RUNOFF HARVESTING POTENTIAL FOR CROP PRODUCTION IN KITUI, KENYA

By

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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DEDICATION

This thesis is dedicated to my late father, an ardent believer in the value of an education.

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Finally, I am greatly indebted to my family who have great support and understanding.

LIST OF SYMBOLS

Symbol	Description	Unit
a	Kostiakov empirical constant	
A	catchment area	m^2
A_c	cups added to evaporation pan	
b_1	empirical coefficient used in probability	
b	Kostiakov empirical exponent	
B	cropped (basin) area	m^2
β	amount of water above FC	mm
C	runoff coefficient	
CN	curve number	mm^{-1}
D	effective root zone depth	m
dp	daily deep drainage	mmd^{-1}
D_p	Deep drainage below root zone	mm
δ	moisture deficit	mm
e_a	sat. vapour pressure at air temp.	mb
e_d	vap. pressure of air at dew point temp.	mb
E_{at}	energy for evapotranspiration	mmd^{-1}
et	daily evapotranspiration	mmd^{-1}
ET_A	actual daily evapotranspiration	mmd_{-1}
ET_p	monthly potential evapotranspiration	mm
ET_M	maximum daily evapotranspiration	mmd_{-1}
F	empirical parameter	
FC	moisture at field capacity	mm
G	empirical parameter	
h	elevation above sea level	m
h_0	initial water level in auger hole	cm
h_i	instantaneous water level in auger hole	cm
HT	available heat for evapotranspiration	mmd^{-1}
i	infiltration rate	mmh^{-1}
i_r	mean rainfall intensity	mmh^{-1}
K	hydraulic conductivity	md^{-1}
K_c	crop coefficient	
K_p	pan coefficient	
K_y	yield conversion factor	
L	longest flow in a watershed	m
m	rank of monthly rainfall from highest	
M_{ws}	mass of wet soil	g

M_{ds}	mass of dry soil	g
j	number of monthly rainfall data points	
n	actual measured annual sunshine hours	
n	number of soil layers	
N	possible daily sunshine hours	
N_c	soil count	
N_0	shield count	
p	allowable soil mosture depletion percent	
PE	potential evapotranspiration	mmd^{-1}
q	peak runoff flow rate	m^3s^{-1}
Q_i	daily runoff depth	mm
r	radius of auger hole	cm
r	albedo	
R_a	terrestrial radiation	mmd^{-1}
R	rainfall	mm
RI	runoff into the cropped area	mm
RO	runoff topping over embankments	mm
R_0	incoming short wave radiation	mmd^{-1}
R_l	outgoing long wave radiation	mmd_{-1}
R_d	design rainfall	mm
ρ_s	soil bulk density	gcm^{-3}
ρ_w	density of water	gcm^{-3}
S_L	watershed gradient percentage	m/m
S	catchment storage parameter	mm
S_c	cups subtracted from evaporation pan	
SW	root depth soil moisture status	mm
t	soil layer thickness	mm
T	time to drain soil profile	h
T_a	mean monthly temperature	°C
T_c	time of concentration	min
T_K	mean air temperature	°K
θ_m	water content on weight basis	%
θ_v	volumetric water content	%
u_t	daily wind run	$mi.d^{-1}$
PWP	soil moisture at permanent wilting point	mm
Ya	actual yield	kg
Ym	maximum yield	kg

I_c	cumulative infiltration	mm

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ABSTRACT

A 24 year rainfall data study was done for Mutomo, southern Kitui. Seasonal rainfall was found inadequate in 71% and 57% of the dry "long" and "short" rains, respectively. Monthly rainfall was highly variable between years, with coefficient of variation often above 100%; there were also many small storms compared to big ones as evidenced by large data skewness. The "long" rains last shorter than the "short" rains, and by virtue of seasonal total, the former was classified as unfavourable for a crop like maize. On average, 58% and 67% of rainfall in April and November were found to be potentially runoff-producing. These results justified water harvesting for supplementing rainfall to improve maize production in the area.

A water harvesting experiment for maize production was conducted at the Mutomo site in the "short" rains of 1990 on a field of 5% slope. The experimental area consisted of twelve plots in three blocks of four plots each. Treatments were 0 (control), 13.6, 19.6 and 27.2 m^2 of sloping catchment areas above each 16 m^2 level cropped area. The soil was deep with no apparent restriction within 150 cm. The soil texture was sandy clay for the top 60 cm and clay below this depth. Bulk densities varied from 1490 for the top 15 cm to 1540 kgm^{-3} from 60-105 cm. Infiltration tests conducted with double ring infiltrometer gave a range of final infiltration rates of 14.2 to 75.5 mmh^{-1}. The mean organic matter content was 3.68%. The soil was high in base saturation and low in macro nutrients especially nitrogen and phosphorus, but showed no hazards of salinity or sodicity.

Soil sampling for moisture determination was done to 105 cm depth every ten days. A water balance was done for each treatment for 82 days of the rainfall season. Runoff simulation was done using a portable rainfall simulator. Computer generated daily runoff values were determined for each rainfall event. The rainfall was 606.3 mm and pan evaporation was 341.9 mm. High intensity rainfall resulted in a high mean runoff of 61%. Computer generated runoff ranged from 8.5% to 84% early in the dry and in the wettest periods of the season, respectively, showing high sensitivity to antecedent moisture. The total runoff was estimated at 287.0, 259.7, 185.9 and 0 mm and the percolation below root zone at 368.5, 341.9, 268.6 and 84.4 mm for the 27.2, 19.6, 13.6 and 0 m2 catchments, respectively. Soil moisture increased to saturation in the wet period, and reduced to 183 mm at the end of the season. Yields of Katumani maize grown at the experimental site were not significantly different at P=0.05, a fact attributed to the above average rainfall in the season.

1 INTRODUCTION

1.1 General Background

The arid and semi-arid lands (ASAL) in Kenya cover about 80% of the total land area, and holds over 50% of the Nation's livestock and 25% of it's human population. The common characteristics of ASAL areas are erratic rainfall with great annual variability about the mean; annual potential evapotranspiration exceeding the rainfall; high amounts of runoff due to low infiltration into the crusting soils; and recurrent soil moisture deficits limiting crop production (Evenari et al., 1971).

Soil moisture is often inadequate for crop production. This situation can be mitigated through irrigation development or water harvesting. Water harvesting may be practised where high amounts of runoff can be generated from crusting soils e.g. Luvisols and Acrisols which are predominant in ASAL. It is important to examine methods of conserving enough soil moisture to sustain crop growth during critical crop growth periods. Runoff water harvesting increases soil moisture as water ponded in the field is given more time to infiltrate into the soil. Bruins et al. (1986) considered water harvesting as the most promising agricultural system for ASAL, especially in Africa. Water harvesting techniques have been used on a small scale to improve water supply for crop production in Turkana, Baringo and Kitui areas of Kenya. These techniques were found to be effective in impounding runoff and increasing soil moisture; in some cases, remarkable crop yields increases have been observed (Pacey and Cullis, 1986).

1.2 Justification of Study

The study area of Kitui District receives bimodal rainfall. The "long" rains come in March to May and the "short" rains in October to December. In both seasons there are wide variations in the distribution of rainfall. The rainfall is often of very high intensity and short duration hence generating very high amounts of runoff. Up to 64% of rainfall may be lost as runoff from degraded surfaces (Thomas et al., 1981). The high runoff rates is attributed to the low infiltrability of the soils due to their surface sealing and crusting properties.

The generation of high amounts of runoff in marginal rainfall areas often results in soil moisture deficits. These deficits significantly influence crop performance and yields, especially if they occur during critical crop growth periods. Thus to sustain crop growth and subsequently improve crop performance and yield, it is imperative that runoff water be harnessed and conserved *in situ*. Due to the significant loss of the limited rainfall as runoff in ASAL, there is need to evaluate potential runoff water harvesting techniques that would provide adequate soil moisture to sustain crop growth during the dry spell.

The *in situ* conservation of runoff requires some comprehensive understanding of soil moisture dynamics as influenced by soil properties and rainfall characteristics. The amount of soil moisture available for plant growth would depend on the amount of runoff generated, and the amount subsequently conserved in the soil. The rate at which the impounded water infiltrates into the soil or is lost through evaporation or deep percolation significantly influence the soil water balance. This study examines the effect of microcatchment size on the water balance of a Luvisol in Kitui, Kenya.

1.3 Objectives and Scope of Study

1.3.1 Objectives of Study

Overall Objective

To evaluate the potential for the application of *micro catchment water harvesting* techniques for crop production in marginal rainfall areas of Kitui.

<u>Specific Objectives</u>

1) To review existing water harvesting techniques in Kitui.
2) To study the rainfall pattern and distribution for Mutomo Agriculture Station.
3) To monitor rainfall and pan evaporation, soil properties and soil moisture status at the experimental site.
4) To simulate runoff rates from different micro-catchment areas.
5) To determine soil water balances for the water harvesting collection areas at the experimental site.
6) To develop a computer programme for simulating the soil water balance and the expected crop yield based on prevailing soil moisture status.

1.3.2 Scope of Study

This study was aimed at evaluating existing runoff water harvesting potential for crop production in Kitui. This involved an assessment of the applicability of micro catchment water harvesting techniques (section 2.3.3.2) in agro-ecological zone LM4 (Marginal Cotton Zone).

At the Mutomo experimental site, Southern Kitui, established water harvesting plots were used to monitor changes in soil moisture content under different catchment sizes. The catchment areas were exposed to both natural and simulated rainfall. The runoff generated by natural rainfall was conserved in the runoff collection plots. A soil moisture balance was determined for the experimental site by taking measurements of the various water balance components ie evapotranspiration, rainfall, soil moisture, runoff and percolation, out of which it was possible to determine stored soil moisture. Katumani maize was planted to monitor the effects of extra moisture on crop performance and yield. This study culminated in the development of a computer programme for simulating the soil moisture balance and the expected maize yield based on the prevailing soil moisture status.

1.4 The Study Area

1.4.1 Physical Environment of Kitui

Kitui District lies between latitude 0°3'S and 2°23'S, and longitude 37°6'E to 39°0'E and covers an area of 29,388 km^2. The major rivers forming the drainage pattern are Tana, Athi, Tiva and Thua. Apart from perennial Tana and Athi, all other rivers and their tributaries are seasonal. The District is dissected by a range of hills running in a North-South direction. To the west is the Yatta Plateau, and to the east and north are extensive plains. The altitude ranges from 550 to 1620 metres above sea level. The soils of Kitui

District have formed from the Basement System rocks of Precambrian age. They are made up of a variety of gneisses and schists (MOA, 1978). The gneisses are generally of two types, the granitoid and the banded. Soils derived from the banded gneisses are highly vulnerable to erosion eg sandy loams. The dominant soil types are Luvisols and Vertisols. Luvisols are of a sandy clay loam texture and are low in organic matter and water holding capacity. The average annual rainfall ranges from 1050 around Kitui Town, to 350mm in the eastern and southern regions (Jaetzold and Schmidt, 1983). More rain falls in the central highlands and around the hills (see Fig. 1.2).

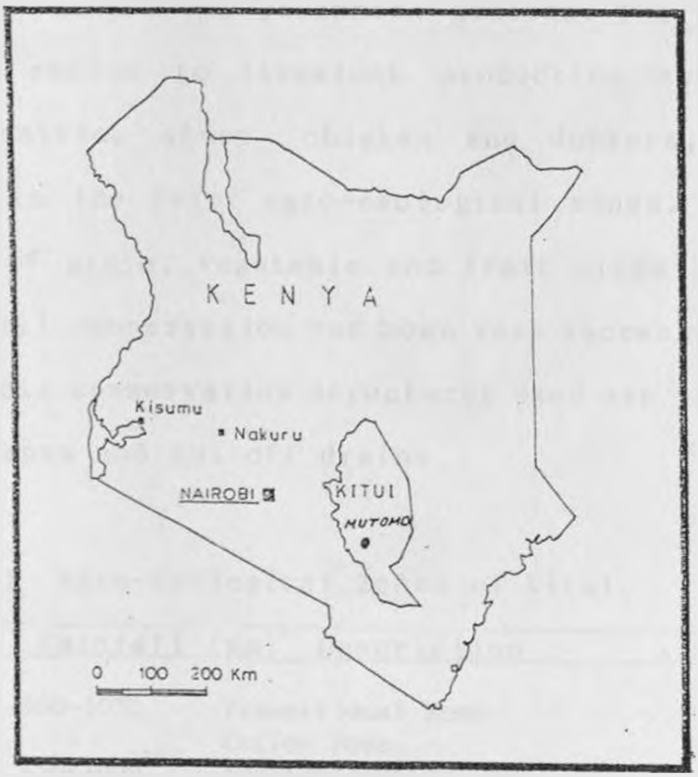


Fig. 1.1 Location of Kitui District and the Mutomo Experimental Site

Mean annual temperatures and evaporation range from 18.6°C and 1800 mm per year at Kitui town, to 25.3°C and 2200 mm in the drier fringes, respectively. The District has seven *agro-ecological zones* (Jaetzold and Schmidt, 1983) as given in Table 1. Ranching zone IL6 is not suitable for any rainfed agriculture except under runoff farming techniques. The vegetation of Kitui consists of wooded bushland and wooded grassland (Survey of Kenya, 1970). The main tree species are *Adansonia digitata* (baobab), *Acacia albida*, *Prosopis juliflora* and thorn bushes. The commom grasses include *Panicum spp*., *Eragrostis superba*, *Cenchrus ciliaris* and other annual and perennial grasses. The district is well suited to livestock production especially goats, cattle, sheep, chicken and donkeys, mostly located in the drier agro-ecological zones. A large variety of grain, vegetable and fruit crops are also grown. Soil conservation has been very successful. The common soil conservation structures used are the Fanya Juu terraces and cut-off drains.

