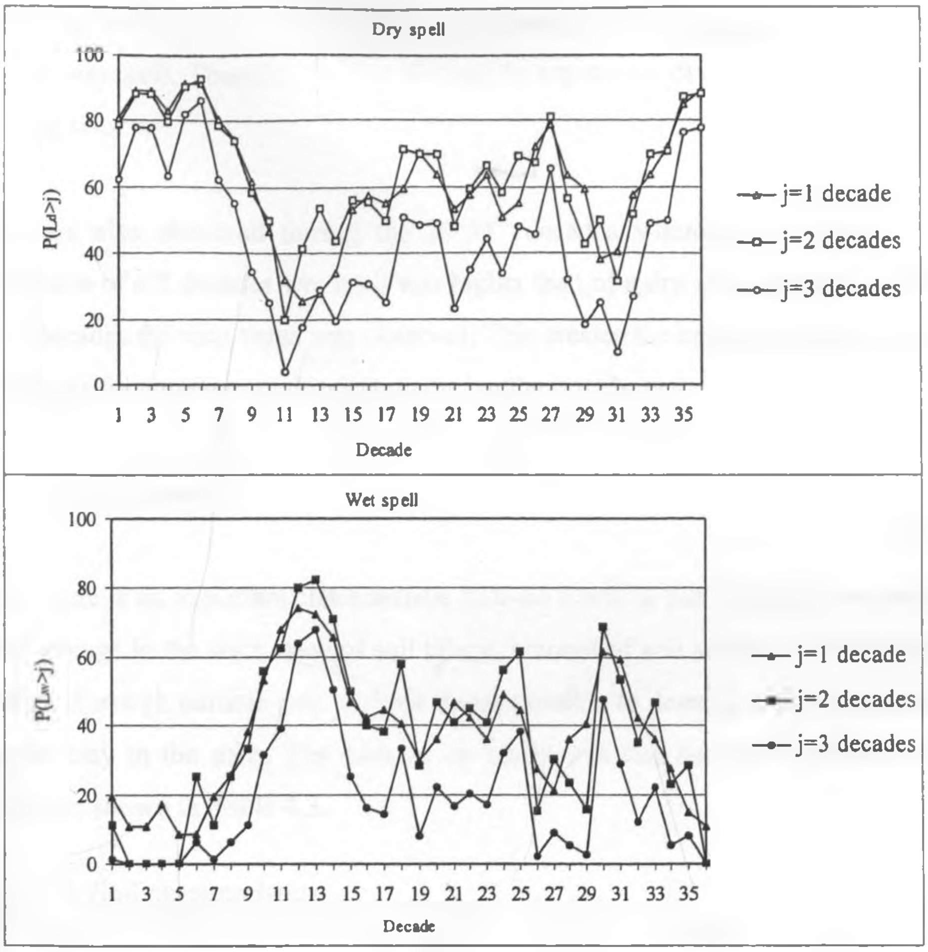


Figure 4.5: Length of wet and dry spell

In the 11th to 17th decades, marking the first growing season, the probability of having a dry spell longer than 2 decades, ranges from 20% in decade 11 to 50% in decade 17. The probability of having a dry spell longer than 3 decades increases from 4% in decade 11 to peak at 31% in decade 18. There is a general increase in expected dry spells as the season progresses. This trend also occurs between the 27th to 36th decades with the least occurrence of dry spell being in decade 31. However a dry spell longer than 3 decades was more likely to be expected than a dry spell of 1 decade. This occurs between decades 11 and 16.

A dry spell longer than 2 decades may have a tremendous impact in reducing the yields of a crop. During the 11 -17th decade the probability of occurrence of a wet spell longer than 2 decades is higher than 50% in 6 of the decades while from 29-34th decades, 2 of the decades have a wet spell occurrence higher than 50%. During the 1st growing season, in 5 of the decades the probability of occurrence of a wet spell longer than 2 decades was higher than the occurrence of a 2 decades dry spell. However, the situation changes and in the last 3



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This was also observed during the 29-34th decades whereby in 2 of the decades the occurrence of a 2 decades wet spell was higher than of a dry spell of same length and in the last 3 decades the vice versa was observed. This creates the need to harvest water during the wet phases for supplemental irrigation during the dry phases.

4.5 Soil Analysis

Soil texture is an important characteristic because it will in part determine water intake rates, water storage in the soils, ease of soil tillage, amount of soil aeration and will influence soil fertility. Through particle size analysis it was possible to determine the percentages of sand, silt and clay in the soils. The soils in the study area can be characterized as clayey. The results are shown in Table 4.3.

Table 4 3: Soil characteristics

Layer (cm)	Sand (%)	Silt (%)	Clay (%)	Bulk density (g/cm^3)	Availabl water mm	Hydraulic conductivity (cm/hr)	Textura class
Field 1							
0-10	26.2	14.9	58.9	1.29	8.4	0.86	Clay
10-20	26.0	14.0	60.0	1.30	8.8	0.87	Clay
20-40	23.2	16.8	60.0	1.31	17.7	0.84	Clay
40-60	24.0	16.0	60.0	1.36	20.4	0.86	Clay
Field 2							
0-10	26.8	15.2	58.0	1.19	10.3	0.87	Clay
10-20	26.1	18.0	60.9	1.19	10.5	0.78	Clay
20-40	25.4	12.6	62.0	1.21	21.2	0.82	Clay
40-60	27.0	13.0	60.0	1.24	23.7	0.82	Clay

The soils have high clay contents ranging from 58-62%. Clay soils swell when wet and shrink when dry. The cracks resulting from shrinkage helps water entry and drainage through the soil. The cracks can cause an increase in seepage water losses in earth pans. On swelling, water movement is inhibited resulting to surface ponding.

The rate of infiltration is low and hence the soils are also not readily wetted. Addition, of organic matter in the soils helps to improve the soil structure. In dam construction the aggregating characteristic of clay soils is of importance. Thorough compaction of the soils will reduce seepage losses in dams. The average hydraulic conductivity of the soil was 0.82 cm/hr.

4.5.1 Soil water retention

In irrigated agriculture, soils capable of holding large quantities of available moisture are desirable because they require less frequent applications of irrigation water. The soil water characteristics show the behavior of soil water content and the matric suction as a soil dries up. The soil water retention at various depths within the soil horizons is shown in Appendix 7 and Figure 4.6.

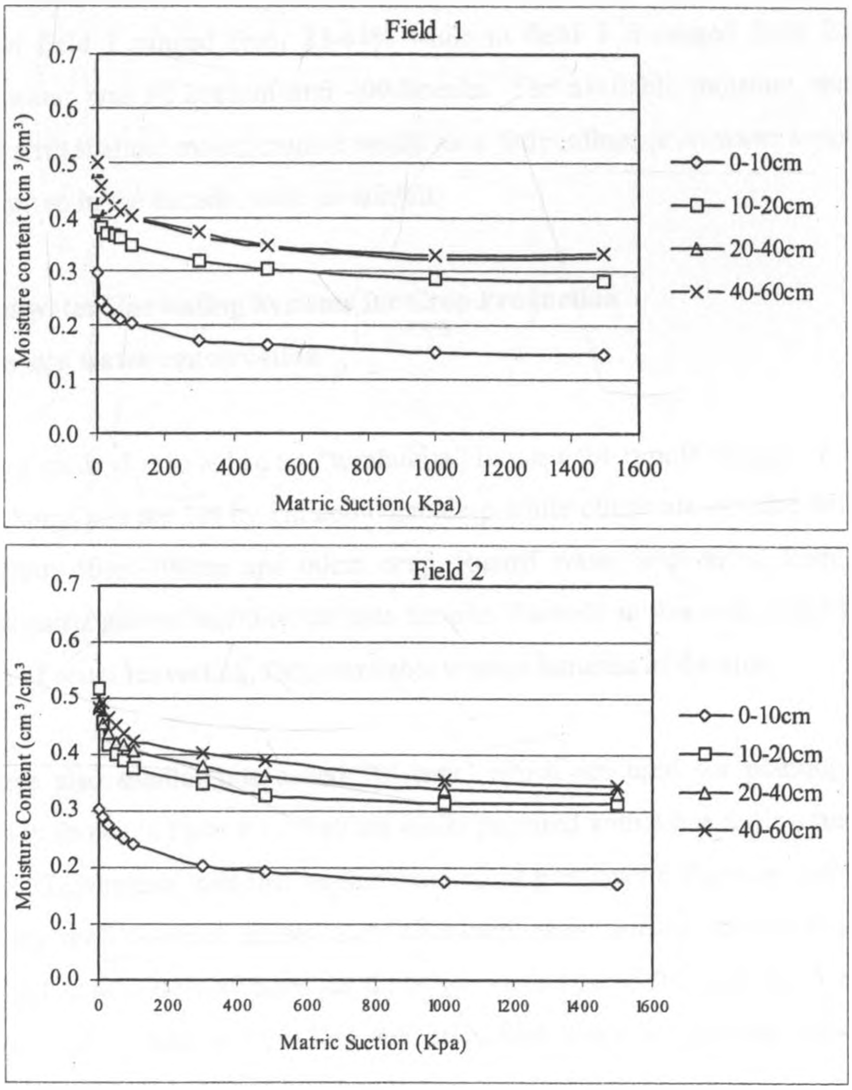


Figure 4.6: Soil water retention characteristics.

The top soils retained less water than all other layers in the two fields. At higher suctions, there is no marked difference in water retention. The soils in field 1 at 20-40cm and 40-60cm depths have nearly the same soil moisture retention abilities. In both fields, the soils at 40-60cm depth have a higher water holding capacity than the top soil. This may be as a result of the high clay content in soils at 20-40cm depth as compared to the content in top soil. The moisture retention by the soil is low especially at the top soil. This means the soil would require frequent irrigation to replenish the moisture lost by the crop through evapotranspiration. The application of organic matter to the field would improve the amount of available water.

The available water is the difference between the moisture retained at field capacity and permanent wilting point. The water retained at 33Kpa is the field capacity. The field capacity in field 1 ranged from 23-44% while in field 2 it ranged from 28-46%. The available water was 92.2mm/m and 109.6mm/m. The available moisture storage is low especially with shallow rooted crops it would have little influence on water supply to the crop. This is more so in the decades with no rainfall.

4.6 Rainwater Harvesting Systems for Crop Production

4.6.1 In-situ water conservation

The pitting method referred to as "tumbukiza" is used for runoff storage in banana trees growing. Some pits are 1m by 1m and 60cm deep while others are circular with a diameter ranging from 50cm-100cm and 60cm deep. Runoff water is diverted from the external catchment using gutters and directed into the pits. Farmers in this area noted that with this technique of water harvesting, they were able to grow bananas in the area.

There were also smaller pits called "Mategu" which are used for planting maize. This technique is shown in Plate 4.1. They are easily prepared with a hoe during land preparation unlike the "Tumbukiza" pits that require more effort to excavate. Farmers noted that in cases where a dry spell occurred immediately after crop establishment, the maize plants in the pits was not as adversely affected, as those not planted using this technique. Some farmers used square earth bunds 1m x 1m long with 10cm high bunds for growing onions a small scale.

Water spreading is practiced using excavated furrows. These are shallow excavations, which harvest runoff from external catchments and footpaths within the farm. The runoff is directed to the field through furrows and once in the field it is allowed to spread into the cropped area. Plate 4.2 shows the water retention furrow with the furthest end closed.

Plate: 4. 1 Maize planted on small pits ("Mategu")

Other furrows are excavated deeper to around 30cm with one end closed. The water is then allowed to collect into the furrow from where it infiltrates slowly into the cropped area. The different rainwater harvesting systems were used within the farm. It was possible to find farmers who practiced all the above mentioned in-situ rainwater harvesting technologies as well as storage system for supplemental irrigation. However in-situ storage practices were the most common. One reason for this bias is the cost implication. The in-situ water storage practices were carried out together with other land preparations and do not involve extra labour like the storage systems. In-situ water conservation systems are also deemed to be cheaper than the water storage systems and hence were much easily adopted by the farmers.

Plate 4.2: Runoff retention furrow

4.6.2 Runoff storage for supplemental irrigation.

The water pans were developed on individual farms for multipurpose use. They are used for livestock water and irrigating small kitchen gardens. The water is hardly used for domestic purposes. Most homesteads with the help of several NGO's operating within the area have constructed ferro-cement water tanks for roof runoff harvesting.

The water from the small sized water pans of 30-40m^3 was mostly used for supplemental irrigation of small kitchen gardens, Kale and onions as well as watering livestock. The large water requirement for crop production also meant that these water pans could only be used for supplementing the crops during the water stress periods. The storage capacities would not support full irrigation of a crop during the dry periods.

The main method of abstracting water from the water pans is using the buckets for spot irrigation. The farmers make steps to reach the water when the water level goes down. A few farmers use the micro-irrigation pumps to draw water from the pans. One of the farmers in the area had a diesel 3hp pump for water abstraction. The abstraction through buckets poses a problem as frequent stepping on the water pan walls also caused the soil to become loose and would later be washed back into the ponds

4.6.3 Design and construction of water pan

The water pans in all the sites had slight differences in the way they were constructed. All the pans had a similar inverted truncated cone shape. The side slopes ranged from 1:2 and 1:3 while the capacities were small ranging from 30-40m^3. The farmers formed several self help groups. A water pan took approximately 20 man days to complete. The excavation and sides compaction work was done manually using hoes and spades. The side walls were either lined with concrete or rubble masonry or were unlined.

On completion, the water pan sides were planted with grass to prevent loose soil being washed back into the pan. The gutters were then excavated in the catchment and planted with grass. Missing component in the design was that there was no provision for a spillway or freeboard. Incase of overflows the water mostly overtopped the embankments destroying it. The water pans were designed with a siltation chamber at the center. Sediment deposited into the chamber and once full sediment was supposed to be scooped out.

The gutters leading the runoff into the water pan were planted with grass to help reduce siltation of the water pans. In most of the water pans, a 1m x 1m x 0.6m siltation pool situated about 2 meters from the pond was excavated. The water settles here before getting into the main water pan as shown in Plate 4.3. These pools are desilted once they are filled with sediment. Siltation of the ponds was not found to be a major problem in the well managed catchments. This was mainly because most of the catchments areas used were covered with grass. However in the water pans which were harvesting runoff from the road catchments silting was evident and desilting had to be carried out when the pans were dry.

Plate 4.3: Masonry lined water pan showing a grassed inlet and siltation pool

4.7 Evaluation of RWH Storage Systems

The water pans harvested runoff from either grassed catchment located next to the ponds or from road runoff. The runoff was directed to the water pan through excavated gutters. There were 5 water pans in the area, 2 of which had been abandoned while the third one was not accessible. Two of the water pans in Rugutu location were used for the evaluation studies. The water pan characteristics are shown in Table 4.4.

Table 4.4: Characteristics of unlined water pans in Rugutu Location

Characteristics	Water pan	
	Field 1	Field 2
Construction date	1990	1990
Total volume (m^3)	31.8	40.5
Catchment area (ha)	0.5	0.4
Slope of catchment area	0	0
Open water surface area (m^2)	61.2	74.8
Radius, r_1 (m)	4.4	4.9
Bottom radius, r_o (m)	1.0	1.1
Side Slope, n^{-1}	2.8	3.0
Maximum water pan depth (m)	1.2	1.3

4.7.1 Depth-volume and Depth-exposed surface area graphs

The dimensions of the water pans were obtained to determine the storage capacity of the water pans. Using Equations 3.4 and 3.5 the depth-volume graphs and depth-exposed surface area graphs and their respective regression equations were developed. The resulting graphs are shown in Figure 4.7 and 4.8.

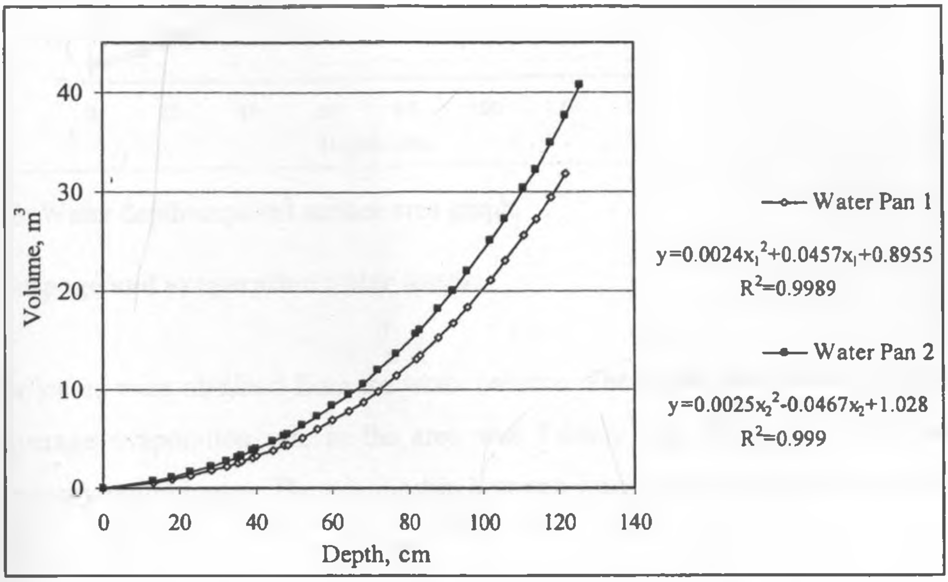


Figure 4.7: Depth-Volume graph.

The regression equations were used in determination of evaporation and seepage water loss from the water pan. Though the shape of the water pans was similar--truncated cone, their dimensions differed and hence the difference in gradient of the two curves. The dimensions were as given in Table 4.4. The water pans have low storage capacity with a maximum storage of 31.8 and 40.5m^3. This water was not enough to sustain any crop to maturity and was being used to supplement only a few plants.

The maximum exposed surface area was 61.2 and 74.8m^2 for water pan 1 and 2 respectively while the minimum exposed area was 3.14 and 3.8 m^2. The storage capacity of water pan 2 was higher than of water pan 1 and so was the exposed surface area. The exposed surface area was high and the water depth shallow. Evaporation rates in the study area are high ranging from 5-8 mm/day and due to the fact that the water pans are not covered, a big fraction of the stored water was lost to evaporation

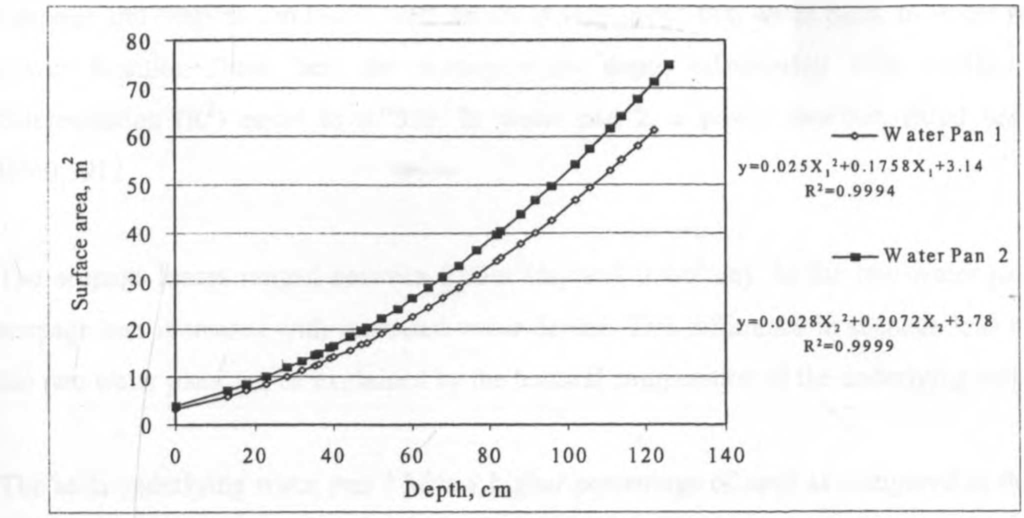


Figure 4.8: Water depth-exposed surface area graph.

4.7.2 Seepage and evaporation water losses.

The water losses were obtained from the water balance. The results are shown in Appendix 8. The average evaporation rate in the area was 5.6mm/ day. This value was used to determine evaporation losses. The relationship between water losses and depth are shown in Figure 4.9.

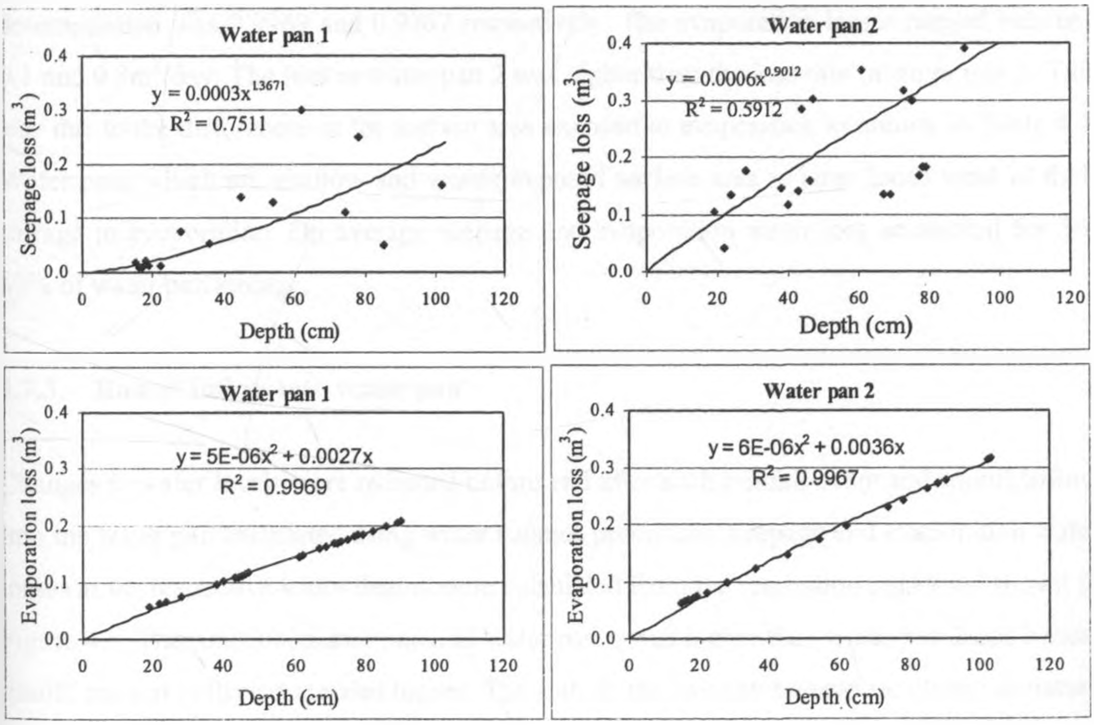
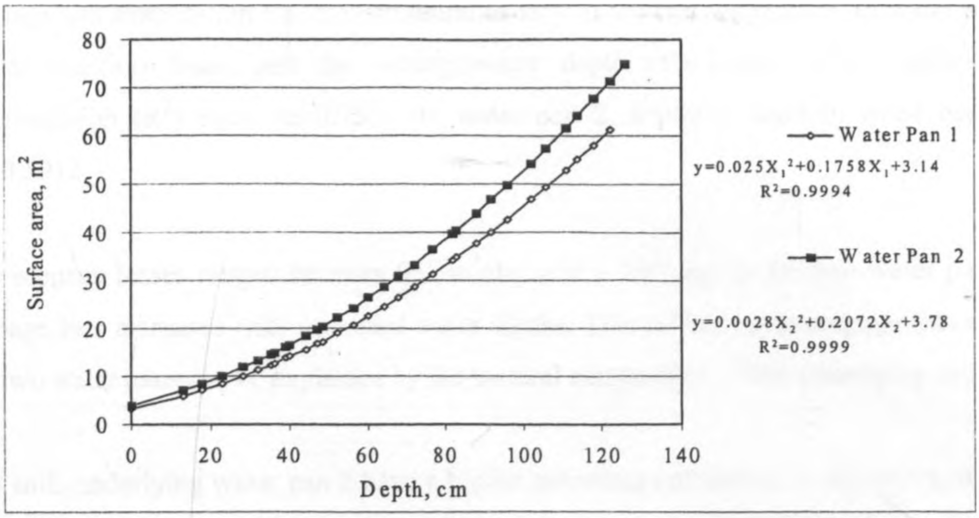


Figure 4.9: Seepage and evaporation water losses



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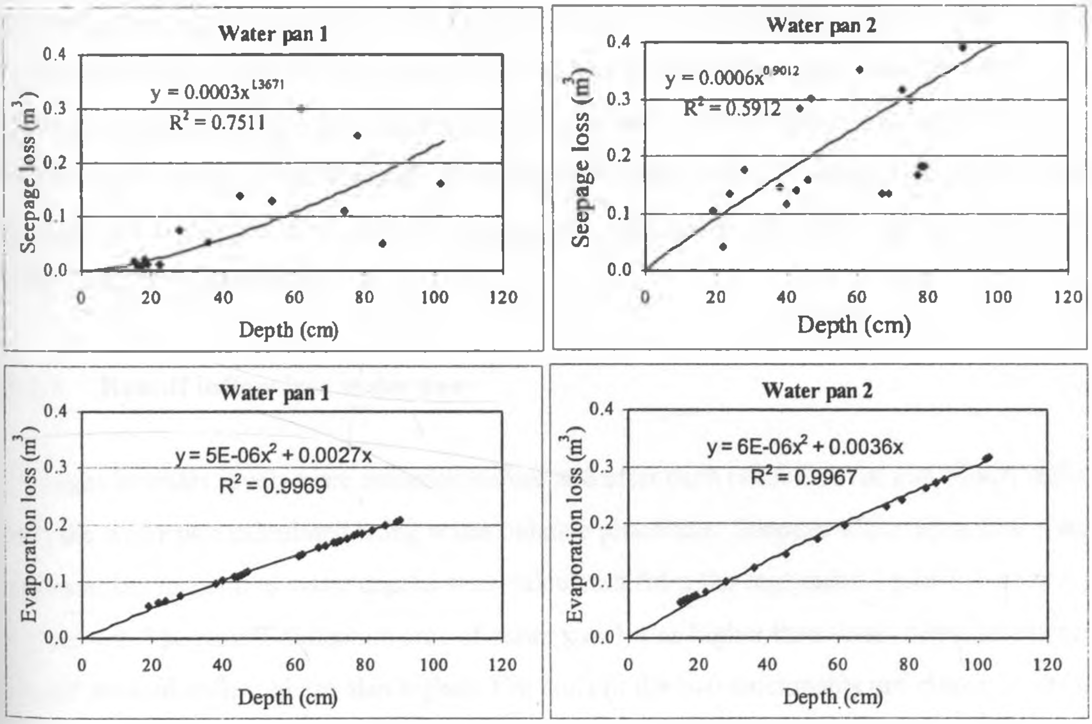

Figure 4.9: Seepage and evaporation water losses

Seepage and evaporation losses were found to vary in the two water pans. In water pan 1 a power function fitted best the seepage-water depth relationship with coefficient of determination (R^2) equal to 0.7511. In water pan 2, a power function fitted best with R^2=0.5912

The seepage losses ranged between 0.03m^3/day and 0.4m^3/day. In the two water pans, the seepage loss increases with increased water depths. This difference in seepage loss rates in the two water pans can be explained by the textural composition of the underlying soils.

The soils underlying water pan 2 have a higher percentage of sand as compared to the soils underlying water pan 1 as shown in Table 4.3. The high seepage loss can also be attributed to the poorly compacted wall materials. The water pans had been desilted and therefore it is expected that due to continuous settlement of the sediment materials the rate of water loss through seepage would reduce considerably.

The average daily evaporation rate was obtained from the nearest meteorological station and used to separate the seepage water losses from the evaporation water losses. The regression line that best fitted evaporation depth data was a polynomial function. The coefficient of determination was 0.9969 and 0.9967 respectively. The evaporation losses ranged between 0.1 and 0.3m^3/day. The loss in water pan 2 was higher than the loss rate in water pan 1. This was due to the differences in the surface area exposed to evaporation as shown in Table 4.4. Water pans which are shallow and whose exposed surface area is large loose most of their storage to evaporation. On average seepage and evaporation water loss accounted for 30-50% of water pan storage.

4.7.3 Runoff inflow into water pan

Changes in water levels were recorded before and after each rainfall event and runoff inflow into the water pan calculated using water balance procedure. Seepage and evaporation water losses at the respective water depths were calculated from the regression equations shown in Figure 4.9. The runoff collection area of water pan 1 was higher than water pan 2 and hence, runoff amount collected are also higher. The soils in the two catchments are clayey in nature and a large fraction of the rainfall was lost as runoff. Table 4.5 shows the water balance.

Table 4.5: Pan water balance

Initial volume m^3	Final volume m^3	Inflow volume m^3	Direct rainfall m^3	Evaporated volume m^3	Seepage Volume m^3	Runoff volume m^3
Water pan 1						
1.7	14.6	12.9	0.1	0.04	0.028	12.7
0.2	24.9	24.7	1.2	0.03	0.012	23.5
9.9	19.3	9.4	0.2	0.08	0.031	9.1
12.4	15.5	3.2	0.2	0.10	0.002	2.9
13.7	32.2	18.4	0.4	0.11	0.037	17.8
Water pan 2						
11.3	16.9	5.7	0.1	0.10	0.028	5.5
2.1	16.7	14.6	0.2	0.04	0.012	14.3
14.8	32.2	17.2	0.4	0.14	0.031	16.6
0.2	22.8	22.7	1.0	0.04	0.002	21.7
23.2	28.5	4.8	0.1	0.25	0.037	4.4

4.7.4 Shortcomings in storage systems

The catchment area for the water pans was not limiting in the study area. There were vast grassland areas adjacent to most of the farms, which generated a lot of runoff. Though farmers may not own this land, they were using the catchments to collect runoff for storage. Some of the runoff collecting areas was however overgrazed. Other farmers harvested runoff collected from the road drainage. The farmers interviewed had water pans of the same capacity. The capacity was predetermined by the agencies working together with the farmers with little or no consideration of the available catchment area. The water pans were, therefore, either over or under designed for the given available catchment and water uses.

There are 5 farmers who already have their water pans in use however they explained that the biggest challenge was on how to reduce the seepage water losses. As a result of the high water losses, the water pans have not been fully exploited by the farmers and this has also contributed to the low technology adoption rate.

Some farmers had abandoned their water pans claiming they did not see the use of the water pan as they only stored water during the wet season. There were the innovative farmers too who had tried several techniques to reduce the seepage. These included;

- Use of goats to help in soil compaction;
- The use of cow dung mixed with clay soil as a sealant;

- The use of polythene sheet on the water pans. The polythene linings only lasted 3 seasons after which they were destroyed by the sun;
- The Ministry of Agriculture, Laikipia district was made aware of the farmer's problems. They were helping farmers to seal the water pans using bitumen mixed with the soil; and
- One farmer in a desperate attempt to improve the water pan storage thought that if he planted a tree in the middle of the water pan he could shade the pan and hence reduce the evaporation losses. He latter abandoned the water pan.

In spite of the high evaporative water losses in these areas, non-of the water pans visited had roof coverings. It was noted that the selection of appropriate side slope was sometimes ignored. This led to some farmers constructing water pans with very steep side slopes, which were difficult to stabilize. Soils in some parts of the study area were unstable and with time the soils caved in reducing the storage capacity of the water pans. Plate 4.4 shows a water pan with collapsed walls as a result of steep side slope. For the unlined water pans, farmers planted grass on the sides to stabilize the soils.

Plate 4.4: Water pan with collapsed walls

The farmers did not pay much attention to identification of suitable sites for water pan construction. This was partly attributed to lack of know-how and expertise on proper site selection criteria. Some of the water pans were constructed far away from the catchment areas whereas there were proper sites near the catchment area.

The gutters leading the runoff into the water pans were also not properly excavated. Though the catchments were big, the gutters failed to concentrate enough runoff into the water pans. Most of the water pans visited did not also have spillways. This was an oversight in the design and construction. As a result once the water pans were full, water overtopped its walls causing erosion to the embankments. Another constraint in runoff storage systems was the conflicts between the upstream and downstream farmers on diversion of road runoff. The upstream farmers would divert most of the runoff. This resulted into runoff diversion conflicts.

Runoff storage systems offer, to the farmer, a tool for crop water stress control. Risks for crop failure are reduced with supplemental irrigation. However, these systems will only work if they are properly designed and constructed. The farmers need to be given technical guidance on the construction so that they can experience the full benefits of runoff storage systems.

4.7.5 Control of seepage and evaporation losses

The amount of evaporation is directly related to the local climate while seepage losses are related to soil type and on water pan design. These loses were a major concern to the farmers and several methods can be used to minimise the losses. These technologies are available and farmers are aware of some of them. However their application has some cost implications. This has made the farmers to take a low stand in their adoptions though they know that they can provide a solution to the problems.

A cheaper method in seepage control is proper site selection and thoroughly compacting the walls by working on it while moist. Some farmers have their water pans already lined with rubble stones as shown in Plate 4.3 above. These farmers do not have serious problems with seepage losses. But in cases where the curing process was not carried out properly, the walls have cracks allowing water to seep through.