Table 1.1 Agro-Ecological Zones of Kitui.

ZONE	Rainfall (mm)	Description	Area (Km^2)
UM3-4	900-1050	Transitional Zone-Coffee Zone	69
UM4	850-1000	Sunflower-Maize Zone	275
LM3		Cotton Zone	25
LM4	720-1000	Marginal Cotton Zone	2533
LM5	550-790	Livestock-Millet Zone	9380
IL5	450-700	Livestock-Millet Zone	786
IL6	350-550	Ranching Zone	6996

Source: Jaetzold and Schmidt (1983)

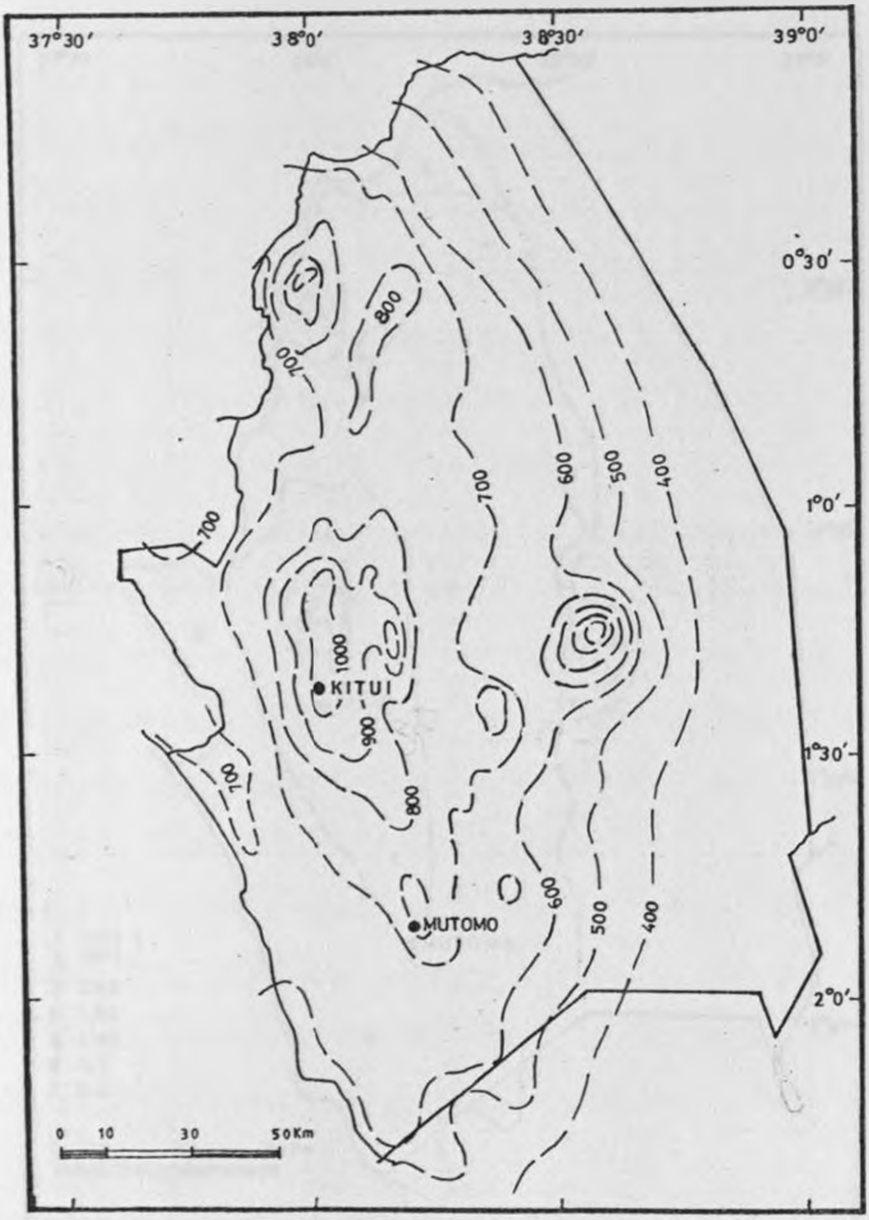


Fig. 1.2 Mean annual rainfall of Kitui. *(after Jaetzold and Schmidt, 1983)*

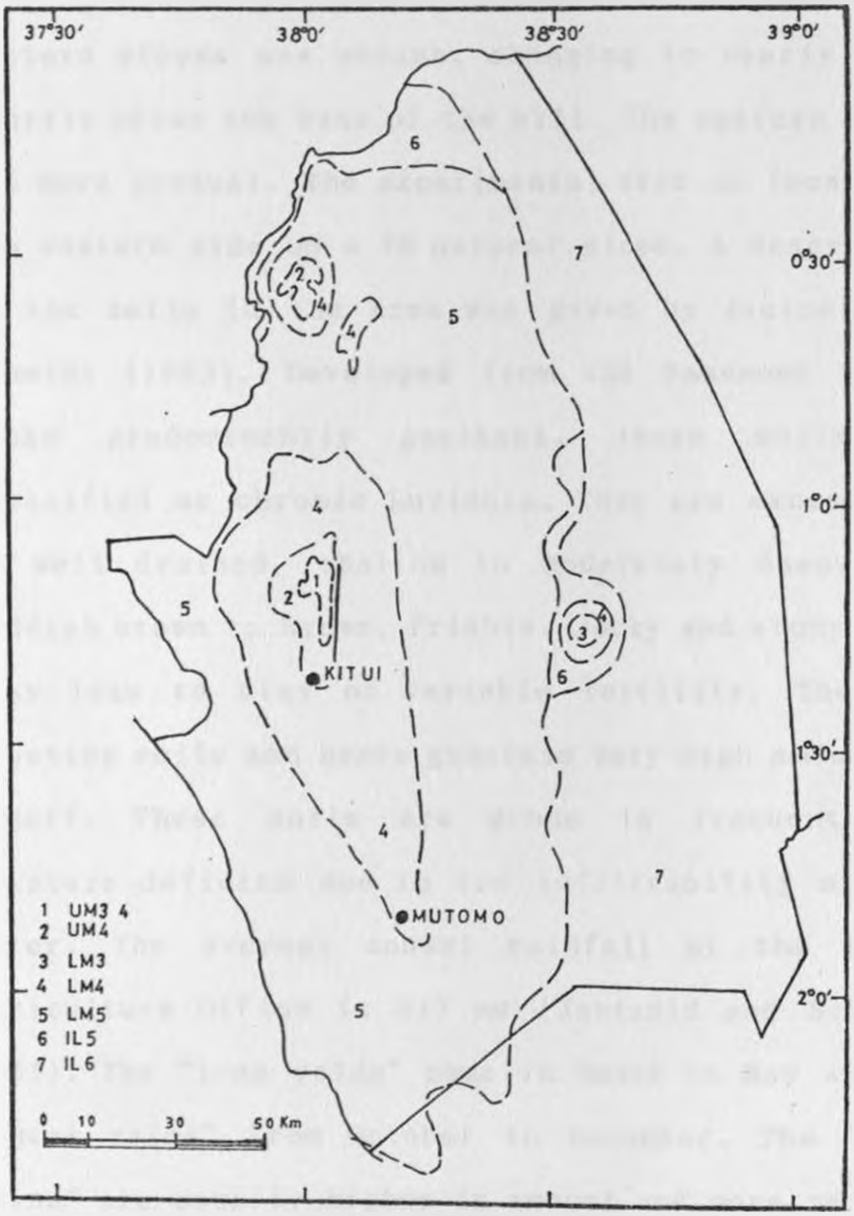


Fig. 1.3 Agroecological zones of Kitui. *(after Jaetzold and Schmidt, 1983)*

1.4.2 Mutomo Experimental Site

Mutomo is located at longitude 38°12'E, latitude 1°50'S and the altitude is 900m. To the east is Mutomo hill and to the west a plain running down to Tiva river. The hill is covered by gneisses and bushes. The western slopes are abrupt, changing to nearly level shortly after the base of the hill. The eastern slopes are more gradual. The experimental site is located on the eastern side on a 7% natural slope. A description of the soils in the area was given by Jaetzold and Schmidt (1983). Developed from the Basement System rocks predominantly gneisses, these soils are classified as chromic Luvisols. They are excessively to well drained, shallow to moderately deep, dark reddish brown to brown, friable, rocky and stony sandy clay loam to clay of variable fertility. They are crusting soils and hence generate very high amounts of runoff. These soils are prone to frequent soil moisture deficits due to low infiltrability of rain water. The average annual rainfall at the Mutomo Agriculture Office is 817 mm (Jaetzold and Schmidt, 1983). The "long rains" come in March to May and the "short rains" from October to December. The "short rains" are usually higher in amount and more reliable than the "long rains". The vegetation at the site consists mainly of wooded bushland. The dominant grass is *Eragrostis superba*. Baobab and various Acacia species are also found. The area falls under agro-ecological zone LM4 which is a Marginal Cotton Zone. No irrigation is practised in the area; most of the subsistence farming activities are dependent on the two rain seasons.

2 REVIEW OF LITERATURE

2.1 The Origin of Water Harvesting

Water harvesting is an old technology. Archeological evidence shows that the technology was used in crop production in the dry areas of North Africa, Asia and the Americas for thousands of years. The technology is most applicable in semi-arid areas where rainfall is low and poorly distributed (Reij et al., 1988). Though also affected by management practices, poor yield of crops in ASAL is largely due to low rainfall. However, poor rainfall distribution within the season may have the greater influence depending on time distribution of the resulting water deficits. Thus Water harvesting aims at a) increasing the amount of moisture in the soil, and b) improving the moisture distribution in the season. Reliability of crop and fodder production may be improved by enhancing water availability.

A comprehensive history on water harvesting in ASAL has been given by Bruins et al., (1986). In the Negev Desert, water harvesting systems have been in use for twelve centuries, peaking around AD 100 to 700 when 4000 ha were cultivated using this technology. In Jordan, the technology has been in use for some 9000 years. In Yemen, the Marib diversion dam was used around 750 BC to raise the water level for irrigating adjacent fields. The technology has also been used in

Thar Desert (India) and in the USSR. In Africa, most of the evidence is in North Africa where complex systems were used in Egypt, Libya and Algeria; in Tunisia, 10 million olive trees are still sustained by harvested water in the Southern and Central regions.

2.2 Water Harvesting in Kenya

2.2.1 General Background

Inspite of no written historical evidence, water harvesting in Kenya was known and practised by people living in the ASAL areas. The traditional systems used by the Turkana to grow sorghum were well adapted water harvesting systems (Pacey and Cullis, 1986; Heijenga, 1985). More recently, work has been done elsewhere including Baringo and Kitui (Reij et al., 1988).

The first attempts at a systematic water harvesting in Kenya was done in Turkana by Ministry of Agriculture, the Salvation Army and Finkel (Heijenga, 1985; Pacey and Cullis, 1986; Reij et al., 1988). The work involved diversion of Turkwell flood water in 1951 (Mbote, 1989) but did not fare very well. There has been a revival of the technology, particularly from the late 1970s. The most commonly used harvesting structures are micro-catchments, semi-circular hoops and trapezoidal bunds. Tree seedlings planted using water harvesting have had a 95% survival rate, and yields of sorghum improved significantly.

Elsewhere, water harvesting at Katiorin (1982 and 1985) and Marigat (1983) in Baringo showed promise (Imbira, 1989). Micro and macro-catchments were used for crops and for reseeding pasture land. Using a 2:1 and 1:1 ratios between the catchment and the cropped area, sorghum yield was 6 and 54 times that of the control plot at Katiorin and Marigat in 1982 and 1983, respectively . At Katiorin in 1985, a micro-catchment had nearly double the 867 kg/ha yield from a macro-catchment, while the control had zero.

At Isiolo CPK plots, semi-circular bunds yielded 195 and 813 kg/ha of Katumani maize and Serena sorghum. Conventional farming produced 6.3 and 25 kg/ha, respectively (Burges, 1988).

2.2.2 Water Harvesting in Kitui

In Kitui, water harvesting has mainly been for domestic and livestock supply. Rock catchments are a trade mark in the district. Harvesting from roofs is also common, and both ferrocement and ground tanks have gained wide acceptance as storage structures.

In crop production, the simplest system is the growing of crops in the sandy river beds in the dry seasons.

Some farmers also divert runoff from roads and rivers into cultivated areas, e.g. Mr. Ngove Wali who diverts flood water from upper Nzeeu for irrigating vegetables in Kyangwithya location of central Kitui. Fanya Juu terraces (local name for a terrace in which the soil dug from a ditch is thrown uphill) are widely used for moisture conservation. They increase the opportunity time for infiltration before runoff leaves the field. Newly-made terrace embankments concentrated water above the structure to improve moisture supply and crop yield for the lower third of the terrace. Terraces are therefore effective in runoff harvesting and can be considered as macro-catchment water harvesting systems.

The first serious attempt to evaluate water harvesting techniques was by the ASAL Programme in 1984-1986. Plots were set up at Kyuso, UKAI, Waita and Zombe. The treatments consisted of an external catchment, contour ridges, Fanya Juu and a control. Three seasons were used for testing. The results were mixed due to above average rains. The best results were for 1984 short rains when at UKAI yields of maize were 1875, 1780 and 1610 kg/ha for the external catchment, contour ridge and the control. From three seasons of results, there was no clear advantage of using water harvesting (Critchley, 1989) and perhaps for this reason, there has been no further demonstrations of the methods in the district. Proven and existing water conservation structures (terraces) remained strongly favoured instead. Some sceptism also exists because land is viewed as being wasted by the catchment areas.

2.3 Water Harvesting Technologies

According to Reij et al. (1988), the general characteristics of all water harvesting systems are: a) the methods are common in ASAL and water storage is needed to overcome intermittent supplies from rainfall; b) they are based on utilization of surface runoff requiring runoff-producing and a runoff-receiving area; c) most systems use water as near as possible to where rain falls, and d) they are relatively small scale in terms of the catchment size, storage volume and the capital investment.

Rainfall is the main source of water in dryland farming. In ASAL areas, rainfall varies considerably in time. Crops are adversely affected by water stress depending on the crop adaptability to the environment. The aim of a water harvesting system is to supplement rain water with runoff water and alleviate possible soil moisture deficits in critical crop growth stages.

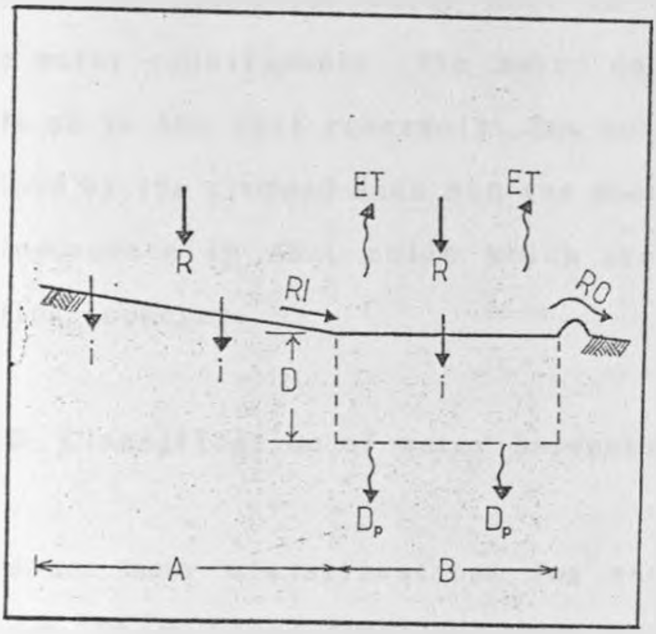
Experiments have shown that forage and grain crops yields could be improved dramatically by addition of water. The yield of rice grown in conservation bench terraces increased by 80% in India (Bhushan, 1979). In Kenya, yield of sorghum grown under contour ridges and semi-circular hoops increased by 231% and 341% respectively (Pacey and Cullis, 1986). The yield of wheat grown under water harvesting in the Negev increased by 333% (Heijenga, 1985). These increases were attributed to the extra runoff water supplied.

2.3.1 Runoff Water Harvesting Terminology

There are many synonyms of runoff water harvesting such as rain water harvesting, runoff harvesting, rain water collection, runoff farming, runoff agriculture, water harvesting for crop production and runoff agriculture (Reij et al., 1988). Water harvesting is an umbrella term describing methods of collecting and concentrating various forms of runoff from various sources and for various purposes. Runoff water harvesting was defined as the deliberate collection of rainwater from a surface (catchment) and its storage to provide a supply of water (UNEP, 1983). It has also been defined as the collection of runoff and its use for the irrigation of crops, pastures, trees, and for domestic and livestock consumption (Finkel and Finkel, 1986(a)). A more balanced hydro-agronomic term is ***rain water harvesting for agriculture*** which expresses both the source and use of moisture (Bruins et al., 1986).

2.3.2 Principles of Water Harvesting Systems

A water harvesting system is used to improve the soil moisture status for crop production. It consists of two subsystems, a *cropped area* and a *catchment area* (fig 2.1).



KEY

A, B	Catchment and cropped areas, respectively
R	Rainfall
ET	Evapotranspiration
RI	Runoff gain
Ro	Runoff loss
D	Crop root zone
Dp	Deep percolation
I	Infiltration

Fig. 2.1 Water Harvesting system and its components.

High runoff generation is desired in the catchment, while minimal runoff and more infiltration is desired in the cropped area. Surface sealing and crusting soils are preferred for the catchment area. Generally the catchment area is normally above the cropped area.

Because of poor distribution of rainfall within the season, the harvested water must be stored to meet crop water requirements. The water can be stored in ponds or in the soil reservoir. The soil reservoir is defined by the cropped area and the root zone, and may be inadequate in ASAL soils which are of low water holding capacity.

2.3.3 Classification of water harvesting systems

There are many classifications for water harvesting systems. These classifications have been based on a) source of water, b) size of catchment, c) the end use of water and d) the storage.

Matlock and Dutt (1986) as quoted by Reij et al. (1988) classified water harvesting systems into three categories of water spreading from ephemeral streams; water diversion from ephemeral streams; and microcatchment water harvesting with no defined stream channel.

Pacey and Cullis (1986) had two classes besed on catchment size and storage. They termed a catchment small if 50 to 150m long, and large if the trajectory is longer. On storage, they considered whether it was a tank, small dam or soil reservoir storage.

Bruins et al. (1986) based their classification on geomorphology. The five classes in order of their geomorphic scale are microcatchment system having a trajectory of 100m or less; terraced *wadi*; hillside conduit system; *Liman* system; and Diversion system.

Boers and Ben-Asher (1982; 1986) classified systems according to the trajectory alone. They had two classes: Runoff Farming Water Harvesting (RFWH) and Micro catchment Water Harvesting (MCWH). Thus the classification by Boers and Ben-Asher lumps all systems into two classes.

2.3.3.1 Runoff Farming Water Harvesting

This is the method of collecting runoff water from a catchment using channels, dams and diversions and storing the water in a surface reservoir or the root zone of the soil. In this classification are so-called macro catchment systems. Typical RFWH systems include *terraced wadi*, water spreading and diversion of spate flow. The catchment to cropped area ratio (CCAR) is in the range of 17 to 30. The system has two major disadvantages: high risk of failure as heavy storms would result in large runoff volume; and high initial investment costs to build strong soil bunds.

2.3.3.2 Micro-Catchment Water Harvesting

According to Boers and Ben-Asher (1982; 1986), runoff in a micro-catchment is collected over a distance of less than 100m and stored in the root zone of the crop to cover the water requirements of the crop. The catchment areas range from $0.5m^2$ to $1000m^2$. They are suited to areas with rainfall not less than 250 mm/year, and on soils of low in infiltration and high runoff. They are used for trees, shrubs and row crops. The CCAR depends on the mean rainfall and varies from 1 to 6 in experiments. The length to width ratio (LWR) is dependent on rainfall characteristics, topography and water spreading properties of the soil. Large LWR are avoided due to large earthworks and dangers of erosion. As the catchment area decreases, the opportunity time for infiltration of runoff in the catchment area reduces. Consequently, the specific yield of runoff is high for a micro-catchment compared to a macro-catchment. Methods in this category include semi-circular hoops, contour catchments, desert strip farming and contour bench farming among others.

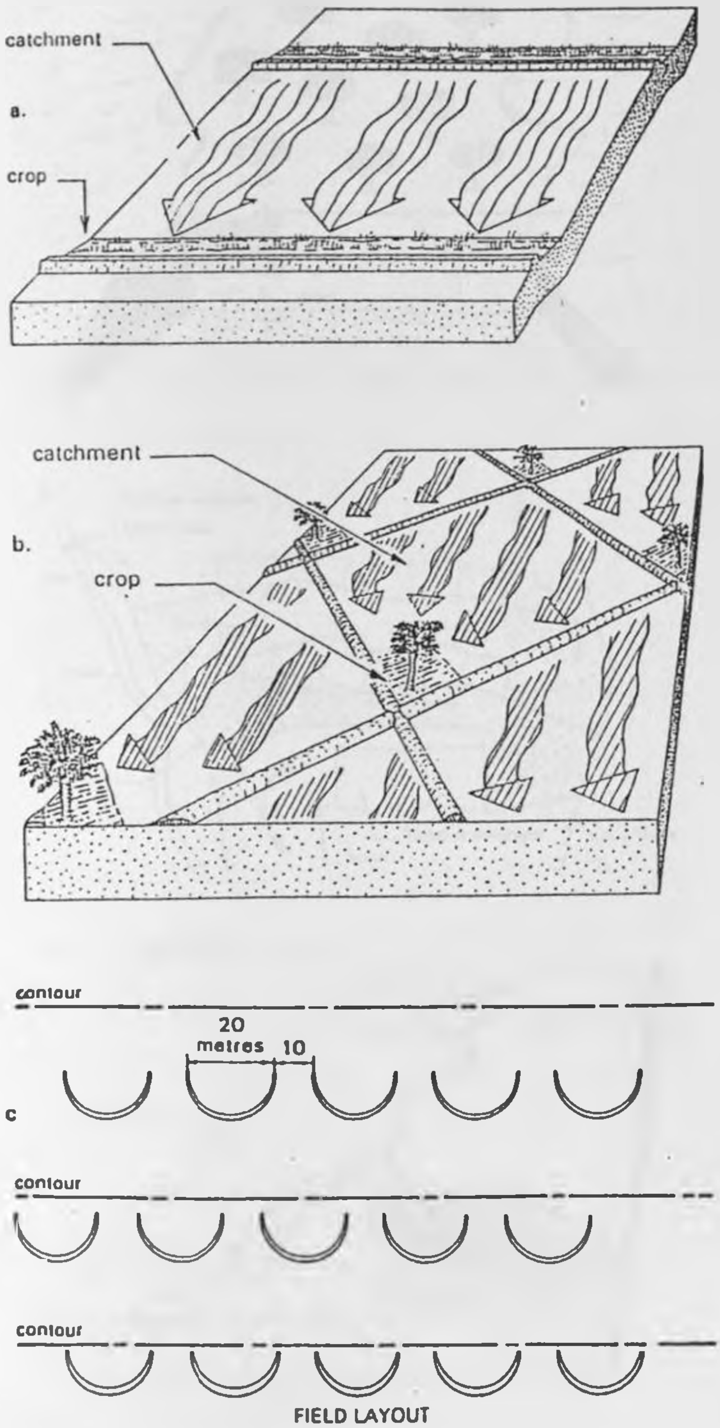


Fig. 2.2 Examples of Micro Catchment Systems. a) contour strips, b) micro- catchments, c) semi-circular hoops (*After Pacey and Cullis, 1986*)

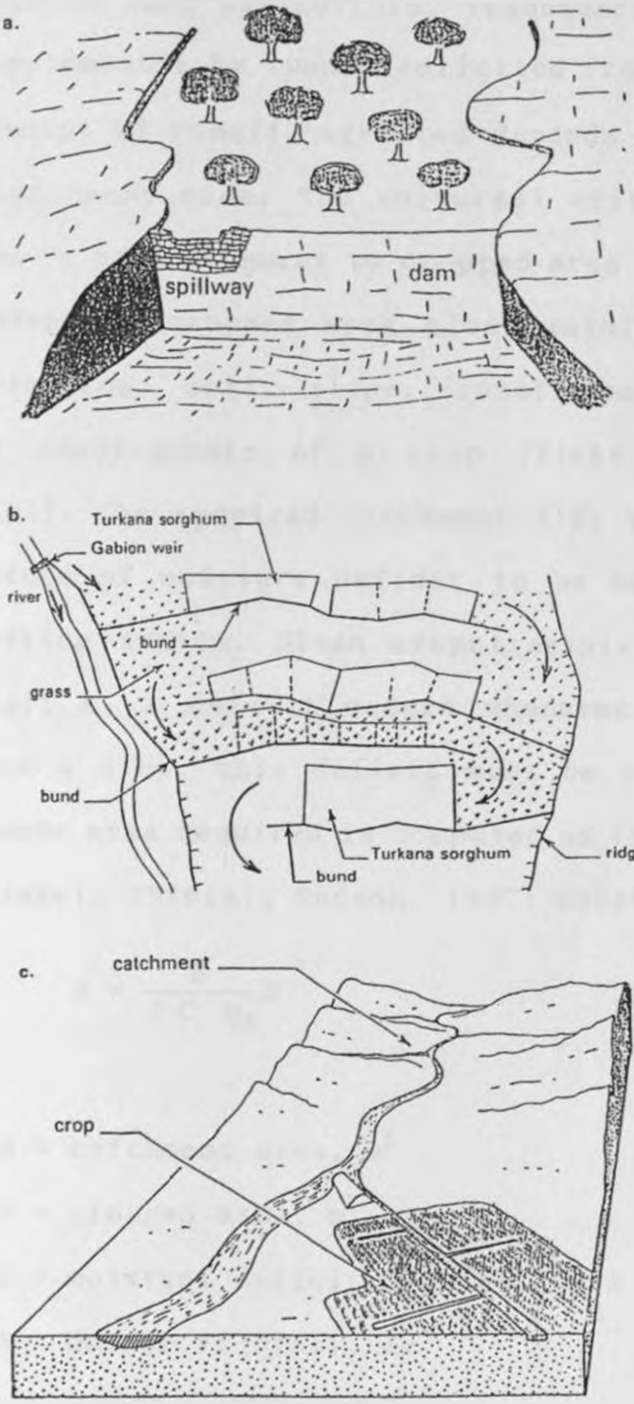


Fig. 2.3 Examples of Macro Catchment Systems a) terraced *wadi*, b) water spreading, c) diversion of spate flow (*After Pacey and Cullis, 1986*)