The Ultra violet resistant polythene linings are available in different thickness. They can be obtained from several dealers and all the farmers need to do is to provide the dealers with designed shape and dimensions of the water pan. The polythene sheet is then formed in the factory using the given information.

The water pans can also be covered with grass, plastic materials or iron sheet to minimise evaporation water losses. Other methods that have proved to work have been given in Appendix 9. Their adoption would however need to be undertaken with a lot of care, as the soil characteristics would largely determine their effectiveness.

4.8 Irrigation Water Management

4.8.1 Crop water requirement

Water demand is crop specific and depends on crop stages of growth. To model the crop water demand Equation 2.1 were used. Crop water demand varied according to changes in evaporation. The amount of evaporation does not change much from year to year and hence the available 5-year data record was used to obtain the water demand. Water is a limiting factor to crop production within the research area. Therefore the selected crop's climatic requirements must be meet by the prevailing climatic conditions and length of growing season.

The short growth duration cabbage with a growing period of 90 days was selected for design purposes. The growth period is still longer than the length of the growing season for the short rains (60days) in the area and irrigation is necessary if the crop is to reach maturity. The crop water requirements at different planting decades are shown in Appendix 4. The crop coefficients used in the calculation are given in Table 3.1.

Planting decade determines the amount of crop water required. ETc was determined for planting in any of the decade in a year. The total ETc for a crop planted on the 10th and 29th decade was 273mm and 294mm. The expected seasonal rainfall total can only meet this water demands at low rainfall reliabilities of 10-30% respectively. Farmers cannot, therefore, depend solely on rainfall if the crop is to reach maturity stage without experiencing extreme water stresses.

4.8.2 Soil moisture balance

The soil moisture balance was carried out to determine the supplemental irrigation water requirement of the crop. This was carried out for cabbage with 90 days growth duration. The water requirements were determined for a crop planted on different decades within a year. The amount and time of applying irrigation water was determined from the soil moisture balance. The water balance was carried out for a crop planted on different decades within a year. Water balance results for a crop planted in decades 10 and 29 at different rainfall reliability levels are shown in Table 4.6.

Table 4.6: Soil water balance at different rainfall reliability levels.

Crop growth	Planting in decade 10							Planting in Decdae 29						
	ETc_t	Ref_t	Sup_t	Aw_t	Aw_{t+1}	Def_t	Sup_{dpt}	ETc_t	Ref_t	Sup_t	Aw_t	Aw_{t+1}	Def_t	Sup_{dot}
	40%													
1	19.1	16.2	0.0	30.0	30.0	0.0	0.0	15.6	11.4	0.0	30.0	25.9	0.0	0
2	19.7	26.0	0.0	27.1	27.1	0.0	0.0	15.8	24.7	8.9	25.9	34.7	0.0	0
3	28.1	31.4	3.4	27.1	30.5	0.0	0.0	23.8	15.8	0.0	25.9	17.8	0.0	0
4	29.9	25.0	0.0	30.5	30.5	0.0	0.0	25.8	11.3	0.0	17.8	3.3	0.0	0
5	30.7	19.0	0.0	25.6	25.6	0.0	0.0	23.4	8.8	0.0	3.3	0.0	11.2	0
6	52.4	11.9	0.0	13.9	13.9	26.5	0.0	40.3	5.1	0.0	0.0	0.0	35.2	0
7	41.2	12.8	0.0	0.0	0.0	28.4	0.0	39.8	1.6	0.0	0.0	0.0	38.2	0
8	41.3	9.7	0.0	0.0	0.0	31.6	0.0	45.9	0.0	0.0	0.0	0.0	45.9	0
	50%													
1	19.1	12.0	0.0	30.0	30.0	0.0	0	15.6	9.0	0.0	30.0	23.4	0.0	0
2	19.7	21.4	0.0	23.0	23.0	0.0	0	15.8	13.0	0.0	23.4	20.6	0.0	0
3	28.1	25.4	0.0	23.0	23.0	0.0	0	23.8	12.9	0.0	20.6	9.8	0.0	0
4	29.9	21.0	0.0	20.3	20.3	0.0	0	25.8	9.0	0.0	9.8	0.0	7.0	0
5	30.7	15.5	0.0	11.4	11.4	3.7	0	23.4	6.5	0.0	0.0	0.0	16.9	0
6	52.4	9.5	0.0	0.0	0.0	42.8	0	40.3	3.7	0.0	0.0	0.0	36.6	0
7	41.2	9.3	0.0	0.0	0.0	31.9	0	39.8	0.0	0.0	0.0	0.0	39.8	0
8	41.3	7.4	0.0	0.0	0.0	33.9	0	45.9	0.0	0.0	0.0	0.0	45.9	0
	60%													
1	19.1	8.5	0.0	30.0	30.0	0.0	0	15.6	6.9	0.0	30.0	21.3	0.0	0
2	19.7	17.4	0.0	19.4	19.4	0.0	0	15.8	10.7	0.0	21.3	16.2	0.0	0
3	28.1	20.5	0.0	17.1	17.1	0.0	0	23.8	10.5	0.0	16.2	3.0	0.0	0
4	29.9	17.5	0.0	9.5	9.5	2.9	0	25.8	7.0	0.0	3.0	0.0	15.8	0
5	30.7	12.6	0.0	0.0	0.0	18.1	0	23.4	4.5	0.0	0.0	0.0	18.9	0
6	52.4	7.5	0.0	0.0	0.0	44.8	0	40.3	1.8	0.0	0.0	0.0	38.5	0
7	41.2	6.4	0.0	0.0	0.0	34.8	0	39.8	0.0	0.0	0.0	0.0	39.8	0
8	41.3	4.0	0.0	0.0	0.0	37.3	0	45.9	0.0	0.0	0.0	0.0	45.9	0
	70%													
1	19.1	4.8	0.0	30.0	30.0	0.0	0	15.6	4.9	0.0	30.0	19.3	0.0	0
2	19.7	13.7	0.0	15.8	15.8	0.0	0	15.8	8.4	0.0	19.3	11.9	0.0	0
3	28.1	16.1	0.0	9.7	9.7	2.2	0	23.8	8.4	0.0	11.9	0.0	3.5	0
4	29.9	14.4	0.0	0.0	0.0	15.5	0	25.8	5.2	0.0	0.0	0.0	20.6	0
5	30.7	10.0	0.0	0.0	0.0	20.6	0	23.4	2.5	0.0	0.0	0.0	20.8	0
6	52.4	5.7	0.0	0.0	0.0	46.7	0	40.3	0.0	0.0	0.0	0.0	40.3	0
7	41.2	3.5	0.0	0.0	0.0	37.7	0	39.8	0.0	0.0	0.0	0.0	39.8	0
8	41.3	0.0	0.0	0.0	0.0	41.3	0	45.9	0.0	0.0	0.0	0.0	45.9	0
	80%													
1	19.1	0.0	0.0	30.0	30.0	0.0	0	15.6	2.2	0.0	30.0	16.6	0.0	0
2	19.7	9.6	0.0	10.9	10.9	0.0	0	15.8	5.7	0.0	16.6	6.5	0.0	0
3	28.1	11.5	0.0	0.8	0.8	15.8	0	23.8	6.3	0.0	6.5	0.0	11.0	0
4	29.9	10.9	0.0	0.0	0.0	19.0	0	25.8	2.9	0.0	0.0	0.0	22.8	0
5	30.7	7.3	0.0	0.0	0.0	23.4	0	23.4	0.0	0.0	0.0	0.0	23.4	0
6	52.4	3.8	0.0	0.0	0.0	48.6	0	40.3	0.0	0.0	0.0	0.0	40.3	0
7	41.2	0.0	0.0	0.0	0.0	41.2	0	39.8	0.0	0.0	0.0	0.0	39.8	0
8	41.3	0.0	0.0	0.0	0.0	41.3	0	45.9	0.0	0.0	0.0	0.0	45.9	0

From the water balance analysis, moisture deficit increases towards the end of the growing period. The cabbage crop is harvested fresh. From the crop coefficient factors, the crop requires more water towards maturity. The maturity period also coincides with the time when the rainfall amounts are low hence the increase in moisture deficit.

The deficit represents the amount of irrigation water which should be added to the soil to meet the full crop water requirement. The usual practice is to fill the soil to field capacity. The water supply in this case is limiting and it is recommended that the soil be partially filled with water.

With limited water supply, considerations on crop selection and acreage is based on crop yields as affected by the extent to which crop water requirements are met by the available water supply. Where the amount of water in storage is enough to meet the full decade irrigation requirement, then the soil is refilled with an amount equal to the moisture deficit in the given decade. If the amount of water in storage cannot meet the full irrigation requirement, deficit irrigation would be recommended. This can be accomplished by allowing the crop to undergo water stress during specific stages of the growing period. For cabbages, this should take place during the vegetative period, the period when the crop is little affected by water deficit (Doorenbos and Kassam, 1979).

4.8.3 Irrigation water requirement

The irrigation requirements from moisture balance are given in Appendix 5. From these tables a farmer will be able to determine when and how much water to apply. The total IR follows a cyclic pattern. The cycles define the period when the long and the short rains are expected. The amounts of IR increases as the planting decade draws further away from the onset of rains. Figure 4.10 shows the relationship between total IR, planting decade and rainfall reliability level.

The lowest IR occurs when planting is done on the 10th and 29th decades but the IR in the 29th decade is much higher compared to the IR in the 10th decade. This is because the expected decade rainfall amounts during the long rains are much higher than those expected during the short rains.

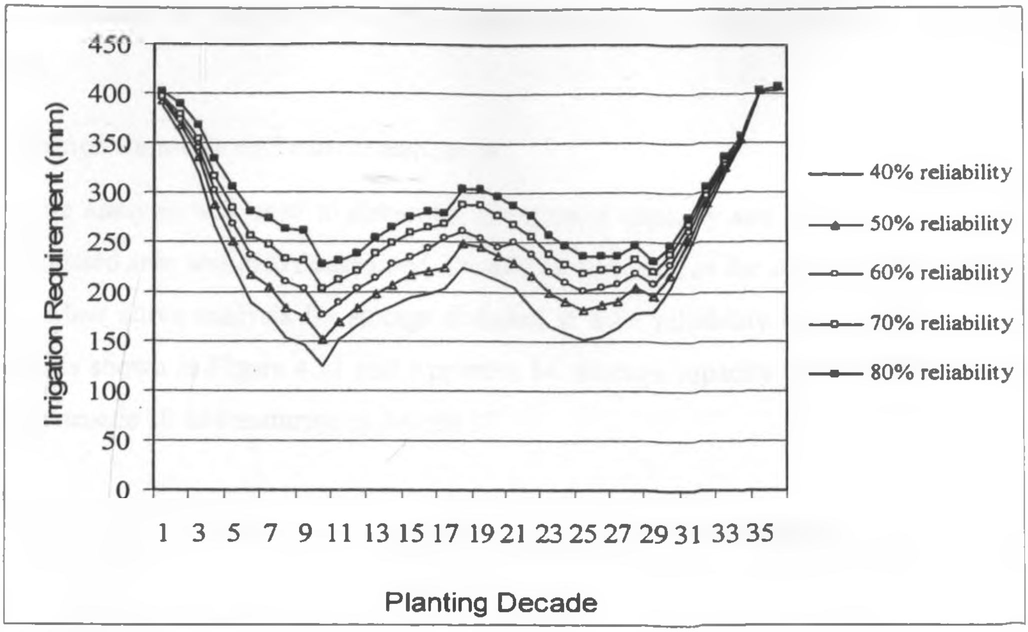

Figure 4.10: Total irrigation requirement at different planting decades and rainfall reliability

At lower reliability levels, the total irrigation amount required to bring the crop to maturity is low. A crop planted at the start of long rains reaches maturity with no supplemental irrigation. However, these high rainfall events are hardly experienced. Therefore although no irrigation is required the expected failure rate of a system designed at this reliability would be very high. On the contrary as the reliability level increases, total irrigation amounts also increases and the system failure rate decreases.

The IR is highest when planting was carried out in decades 1 and 36. This represents a case where dry cropping is practiced and crop water requirement is fully supplied through irrigation. It would not be recommended to practice dry planting because the storage capacity required would be very high and so would be the cost of construction. The land holdings are also not large and catchment area would be limiting.

The main method of water application used by farmers is spot watering with buckets. The method has a high wastage of water. Water productivity in the case of limited water supply should be maintained high. This will be partially achieved by using highly efficient water application methods. The low-pressure drip irrigation systems that save on water and labour are available in the markets at low cost. A combination of water harvesting with drip irrigation can result in very significant improvements in water productivity for supplemental irrigation.

4.9 Storage Capacity and Catchment Area

Mass curve analysis was used to determine the storage capacity and catchment area. The size of irrigated area was also determined. Decade 10 was used as the starting decade for the analysis. Mass curve analysis for storage designed at 80% reliability level and planting in decade 10 is shown in Figure 4.11 and Appendix 14. Storage capacity was 40 m^3 for a crop planted in decade 10 and maturing in decade 17.

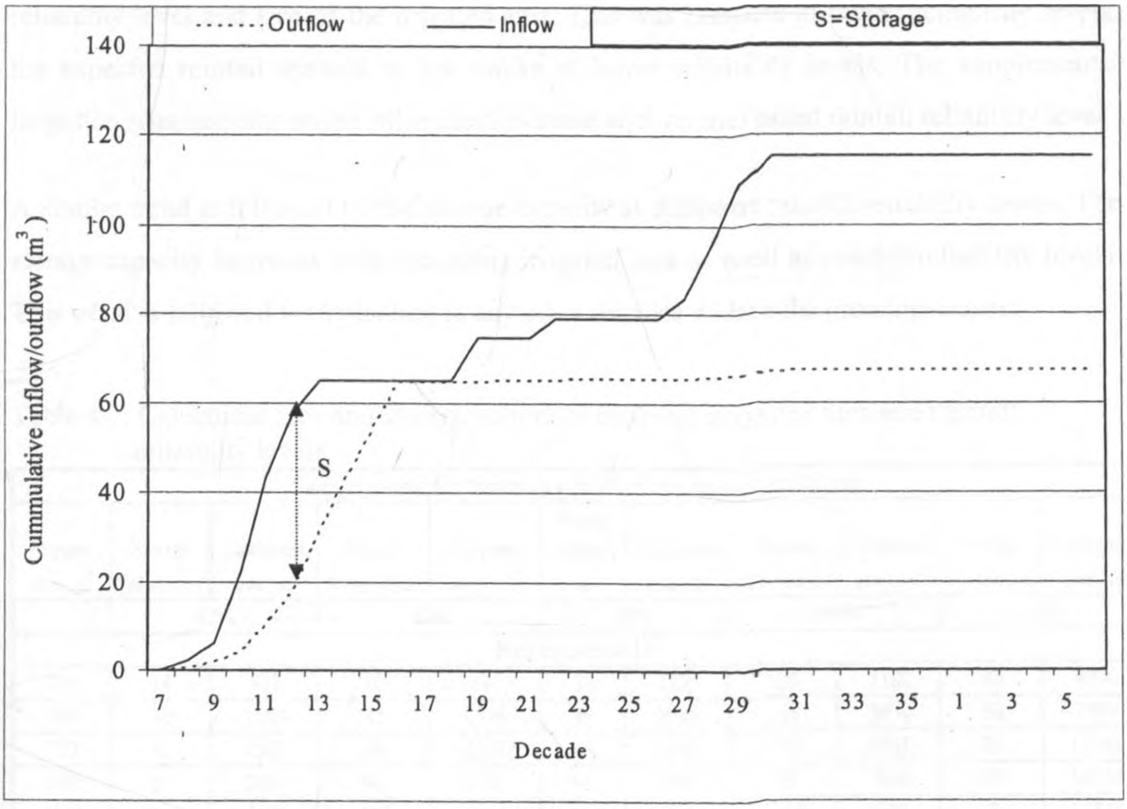

Figure 4.11: Mass curve analysis

The size of the catchment determines the amount of runoff, which can be harvested from a given catchment. Inflow into the water pan was determined by iterative method. The catchment area was iterated and the iteration ended when the optimal storage capacity to offset any decade water demand during the growing season was obtained. This was arrived at when inflow volume equaled outflow volume in decades 16 to 18 as shown in Figure 4.1. Any further reduction in catchment size would result into the stored water not meeting the water demand. There is vast open grassed land in the study area which is normally used as grazing land. Though a farmer may not own the land there is no limit to the area from which they can collect runoff. Therefore in the design procedure the catchment area as well as the storage capacity has been described as non-constrained. A runoff coefficient of 0.3 selected from Appendix 11 was used in the design. The resulting storage capacity and catchment area at different sizes of irrigated area and planting decades are shown in Appendix 6. Table 4.7 shows the optimum catchment and storage capacity for a crop planted on the 10th and 29th decades.