2.3.4 Water Harvesting System Design

In rainfed ASAL agriculture, inadequate rainfall may be supplemented by runoff collected from a catchment. The amount of runoff harvested depends on the size of the catchment area. The universal criterion for the design is the catchment to cropped area ratio which is dependent on cropped area size, rainfall depth and distribution, soil, slope, runoff coefficient and water requirements of a crop (Finkel and Finkel, 1986(a)). The required catchment size depends on the magnitude of moisture deficit to be met by a water harvesting system. Given evapotranspiration, ET and rainfall R, a deficit occurs whenever (R-ET)<0. To produce a crop, this deficit must be satisfied. The catchment area required is computed as follows (Finkel and Finkel, 1986(a); Hudson, 1987; Gichuki, 1989):

$$A = \frac{\delta}{R\, C_a\, \eta_b} B \qquad 2.1$$

where

A = catchment area, m^2

B = cropped area, m^2

δ = moisture deficit, mm, for ET>R

R = design rainfall, mm

C_a = runoff coefficient

η_b = water utilization efficiency

2.3.4.1 Design Rainfall

This is the rainfall depth by which a project is sized. In the ASAL, rainfall is often bimodal and rainy seasons are seperated by dry periods. Time is a very important factor as a water harvesting system aims to improve the water supply to a growing crop. Growing seasons for most crops are shorter than one year, and there can be very wide variations in annual rainfall. Therefore mean annual rainfall is not informative. And due to poor rainfall distribution in the growing season, seasonal rainfall is inadequate for design (Hudson, 1987) and data from shorter intervals is preferred. For water deficits in a season, monthly rainfall data is adequate, but it must be reliable and of at least 20 years record (Kessler and de Raad, 1974).

The simplest useful approach to evaluating rainfall data is by studying the probability of occurence of rainfall. Probability of monthly rainfall is more useful in designing water harvesting systems (Finkel and Finkel, 1986(b). Probability rainfall has advantage over mean or median rainfall as it gives the chance of rainfall falling below a selected level, and the effect the resulting moisture deficit would have on crop yield. The probability distribution for monthly rainfall totals can be obtained using normal distribution (Linsley et al.,1982; Shaw 1984; Chow et al., 1988). Where there are very wide variations as in ASAL, a log-normal distribution can be used (Van Dam et al., 1972). The log-normal distribution tends to reduce positive skewness found in hydrologic data (Chow et al., 1988). Probability plotting is a check that a distribution fits a set of hydrologic data; a distribution is linearised by using specially designed probability paper (Chow et al., 1988). Monthly rainfall data is arranged in descending order and ranked. The probability P of equalling or exceeding a certain rainfall value is obtained by making a plot of the data using the general equation:

$$P(x \geq x_m) = \frac{m - b}{n + 1 - 2b} \qquad 2.2$$

where

m = rank from highest value

n = total number of data considered.

b = empirical value ranging from 0 to 1

Of about six plotting positions, the most commonly used are Weibull and Gringorten with b=0 and b=0.44 respectively (Shaw, 1984). Studies of the common plotting positions by Cunnane (1978) on bias and minimum variance found the method of Blom (b=3/8) to be least biased (Chow et al., 1988). A theoretical normal line is drawn through the mean ± one standard deviation at 84% and 16% (Haan, 1977).

2.3.4.2 Effective Rainfall Data

Effective rainfall is that portion of rainfall that is directly or indirectly used for crop production at the site where it falls without pumping (Dastane, 1974). The SCS method has been applied to estimate effective rainfall (Burman et al., 1983). This method is used to evaluate mean monthly effective rainfall by interpolation from tables using monthly values of rainfall and evapotranspiration. The effective rainfall is high for soils of high water holding capacity. It is also high for unirrigated areas, areas with deep ground water table, and where salinity is being controlled using rainfall. Soil and water conservation structures eg terracing, ridging and mulching also increase the effective rainfall by reducing runoff losses. For a runoff harvesting systems, the effective rainfall is increased by increasing the amount of water received by the crop area and reducing overflow losses. Runoff is increased by surface treatment or increasing the catchment area. The major limitation in increasing effective rainfall is low water holding capacity of the ASAL soils.

2.4 Estimation of Catchment Runoff

Hydrology is the science that deals with the processes governing the depletion and replenishment of the water rates as infiltration gets drastically reduced. Runoff efficiency vary with soil water holding capacity and antecedent soil moisture. It accounts for differences between rainfall distribution and the rate of water use by the growing crop. A well distributed rainfall has high efficiency factor. High runoff volume from high intensity rainfalls result in excess water being lost as deep drainage or overflow. Efficiency factors of 0.25-0.85 have been suggested (Finkel and Finkel, 1986(a)). The runoff coefficient is never a constant, and single storms generally have higher coefficients than longer period rainfall totals (Finkel and Finkel, 1986(b)). The rational method has been improved by the time-area method (Shaw, 1984). The flow is the sum of the contributions from small areas of the catchment defined by lines of equal flow-time (*isochrones*). The flow from each contributing area is a product of mean intensity of effective rainfall and the small area.

2.4.1.2 The SCS Method

The SCS curve number method (Schwab et al., 1981) is widely applied in estimating runoff depth. It has been consistent in estimating total runoff from large catchments in the United States of America where rainfall intensities are low. The method has also been applied by Carneiro and de Jong (1985) in Brazil and by Pathak et al. (1990) in India. However, its performance on small watersheds with high intensity, low duration storms is not well documented. Some shortcomings of the method were highlighted by Hawkins (1978). The most contentious is the concept of a curve number, which lacks a physical basis and appears to be a constant. But in their work at ICRISAT, Pathak et al.(1990) seemed to overcome the seemingly "quantum" leaps in the values of curve number, the derived storage parameter and runoff depths. They used the method to compute the runoff generated by small watersheds less than 50 ha. By considering the changes in soil moisture throughout the season, they were able to get a high coefficient of determination (R^2=.983) between actual and predicted runoff.

The amount of runoff generated by a given storm depth is given by the following relation for (P-0.2S)>0:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad 2.5$$

where

Q = daily runoff depth, mm

P = daily precipitation, mm

S = max. potential difference between rainfall and runoff, mm

and S is given by:

$$S = \frac{25400}{CN} - 254 \qquad 2.6$$

where

CN = curve number for soil, cover and moisture condition

Curve numbers range from 0 to 100 and are listed in Schwab et al.(1981). These values reflect the soil type, the vegetation and the antecedent soil moisture status. For the ASAL, Hromadka and Whitley (1989) and Hoggan (1990) have given recommended values. Three curve number classes are given for average, dry and wet soil conditions. The most reasonable runoff estimates are those based on a curve number that is dynamic throughout the season (Hawkins, 1978). By assuming dependence between one CN and the next, it can be shown that the curve number for each day is given by:

$$CN_{i+1} = \frac{30480}{\frac{30480}{CN_i} - R_i + ET_i + Q_i} \qquad 2.7$$

where

CN_{i+1} = curve number, mm^{-1}

ET_i = evapotranspiration from the catchment, mm

R_i = daily rainfall, mm

Q_i = daily runoff, mm

2.4.2 Runoff Models

Runoff models are used to simplify complex processes. They estimate catchment response to rainfall input relative to conditions in the catchment and the rainfall characteristics. The response is often the rate and depth of runoff. Some of the rain incedent on the catchment is retained in ditches and depressions. Rainfall loss is the rainfall that does not contribute to runoff (Hoggan, 1990). Most runoff models use the concept of loss rate functions which include constant proportion, Phi-index, Horton, exponential, initial abstractions and the SCS loss separation (Hromadka and Whitley, 1989).

The earliest postulate on overland flow mechanism was by Horton (Emmett, 1978; Chow et al, 1988). Runoff flow is the net balance between rainfall intensity r and infiltration rate i, which Horton termed "rainfall excess". But experience has found this simple concept deficient in estimating the amount of runoff from a catchment (Linsley et al., 1982). The deficiency has been attributed to a) variability of rainfall intensity above and below the infiltration rate; and b) failure to account for storm-flow generation mechanism e.g. surface storage. Modern models physically describe the rainfall, infiltration and flow processes. A review of common overland flow models under rainfall was given by de Lima (1989).

2.4.3 Rainfall and Runoff Simulation

Rainfall simulators have been developed for use in laboratory studies of the runoff process. Simulation studies under controlled environments have the advantage of time economy in gathering information. The performance of a simulator is measured by its ability to produce characteristics similar to those of natural rainfall (Robertson et al., 1966; Tossell et al., 1990). The most important characteristics of rainfall include drop size distribution, velocity and intensity in so far as they influence soil crusting, infiltration and runoff.

A simple portable rainfall simulator was developed at Wagenigen Agricultural University, the Netherlands (Kamphorst, 1987). With high uniform intensity, it can be used for laboratory or field studies. The simulator characteristics are given herebelow.

Table 2.1 Specifications of the Portable Rainfall Simulator. (*after Kamphorst, 1987*)

Intensity	360 mm/h
Magnitude of shower	18 mm
Duration	3 min
Average fall height of drop	400 mm
Diameter of drop	5.9 mm
Kinetic energy of shower	35.4 J/mm
Surface area of test plot	0.0625 m^2

2.5 Soil Water Balance

Crops extract water from the effective rooting zone. The water balance of a water harvesting system has rainfall and runoff as inputs, and losses includes run-out, deep percolation, evapotranspiration and interflow across the walls of the system (fig. 2.1). Interflow may be negligible unless the soil has a high horizontal hydraulic conductivity. The components making a soil water balance are measured or estimated.

2.5.1 The Water Balance Equation

The water balance is calculated for a time interval. The interval between consecutive water balance component readings could be 1, 5, 7 or 10 days. The change in soil moisture in mm/d is given by (Slatyer, 1966; Hillel, 1980a):

$$\frac{dS}{dt} = (p+r_i)-(r_o+d+et) \qquad 2.8$$

where

p = rainfall, mmd^{-1}

r_i = runoff gained by the cropped area, mmd^{-1}

r_o = runoff lost from the cropped area, mmd^{-1}

d_p = deep drainage, mmd^{-1}

et = evapotranspiration, mmd^{-1}

2.5.1.1 Estimation of Deep Percolation Rate

The water percolating beyond the crop root zone is unavailable to the crop. There are various methods for estimating the amount of water percolating through the profile. The most accurate methods include numerical solution of a physical models, and the lysimeter.

Percolation loss can also be estimated by assuming that all water in excess of field capacity will percolate below the root zone (Kessler and de Ridder, 1974; Carneiro and de Jong, 1985; de Vries et al., 1989). The field capacity approach was successfully used by Vaigneur and Johnson (1966) and by Maule and Chanasyk (1987). The following equation has been suggested for computing the amount of water drained each day from the root zone based on an upper limit of available soil water (FC) and the time taken to drain a layer of a profile (Steiner et al., 1987):

$$D_p = \beta(1-e^{-T/\alpha}) \qquad 2.9$$

where

D_p = percolation below root zone, mm

β = water above FC (SW-FC), mm

FC = water held at field capacity, mm

SW = actual water content of soil, mm

T = time, 24 hours

α = time to drain the soil (β/K), hours

K = hydraulic conductivity of the soil layer, mm/day

Hillel (1980a) argued that FC and WP are not "constant" but dynamic and therefore limit the accuracy of data collected using such a method.

2.5.2 Measurement of Soil Water

Many methods have been applied for measuring the amount of moisture in the soil. Some directly measure the soil water content, and others measure other factors (eg soil water potential) which are positively correlated with the amount of water in the soil.

2.5.2.1 <u>Electrical Resistance Method</u>

Electrical resistance methods are commonly used in irrigation scheduling. They measure the electrical resistance of a porous medium. Resistance blocks are made of porous materials such as gypsum, fibreglass or nylon into which electrodes are embedded (Ravina, 1982; Campbell and Mulla, 1990). Electrical resistance of a porous material is a function of water content. When placed in a soil medium, the block matrix equilibriates with the soil water potential. With calibration, the recorded electrical resistance can be related to the water content of the soil matrix, which is dependent on the water potential of the sorrounding soil. The equipment is sensitive to temperatures change and high salinity of the soil solution. These make calibration difficult and limit the usefulness of the equipment. The method is quite accurate at higher soil moisture tensions above 1 bar (Doneen and Wescot, 1988).