In any of the planting decade, the catchment area increased with an increase in rainfall reliability level and size of the irrigated area. This was because at higher reliability levels, the expected rainfall amount is low unlike at lower reliability levels. The supplemental irrigation requirements on the other hand increase with an increased rainfall reliability level.

A similar trend is followed by the storage capacity at different rainfall reliability levels. The storage capacity increases with increasing irrigated area as well as rainfall reliability levels. This trend is followed with planting in any other decades within the growing season.

Table 4.7: Catchment area and storage volume at different irrigated area and rainfall reliability levels.

Storage volume and catchment area at different rainfall reliabilities										
Irrigated area, m^2	Storage Volume, m^3	Catchment area , m^2	Storage Volume, m^3	Catchment area , m^2	Storage Volume, m^3	Catchment area , m^2	Storage Volume, m^3	Catchment area , m^2	Storage Volume, m^3	Catchment area , m^2
	40%		50%		60%		70%		80%	
Planting decade 10										
250	14	511	20	790	28	1225	36	2120	40	4290
500	40	1003	43	1598	45	2397	48	3970	50	7499
750	61	1505	64	2398	68	3595	72	5955	75	11249
1000	81	2006	86	3197	91	4794	95	7940	101	14998
1250	101	2508	107	3996	114	5992	119	9926	126	18748
1500	121	3009	128	4795	136	7190	143	11911	151	22497
1750	141	3511	150	5594	159	8389	167	13896	176	26247
2000	162	4012	171	6394	182	9587	191	15881	201	29996
Planting decade 29										
250	40	1003	43	1598	45	2397	48	3970	50	7499
500	81	2006	86	3197	91	4794	95	7940	101	14998
750	121	3009	128	4795	136	7190	143	11911	151	22497
1000	162	4012	171	6394	182	9587	191	15881	201	29996
1250	202	5016	214	7992	227	11984	239	19851	252	37496
1500	242	6019	257	9590	272	14381	286	23821	302	44995
1750	283	7022	300	11189	318	16778	334	27791	352	52494
2000	323	8025	342	12787	363	19174	382	31762	402	59993

The size of storage capacity has a direct implication on its cost and failure rate. At high reliability levels the capacity is also high and so is the cost of construction. However, a tank designed at higher rainfall reliability levels would also have a lower expected failure rate. A farmer would, therefore, have to be guided by their economic situation to be able to choose the capacity of the water pan.

The onset of the rains is expected on the 10th and 29th decades for the long and short rains respectively. It was realized that based on optimal storage sizes, this was the most optimal time to carry out the planting. The storage capacity and hence the cost of its construction is at its lowest when the crop is planted on the 10th and 29th decades.

A crop planted on these decades would make maximum use of rainfall and the supplemental irrigation requirement would be at its lowest. However, a farmer is not restricted to the time when planting can be carried out. This is because the planting date may be more influenced by the expected prices at the time of planting. Water storage for supplemental irrigation will enable the farmer to plant so that the harvesting period coincides with a time when the produce prices are highest.

Although farmers have excavated water pans, none of the farmers managed to grow and sell farm produce irrigated from the stored water. This was mainly due to mismatch in storage and catchment sizes. The tables developed will guide the farmer in selecting the capacity of the water pan, the catchment area and size of irrigated area at the respective planting decades. It is expected that with the proper selections and crop management practices, farmers will now be able to expand their financial sources from the farms. Storage capacity and catchment area for any other size of irrigated area can be obtained by interpolation.

Due to financial constraints a farmer may not be able to line or roof the water pan. The optimal storage size is then increased to take into accounts the evaporation and seepage water losses. Average seepage and evaporation loss as given in Appendix 8 was $0.055m^3$/day and $0.068m^3$/day respectively. The water is to be held in storage for a total of 90 days and therefore the seasonal water loss was $11.1m^3$. The water pan storage capacity was $40m^3$ and hence water loss is equivalent to 30% of storage. This factor is used to increase the selected optimal storage capacity given in Appendix 6 in situations whereby farmers cannot line or roof the water pan to entirely control seepage and evaporation water losses as shown in Table 4.8.

Table 4.8: Characteristics of an unlined and unroofed water pan designed at 80% rainfall reliability level.

	Water pan parameter	
Characteristics	**Planting decade 10**	**Planting decade 29**
Design capacity (m^3)	53	65
Catchment area (m^2)	4290	7499
Slope of catchment area	0	0
Irrigated area, m^2	250	250
Open water surface area (m^2)	36	46
Radius, r_1 (m)	3.5	3.4
Bottom radius, r_o (m)	2.0	2.2
Maximum pan depth (m)	2.0	2.0
Side Slope	1	1

Table 4.8 shows the design parameters of a water pan designed with neither a wall lining nor a roof. The storage capacity increases from $40m^3$ to 53 m^3 and from 50.3 to 65 m^3 when planting is carried out in decades 10 (Long rains) and 29 (short rains) respectively. The water pan depth is maintained at 2m. Using drip irrigation system, this storage capacity can be used to irrigate $250m^2$ area The optimal catchment area is $4290m^2$ and $7499m^2$ for planting in decades 10 and 29 respectively.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Rainwater harvesting has a large potential to diversify sources of income of farmers in the area. This potential has, however, to a large extent not been fully tapped in spite of the many indigenous water harvesting techniques in the study area. In most of the farm holdings, farmers practiced a combination of in-situ water conservation and storage water harvesting systems. However, farmers had a strong focus on the in-situ water conservation systems unlike with the storage water harvesting systems. The pitting method of water harvesting was the most commonly used.

Water from the water pans is used to irrigate small kitchen gardens. Most of the stored water is lost through evaporation and seepage. The average evaporation rate from the area was found to be 0.1 to $0.16m^3$/day while the seepage rate ranged from 0.01 to $0.16m^3$/day. It was therefore found advisable for the farmers to either line the water pans with seepage resistant materials.

There was a mismatch in sizes of the catchment and the storage capacity. Therefore, mass curve analysis was used to determine the optimal storage capacity and size of runoff catchment area. The size of the irrigated area for different storage capacities has been presented in tables. From the developed tables farmers can decide the best time to plant, size of the cropped area, storage capacity and catchment area required bearing in mind factors like financial capability, availability of labour and the expected market prices. In situations where the constructed water pan is not lined seepage resistant materials and roofed, the selected storage capacity is increased by 30% to cater for storage loss due to seepage and evaporation. It is however worth noting that since the storage systems largely depend on rainfall, they are likely to fail in case of severe drought.

Tables have been developed to enable farmers determine timing of irrigation and the amount to apply. From these tables a farmer can determine when to irrigate and depending on the amount of water stored determine how to apportion the water in the different crop development stages while at the same time avoiding extensive crop yield losses.

5.2 Recommendations

- Further research is required to determine water productivity for supplemental irrigated crops as well as deficit irrigation under specific crop management practices. Through such a study, the farmers will be able to exactly determine the amount applied as well as the best crop management practices to give maximum productivity.
- Water harvesting technologies cannot be isolated if it is to improve the peoples' livelihood. The communities need to be educated on other agronomic practices that go hand in hand with water harvesting technologies.
- The introduction of water harvesting has culminated into increased conflicts between the water users. With up-scaling of the technology water conflicts are bound to increase. There is, therefore, need to come up with appropriate policies that properly address the complex issue of upstream and downstream water conflict.

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7 APPENDICES

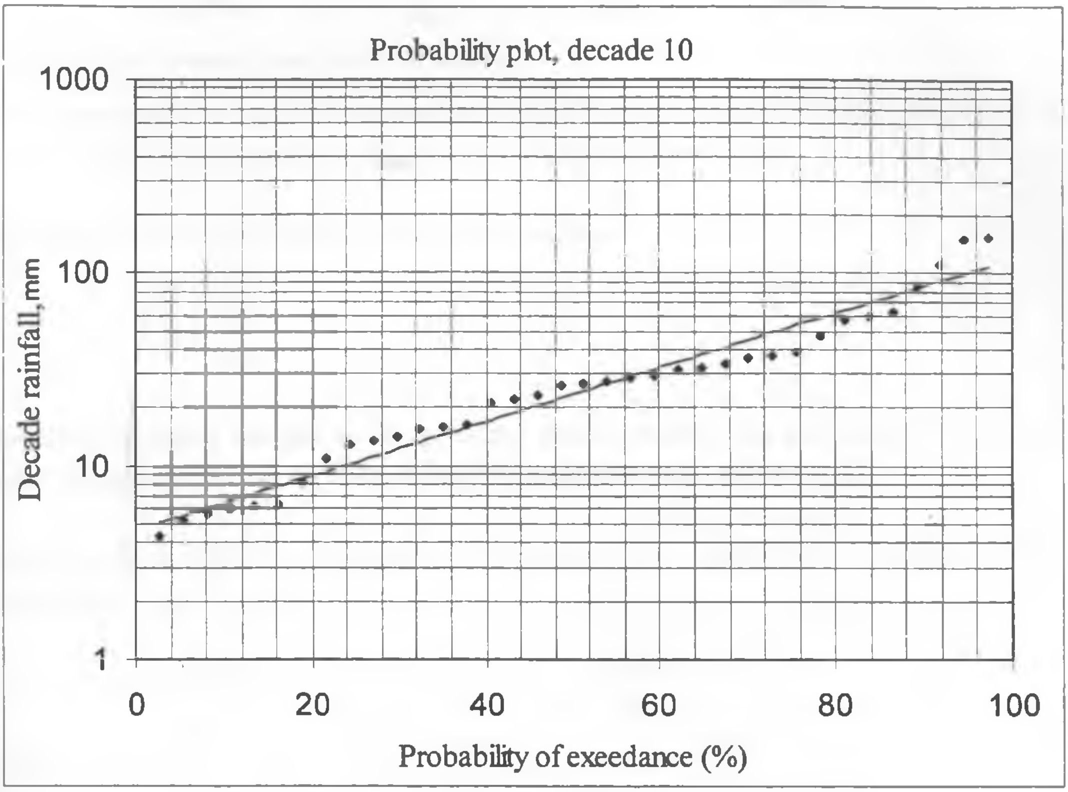
APPENDIX 1: DECADE RAINFALL AMOUNTS FOR LOLDOTO STATION

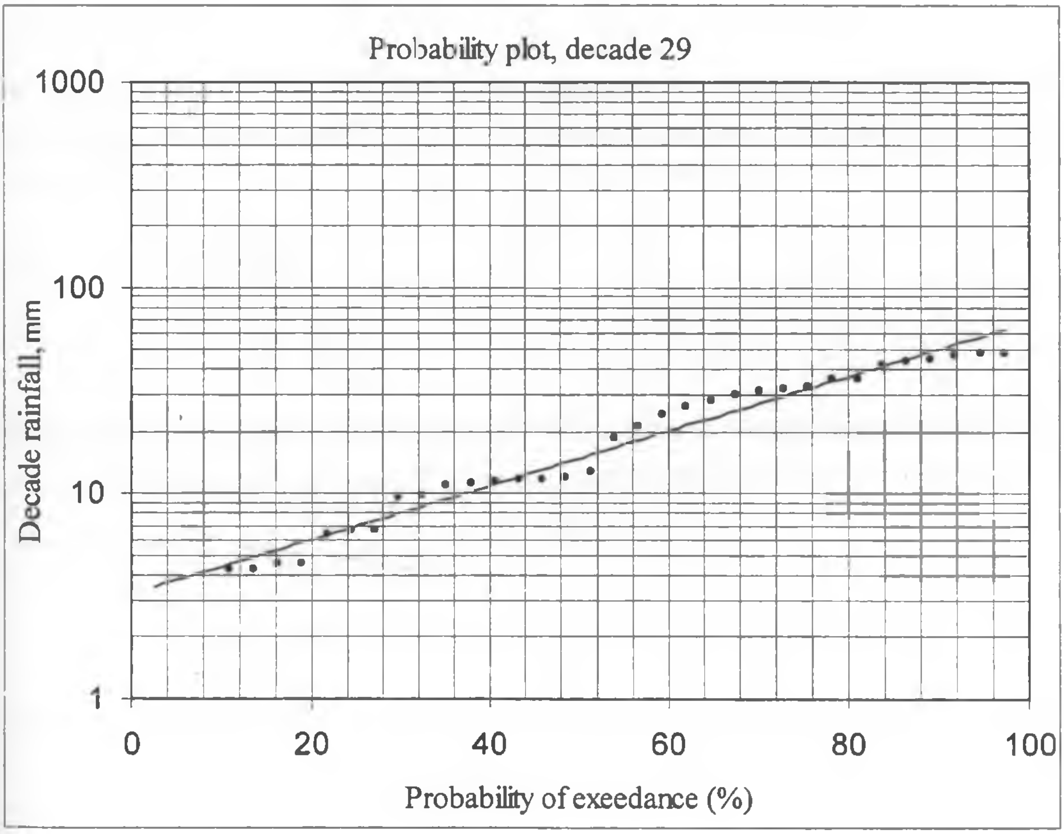
DECADE RAINFALL (MM) FOR 48 YEARS																		
year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1951	0	0	0	0	0	0	0	6	102	38	80	48	0	90	17	20	0	6
1952	0	0	0	0	0	0	0	0	0	0	0	0	85	5	10	1	1	9
1953	0	0	0	0	0	0	3	0	29	23	0	70	93	5	2	29	0	20
1954	0	0	0	0	0	0	13	0	10	62	26	18	43	77	43	25	22	80
1955	0	20	0	47	0	0	0	0	0	0	14	28	26	43	1	0	3	40
1956	4	12	32	0	5	0	0	0	0	21	89	103	31	17	12	0	0	175
1957	0	0	4	0	0	0	39	2	35	8	7	177	66	26	74	75	6	31
1958	0	0	46	13	56	0	0	21	0	4	30	29	10	62	24	16	29	46
1959	0	0	11	6	4	3	5	0	2	5	72	23	56	3	57	0	54	19
1960	0	0	17	0	0	0	0	20	36	16	52	17	21	7	49	3	1	28
1961	0	4	0	6	0	0	0	45	18	58	27	54	121	0	16	1	42	26
1962	50.5	0	0	0	0	0	0	52	8	15	57	36	26	9	11	17	9	7
1963	17.6	0	0	26	0	0	13	7	11	13	55	50	23	19	90	42	0	0
1964	0	0	0	0	0	0	20	0	9	39	47	15	28	23	0	8	17	19
1965	30.3	2	0	0	0	0	0	1	2	0	65	24	36	10	1	0	0	16
1966	0	2	2	2	0	52	0	1	27	6	67	25	16	9	8	42	54	0
1967	0	0	0	0	0	0	21	0	11	48	17	76	99	31	4	28	40	3
1968	0	0	0	0	0	57	54	5	36	34	19	105	39	17	47	48	36	11
1969	0	0	11	0	0	20	1	21	29	0	7	5	72	21	8	0	0	6
1970	0	0	11	4	0	0	16	0	19	6	25	78	53	3	51	13	39	0
1971	0	0	3	0	0	4	0	0	4	14	33	56	49	77	4	89	0	48
1972	81.9	0	0	87	0	0	0	0	0	0	12	44	93	36	27	2	26	15
1973	0	18	0	0	51	0	0	0	0	0	67	8	15	23	11	8	5	9
1974	0	9	0	0	3	0	0	0	52	27	0	0	10	30	36	111	19	29
1975	0	0	0	0	0	0	0	0	0	31	49	58	15	148	25	0	0	46
1976	0	0	0	0	0	0	0	0	0	16	54	21	44	32	26	9	5	5
1977	44.3	0	0	0	0	9	0	0	30	156	7	77	67	26	42	13	9	0
1978	0	25	0	0	0	0	11	37	17	60	46	5	17	72	0	42	31	10
1979	0	0	70	38	1	0	0	40	31	112	0	0	33	39	11	11	0	0
1980	0	0	0	0	19	0	3	0	9	0	10	2	56	58	0	22	0	54
1981	0	0	0	0	0	0	0	18	130	0	140	27	51	61	0	8	0	14
1982	15.2	0	0	0	0	0	0	0	13	29	65	96	50	21	5	0	0	11
1983	0	0	0	38	0	0	0	26	0	6	72	128	65	0	20	0	21	47
1984	0	0	0	0	0	0	0	0	0	0	4	15	3	11	5	11	28	0
1985	33.8	0	6	0	0	0	0	0	37	11	53	78	29	52	10	0	23	2
1986	0	0	0	0	0	0	22	8	3	22	51	214	50	3	28	0	118	8
1987	17	0	0	0	0	0	0	3	6	6	1	3	51	38	25	91	46	14
1988	0	0	0	0	0	0	53	24	10	26	154	112	0	0	0	0	0	0
1989	0	16	0	36	0	0	0	11	11	85	0	10	10	56	18	85	0	0
1990	0	0	0	14	9	35	85	28	29	27	50	0	0	29	23	4	29	10
1991	0	0	0	0	0	0	10	0	11	37	12	8	14	11	7	9	0	2
1992	0	0	0	0	0	0	0	0	0	30	0	37	2	15	32	0	0	0
1993	26.2	98	19	21	0	0	0	0	0	0	74	28	6	35	36	81	0	0
1994	0	0	0	0	97	0	0	0	23	0	38	162	11	35	2	4	18	43
1995	0	0	0	42	9	0	72	0	0	32	27	34	18	0	14	25	3	19
1996	0	0	0	0	0	0	0	22	12	0	21	32	0	20	0	184	52	6
1997	0	0	0	0	0	0	0	0	44	151	23	82	38	21	14	17	55	15
1998	85	52	0	84	12	0	0	12	2	14	18	41	108	47	0	58	2	2
Decade mean	**8.5**	**5**	**5**	**10**	**6**	**4**	**9**	**9**	**18**	**27**	**38**	**49**	**38**	**31**	**20**	**26**	**18**	**20**

APPENDIX 1 CONTD.

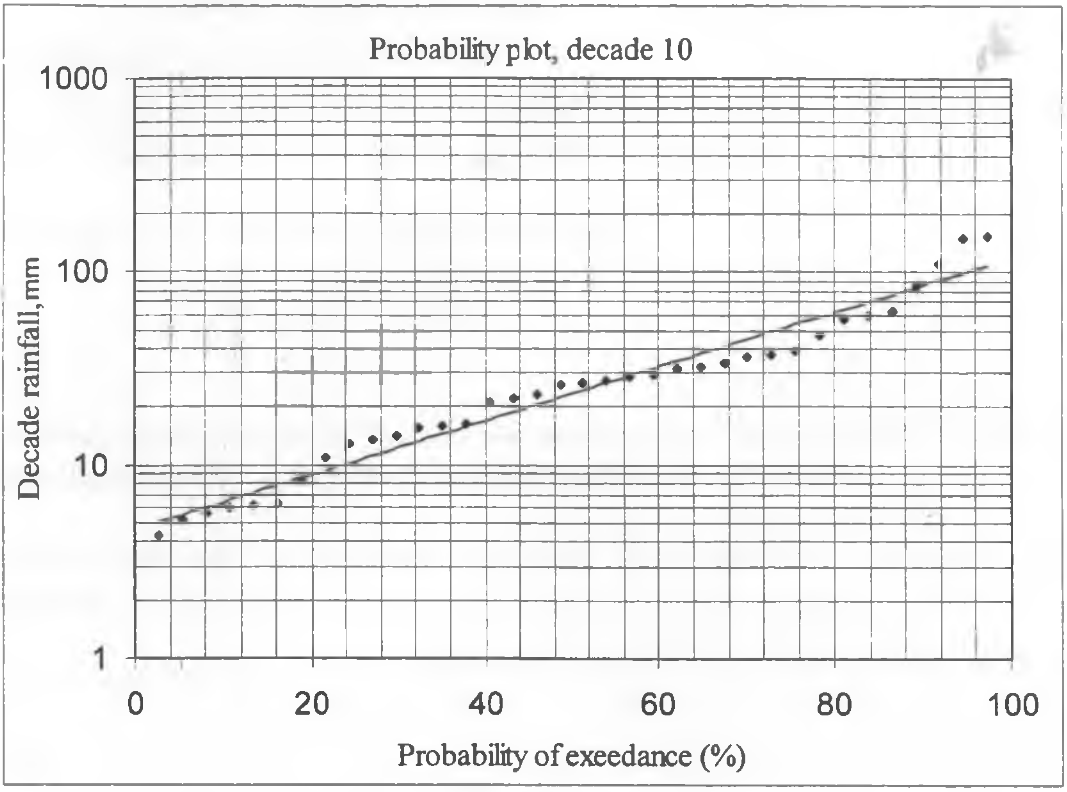
DECADE RAINFALL (MM) FOR 48 YEARS																		Annual total
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
2	33	56	6	44	11	54	2	1	3	12	36	33	35	17	33	9	1	**794**
0	9	9	4	8	9	15	49	8	37	11	0	0	11	52	0	0	7	**338**
13	0	13	15	20	2	22	2	1	6	44	7	31	38	0	2	0	0	**490**
20	2	36	8	3	42	107	6	14	37	0	14	9	15	1	43	0	0	**774**
4	11	31	11	130	19	35	16	35	8	19	21	16	5	1	6	11	12	**613**
4	1	28	0	45	63	18	0	31	3	0	11	1	14	28	0	0	2	**748**
0	0	6	27	4	20	9	0	0	1	30	51	64	2	11	58	4	0	**835**
19	42	28	46	1	21	34	36	3	36	11	1	15	1	21	27	30	6	**764**
0	55	2	31	55	0	6	6	3	2	0	8	0	6	35	12	4	0	**544**
6	1	0	8	53	76	1	7	4	0	12	57	24	41	13	1	8	0	**580**
16	3	12	184	6	1	22	4	0	35	48	77	109	48	105	0	24	3	**1115**
11	2	26	49	2	23	35	12	1	16	33	20	2	2	18	3	0	6	**558**
3	0	5	13	81	28	32	0	12	4	13	2	3	46	11	103	16	20	**757**
37	0	78	78	41	20	61	41	0	8	11	22	12	0	3	12	18	3	**671**
0	10	1	0	0	20	0	3	0	34	36	42	56	72	10	0	6	0	**477**
0	32	10	12	38	75	8	9	5	0	1	45	72	0	0	0	4	0	**622**
27	54	21	21	10	14	12	0	0	0	47	41	27	43	54	0	0	0	**749**
11	0	91	0	0	0	0	0	3	3	2	67	20	3	47	31	2	6	**795**
5	47	8	0	1	19	1	19	0	4	36	38	20	4	67	0	0	0	**468**
46	0	19	36	45	22	0	0	33	0	31	17	6	10	10	0	0	0	**592**
0	0	11	42	238	81	13	20	26	3	4	59	4	6	24	0	9	53	**974**
0	58	0	21	58	11	4	0	10	0	33	36	40	32	23	0	3	0	**754**
5	2	5	130	18	14	6	0	82	21	7	16	30	4	0	3	0	0	**556**
52	0	54	0	11	85	54	14	0	0	0	17	0	21	0	15	15	0	**664**
11	8	37	10	10	0	34	28	33	25	2	51	6	10	8	4	0	0	**649**
56	2	85	24	8	37	71	0	13	6	10	0	55	6	7	3	0	0	**595**
22	11	13	17	0	0	19	49	0	14	10	14	46	44	85	0	9	10	**842**
0	10	25	10	0	5	12	0	28	50	22	22	28	0	1	6	3	0	**592**
11	8	21	16	10	5	0	0	72	8	0	30	30	12	0	0	0	0	**608**
0	0	1	0	6	21	0	0	0	9	29	0	19	18	0	0	2	0	**335**
13	74	39	20	0	36	21	7	26	19	0	8	13	19	15	0	3	0	**760**
10	0	14	31	3	25	2	28	0	19	105	30	73	0	32	9	0	0	**683**
0	29	30	41	37	11	15	18	0	58	5	22	3	0	0	5	0	50	**746**
0	11	8	13	6	3	20	13	0	29	24	2	18	44	2	11	0	0	**281**
0	33	32	0	0	5	32	83	0	9	6	0	38	7	0	19	0	0	**600**
0	20	17	9	36	0	19	77	4	3	45	18	6	35	2	51	0	0	**867**
0	0	3	13	1	2	0	0	0	0	7	0	23	61	0	11	0	0	**419**
14	110	0	0	4	39	0	0	0	0	0	0	18	36	0	0	0	0	**599**
0	114	0	17	0	0	0	0	12	23	0	32	10	45	15	0	0	27	**632**
0	23	13	0	82	25	6	0	10	0	42	53	25	0	0	52	0	6	**707**
28	0	10	22	8	133	44	0	0	33	53	9	6	0	25	12	0	0	**506**
69	13	29	9	0	7	0	0	29	0	5	13	28	0	12	54	30	12	**423**
0	0	42	0	0	0	11	0	12	0	0	0	44	10	6	4	18	0	**573**
0	20	0	0	54	35	16	0	3	4	26	23	70	25	5	11	0	0	**724**
47	20	3	6	0	0	0	22	0	24	4	64	14	7	0	19	0	0	**526**
28	31	39	7	1	6	13	0	0	0	12	23	8	2	0	0	0	0	**519**
35	0	12	71	0	0	0	0	0	50	72	84	78	70	34	41	0	66	**1073**
30	23	59	0	51	64	0	0	11	18	48	30	63	21	11	7	3	0	**976**
14	**19**	**23**	**22**	**26**	**24**	**18**	**12**	**11**	**14**	**20**	**26**	**27**	**19**	**17**	**14**	**5**	**6**	655

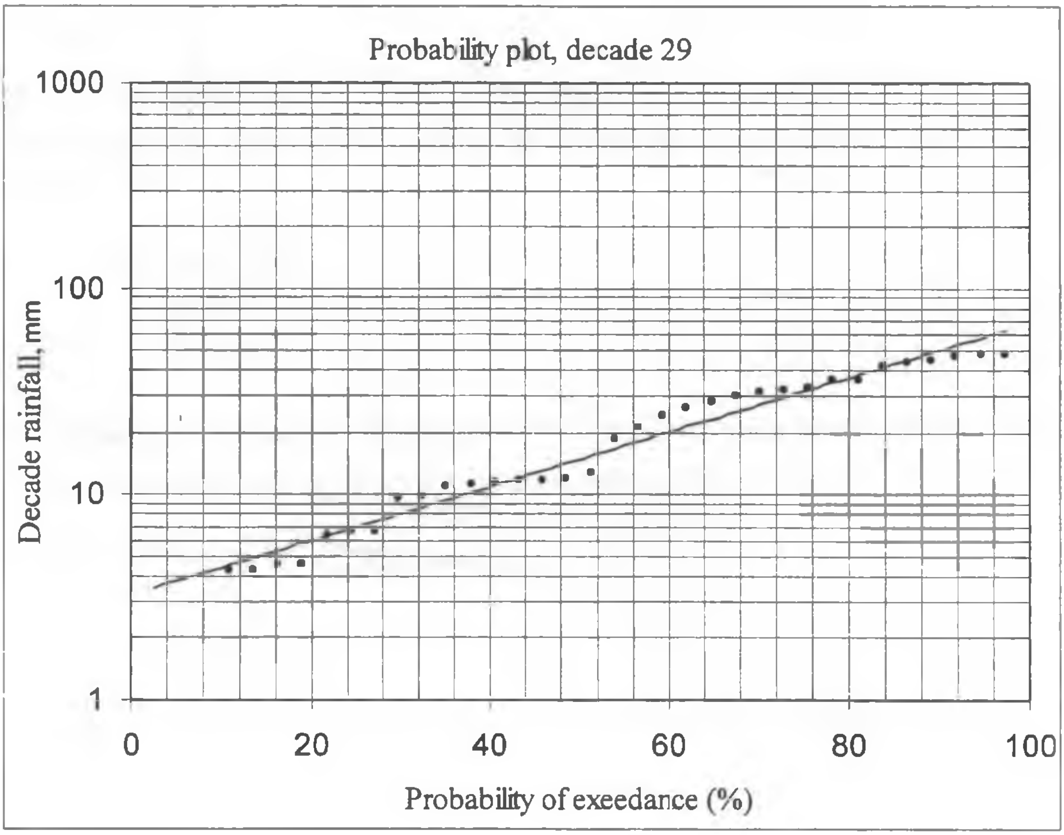
APPENDIX 2: PROBABILITY PLOTS FOR NON ZERO VALUES





APPENDIX 2: PROBABILITY PLOTS FOR NON ZERO VALUES





APPENDIX 3: SAMPLE CALCULATION FOR DESIGN RAINFALL

Calculation for Decade 10 at 30% Probability

From Appendix 1, a count of the non-zero rainfall values in decade 10 was carried out. The number of non zero values is 36 and the total number of values is 48.

Probability of a non zero value, *K* was then calculated

$$K = \frac{36}{48} = 0.75$$

Probability plotting analysis of the non-zero rainfall values was performed. The data was found to graphically fit a log normal distribution as shown in Appendix 2.

Using equation 3.6b, the magnitude of an event with probability of occurrence P was calculated.

For P=0.3 and K=0.75

Then,

$$P_x^{\bullet}(X) = \frac{(1-0.3)-1+0.75}{0.75} = 0.6$$

The frequency factor, K_T at $P_x^{\bullet}(X)=0.6$ was determined from Appendix 10 by interpolation while the statistical parameters for the log transformed data were calculated using Equations 3.7a and 3.7 b.

K_T=0.2529
$\mu_y = 3.21$
$\delta_y = 0.85$

The magnitude of an event corresponding to $P_x^{\bullet}(X)=0.6$ was obtained using Equation 2.7 for the log-transformed data, then using the inverse transformation to obtain the value of X.

Y=3.21+ (0.2529*0.85)
=3.43
X = Exp (3.43)
=30.9 mm

The design rainfall in decade 10 at 30% probability of occurrence is 30.9mm.

APPENDIX 4: CROP WATER REQUIREMENT

Epan, ETo, and ETc , mm at different planting Decades											
Planting Decade	Growth period										
		1	2	3	4	5	6	7	8	9	Total ETc
	Kc	0.45	0.45	0.75	0.75	0.75	1.03	1.03	0.95	0.95	
	Kpan	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
1	Epan	64.4	59.5	73.6	75.9	82.7	74.2	77.9	64.7	64.4	
	ETo	51.5	47.6	58.9	60.7	66.1	59.4	62.3	51.8	45.9	
	ETc	23.2	21.4	44.1	45.5	49.6	61.1	64.2	49.2	43.6	**402.0**
2	Epan	59.5	73.6	75.9	82.7	74.2	77.9	64.7	57.4	59.5	
	ETo	47.6	58.9	60.7	66.1	59.4	62.3	51.8	45.9	42.3	
	ETc	21.4	26.5	45.5	49.6	44.5	64.2	53.3	43.6	40.2	**388.9**
3	Epan	73.6	75.9	82.7	74.2	77.9	64.7	57.4	52.9	73.6	
	ETo	58.9	60.7	66.1	59.4	62.3	51.8	45.9	42.3	43.8	
	ETc	26.5	27.3	49.6	44.5	46.8	53.3	47.3	40.2	41.6	**377.1**
4	Epan	75.9	82.7	74.2	77.9	64.7	57.4	52.9	54.8	75.9	
	ETo	60.7	66.1	59.4	62.3	51.8	45.9	42.3	43.8	37.4	
	ETc	27.3	29.8	44.5	46.8	38.8	47.3	43.6	41.6	35.5	**355.2**
5	Epan	82.7	74.2	77.9	64.7	57.4	52.9	54.8	46.8	82.7	
	ETo	66.1	59.4	62.3	51.8	45.9	42.3	43.8	37.4	39.8	
	ETc	29.8	26.7	46.8	38.8	34.4	43.6	45.1	35.5	37.8	**338.6**
6	Epan	74.2	77.9	64.7	57.4	52.9	54.8	46.8	49.8	74.2	
	ETo	59.4	62.3	51.8	45.9	42.3	43.8	37.4	39.8	40.9	
	ETc	26.7	28.1	38.8	34.4	31.8	45.1	38.5	37.8	38.8	**320.1**
7	Epan	77.9	64.7	57.4	52.9	54.8	46.8	49.8	51.1	77.9	
	ETo	62.3	51.8	45.9	42.3	43.8	37.4	39.8	40.9	50.8	
	ETc	28.1	23.3	34.4	31.8	32.9	38.5	41.0	38.8	48.3	**317.1**
8	Epan	64.7	57.4	52.9	54.8	46.8	49.8	51.1	63.6	64.7	
	ETo	51.8	45.9	42.3	43.8	37.4	39.8	40.9	50.8	40.0	
	ETc	23.3	20.7	31.8	32.9	28.1	41.0	42.1	48.3	38.0	**306.1**
9	Epan	57.4	52.9	54.8	46.8	49.8	51.1	63.6	50.0	57.4	
	ETo	45.9	42.3	43.8	37.4	39.8	40.9	50.8	40.0	43.5	
	ETc	20.7	19.1	32.9	28.1	29.9	42.1	52.4	38.0	41.3	**304.3**
10	Epan	52.9	54.8	46.8	49.8	51.1	55.1	50.0	54.4	52.9	
	ETo	42.3	43.8	37.4	39.8	40.9	44.1	40.0	43.5	40.8	
	ETc	19.1	19.7	28.1	29.9	30.7	45.4	41.2	41.3	38.7	**294.0**
11	Epan	54.8	46.8	49.8	51.1	63.6	50.0	54.4	51.0	54.8	
	ETo	43.8	37.4	39.8	40.9	50.8	40.0	43.5	40.8	47.0	
	ETc	19.7	16.8	29.9	30.7	38.1	41.2	44.8	38.7	44.7	**304.7**
12	Epan	46.8	49.8	51.1	63.6	50.0	54.4	51.0	58.8	46.8	
	ETo	37.4	39.8	40.9	50.8	40.0	43.5	40.8	47.0	38.9	
	ETc	16.8	17.9	30.7	38.1	30.0	44.8	42.0	44.7	36.9	**302.0**
13	Epan	49.8	51.1	63.6	50.0	54.4	51.0	58.8	48.6	49.8	
	ETo	39.8	40.9	50.8	40.0	43.5	40.8	47.0	38.9	48.0	
	ETc	17.9	18.4	38.1	30.0	32.6	42.0	48.5	36.9	45.6	**310.0**
14	Epan	51.1	63.6	50.0	54.4	51.0	58.8	48.6	60.0	51.1	
	ETo	40.9	50.8	40.0	43.5	40.8	47.0	38.9	48.0	43.5	
	ETc	18.4	22.9	30.0	32.6	30.6	48.5	40.0	45.6	41.4	**309.9**
15	Epan	63.6	50.0	54.4	51.0	58.8	48.6	60.0	54.4	63.6	
	ETo	50.8	40.0	43.5	40.8	47.0	38.9	48.0	43.5	45.4	
	ETc	22.9	18.0	32.6	30.6	35.3	40.0	49.4	41.4	43.1	**313.3**
16	Epan	50.0	54.4	51.0	58.8	48.6	60.0	54.4	56.7	50.0	
	ETo	40.0	43.5	40.8	47.0	38.9	48.0	43.5	45.4	50.3	
	ETc	18.0	19.6	30.6	35.3	29.1	49.4	44.8	43.1	47.8	**317.7**
17	Epan	54.4	51.0	58.8	48.6	60.0	54.4	56.7	62.9	54.4	
	ETo	43.5	40.8	47.0	38.9	48.0	43.5	45.4	50.3	39.5	
	ETc	19.6	18.3	35.3	29.1	36.0	44.8	46.7	47.8	37.5	**315.2**
18	Epan	51.0	58.8	48.6	60.0	54.4	56.7	62.9	49.4	51.0	
	ETo	40.8	47.0	38.9	48.0	43.5	45.4	50.3	39.5	40.2	
	ETc	18.3	21.2	29.1	36.0	32.7	46.7	51.8	37.5	38.2	**311.6**