2.5.2.2 The Neutron Probe Method

The application of the neutron probe method is described by Campbell and Mulla (1990), Skaggs (1983) and Ravina (1982). High energy neutrons are emitted into a soil from a neutron source. These neutrons experience inelastic collisions with atomic nuclei in the soil. When the particle colliding with the neutron is of low atomic mass as the neutron, the neutrons rapidly lose energy and the velocity of the neutron is halved. The atomic nucleus most effective in slowing neutrons is that of hydrogen. Hydrogen is abundantly found in soil water. The slowed neutrons are counted using a detector. With calibration, the count rate provides an indirect measure of volumetric water content. The volumetric water content is given by (Ravina, 1982):

$$\theta_v = \frac{1}{F}\frac{N_c}{N_o} \qquad 2.10$$

where

F = experimentally determined parameter

N_c = soil count

N_0 = shield count

The neutron probe is one of the most accurate techniques of determining soil water content. The major drawback of the method is the high cost of the equipment. The method is otherwise non-destructive and suited for uniform, coarse, medium textured soils.

2.5.2.3 The Gravimetric Method

The gravimetric method is the standard method of soil moisture determination (Hillel, 1980a; Ravina, 1982; Donahue, 1983; Hausenberg, 1987; White, 1987 ; Walker, 1989; Warrick, 1990). A wet soil sample is weighed in container of known weight. It is oven-dried at 105°C for at least 24 hours until there is negligible change in weight. The loss in weight represents the moisture lost from the soil sample. Dividing the mass of water by the mass of the dry soil gives the soil moisture content on a mass basis:

$$\theta_m = \frac{M_{ws} - M_{ds}}{M_{ds}} \qquad 2.11$$

where

θ_m = % moisture on mass basis

M_{ws} = mass of wet soil, g

M_{ds} = mass of dry soil, g

The volumetric water content is:

$$\theta_v = \theta_m \frac{\rho_s}{\rho_w} \qquad 2.12$$

where

θ_v = % moisture on volume basis

ρ_s = bulk density of the soil, g/cm^3

ρ_w = density of water, g/cm^3

Sampling at several depths is recommended to cater for variations in bulk density in non-homogeneous profiles. The total amount of water at any time for the whole root zone is computed by summing water depth values for each layer of thickness *t* over the *n* layers sampled:

$$SW = \sum_{j=1}^{n} \theta_{v_j}\, t_j \qquad 2.13$$

where

SW = soil moisture over the root zone, mm

2.5.3 Soil Water Movement

The movement of water into and through a soil profile can be described by a series of related events. The main processes are infiltration and percolation.

2.5.3.1 <u>Soil Infiltration Rates</u>

Infiltration is the process of entry of water into the soil (Hillel, 1971). It is a function of the soil texture and structure, wetness and uniformity of the soil profile. Sandy soils generally have higher infiltration rates than clay soils. The initial infiltration rate is high and is dependent on the soil moisture and the presence of a surface crust. Over time, infiltration rate reduces monotonically and approaches a constant rate called *steady infiltration rate*. The low and constant infiltration rate is also controlled by the profile characteristics. The factors responsible for the drop in infiltration rate include surface crusting, swelling of clay, entrapment of air bubbles, decrease in matric suction gradient, and filling of the pore space (Hillel, 1980a). A thorough discussion on the profiles of infiltrating water is offered by Hillel (1980a) and White (1987).

A number of infiltration models have been developed over the years for predicting the infiltration rate of soils. These include *Green and Ampt* (Hillel, 1980; Chow et al., 1988), *Horton* (Hillel, 1971; Hillel, 1980a; Shaw, 1983; Chow et al., 1988; Skaggs et al., 1983), *Phillip* (Hillel, 1971; 1980a; 1980b), *Kostiakov* (Michael, 1978; Ravina, 1982; Clemens, 1983; Skaggs et al., 1983), *USDA* (Hart et al., 1983); Marshall and Holmes, 1988) and the *physical model*. There has been limited use for most of these models due to their complexity.

The Kostiakov model is the most commonly used in field applications. The formula relates the cumulative infiltration to the elapsed time and soil-dependent empirical constants a and b as follows:

$$Z = at^b \qquad 2.14$$

where

Z = cumulative infiltration rate, mm

a = empirical constant

b = empirical constant

t = time, min.

The cumulated infiltration is plotted against elapsed time on a log-log graph paper. The y-intercept of the graph fot t=1 is equal to a and the slope is equal to b. Better values for a and b are obtained by using the method of least squares on data transformed by taking their logarithms. The instantaneous infiltration rate is obtained by taking the first derivative of the cumulative infiltration function (Warrick, 1990). Walker (1989) suggested a more general formula for which the instantaneous infiltration rate does not approach zero but a final value f_0 (mm/h) for large values of time. The exponent of the instantaneous rate ranges from -0.5 to 0 (Nugteren, 1970).

The measurement of infiltration rate into a soil is done using equipments suited to the purpose of the infiltration data. The double-ring infiltrometer method is the most commonly used and is described in many texts of irrigation eg Michael (1978) and Skaggs (1983). It consists of two cylinders of 25cm height and diameters of 30cm and 60cm. The cylinders are driven into the ground parallel to each other, usually to a depth of 10cm. Water is poured into the cylinders to a depth of 7-12cm, starting with the outer core. The water levels for both cylinders are kept the same. More care is taken in pouring water into the inner core to ensure that no crusting takes place on the surface soil. Initially, readings are taken at small intervals of seconds, then full minutes and as multiples of a minute. Water is added after a drop of 1 cm. The infiltration rate is determined by plotting cumulative infiltation against time on a log-log scale. The equation parameters can be estimated from the log-log plot or determined statistically.

2.5.3.2 Soil Hydraulic Conductivity

The movement of water through a profile starts with infiltration. After infiltration, redistribution occurs. This may take days and proceeds until the soil moisture is uniform within a profile. The rate of water movement into and through a profile is determined by the hydraulic conductivity of the soil.

Distinction is made between saturated and unsaturated hydraulic conductivity. Saturated conductivity values have been given by Smedema and Rycroft (1988) as 0.2-0.5 m/d for very fine sandy loam, 0.5-2.0 m/d for well structured loam/clay loam and clay, and 1-3 m/d for a sandy loam. For dryland agriculture where the water table is very deep, the unsaturated conductivity is more important.

The basic infiltration rate can be a good estimate of the hydraulic conductivity (Hausenberg, 1987). It is the relatively constant rate achieved after 3-4 hours. An approximate value can also be taken as the rate achieved such that the difference from the previous hour is less than 10%, and the time by which final infiltration rate is achieved was given by Van der Meer et al. (1974) as:

$$t = 10(1-b) \qquad 2.15$$

where

t = time in hours

b = infiltration equation exponent

Unsaturated hydraulic conductivity can be determined by using the inverse auger hole method (Kessler and Oosterbaan (1974); Smedema and Rycroft (1983). The method is used for measurements above the water table. An auger pit is made into the soil layer and a pipe of 8 cm diameter is installed. A cavity may be left at the bottom, or the entire vertical wall of the pit is covered. The soil is pre-saturated before doing the test. With the use of a floating measuring device, the fall in the water level is recorded for sufficient data to be obtained. The length of time required for the test depends on the soil type. The hydraulic conductivity is then computed using:

$$K = \frac{1.15\ r \log(h_0+r/2)-\log(h_t+r/2)}{t} \qquad 2.16$$

where

K = hydraulic conductivity, m/day

r = radius of piezometer tube, cm

h_0 = initial height of water, cm

h_t = final height of water, cm

t = time taken for the test, min

2.5.4 Estimating Evapotranspiration

Plants use water for nutrient transport, cooling and to maintain turgidity. The amount of water used by plants depends on the crop type, growth stage, soil water availability and the weather. Water is lost from a cropped field by evapotranspiration. The critical stages when yields of maize would be most adversely affected are from flowering to grain filling. Plants drastically reduce water abstraction upon reaching physiological maturity.

The amount of water used by a crop can be measured or estimated. Measurement can be done using sophisticated instruments like lysimeters (Davis and Grass, 1966; Hatfield, 1990) which gives the most accurate direct results.

There are also many methods for estimating crop evapotranspiration. These are of three general classes: mass balance, energy balance and empirical or combination methods. These methods include Blaney-Criddle, Jensen-Haise, Pan Evaporation, Radiation and

Penman methods (Doorenbos and Pruitt, 1977; Doorenbos and Kassam, 1979; Schwab et al., 1981; Linsley et al., 1982; Shaw, 1984). The first four are empirical, while Penman method is a combination method. These methods are described in greater detail in the quoted texts.

2.5.4.1 Modified Penman Method

This is the standard method used for computing evaporation and evapotranspiration. It is well outlined by Schwab et al.(1980), Burman et al.(1983) and Shaw (1984) among others. It is a combination method derived from energy balance and a mass transport. Combination methods are the most accurate for a wide range of climatic conditions and can be used for periods of 1 hour to 1 month (Burman et al. (1983). The following is the Penman equation as given by Shaw (1983):

$$PE = \frac{(\Delta/\gamma) H_T + E_{at}}{(\Delta/\gamma) + 1} \qquad 2.17$$

where

H_T = available heat, mmd^{-1}

E_{at} = energy for evapotranspiration, mmd^{-1}

Δ = slope of vapour pressure-Temp. curve, mb^0C^{-1}

γ = psychrometric constant, mb^0C^{-1}

The terms H_T and E_{at} are computed as follows:

$$H_T = 0.75R_I - R_O \qquad 2.18$$

where

R_I = incoming short wave radiation, mm/d

R_O = outgoing long wave radiation, mm/d

which applies for reflected short wave radiation (albedo) of 0.25; and

$$E_{at} = 0.35(1 + u_2/100)(e_a - e_d) \qquad 2.19$$

where

u_2 = daily run of wind, miles day^{-1}

e_s = saturation vapour pressure at the air temperature, mb

e_d = vapour pressure of air at dew point temperature, mb.

Doorenbos and Kassam (1979) gave a wind function based on metric units; with wind speed given in km d^{-1}, the factor outside the brackets becomes 0.27.

The value of R_I is computed as follows:

$$R_I(1-r) = 0.95R_a\, f_a(n/N) \qquad 2.20$$

where

R_s = terrestrial radiation, mm d^{-1}

$f_s(n/N)$ = sunshine modulating function

n = actual measured annual sunshine hours

N = possible daily sunshine hours

The value of R_O is computed as follows:

$$R_O = \sigma T_K^4(0.47 - 0.075\sqrt{e_d})(0.17 + 0.83n/N) \qquad 2.21$$

where

= Stephan-Boltzman constant (5.67×10^{-8} Wm^{-2}K^{-4})

T_K = air temperature, ^{0}K

2.5.4.2 Hargreaves Method

A modified Blaney-Criddle method for evaluating monthly evapotranspiration has also been proposed (Hargreaves and Samani, 1988). In their work the authors found good correlation of ET values estimated using the method and those measured using a lysimeter. The method uses the extraterrestrial radiation (Ra) received on the ground, the monthly maximum (TMAX) and monthly minimum (TMIN) temperatures:

$$ETP = 0.0023\ R_a\ TD^{0.5}(T_c + 17.8) \qquad 2.22$$

where

R_s = radiation, mm d^{-1}

Tc = the mean monthly temperature, ^{0}C

TD = the difference between TMAX and TMIN, ^{0}C.

This relation is useful where only temperature data is available. If temperature data does not exist, an estimation using an empirical temperature-altitude relationship can be applied. From his extensive study on this relationship, Braun (1986) suggested the following equation:

$$T = F - Gh \qquad 2.23$$

where

T = mean temperature, ^{0}C;

F = regression factor 1;

G = regression factor 2;

h = elevation, metres.

He worked out regression factors for mean maximum, mean minimum, and average values for annual or monthly temperatures based upon elevation. Regression value for monthly temperatures are given in table 2.2. These values can be used to generate maximum and minimum values of temperatures to be used in estimating daily or monthly evapotranspiration. For the coastal belt, other relations were preferred.

Table 2.2: Regression factors based on maximum and minimum temperatures (*After Braun, 1986*).

Month	Mean	Maximum	Mean	Minimum
	F	G	F	G
January	36.7	.00174	25.8	.00227
February	37.4	.00176	25.8	.00232
March	37.6	.00176	26.3	.00230
April	35.8	.00175	26.1	.00215
May	34.6	.00179	25.1	.00208
June	33.9	.00178	23.8	.00203
July	33.5	.00183	22.8	.00194
August	33.7	.00186	23.2	.00197
September	35.4	.00184	24.1	.00215
October	36.4	.00187	24.8	.00217
November	36.2	.00196	25.2	.00216
December	35.5	.00179	24.8	.00215

2.5.4.3 The Pan Evaporation Method

The pan evaporation method is used extensively for estimating crop evapotranspiration and integrates the influence of radiation, temperature, humidity and wind (Dov Nir and Finkel, 1981).