APPENDIX 4 CONTD

Epan, ETo, and ETc , mm at different planting Decades											
Planting Decade		Growth period									Total ETc
		1	2	3	4	5	6	7	8	9	
	Kc	0.45	0.45	0.75	0.75	0.75	1.03	1.03	0.95	0.95	
	Kpan	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	
19	Epan	58.8	48.6	60.0	54.4	56.7	62.9	49.4	50.3	58.8	
	ETo	47.0	38.9	48.0	43.5	45.4	50.3	39.5	40.2	40.6	
	ETc	21.2	17.5	36.0	32.7	34.0	51.8	40.7	38.2	38.6	**310.6**
20	Epan	48.6	60.0	54.4	56.7	62.9	49.4	50.3	50.7	48.6	
	ETo	38.9	48.0	43.5	45.4	50.3	39.5	40.2	40.6	40.9	
	ETc	17.5	21.6	32.7	34.0	37.7	40.7	41.4	38.6	38.9	**303.1**
21	Epan	60.0	54.4	56.7	62.9	49.4	50.3	50.7	51.2	60.0	
	ETo	48.0	43.5	45.4	50.3	39.5	40.2	40.6	40.9	34.6	
	ETc	21.6	19.6	34.0	37.7	29.6	41.4	41.8	38.9	32.9	**297.6**
22	Epan	54.4	56.7	62.9	49.4	50.3	50.7	51.2	43.3	54.4	
	ETo	43.5	45.4	50.3	39.5	40.2	40.6	40.9	34.6	35.2	
	ETc	19.6	20.4	37.7	29.6	30.2	41.8	42.2	32.9	33.4	**287.8**
23	Epan	56.7	62.9	49.4	50.3	50.7	51.2	43.3	44.0	56.7	
	ETo	45.4	50.3	39.5	40.2	40.6	40.9	34.6	35.2	31.7	
	ETc	20.4	22.6	29.6	30.2	30.4	42.2	35.6	33.4	30.1	**274.6**
24	Epan	62.9	49.4	50.3	50.7	51.2	43.3	44.0	39.6	62.9	
	ETo	50.3	39.5	40.2	40.6	40.9	34.6	35.2	31.7	34.4	
	ETc	22.6	17.8	30.2	30.4	30.7	35.6	36.2	30.1	32.7	**266.4**
25	Epan	49.4	50.3	50.7	51.2	43.3	44.0	39.6	43.0	49.4	
	ETo	39.5	40.2	40.6	40.9	34.6	35.2	31.7	34.4	31.2	
	ETc	17.8	18.1	30.4	30.7	26.0	36.2	32.7	32.7	29.6	**254.1**
26	Epan	50.3	50.7	51.2	43.3	44.0	39.6	43.0	39.0	50.3	
	ETo	40.2	40.6	40.9	34.6	35.2	31.7	34.4	31.2	39.1	
	ETc	18.1	18.3	30.7	26.0	26.4	32.7	35.4	29.6	37.2	**254.2**
27	Epan	50.7	51.2	43.3	44.0	39.6	43.0	39.0	48.9	50.7	
	ETo	40.6	40.9	34.6	35.2	31.7	34.4	31.2	39.1	38.6	
	ETc	18.3	18.4	26.0	26.4	23.8	35.4	32.1	37.2	36.7	**254.2**
28	Epan	51.2	43.3	44.0	39.6	43.0	39.0	48.9	48.3	51.2	
	ETo	40.9	34.6	35.2	31.7	34.4	31.2	39.1	38.6	48.3	
	ETc	18.4	15.6	26.4	23.8	25.8	32.1	40.3	36.7	45.9	**264.9**
29	Epan	51.2	43.3	44.0	39.6	43.0	39.0	48.9	48.3	43.3	
	ETo	34.6	35.2	31.7	34.4	31.2	39.1	38.6	48.3	51.5	
	ETc	15.6	15.8	23.8	25.8	23.4	40.3	39.8	44.2	45.3	**273.9**
30	Epan	43.3	44.0	39.6	43.0	39.0	48.9	48.3	60.4	44.0	
	ETo	35.2	31.7	34.4	31.2	39.1	38.6	48.3	51.5	47.6	
	ETc	15.8	14.3	25.8	23.4	29.3	39.8	49.7	48.9	45.2	**292.2**
31	Epan	44.0	39.6	43.0	39.0	48.9	48.3	60.4	64.4	39.6	
	ETo	31.7	34.4	31.2	39.1	38.6	48.3	51.5	47.6	58.9	
	ETc	14.3	15.5	23.4	29.3	29.0	49.7	53.0	45.2	55.9	**315.3**
32	Epan	39.6	43.0	39.0	48.9	48.3	60.4	64.4	59.5	43.0	
	ETo	34.4	31.2	39.1	38.6	48.3	51.5	47.6	58.9	60.7	
	ETc	15.5	14.0	29.3	29.0	36.2	53.0	49.0	55.9	57.7	**339.6**
33	Epan	39.6	43.0	39.0	48.9	48.3	60.4	64.4	59.5	39.0	
	ETo	31.2	39.1	38.6	48.3	51.5	47.6	58.9	60.7	66.1	
	ETc	14.0	17.6	29.0	36.2	38.6	49.0	60.6	57.7	62.8	**365.5**
34	Epan	43.0	39.0	48.9	48.3	60.4	64.4	59.5	73.6	48.9	
	ETo	39.1	38.6	48.3	51.5	47.6	58.9	60.7	66.1	59.4	
	ETc	17.6	17.4	36.2	38.6	35.7	60.6	62.5	62.8	56.4	**387.8**
35	Epan	39.0	48.9	48.3	60.4	64.4	59.5	73.6	75.9	48.3	
	ETo	38.6	48.3	51.5	47.6	58.9	60.7	66.1	59.4	62.3	
	ETc	17.4	21.7	38.6	35.7	44.1	62.5	68.1	56.4	59.2	**403.8**
36	Epan	48.9	48.3	60.4	64.4	59.5	73.6	75.9	82.7	60.4	
	ETo	48.3	51.5	47.6	58.9	60.7	66.1	59.4	62.3	51.8	
	ETc	21.7	23.2	35.7	44.1	45.5	68.1	61.1	59.2	49.2	**407.9**

APPENDIX 5: IRRIGATION REQUIREMENT

Reliability level (%)	Growing decade	Irrigation water requirement (mm) at different planting decade and rainfall reliability levels.											
		7	8	9	10	11	12	13	14	15	16	17	18
40	1	28.1	19.7	10.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.5
	2	19.7	10.3	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2
	3	24.0	15.6	6.8	0.0	0.0	0.0	0.0	0.0	9.0	14.8	24.7	19.4
	4	15.6	6.8	0.0	0.0	0.0	7.9	13.4	21.0	29.8	27.4	19.4	23.4
	5	6.8	0.0	4.9	0.0	12.8	17.2	22.9	29.8	27.4	19.4	23.4	21.2
	6	7.1	16.0	23.1	26.5	28.4	35.1	41.2	40.5	30.2	36.8	33.4	34.6
	7	16.0	23.1	40.4	28.4	35.1	41.2	40.5	30.2	36.8	33.4	34.6	38.1
	8	19.9	36.4	25.2	31.6	37.9	36.8	27.1	33.0	29.9	31.0	34.0	28.0
	9	36.4	25.2	31.6	37.9	36.8	27.1	33.0	29.9	31.0	34.0	28.0	29.0
Seasonal Total		**173.5**	**153.1**	**145.2**	**124.4**	**150.9**	**165.2**	**178.1**	**184.4**	**194.1**	**196.7**	**197.5**	**224.4**
50	1	28.1	23.3	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0
	2	23.3	12.5	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	15.6
	3	26.3	19.7	11.4	0.0	0.0	0.0	1.5	6.9	17.2	21.0	29.7	22.1
	4	19.7	11.4	2.6	0.0	0.0	13.8	20.7	25.2	30.2	29.7	22.1	25.8
	5	11.4	2.6	8.9	3.7	22.7	20.7	25.2	30.2	29.7	22.1	25.8	24.4
	6	13.1	20.1	26.6	42.8	31.9	37.4	41.6	42.8	33.0	39.3	36.6	38.1
	7	20.1	26.6	42.8	31.9	37.4	41.6	42.8	33.0	39.3	36.6	38.1	41.2
	8	23.3	38.8	28.7	33.9	38.3	39.1	29.9	35.4	33.1	34.5	37.2	30.3
	9	38.8	28.7	33.9	38.3	39.1	29.9	35.4	33.1	34.5	37.2	30.3	33.2
Seasonal Total		**204.1**	**183.7**	**174.5**	**150.7**	**169.3**	**182.4**	**197.1**	**206.7**	**216.9**	**220.3**	**219.9**	**248.6**
60	1	28.1	23.3	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.3
	2	23.3	14.3	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.9	20.3
	3	28.1	23.3	15.4	0.0	0.0	0.0	11.8	18.2	29.6	32.7	35.5	3.8
	4	23.3	15.4	7.6	2.9	2.7	19.1	28.6	32.1	34.4	37.4	4.9	30.0
	5	15.4	7.6	12.4	18.1	30.6	23.6	33.6	33.8	36.4	6.8	31.0	29.2
	6	18.1	23.5	29.5	44.8	34.8	40.8	46.8	49.0	16.6	46.4	42.5	43.1
	7	23.5	29.5	44.8	34.8	40.8	41.8	50.5	16.0	45.3	44.4	44.1	45.9
	8	26.2	40.8	31.6	37.3	38.6	41.8	14.5	40.9	39.8	42.4	43.0	34.4
	9	40.8	31.6	37.3	38.6	41.8	9.5	37.5	35.8	37.3	39.8	32.3	36.0
Seasonal Total		**226.8**	**209.3**	**203.6**	**176.5**	**189.3**	**176.6**	**223.5**	**225.8**	**239.3**	**249.8**	**240.3**	**263.0**
70	1	28.1	23.3	15.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.3
	2	23.3	15.8	14.2	0.0	0.0	0.0	0.0	0.0	1.7	4.1	7.9	21.2
	3	29.6	26.9	19.2	2.2	0.0	0.0	14.3	22.0	32.6	30.5	35.3	27.6
	4	26.9	19.2	11.9	15.5	12.9	27.3	26.5	32.6	30.5	35.3	27.6	29.7
	5	19.2	11.9	15.5	20.6	32.4	26.5	32.6	30.5	35.3	27.6	29.7	29.7
	6	22.4	26.7	32.1	46.7	37.7	44.8	41.9	48.5	38.4	43.2	41.9	43.5
	7	26.7	32.1	46.7	37.7	44.8	41.9	48.5	38.4	43.2	41.9	43.5	46.3
	8	28.8	42.6	34.5	41.3	38.7	44.7	35.3	39.3	38.4	39.9	42.3	34.4
	9	42.6	34.5	41.3	38.7	44.7	35.3	39.3	38.4	39.9	42.3	34.4	38.2
Seasonal Total		**247.5**	**233.0**	**231.2**	**202.7**	**211.2**	**220.6**	**238.5**	**249.8**	**260.0**	**264.6**	**262.5**	**288.9**
80	1	28.1	23.3	20.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.3
	2	23.3	20.7	19.1	0.0	0.0	0.0	0.0	0.2	7.1	7.6	7.9	21.2
	3	34.4	31.8	23.3	15.8	4.5	5.8	22.6	30.0	32.6	30.6	35.3	29.1
	4	31.8	23.3	16.6	19.0	23.4	34.3	30.0	32.6	30.6	35.3	29.1	31.6
	5	23.3	16.6	19.0	23.4	34.3	30.0	32.6	30.6	35.3	29.1	31.6	32.7
	6	27.0	30.2	34.8	48.6	41.2	44.8	42.0	48.5	40.0	45.0	44.8	46.7
	7	30.2	34.8	48.6	41.2	44.8	42.0	48.5	40.0	45.0	44.8	46.7	49.5
	8	31.6	44.5	38.0	41.3	38.7	44.7	36.9	41.2	41.4	43.1	45.5	37.5
	9	44.5	38.0	41.3	38.7	44.7	36.9	41.2	41.4	43.1	45.5	37.5	38.2
Seasonal Total		**274.1**	**263.1**	**261.4**	**228.0**	**231.7**	**238.5**	**253.7**	**264.5**	**275.1**	**281.1**	**278.6**	**305.0**