The US Class A pan is the most commonly used for data collection (Schwab et el., 1981; Linsley et al., 1982; Shaw, 1984; Chow et al., 1988). It has a diameter of 122 cm and a depth of 25 cm. It is installed in an open field at least 10m from the nearest obstacle, and the grass around it is kept low. The pan is mounted on a level platform with a 15 cm ground clearance for free movement of air. Water is maintained at a depth of 18-20cm (Howell et al., 1983). Evaporation readings are taken daily by taking the difference in volume between a reference point in the stilling basin and the surface of water in the pan. This procedure is well described by Doorenbos (1976). The Class A pan overestimates potential evaporation; a pan fitted with a screen gives data more closely correlated with the potential evapotranspiration (Howell et al., 1983). Computation of potential evapotranspiration is done using the formula suggested by Kaila (1983):

$$PE = K_p(R - 0.5(S_c - A_c)) \qquad 2.24$$

where

K_p = pan coefficient

R = daily rainfall, mm

S_c = subtracted cups

A_c = added cups

0.5 = volume of standard cup, litres

Pan factors dependent on vegetation condition, whether sparce, bare, green or dry (Kaila, 1983). The actual water use is calculated by applying a crop coefficient

(K_c) dependent on the growth stage of a crop. The crop coefficient is the ratio between maximum and potential evapotranspiration, and is dynamic throughout the season (Stewart et al, 1984). It is low when the crop is young and increases with the stage of the crop up to maturity, subsequently decreasing to drying. Crop coefficients for various crops are found in Burman et al., (1983) and Doorenbos and Kassam (1979).

2.6 Yield Response to Soil Moisture

2.6.1 The Crop

Maize (*Zea Mays*) is a staple food crop in Kenya. It is grown mostly at subsistence level although there are maize-growing commercial farms, especially in the Rift Valley. It is well adapted to the varied Agro-Ecological Zones. There are many local varieties and also high yielding hybrids like the 600 and the 500 series. Other low yielding varieties have been bred to suit environmental constraints, including Katumani, Coast and Makueni composites whose fast growth make them more suitable to the very short growing seasons of ASAL areas. Maize requires well-drained fertile soils and up to 500 mm for evapotranspiration. The crop has four growth stages (Doorenbos and Pruitt, 1977). The most sensitive stage to moisture stress include flowering to grain filling.

2.6.2 Soil Water Availability

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 effective rooting zone of a crop. Different crops and varieties vary in their rooting depth. The amount of water stored by a soil depends on soil characteristics such as soil structure and texture. A coarse textured soil loses water quickly through rapid percolation, whereas finer soils and soils of high organic matter content retain water longer.

The amount of water stored and available to the crop is the difference between the field capacity and permanent wilting point. The field capacity is the water held at a tension of 1/3 bar suction, achieved by a freely draining soil 48 hours after saturation, although some soils take longer to reach this level. This is the high range for water availability to plants. Permanent wilting point is the water held at a suction of 15 bar. Below this suction water is considered unavailable to the growing crop. In practice, plants get stressed before the permanent wilting point is reached.

Field and laboratory method have been used to determine values for field capacity and permanent wilting point. The most common laboratory method is the pressure plate apparatus. Undisturbed soil samples are pre-saturated. Saturated samples are put in a pressure plate apparatus and subjected to suctions as desired. Starting with low suction, the soil sample is pressurised in the apparatus, driving moisture away. Changes in sample weight is monitored at 24-48 hour intervals. New presure is applied when there is no more change in sample weight. The process continues until the highest pressure is used.

Plants easily abstract 40% to 60% of the available moisture (Nutgeren, 1970). This is called readily available moisture (RAM) and is the difference between a critical soil moisture level (above PWP) and FC (James, 1988). The total readily available moisture (TRAM) is found by summing RAM over the rooting depth of a crop.

For maize, about 89% of the water requirements would be extracted from the top 60cm of the root zone, and virtually all the water requirements may be obtained from the top 90cm (Neumann, 1982). For a soil with distinct layers, the extraction pattern by plants is 40%, 30%, 20% and 10% for the successive D/4 layers starting from the top (Withers and Vipond, 1974).

2.6.3 Modelling Yield Response to Soil Moisture

Many models have been formulated for estimating expected crop yield. These include the CERES maize model and the PLANTGRO model (Hargreaves and Samani, 1988). The relation between crop yield and evapotranspiration has long been recognised, and most yield models are based on crop evapotranspiration. From work done at the University of California (Davis) the yield of maize was shown to be linearly correlated with seasonal ET (Stewart and Hagan, 1974). Other results by these authors were not linear but strongly indicated an increase of yield as plant available water increased. Their basic assumption in defining yield versus seasonal ET relations was that except water, no other factors were limiting. More advanced yield models take into account the fertility status of the soil and effects of adverse environmental factors eg drought and water logging.

A simple model for estimating crop yield has been suggested by Doorenbos and Kassam (1979). The actual evapotranspiration is ET_A and the maximum is ET_M, which is a function of the potential evapotranspiration and the crop coefficient. When all crop water needs are fully met from available water, then $ET_A = ET_M$. When the supply is insufficient, then $ET_A < ET_M$. Values of ET_M are evaluated as follows if pan evaporation data is available:

$$ETM = PE \times K_c \qquad 2.25$$

where

PE = potential evapotranspiration, mm

K_c = crop coefficient

The actual evapotranspiration is more complex and dependens on crop type, the stage of crop growth, prevailing weather conditions and availability of water in the soil. When the available soil water is reduced, the actual evapotranspiration is reduced. A crop water stress is defined as the difference between unity and a quotient of actual and potential evapotranspiration (Sudar et al., 1981). The actual evapotranspiration ET_A is estimated as follows (Doorenbos and Kassam, 1979):

$$ET = \frac{Sa.D}{t}(1-(1-p))\,e^{-(\frac{ETM.t}{(1-p)Sa.D}+\frac{p}{1-p})} \qquad 2.26$$

where

Sa = available soil moisture (FC-WP);

D = root zone depth, mm;

p = percent allowable depletion of soil water;

t = time (days) in which available moisture satisfies crop demand ie ET_A=ET_M, and is equal to or geater than p Sa.D/ET_M.

In a constraint-free environment, the actual yield Ya is equal to the maximum yield Ym when full water needs are met, otherwise Ya is less than Ym. When soil water is deficient, the yield is reduced. The most sensitive crop growth stage is silking-pollination, with a susceptibility of 73% (Hiler and Clark, 1971). The relative yield is therefore a function of the maximum yield, ET_A, ET_M and a yield response factor:

$$\frac{Ya}{Ym} = 1 - Ky\left(1 - \frac{ET_a}{ET_m}\right) \qquad 2.27$$

where

Ky = yield response factor.

Crop yield is also influenced by radiation, day-time cloudiness, temperatures, length of the growing season and the vapour pressure deficit. Values of ET_M and ET_A can be evaluated daily or for specific crop growth stages in the growing season.

3 MATERIALS AND METHODS

3.1 Description of the Experimental Site

3.1.1 Location

This study was conducted at Mutomo in Southern Kitui (see Fig. 3.1). The experimental site was on the eastern slopes of Mutomo Hill, about 500 m south of Ministry of Agriculture's Office, on the lowest terrace of Mr. Syindu's Farm. The area was about 2000 m^2 divided into crop-catchment systems and buffer areas protecting the crop from pests.

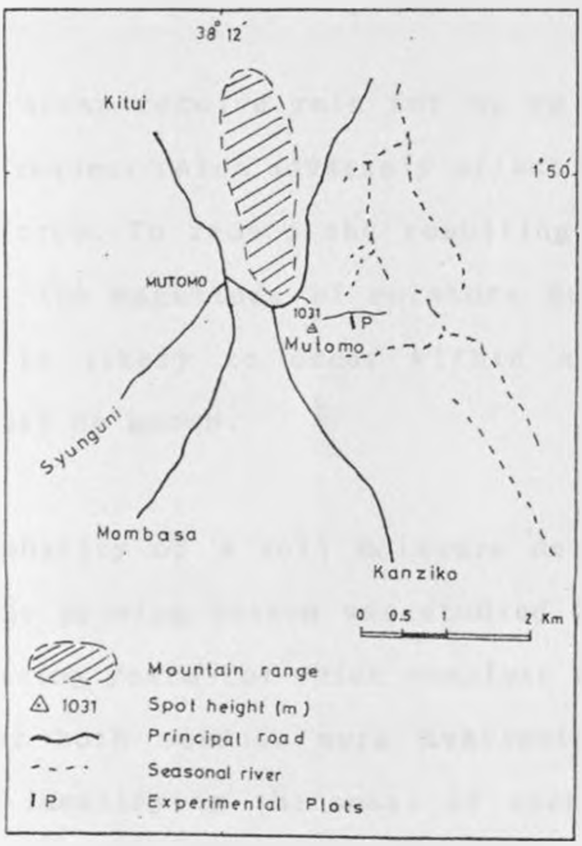


Fig. 3.1 Location of the experimental site, Mutomo

A simple station for collecting rainfall and pan evaporation data was located to the north about 10 m windward. To the north of the site is a motorable access path, and to the south and east are bushes beyond the fences. Fanya Juu terraces that cover the whole land have modified the 7% natural slope to about 5%. The land has been under cultivation for over 30 years, and prior to this study it had been abandoned due to infestation by couch grass.

3.2 Rainfall and Evapotranspiration Analysis

3.2.1 Determination of Moisture Deficit Periods

Many dry areas receive rain for up to 50 days after which infrequent rains adversely affect crop yields of rain-fed crop. To reduce the resulting soil moisture shortage, the magnitude of moisture deficit and the time it is likely to occur within a crop growing season must be known.

The probability of a soil moisture deficit occuring within the growing season was studied for the Mutomo Station using years for which complete daily rainfall data over both seasons were available. The method involved identifying the onset of each "long rains" and "short rains" seasons, which come in March-May and October-January, respectively. The onset was taken as time after the amount of rainfall received in one day or total for 2-3 consecutive days, and was taken as 10 mm minimum. After this onset, rainfall was accumulated for the next 89 days. A mean of the totals was obtained. The data was examined to seperate the "wet" from the "dry" years. A wet year was taken to have a total above 300 mm ("long rains") and above 486 mm ("short rains") which was the 24-year mean, and dry year a total below these figures for the seasons. A daily average of the "wet" and one for the "dry" was computed to represent the average growing season.

The historical daily potential evapotranspiration data for the same length of season were estimated using data for Kitui as given by Woodhead (1968). They were then multiplied by crop coefficients (see section 3.5.5) and then averaged to get the daily average for the number of years.

3.2.2 Seasonal Rainfall Reliability

Daily rainfall was added for 90 days of each season from onset. The rainfall total was then analysed for reliability for the 24 years of data (1966-1989) for both "long rains" and "short rains". The analysis was done using the following procedure:

1) the daily rainfalls were accumulated for each 90 day season from season onset
2) exceedance probabilities were computed for the

number of years for predetermined exceedance levels; probability was calculated as the number of exceedance years divided by the total number of years.

3) An analysis of drought frequency was done on the same data. A season was taken as dry if the total rainfall within the season was less than 300 mm for the "long rains" (considered adequate to obtain a maize crop yield) and 486 mm, the mean for the "short rains".

3.2.3 Monthly Rainfall Data Analysis

An analysis of monthly rainfall for both seasons was done for rainfall data covering 24 years of record ie 1966-1989. The data was found to best fit a log-probability distribution. Due some years having zero rainfall, a value of 5 mm was added to all monthly figures for log-transformation to work. Some selected rainfall parameters were computed using the following equations as suggested by Haan (1981). The mean monthly rainfall is given by:

$$\mu = \exp[\mu_y + \frac{\sigma_y}{2}] \qquad 3.1$$

and the variance is given by:

$$\sigma^2 = \mu^2[\exp(\sigma_y^2) - 1] \qquad 3.2$$

where

σ = standard deviation of monthly rainfall, mm

μ = mean of the actual data, mm

σ_y = standard deviation of log-transformed data

μ_y = mean of log-transformed data, mm

The coefficient of skewness is given by:

$$C_s = 3C_v + C_v^3 \qquad 3.3$$

where

C_s = coefficient of skewness

C_v = coefficient of variation

and the coefficient of variation is given by:

$$C_v = \sqrt{\exp((\sigma_y^2) - 1)} \qquad 3.4$$

Selected statistics for monthly rainfall for both cropping seasons are given in table 4.2.

3.3 Soil Properties

3.3.1. Soil Texture and Bulk Density

Soil texture was determined using soil samples taken from a profile pit dug 10 m south of the experimental site. Samples were taken at 7.5, 30, 60 and 90 cm. The texture was determined using the standard hydrometer method.

Bulk densities were determined for samples taken from the same pit and depths. At least two samples were taken at each depth. Samples were taken in December

1990 when the soil was quite wet, using standard 100 cm^3 core rings of height 5 cm and diameter 5 cm. The samples were extracted by inserting the core in an auger and slowly driving it into the pit at the required depth. After extraction, the samples were trimmed on both sides with a sharp knife and then secured in a sampling box for transportation. In the laboratory, the samples were first weighed with a balance sensitive to 0.01 g. They were then dried in an oven at 105°C until no more weight was lost. The soil was removed from the core and the weight of the core was determined. The bulk density was then calculated as follows:

$$BD = \frac{W_1 - W_2}{V} \qquad 3.5$$

where

BD = bulk density, gcm^{-3};

W_1 = wet mass of soil sample, g;

W_2 = dry mass of soil sample, g; and

V = standard volume of core, 100 cm^3.