APPENDIX 5: IRRIGATION REQUIREMENT

Reliability level (%)	Growing decade	Irrigation water requirement (mm) at different planting decade and rainfall reliability levels.											
		7	8	9	10	11	12	13	14	15	16	17	18
40	1	28.1	19.7	10.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	17.5
	2	19.7	10.3	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.2
	3	24.0	15.6	6.8	0.0	0.0	0.0	0.0	0.0	9.0	14.8	24.7	19.4
	4	15.6	6.8	0.0	0.0	0.0	7.9	13.4	21.0	29.8	27.4	19.4	23.4
	5	6.8	0.0	4.9	0.0	12.8	17.2	22.9	29.8	27.4	19.4	23.4	21.2
	6	7.1	16.0	23.1	26.5	28.4	35.1	41.2	40.5	30.2	36.8	33.4	34.6
	7	16.0	23.1	40.4	28.4	35.1	41.2	40.5	30.2	36.8	33.4	34.6	38.1
	8	19.9	36.4	25.2	31.6	37.9	36.8	27.1	33.0	29.9	31.0	34.0	28.0
	9	36.4	25.2	31.6	37.9	36.8	27.1	33.0	29.9	31.0	34.0	28.0	29.0
Seasonal Total		**173.5**	**153.1**	**145.2**	**124.4**	**150.9**	**165.2**	**178.1**	**184.4**	**194.1**	**196.7**	**197.5**	**224.4**
50	1	28.1	23.3	12.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.0
	2	23.3	12.5	7.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	15.6
	3	26.3	19.7	11.4	0.0	0.0	0.0	1.5	6.9	17.2	21.0	29.7	22.1
	4	19.7	11.4	2.6	0.0	0.0	13.8	20.7	25.2	30.2	29.7	22.1	25.8
	5	11.4	2.6	8.9	3.7	22.7	20.7	25.2	30.2	29.7	22.1	25.8	24.4
	6	13.1	20.1	26.6	42.8	31.9	37.4	41.6	42.8	33.0	39.3	36.6	38.1
	7	20.1	26.6	42.8	31.9	37.4	41.6	42.8	33.0	39.3	36.6	38.1	41.2
	8	23.3	38.8	28.7	33.9	38.3	39.1	29.9	35.4	33.1	34.5	37.2	30.3
	9	38.8	28.7	33.9	38.3	39.1	29.9	35.4	33.1	34.5	37.2	30.3	33.2
Seasonal Total		**204.1**	**183.7**	**174.5**	**150.7**	**169.3**	**182.4**	**197.1**	**206.7**	**216.9**	**220.3**	**219.9**	**248.6**
60	1	28.1	23.3	14.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.3
	2	23.3	14.3	10.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.9	20.3
	3	28.1	23.3	15.4	0.0	0.0	0.0	11.8	18.2	29.6	32.7	35.5	3.8
	4	23.3	15.4	7.6	2.9	2.7	19.1	28.6	32.1	34.4	37.4	4.9	30.0
	5	15.4	7.6	12.4	18.1	30.6	23.6	33.6	33.8	36.4	6.8	31.0	29.2
	6	18.1	23.5	29.5	44.8	34.8	40.8	46.8	49.0	16.6	46.4	42.5	43.1
	7	23.5	29.5	44.8	34.8	40.8	41.8	50.5	16.0	45.3	44.4	44.1	45.9
	8	26.2	40.8	31.6	37.3	38.6	41.8	14.5	40.9	39.8	42.4	43.0	34.4
	9	40.8	31.6	37.3	38.6	41.8	9.5	37.5	35.8	37.3	39.8	32.3	36.0
Seasonal Total		**226.8**	**209.3**	**203.6**	**176.5**	**189.3**	**176.6**	**223.5**	**225.8**	**239.3**	**249.8**	**240.3**	**263.0**
70	1	28.1	23.3	15.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.3
	2	23.3	15.8	14.2	0.0	0.0	0.0	0.0	0.0	1.7	4.1	7.9	21.2
	3	29.6	26.9	19.2	2.2	0.0	0.0	14.3	22.0	32.6	30.5	35.3	27.6
	4	26.9	19.2	11.9	15.5	12.9	27.3	26.5	32.6	30.5	35.3	27.6	29.7
	5	19.2	11.9	15.5	20.6	32.4	26.5	32.6	30.5	35.3	27.6	29.7	29.7
	6	22.4	26.7	32.1	46.7	37.7	44.8	41.9	48.5	38.4	43.2	41.9	43.5
	7	26.7	32.1	46.7	37.7	44.8	41.9	48.5	38.4	43.2	41.9	43.5	46.3
	8	28.8	42.6	34.5	41.3	38.7	44.7	35.3	39.3	38.4	39.9	42.3	34.4
	9	42.6	34.5	41.3	38.7	44.7	35.3	39.3	38.4	39.9	42.3	34.4	38.2
Seasonal Total		**247.5**	**233.0**	**231.2**	**202.7**	**211.2**	**220.6**	**238.5**	**249.8**	**260.0**	**264.6**	**262.5**	**288.9**
80	1	28.1	23.3	20.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.3
	2	23.3	20.7	19.1	0.0	0.0	0.0	0.0	0.2	7.1	7.6	7.9	21.2
	3	34.4	31.8	23.3	15.8	4.5	5.8	22.6	30.0	32.6	30.6	35.3	29.1
	4	31.8	23.3	16.6	19.0	23.4	34.3	30.0	32.6	30.6	35.3	29.1	31.6
	5	23.3	16.6	19.0	23.4	34.3	30.0	32.6	30.6	35.3	29.1	31.6	32.7
	6	27.0	30.2	34.8	48.6	41.2	44.8	42.0	48.5	40.0	45.0	44.8	46.7
	7	30.2	34.8	48.6	41.2	44.8	42.0	48.5	40.0	45.0	44.8	46.7	49.5
	8	31.6	44.5	38.0	41.3	38.7	44.7	36.9	41.2	41.4	43.1	45.5	37.5
	9	44.5	38.0	41.3	38.7	44.7	36.9	41.2	41.4	43.1	45.5	37.5	38.2
Seasonal Total		**274.1**	**263.1**	**261.4**	**228.0**	**231.7**	**238.5**	**253.7**	**264.5**	**275.1**	**281.1**	**278.6**	**305.0**

APPENDIX 5 CONTD

Reliability level (%)	Growing decade	Irrigation water requirement (mm) at different planting decade and rainfall reliability levels.											
		25	26	27	28	29	30	31	32	33	34	35	36
40	1	8.3	8.9	13.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	15.8	21.7
	2	8.9	13.5	10.5	4.1	0.0	0.0	0.0	0.0	0.0	0.0	21.7	23.2
	3	25.7	22.8	14.5	1.7	0.0	0.0	0.0	3.7	15.1	34.5	38.6	35.7
	4	22.8	14.5	1.7	8.0	0.0	0.0	13.0	27.4	36.2	38.6	35.7	44.1
	5	14.5	1.7	8.0	14.5	11.2	23.3	27.4	36.2	38.6	35.7	44.1	45.5
	6	11.5	16.9	24.1	23.3	35.2	38.2	49.7	53.0	49.0	60.6	62.5	68.1
	7	16.9	24.1	23.3	35.2	38.2	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	21.4	20.8	32.1	35.1	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	20.8	32.1	35.1	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	45.6
Seasonal Total		**150.8**	**155.3**	**162.8**	**178.3**	**179.4**	**205.3**	**244.2**	**282.9**	**320.1**	**351.2**	**402.2**	**404.3**
50	1	10.5	13.0	15.3	12.3	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	13.0	15.3	12.3	6.6	0.0	0.0	0.0	0.0	0.0	1.2	21.7	23.2
	3	27.5	24.6	17.0	13.3	0.0	0.0	0.0	9.6	20.4	36.2	38.6	35.7
	4	24.6	17.0	13.3	10.9	7.0	7.8	20.3	29.0	36.2	38.6	35.7	44.1
	5	17.0	13.3	10.9	16.8	16.9	25.6	29.0	36.2	38.6	35.7	44.1	45.5
	6	23.2	19.7	26.4	25.6	36.6	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	19.7	26.4	25.6	36.6	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	23.7	23.1	33.4	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	23.1	33.4	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**182.3**	**185.9**	**190.9**	**204.6**	**195.0**	**217.0**	**253.1**	**290.4**	**325.3**	**354.1**	**403.8**	**407.9**
60	1	12.5	15.9	17.5	13.9	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	15.9	17.5	13.9	8.7	0.0	0.0	0.0	0.0	0.0	3.2	21.7	23.2
	3	29.7	26.2	19.0	15.7	0.0	0.0	1.0	15.5	24.3	36.2	38.6	35.7
	4	26.2	19.0	15.7	13.2	15.8	16.5	27.5	29.0	36.2	38.6	35.7	44.1
	5	19.0	15.7	13.2	18.8	18.9	27.5	29.0	36.2	38.6	35.7	44.1	45.5
	6	25.6	22.1	28.4	27.6	38.5	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	22.1	28.4	27.6	38.5	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	25.6	25.1	35.3	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	25.1	35.3	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**201.7**	**205.2**	**207.4**	**218.9**	**207.7**	**227.6**	**261.4**	**296.3**	**329.2**	**356.0**	**403.8**	**407.9**
70	1	14.6	18.1	18.3	15.6	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	18.1	18.3	15.6	10.7	0.0	0.0	0.0	0.0	0.0	5.0	21.7	23.2
	3	30.4	27.9	21.0	18.0	3.5	3.9	7.0	21.1	28.1	36.2	38.6	35.7
	4	27.9	21.0	18.0	15.4	20.6	20.8	29.3	29.0	36.2	38.6	35.7	44.1
	5	21.0	18.0	15.4	20.6	20.8	29.3	29.0	36.2	38.6	35.7	44.1	45.5
	6	27.9	24.2	30.2	29.6	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	24.2	30.2	29.6	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	27.5	27.1	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	27.1	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**218.8**	**222.1**	**222.0**	**232.7**	**219.8**	**237.7**	**269.2**	**301.9**	**333.0**	**357.8**	**403.8**	**407.9**
80	1	17.8	18.1	18.3	18.4	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	18.1	18.3	18.4	13.4	0.0	0.0	0.0	0.0	1.6	5.0	21.7	23.2
	3	30.4	30.7	23.8	20.7	11.0	10.9	13.9	25.9	29.0	36.2	38.6	35.7
	4	30.7	23.8	20.7	17.5	22.8	23.4	29.3	29.0	36.2	38.6	35.7	44.1
	5	23.8	20.7	17.5	22.8	23.4	29.3	29.0	36.2	38.6	35.7	44.1	45.5
	6	30.5	26.3	32.5	32.1	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	26.3	32.5	32.1	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	29.7	29.6	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	29.6	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**237.0**	**237.1**	**237.1**	**247.8**	**232.1**	**247.2**	**276.0**	**306.7**	**335.5**	**357.8**	**403.8**	**407.9**

APPENDIX 5 CONTD

Reliability level (%)	Growing decade	Irrigation water requirement (mm) at different planting decade and rainfall reliability levels.											
		25	26	27	28	29	30	31	32	33	34	35	36
40	1	8.3	8.9	13.5	10.5	0.0	0.0	0.0	0.0	0.0	0.0	15.8	21.7
	2	8.9	13.5	10.5	4.1	0.0	0.0	0.0	0.0	0.0	0.0	21.7	23.2
	3	25.7	22.8	14.5	1.7	0.0	0.0	0.0	3.7	15.1	34.5	38.6	35.7
	4	22.8	14.5	1.7	8.0	0.0	0.0	13.0	27.4	36.2	38.6	35.7	44.1
	5	14.5	1.7	8.0	14.5	11.2	23.3	27.4	36.2	38.6	35.7	44.1	45.5
	6	11.5	16.9	24.1	23.3	35.2	38.2	49.7	53.0	49.0	60.6	62.5	68.1
	7	16.9	24.1	23.3	35.2	38.2	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	21.4	20.8	32.1	35.1	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	20.8	32.1	35.1	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	45.6
Seasonal Total		**150.8**	**155.3**	**162.8**	**178.3**	**179.4**	**205.3**	**244.2**	**282.9**	**320.1**	**351.2**	**402.2**	**404.3**
50	1	10.5	13.0	15.3	12.3	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	13.0	15.3	12.3	6.6	0.0	0.0	0.0	0.0	0.0	1.2	21.7	23.2
	3	27.5	24.6	17.0	13.3	0.0	0.0	0.0	9.6	20.4	36.2	38.6	35.7
	4	24.6	17.0	13.3	10.9	7.0	7.8	20.3	29.0	36.2	38.6	35.7	44.1
	5	17.0	13.3	10.9	16.8	16.9	25.6	29.0	36.2	38.6	35.7	44.1	45.5
	6	23.2	19.7	26.4	25.6	36.6	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	19.7	26.4	25.6	36.6	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	23.7	23.1	33.4	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	23.1	33.4	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**182.3**	**185.9**	**190.9**	**204.6**	**195.0**	**217.0**	**253.1**	**290.4**	**325.3**	**354.1**	**403.8**	**407.9**
60	1	12.5	15.9	17.5	13.9	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	15.9	17.5	13.9	8.7	0.0	0.0	0.0	0.0	0.0	3.2	21.7	23.2
	3	29.7	26.2	19.0	15.7	0.0	0.0	1.0	15.5	24.3	36.2	38.6	35.7
	4	26.2	19.0	15.7	13.2	15.8	16.5	27.5	29.0	36.2	38.6	35.7	44.1
	5	19.0	15.7	13.2	18.8	18.9	27.5	29.0	36.2	38.6	35.7	44.1	45.5
	6	25.6	22.1	28.4	27.6	38.5	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	22.1	28.4	27.6	38.5	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	25.6	25.1	35.3	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	25.1	35.3	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**201.7**	**205.2**	**207.4**	**218.9**	**207.7**	**227.6**	**261.4**	**296.3**	**329.2**	**356.0**	**403.8**	**407.9**
70	1	14.6	18.1	18.3	15.6	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	18.1	18.3	15.6	10.7	0.0	0.0	0.0	0.0	0.0	5.0	21.7	23.2
	3	30.4	27.9	21.0	18.0	3.5	3.9	7.0	21.1	28.1	36.2	38.6	35.7
	4	27.9	21.0	18.0	15.4	20.6	20.8	29.3	29.0	36.2	38.6	35.7	44.1
	5	21.0	18.0	15.4	20.6	20.8	29.3	29.0	36.2	38.6	35.7	44.1	45.5
	6	27.9	24.2	30.2	29.6	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	24.2	30.2	29.6	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	27.5	27.1	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	27.1	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**218.8**	**222.1**	**222.0**	**232.7**	**219.8**	**237.7**	**269.2**	**301.9**	**333.0**	**357.8**	**403.8**	**407.9**
80	1	17.8	18.1	18.3	18.4	0.0	0.0	0.0	0.0	0.0	0.0	17.4	21.7
	2	18.1	18.3	18.4	13.4	0.0	0.0	0.0	0.0	1.6	5.0	21.7	23.2
	3	30.4	30.7	23.8	20.7	11.0	10.9	13.9	25.9	29.0	36.2	38.6	35.7
	4	30.7	23.8	20.7	17.5	22.8	23.4	29.3	29.0	36.2	38.6	35.7	44.1
	5	23.8	20.7	17.5	22.8	23.4	29.3	29.0	36.2	38.6	35.7	44.1	45.5
	6	30.5	26.3	32.5	32.1	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1
	7	26.3	32.5	32.1	40.3	39.8	49.7	53.0	49.0	60.6	62.5	68.1	61.1
	8	29.7	29.6	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2
	9	29.6	37.2	36.7	45.9	48.9	45.2	55.9	57.7	62.8	56.4	59.2	49.2
Seasonal Total		**237.0**	**237.1**	**237.1**	**247.8**	**232.1**	**247.2**	**276.0**	**306.7**	**335.5**	**357.8**	**403.8**	**407.9**

APPENDIX 6: CATCHMENT SIZE, STORAGE CAPACITY AND IRRIGATED AREA AT DIFFERENT RELIABILITIES

Catchment area , m^2 at different rainfall reliability						Storage volume , m^3 at different rainfall reliability					
Irrigated	40	50	60	70	80	Irrigated	40	50	60	70	80
	Planting decade 10						Planting decade 10				
250	14	20	28	36	40	250	511	790	1225	2120	4290
500	28	40	56	72	82	500	1021	1580	2451	4240	8580
750	42	60	84	108	123	750	1532	2370	3676	6361	12870
1000	56	80	112	144	163	1000	2042	3160	4902	8481	17160
1250	70	100	140	180	204	1250	2553	3950	6127	10601	21450
1500	84	120	168	216	245	1500	3063	4739	7352	12721	25740
	Planting decade 11						Planting decade 11				
250	22	26	33	41	50	250	549	848	1315	2258	4320
500	44	52	67	82	99	500	1097	1696	2631	4515	8641
750	67	78	100	123	149	750	1646	2544	3946	6773	12961
1000	89	104	133	164	199	1000	2195	3392	5262	9030	17282
1250	111	130	167	205	249	1250	2744	4241	6577	11288	21602
1500	133	156	200	246	298	1500	3292	5089	7892	13546	25922
	Planting decade 12						Planting decade 12				
250	27	30	37	47	57	250	595	910	1410	2426	4404
500	55	60	73	95	114	500	1190	1821	2819	4852	8808
750	82	90	110	142	170	750	1784	2731	4229	7279	13211
1000	110	120	147	189	227	1000	2379	3641	5638	9705	17615
1250	137	150	184	237	284	1250	2974	4552	7048	12131	22019
1500	165	180	220	284	341	1500	3569	5462	8458	14557	26423
	Planting decade 13						Planting decade 13				
250	30	33	39	50	62	250	614	932	1437	2456	4520
500	60	65	78	100	124	500	1227	1864	2873	4912	9040
750	89	98	117	150	186	750	1841	2796	4310	7368	13560
1000	119	130	156	200	248	1000	2455	3728	5746	9824	18080
1250	149	163	195	250	310	1250	3069	4660	7183	12280	22600
	Planting decade 14						Planting decade 14				
250	32	35	42	54	65	250	646	957	1452	2600	4640
500	64	70	85	107	130	500	1291	1914	2904	5199	9280
750	96	105	127	161	195	750	1937	2872	4356	7799	13920
1000	128	140	169	214	260	1000	2582	3829	5808	10398	18560
1250	160	175	212	268	325	1250	3228	4786	7260	12998	23200
	Planting decade 15						Planting decade 15				
250	32	36	43	54	66	250	665	984	1501	2701	4682
500	64	72	85	108	132	500	1330	1969	3001	5403	9363
750	96	108	128	162	198	750	1995	2953	4502	8104	14045
1000	128	144	171	216	264	1000	2660	3937	6002	10805	18726
1250	160	181	213	270	330	1250	3325	4922	7503	13507	23408
1500	192	217	256	324	396	1500	3989	5906	9004	16208	28090
	Planting decade 16						Planting decade 16				
250	32	37	44	54	67	250	671	1010	1530	2820	4893
500	65	75	88	108	133	500	1343	2020	3060	5640	9785
750	97	112	132	162	200	750	2014	3030	4590	8460	14678
1000	129	149	176	216	266	1000	2686	4040	6120	11280	19570
1250	161	187	220	270	333	1250	3357	5050	7650	14100	24463
	Planting decade 17						Planting decade 17				
250	32	39	45	55	67	250	675	1039	1583	2896	5030
500	64	79	89	110	134	500	1350	2077	3165	5792	10060
750	96	118	134	164	202	750	2025	3116	4748	8687	15090
1000	128	158	178	219	269	1000	2700	4154	6331	11583	20120
1250	160	197	223	274	336	1250	3375	5193	7914	14479	25150
1500	192	236	267	329	403	1500	4050	6232	9496	17375	30180