3.3.2 Infiltration Rates

Two infiltration tests were done per block using the double ring infiltrometer. As the soil was dry, test sites were pre-wetted before installing the equipment. The 25 cm deep rings were 32 cm and 57 cm in diameter. They were driven into the soil parallel to each other to a depth of 11 cm. The interface between the soil and the rings were filled with wet soil to minimize distorted infiltration. A graduated float was fixed in the inner ring for taking measurements of water levels. Water was filled to a depth of 12 cm, starting with the space between the rings. Readings were taken starting with half, one, two minute intervals and so on as necessary. The head was not allowed to fall by more than 4 cm between fillings. The tests were conducted for 1.5-2 hours. This time was justified by the fact that most storms in the ASAL are of short duration, and was taken as the most important time when runoff can be generated. Cumulative infiltration values were used to obtain the infiltration parameters of the Kostiakov equation chosen for the study. Common logarithm of time and cumulative infiltration were taken. A least squares fit of transformed data was done and regression values obtained. The value of a was obtained by taking the antilog of the constant, while that of b was obtained by taking the value of the coefficient.

$$I_c = at^b \qquad 3.6$$

The cumulative infiltration (mm) was determined using the derived parameters (equation 3.6). Instantaneous infiltration was computed using the first derivative of the cumulative equation multiplied by 60:

$$I_{ins} = 60\ a\ bt^{b-1} \qquad 3.7$$

where

I_{ins} = instantaneous infiltration rate, mmh^{-1}

3.3.3 Saturated Hydraulic Conductivity

Values for saturated hydraulic conductivity were estimated using final infiltration rate, taken as the rate at time (hours) computed using the method described in section 2.5.3.2 and equation 2.15.

3.3.4 Field Capacity and Permanent Wilting Points

Field capacity (FC) and permanent wilting point (PWP) values were estimated for the chromic Luvisol using the three-field average 1/3 and 15 bar moisture content data presented by Kilewe and Ulsaker (1984) for a similar soil at Katumani Dryland Farming Research Station. As the data had been taken at 10, 30, 60 and 90 cm depths, it was converted first to unit volumetric moisture at each depth. The unit volumetric moisture was then multiplied by 15, 30, 30 and 30 cm, respectively, to get the field capacity and permanent wilting point moisture for the Mutomo soil at 7.5, 30, 60 and 90 cm depths. These are summarised in table 3.1.

Table 3.1 FC and PWP values for a chromic Luvisol.

Depth (cm)	FC (% vol.)	FC (mm)	PWP (% vol.)	PWP (mm)
0-15	0.270	40.6	0.126	18.9
15-45	0.263	78.9	0.156	46.7
45-75	0.299	89.6	0.172	51.6
75-105	0.388	116.4	0.236	70.6

Source: Kilewe and Ulsaker (1984)

3.3.5 Estimation of Percolation Losses

Drainage below the crop root zone was estimated using the method discussed in section 2.5.1.1. The basic assumption was that water above the field capacity drains below the root zone. The net horizontal drainage was assumed to be zero. Water was assumed to drain exponentially depending on the amount of water above field capacity, the soil hydraulic conductivity and time (24 hours) allowing for daily water balance calculations.

3.4 Design of the Water Harvesting System

A water harvesting system consists of a cropped and a catchment area. In this study, Micro-Catchment Water Harvesting was used (see section 2.3.3.2). In a MCWH system, a small cropped area collects runoff water from a small catchment area a short distances away. Catchment areas may range from 0.5 to 1000 m^2. The cropped area was selected to be 16 m^2.

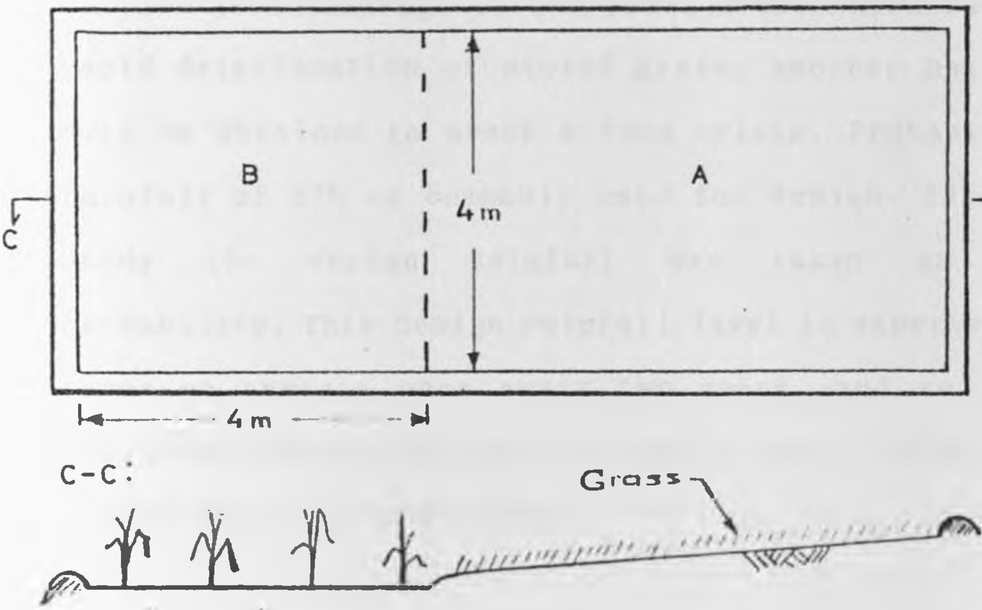


Fig. 3.2 Details of the MCWH system.

3.4.1 Selection of Design Rainfall

The month was selected as the time scale for design rainfall because annual or seasonal time scales are too long. A shorter period would give better information but increase the amount of work needed for the analysis. Monthly rainfall totals for each cropping season were arranged in a descending order. Plotting positions were computed using equation 2.2. (b = 0.375). The monthly totals were plotted against their plotting positions on a log-probability paper. The probability level selected for design was based on the allowable risk of crop failure due to poor rainfall, the risk criteria being to allow for a maximum grain storage of two years after which due to rapid deterioration of stored grain, another harvest must be obtained to avert a food crisis. Probability rainfall of 67% is commonly used for design. In this study the design rainfall was taken as 50% probability. This design rainfall level is expected to occur on average once every two years, and so food shortages can be averted by using a water harvesting system based on this design.

3.4.2 Monthly Evapotranspiration

The potential evaporation data for Kitui provided by Woodhead (1968) was used for estimating monthly potential evapotranspiration for Mutomo.

Table 3.2 Mean Monthly Potential evapotranspiration for Kitui Agric. Station (*After Woodhead, 1968*)

Month	Mean monthly	Mean daily
January	189	6.1
February	191	6.8
March	200	6.4
April	169	5.6
May	168	5.4
June	152	5.1
July	149	4.8
August	162	5.2
September	183	6.1
October	203	6.5
November	163	5.4
December	167	5.4

This data covers the period 1948-1954 and was done for Kitui Agriculture Station. Kitui is higher than Mutomo and has lower evapotranspiration than Mutomo. For lack of measured data, this data was assumed to represent Mutomo adequately, and is presented as table 3.2.

3.4.3 Catchment Size

The catchment area was designed using the method described in section 2.3.4. and was based on the "short rain" season which starts in October. The procedure involved working out monthly deficits between rainfall and evapotranspiration. Potential evapotranspiration and probability rainfall values were assigned to each month. The rainfall onset for the short rains is around 20th of October (Alusa, 1978; Stewart and Hash, 1982). Thus computations were assumed relevant for 11 days in that month. A maize growing seasons for Katumani Composite B are generally shorter in lower altitudes, and may be as few as 85 days in a dry season (Kashasha, 1982). Based on these facts, computations were done to include 13 days in January. Deficits were assumed to occur whenever the difference between monthly evapotranspiration and the 50% probability rainfall exceeded zero. The monthly deficits were cumulated. Rainfall was assumed well distributed and the soil has a reasonable water holding capacity to store the runoff. Table 3.3

summarises these calculations.

Table 3.3 Determination of seasonal water deficit.

Month	R_d	PE	PE-Rd	Cumulative deficit, mm
October	21.4	63.9	42.5	42.5
November	204.0	164.7	-39.3	3.2
December	68.0	163.9	95.9	99.1
January	20.0	74.8	54.8	153.9
Total	313.4	467.3		153.9

Rd = design rainfall (50% probability)
PE = potential evapotranspiration

The resulting 153.9 mm as seasonal moisture deficit which must be met in order to grow a maize crop. This is the amount of water that a water harvesting system would have to supply to the crop. A runoff coefficient of 0.72 was used; such a runoff rate is possible on highly crusting soils during high intensity storms (Chiti, 1991). An efficiency of 0.8 was assumed to adequately estimate the conditions in the field. Common irrigation efficiencies range from 40 to 80% for basin and sprinkler, respectively. The catchment area required to supplement incedent rainfall on a crop was then calculated using equation 2.1.

3.4.4 Experimental Layout and Design

This study was aimed at examining the effect of the amount of available water on crop yield. A large catchment area would give a large runoff depth. By using a standard cropped area of 16m^2, four treatment levels were used based on a fraction of the design rainfall: a) 50% ; b) 70% ; c) 100% and a control with (no catchment) as shown in table 3.4. The four treatments were randomized and replicated thrice (see fig. 3.2). Each cropped and catchment areas was a closed system with soil bunds of about 0.15 m height forming the boundaries (see fig 3.3).

Table 3.4 Size of catchment areas

% Rd	Length, m	Area, m^2	A/B	CCAR
50	3.4	27.2	1:1.7	1.7
70	4.9	19.6	1:1.2	1.2
100	6.8	13.6	1:0.9	0.9
Control	0	0	-	-

R_d = design rainfall
A, B = catchment and cropped areas
CCAR = Catchment to cropped area ratio

Thus moisture received could only be lost through deep percolation, overflow or evapotranspiration.

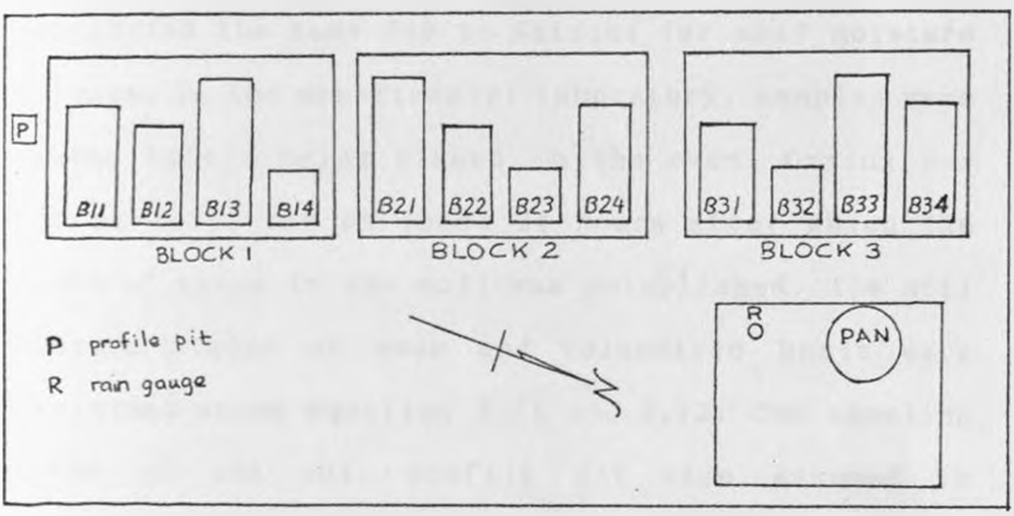


Fig. 3.3 Layout of the experimental site.

3.5 Collection of Data

A water balance study of the cropped area was required to determine the amount of available water in the soil over the whole growing season. This involved the determination of the water balance components - rainfall, runoff, evapotranspiration, deep percolation and residual soil moisture. A water balance was done for each treatment for 82 days (whole season) starting from 10/11/90 when the maize crop was planted after a 52.2 mm storm received the previous night.

3.5.1 Soil Moisture Data

Soil moisture status was determined every 10 days from the planting date. It was done at depths of 7.5, 30, 60 and 90 cm on each of the 12 levelled plots. One sample was obtained from the middle of the field. The samples were put in plastic cans, sealed and transported the same day to Nairobi for soil moisture analysis. In the departmental laboratory, samples were weighed before being placed in the oven. Drying was done at 105°C for at least 24 hours after which the weight of water in the soil was established. The soil moisture status on mass and volumetric basis were determined using equation 2.11 and 2.12. The sampling depths of the soil profile pit were assumed to represent soil horizons of homogeneous bulk densities over the whole field. The thickness of each layer are given in table 3.5. The profile volumetric water content was determined by using equation 2.14.

Table 3.5 Thicknesses of individual soil layers.

Sampling Depth, cm	Horizon, cm	Thickness, mm
7.5	0-15	150
30	16-45	300
60	46-75	300
90	76-105	300

3.5.2 Daily Runoff Data

Estimation of daily runoff depth was done using the SCS curve number method as outlined in section 2.4.1.3. This method is discussed in more detail in section 3.6 under "RUNOFF Module". The values of runoff obtained this way were used in the soil water balance as the runoff input.