APPENDIX 6 CONTD

Catchment area, m² at different rainfall reliability levels						Storage volume, m³ at different rainfall reliability levels					
Irrigated area, m²	40	50	60	70	80	Irrigated area, m²	40	50	60	70	80
	Planting decade 29						Planting decade 29				
250	40	43	45	48	50	250	1003	1598	2397	3970	7499
500	81	86	91	95	101	500	2006	3197	4794	7940	14998
750	121	128	136	143	151	750	3009	4795	7190	11911	22497
1000	162	171	182	191	201	1000	4012	6394	9587	15881	29996
1250	202	214	227	239	252	1250	5016	7992	11984	19851	37496
1500	242	257	272	286	302	1500	6019	9590	14381	23821	44995
	Planting decade 30						Planting decade 30				
250	50	52	55	60	65	250	1576	2197	3104	4659	8391
500	100	105	110	121	131	500	3153	4394	6207	9319	16782
750	149	157	165	181	196	750	4729	6590	9311	13978	25172
1000	199	209	220	241	262	1000	6306	8787	12414	18637	33563
1250	249	261	275	302	327	1250	7882	10984	15518	23297	41954
1500	299	314	330	362	393	1500	9458	13181	18621	27956	50345
	Planting decade 31						Planting decade 31				
250	62	65	67	72	77	250	1899	2596	3540	5310	9503
500	124	129	135	145	155	500	3798	5193	7079	10619	19006
750	186	194	202	217	232	750	5697	7789	10619	15929	28509
1000	248	258	269	290	310	1000	7596	10385	14158	21238	38012
1250	311	323	337	362	387	1250	9495	12982	17698	26548	47516
1500	373	387	404	434	465	1500	11393	15578	21238	31857	57019
	Planting decade 32						Planting decade 32				
250	75	78	81	84	87	250	2250	2984	4040	5998	10501
500	151	157	162	168	174	500	4501	5967	8081	11997	21002
750	226	235	242	251	262	750	6751	8951	12121	17995	31503
1000	301	313	323	335	349	1000	9001	11934	16161	23993	42004
1250	377	392	404	419	436	1250	11252	14918	20202	29992	52506
1500	452	470	485	503	523	1500	13502	17901	24242	35990	63007
	Planting decade 33						Planting decade 33				
250	86	89	93	95	97	250	2519	3381	4521	6596	11499
500	172	179	186	189	193	500	5038	6762	9041	13192	22997
750	258	268	278	284	290	750	7558	10143	13562	19787	34496
1000	344	358	371	378	386	1000	10077	13524	18082	26383	45994
1250	430	447	464	473	483	1250	12596	16905	22603	32979	57493
1500	515	536	557	567	579	1500	15115	20285	27123	39575	68992
	Planting decade 34						Planting decade 34				
250	97	98	100	102	104	250	2776	3681	4897	7091	12202
500	194	196	200	203	208	500	5552	7361	9793	14181	24404
750	291	295	299	305	312	750	8327	11042	14690	21272	36607
1000	387	393	399	407	416	1000	11103	14722	19587	28362	48809
1250	484	491	499	509	521	1250	13879	18403	24484	35453	61011
1500	581	589	599	610	625	1500	16655	22083	29380	42543	73213

APPENDIX 7: SOIL WATER RETENTION

Soil water retention (cm^3/cm^3) at suctions 0-1500KPa

Suction (Kpa)	Field 1				Field 2			
	0-10cm	10-20cm	20-40cm	40-60cm	0-10cm	10-20cm	20-40cm	40-60cm
0	0.28	0.43	0.48	0.50	0.30	0.30	0.43	0.52
10	0.23	0.39	0.43	0.45	0.29	0.29	0.37	0.46
30	0.22	0.38	0.42	0.44	0.28	0.28	0.35	0.42
50	0.21	0.38	0.41	0.42	0.26	0.26	0.33	0.40
70	0.20	0.37	0.40	0.41	0.25	0.25	0.33	0.39
100	0.19	0.36	0.40	0.40	0.24	0.24	0.32	0.37
300	0.16	0.33	0.37	0.37	0.20	0.20	0.29	0.35
500	0.15	0.32	0.35	0.35	0.19	0.19	0.27	0.33
1000	0.14	0.30	0.32	0.33	0.18	0.18	0.25	0.31
1500	0.13	0.29	0.33	0.33	0.17	0.17	0.24	0.31
Wt oven dry sample, g	126.7	127.9	128.7	133.9	119.0	119.2	121.0	123.9
Bulk density (g/cm^3)	1.27	1.28	1.29	1.34	1.19	1.19	1.21	1.24

APPENDIX 8: WATER PAN HYDROLOGICAL PARAMETERS

Water pan 1						
Initial Volume m^3	Final Volume m^3	Inflow volume m^3	Direct rainfall m^3	Evaporated volume m^3	Seepage Volume m^3	Runoff volume m^3
1.7	14.6	12.9	0.1	0.04	0.03	12.7
0.2	24.9	24.7	1.2	0.03	0.01	23.5
9.9	19.3	9.4	0.2	0.08	0.03	9.1
12.4	15.5	3.2	0.2	0.10	0.01	2.8
13.7	32.2	18.4	0.4	0.11	0.04	17.9
0.6	0.4	0	0	0.06	0.11	0
1.2	1.1	0	0	0.06	0.04	0
1.7	1.4	0	0	0.08	0.17	0
1.3	1.1	0	0	0.07	0.13	0
3.1	2.9	0	0	0.10	0.15	0
3.5	3.3	0	0	0.10	0.11	0
4.0	3.8	0	0	0.11	0.14	0
4.5	4.2	0	0	0.11	0.16	0
4.7	4.3	0	0	0.12	0.30	0
4.3	3.8	0	0	0.11	0.43	0
4.1	3.7	0	0	0.11	0.28	0
8.3	7.7	0	0	0.15	0.46	0
18.7	18.2	0	0	0.15	0.35	0
15.0	14.4	0	0	0.28	0.37	0
18.8	18.2	0	0	0.21	0.39	0
15.4	14.8	0	0	0.29	0.32	0
14.0	13.6	0	0	0.20	0.18	0
13.0	12.6	0	0	0.19	0.18	0
12.9	12.5	0	0	0.18	0.17	0
12.7	12.2	0	0	0.18	0.30	0
12.4	11.9	0	0	0.18	0.32	0
12.1	11.5	0	0	0.24	0.36	0
11.7	11.4	0	0	0.17	0.13	0
10.1	9.8	0	0	0.17	0.13	0

APPENDIX 8 CONTD

Water pan 2						
Initial Volume m^3	Final Volume m^3	Inflow volume m^3	Direct rainfall m^3	Evaporated Volume m^3	Seepage Volume m^3	Runoff volume m^3
11.3	16.9	5.7	0.08	0.10	0.03	5.4
2.1	16.7	14.6	0.22	0.04	0.01	14.3
14.8	32.2	17.2	0.37	0.14	0.03	16.9
0.2	22.8	22.7	0.96	0.04	0.00	21.7
23.2	28.5	4.8	0.14	0.25	0.04	4.9
0.6	0.5	0	0	0.07	0.02	0
0.5	0.4	0	0	0.06	0.01	0
0.4	0.3	0	0	0.06	0.02	0
20.5	20.0	0	0	0.31	0.16	0
13.0	12.7	0	0	0.26	0.05	0
7.1	6.6	0	0	0.20	0.30	0
10.0	9.7	0	0	0.23	0.11	0
11.1	10.6	0	0	0.24	0.25	0
6.0	5.7	0	0	0.17	0.13	0
3.6	3.3	0	0	0.15	0.14	0
2.2	2.0	0	0	0.12	0.05	0
1.7	1.5	0	0	0.10	0.08	0
0.9	0.8	0	0	0.08	0.01	0
0.7	0.6	0	0	0.07	0.01	0
0.5	0.4	0	0	0.07	0.01	0

APPENDIX 9: SEEPAGE SEALANTS

Soil type	Material used	Seepage as a % of control
Sandy loam to sandy clay loam	Clay + Sodium chloride + Sodium carbonate (20:5:1)	19
	Soil : cement (5:1)	30
	Soil : cement (10:1)	42
Sandy loam	Plastic lining overlaid by brick work	9
	Linen mortar (1:6) with Asphalt lining	11
	Cement : Sand (1:6)	19
Sandy loam to loamy sand	Plastic sheet overlaid by cement +plastering	0
	Brick lining overlaid by cement +plastering	0
	Asphalt	13
Sandy loam	Bottom polythene	5
	sides polythene	31
Medium black soil	Soil + cow dung + straw (7:2:1)	12
	Soil compacted to high bulk density	43
Sandy loam	Clay	56
	Core tar	44
Sandy loam to clay loam	Black polythene	4
	Brick lining	4
	Soil: cement (10:1)	24

Source : Vijayalakshmi *et al* (1989)

APPENDIX 10: FREQUENCY FACTORS

Cumulative probability of the standard normal distribution										
K_T	**0.00**	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**
0	0.500	0.496	0.492	0.488	0.484	0.480	0.476	0.472	0.468	0.464
0.1	0.460	0.456	0.452	0.448	0.444	0.440	0.436	0.433	0.429	0.425
0.2	0.421	0.417	0.413	0.409	0.405	0.401	0.397	0.394	0.390	0.386
0.3	0.382	0.378	0.375	0.371	0.367	0.363	0.359	0.356	0.352	0.348
0.4	0.345	0.341	0.337	0.334	0.330	0.326	0.323	0.319	0.316	0.312
0.5	0.381	0.305	0.302	0.298	0.295	0.291	0.288	0.284	0.281	0.278
0.6	0.274	0.271	0.268	0.264	0.261	0.258	0.255	0.251	0.248	0.245
0.7	0.024	0.239	0.236	0.233	0.230	0.227	0.224	0.221	0.218	0.215
0.8	0.212	0.209	0.206	0.203	0.201	0.198	0.195	0.192	0.189	0.187
0.9	0.184	0.181	0.179	0.176	0.174	0.171	0.169	0.166	0.164	0.161
1.0	0.159	0.156	0.154	0.152	0.149	0.147	0.145	0.142	0.140	0.138
1.1	0.136	0.134	0.131	0.129	0.127	0.125	0.123	0.121	0.119	0.117
1.2	0.115	0.113	0.111	0.109	0.108	0.106	0.104	0.102	0.100	0.099
1.3	0.097	0.095	0.093	0.092	0.090	0.089	0.087	0.085	0.084	0.082
1.4	0.081	0.079	0.078	0.076	0.075	0.074	0.072	0.071	0.069	0.068
1.5	0.067	0.066	0.064	0.063	0.062	0.061	0.059	0.058	0.057	0.056
1.6	0.055	0.054	0.053	0.052	0.051	0.050	0.049	0.048	0.047	0.046
1.7	0.045	0.044	0.043	0.042	0.041	0.040	0.039	0.038	0.038	0.037
1.8	0.036	0.035	0.034	0.034	0.033	0.032	0.031	0.031	0.030	0.029
1.9	0.029	0.028	0.027	0.027	0.026	0.026	0.025	0.024	0.024	0.023
2.0	0.023	0.022	0.022	0.021	0.021	0.020	0.020	0.019	0.019	0.018
2.1	0.018	0.017	0.017	0.017	0.016	0.016	0.015	0.015	0.015	0.014
2.2	0.014	0.014	0.013	0.013	0.013	0.012	0.012	0.012	0.011	0.011
2.3	0.011	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.009	0.008
2.4	0.008	0.008	0.008	0.008	0.007	0.007	0.007	0.007	0.007	0.006
2.5	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.005	0.005
2.6	0.005	0.005	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004
2.7	0.004	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
2.8	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
2.9	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.001
3.0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
3.1	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
3.2	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
3.3	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3.4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Source: Haan C.T (1977)

APPENDIX 11: RUNOFF COEFFICIENT

Topography and Vegetation	**Soil Texture**		
	Open sandy clay	**Clay and Silt loam**	**Tight Clay**
Woodland			
Flat 0-5% slope	0.10	0.30	0.40
Rolling 5-10% slope	0.25	0.35	0.5
Hilly 10-30% slope	0.30	0.50	0.60
Pasture			
Flat	0.10	0.30	0.40
Rolling	0.16	0.36	0.55
Hilly	0.22	0.42	0.60
Cultivated			
Flat	0.30	0.50	0.60
Rolling	0.42	0.60	0.70
Hilly	0.52	0.72	0.82
Urban areas	30% of the area impervious	50% of the area impervious	70% of the area impervious
Flat	0.4	0.55	0.65
Rolling	0.5	0.65	0.80

Source : Hudson (1987)

APPENDIX 12: DEPTH -VOLUME AND EXPOSED SURFACE AREA

Depth (cm)	Water Pan 1		Water pan 2	
	Exposed Surface Area, m^2	Volume (m^3).	Exposed surface area , m^2	Volume (m^3)
0	3.1	0	3.8	0
13	5.8	0.6	7.0	0.7
18	7.1	0.9	8.4	1.1
23	8.5	1.3	10.1	1.6
28	10.0	1.7	11.8	2.2
32	11.3	2.2	13.3	2.7
35	12.3	2.5	14.5	3.1
36	12.7	2.7	14.9	3.3
39	13.7	3.0	16.2	3.8
40	14.1	3.2	16.6	3.9
44	15.6	3.8	18.4	4.6
47	16.8	4.3	19.8	5.2
48	17.3	4.4	20.3	5.4
52	18.9	5.2	22.2	6.3
56	20.7	6.0	24.3	7.2
60	22.6	6.8	26.4	8.3
64	24.5	7.8	28.6	9.4
68	26.5	8.8	31.0	10.6
72	28.6	9.9	33.4	11.9
77	31.3	11.4	36.5	13.7
82	34.1	13.0	39.8	15.6
83	34.7	13.4	40.5	16.0
88	37.7	15.2	43.9	18.1
92	40.2	16.7	46.8	20.0
96	42.7	18.4	49.7	21.9
102	46.7	21.1	54.3	25.0
106	49.4	23.0	57.5	27.3
111	53.0	25.5	61.6	30.3
114	55.2	27.2	64.2	32.2
118	58.2	29.4	67.6	34.8
122	61.2	31.8	71.1	37.6
126	63.2	32.8	74.8	40.6

APPENDIX 13: SATURATED HYDRAULIC CONDUCTIVITY

FIELD 1						FIELD 2				
Depth cm	r cm	h_0 cm	h_t cm	t min	K_h cm/hr	r cm	h_0 cm	h_t cm	t min	K_h cm/hr
0-10	4	8	3.0	249	0.940	4	8	2.0	253	0.947
	4	8	3.0	268	0.873	4	8	2.0	319	0.753
	4	8	3.0	300	0.780	4	8	2.0	267	0.898
Average					0.865					0.866
10-20	4	10	3	320	0.800	4	10	2	310	0.844
	4	10	3	275	0.929	4	10	2	332	0.788
	4	10	3	294	0.870	4	10	2	366	0.715
Average					0.866				0	0.783
20-40	4	20	10	374	0.818	4	20	10	360	0.849
	4	20	10	386	0.793	4	20	10	391	0.782
	4	20	10	335	0.912	4	20	10	363	0.842
Average					0.841				0	0.825
40-60	4	20	15	320	0.927	4	20	15	334	0.888
	4	20	15	330	0.899	4	20	15	382	0.777
	4	20	15	391	0.759	4	20	15	367	0.808
Average					0.862					0.824