Peak runoff was simulated to determine the soil runoff generating characteristics. This was done in August 1991 which was a dry period. The simulation sites were pre-wetted before each test. Three simulations were conducted per catchment using the rainfall simulator described in section 2.4.3 which has a constant intensity of 360 mmh^{-1}, a simulation time of 3 minutes and 18 mm rainfall per run. The amount of runoff from each plot for each rainfall was calculated by multiplying the rainfall by the runoff coefficient value of 0.61 and then by scaling factors of 0, 0.5, 0.72 and 1.0 for all catchment areas from 0 to 27.2 m^2, respectively. The values of the runoff obtained by simulation and the SCS method were then compared.

3.5.3 Effective Rainfall Data

Estimates of effective daily rainfall were obtained for every day in the study season. The method had been proposed and applied by Stewart and Hash (1982). Details of the method are in section 3.6 under "EFFECTIVE RAINFALL module".

3.5.4 Daily Evapotranspiration Data

Daily evapotranspiration was estimated using the evaporation data collected with the modified class A pan commonly used in Kenya. The pan has a diameter of 121 cm and a depth of 25 cm. It is painted black in the inside and has a screen with 25 mm openings. The pan was set in October before the onset of the rains. A clearing was made 10 m upwind of the experimental plots. A platform fabricated from 50x50 mm^2 timber treated against insect attack was fixed level into the ground leaving about 10 cm ground clearance. The pan was placed on the platform and water filled to about 5 cm from the brim. The grass in the area near the pan was kept about 15 cm high. Pan evaporation data were recorded daily at 8.00 AM. Evaporation was calculated by converting the removed or added measuring cups to an equivalent depth, and subtracting rainfall that had been received the previous day. Pan evaporation data was corrected to Standard Class A pan data using correction factors suggested by Kaila (1983). These factors are a function of the dryness/wetness of the area and the observed amount of grass cover as it changes in the season. Potential evapotranspiration data was obtained using pan factors as given by Doorenbos and Kassam (1979). Maximum evapotranspiration values were obtained by converting the potential values using crop factors for maize.

Table 3.6 Factors for converting Kenyan pan data to Class A pan data

Period	Estimated length	Factor
Initial dry	18 days	0.98
Midseaon, wet	54 days	1.05
End, dry	11 days	0.98

3.5.4.1 <u>Crop Coefficient</u>

In this study, K_c values were computed for maize using the method suggested by Burman et al. (1983).

1) Crop growth stages:

The crop planted on 10/11/90 was harvested after 93 days. Ripening is often hastened by drying of the soil, so the crop K_c curve was developed for a 90 day season. The best description of the growing stages for Katumani maize is that by Nadar (1984). Still, the length of each stage must be estimated so as to use this method. To determine the length of each stage, field observations were also used. The results are presented in table 3.7.

Table 3.7 Maize growth stages (Katumani variety)

Development stage	approximate length, days
initial	17
crop development	21
midseason	40
late season	12

2) Value for initial stage: For the period of study, the frequency of significant rainfall after onset was at most 2 days. Taking a potential ET of 6.5 mm (Woodhead, 1968), the initial K_c value was read from figure 3.4 as 0.85.

3) For midseason stage, K_c value was taken as 1.1.

4) At harvest, K_c value was taken as 0.6.

The K_c curve was drawn by joining these points using the length of each growing stage.

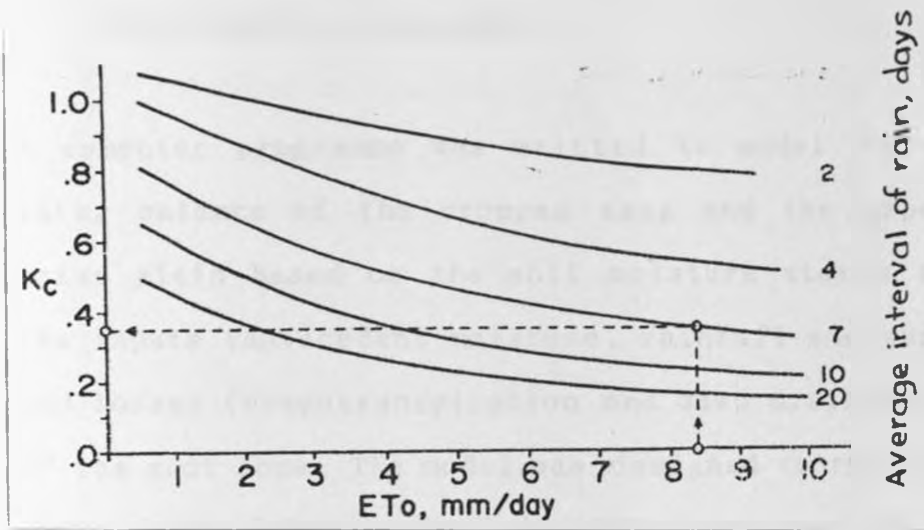


Fig. 3.4 Average K_c for initial crop development stage *(after Doorenbos and Pruitt, 1977)*

3.5.5 Crop Data

The maize test crop was Katumani variety, planted on 10/11/90 after 52.2 mm of rainfall on 9/11/90. Planting was done at 75 cm between rows and 30 cm between plants, 3 seeds per hill placed at 5 cm depth. Two fertilizers were used at planting ie 20:20:0 at 260 kg/ha and 18:46:0 at 234 kg/ha based on the inherently poor state of nitrogen and phosphorus in the soil (see section 4.2.3). Gapping was done a week after germination, and thinning to 2 seedlings was done at 15 cm high. The crop was clean-weeded, and birds and squirrels scared away. A termite attack at silking stage was controlled by using Nova ant-killer (20% Lindane) mixed at 7 ml/l of water and applied at the base of the plants. Harvesting was done on 15/2/91 and the crop subsequently dried and weighed.

3.6 The Computer Programme

A computer programme was writted to model the soil water balance of the cropped area and the expected maize yield based on the soil moisture status using the inputs (antecedent moisture, rainfall and runoff) and losses (evapotranspiration and deep drainage) out of the root zone. The model was designed to run for 82 days of the "short rains" of 1990 using one day time step. Rainfall and ET data are read as the programme runs. This programme is given as fig. 3.5.

Basic Assumptions

1) The root zone partitioned into four layers of distinct properties (FC, PWP, drainage rate) and was considered to expand linearly (Tscheschke and Gilley, 1979) from day 1 to 60 when vertical root extension was assumed to cease after reaching 1.05 m.
2) values of saturated hydraulic conductivity of the profile (Ks) are constant at 2.5 m/d for the upper 750 mm soil (sandy clay) and 1.5 m/d for the lower 300 mm (clay);
3) moisture above field capacity drains exponentially depending on the excess moisture;
4) plants abstraction water only if soil moisture exceeds the permanent wilting point;

5) the SCS curve number method was taken as adequate for calculating runoff from micro-catchments in high intensity storms.
6) FC and PWP were taken as unique to each soil layer and are linear ie each unit soil depth holds a certain unit amount of water at FC and PWP;
7) initial soil moisture is uniform in each layer.
8) the evapotranspiration in the catchment is equal to that of the cropped area;
9) the curve number would be between 75 and 100, the value assigned to dry and saturated conditions, respectively for a poor grassed field; and
10) all rainfall and runoff in the cultivated area infiltrated into the soil.

The Modules

RUNOFF module

This module was designed to generate daily runoff values. The equations used were 2.6, 2.7 and 2.8. The initial curve number was taken as 78 because the catchment was already wet following the heavy storm one day before the water balance started (see App. 6). The storage parameter was computed using equation 2.7. Dependence between one curve number and the next was assumed, and so equation 2.8 was used for the computation of curve numbers.

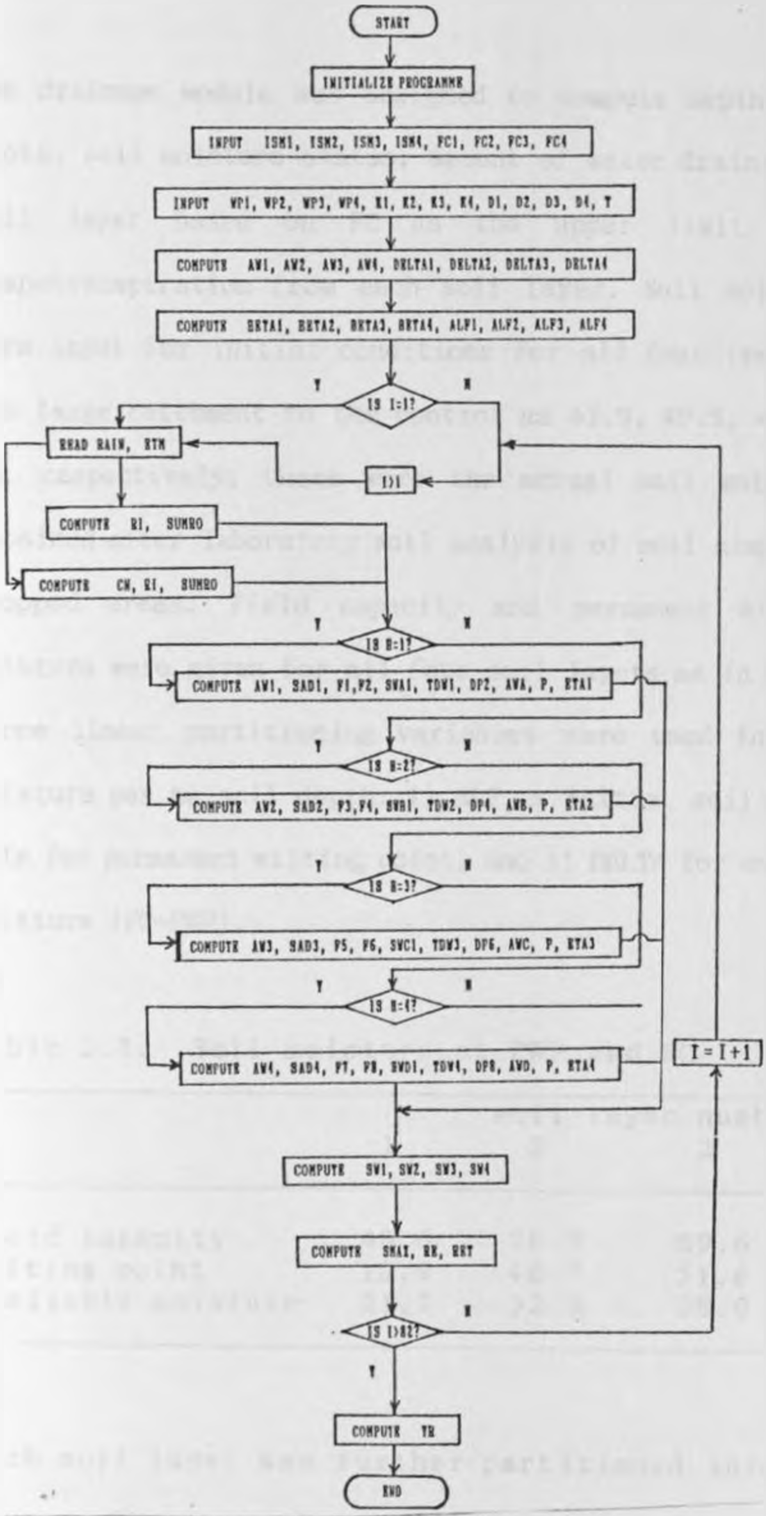


Fig. 3.5 Flow Chart of the Computer Programme.

DRAINAGE module

The drainage module was designed to compute depth of the crop roots, soil moisture status, amount of water draining from each soil layer based on FC as the upper limit, and actual evapotranspiration from each soil layer. Soil moisture values were input for initial conditions for all four treatments from the large catchment to the control as 47.9, 49.5, 49.0 and 47.9 mm, respectively; these were the actual soil moisture values obtained after laboratory soil analysis of soil samples from all cropped areas. Field capacity and permanent wilting point moisture were given for all four soil layers as in table 3.8. Three linear partitioning variables were used for unit soil moisture per mm soil depth: 1) ALF as initial soil moisture; 2) BETA for permanent wilting point, and 3) DELTA for available soil moisture (FC-PWP).

Table 3.8. Soil moisture at PWP and FC

	soil layer number			
	1	2	3	4
Field capacity	40.6	78.9	89.6	116.4
Wilting point	18.9	46.7	51.6	70.6
Available moisture	21.7	32.2	38.0	45.8

Each soil layer was further partitioned into two sub-layers. The top sub-layer starts when roots grow into it. It increases linearly as the roots grow, growing into the bottom sub-layer until the whole soil layer is covered by the roots. The bottom sub-layer exists from day 1 and decreases linearly as the roots penetrate into it, and altogether ceases to exist once roots have completely covered the whole layer.

a) Computing the rooting depth

Assuming that root extension starts on day one, for a maximum rooting depth of 1050 mm assumed attained after 60, the linear equation is

$$D = 50 + \frac{100}{60}\,Day \qquad 3.8$$

where

D = depth of roots zone, mm

Day = sequential day from planting date

b) Computing the soil moisture status

Soil moisture was computed each day by adding all inputs into and losses out of the initial soil moisture for each day. The partitioning factors were used to determine incremental water, drainage and moisture extraction. Where roots were growing, there was an incremental gain in soil moisture by virtue of the roots covering an additional elemental depth of soil.

c) Computing drainage

Drainage was computed daily. It was assumed to occur once soil moisture exceeded the FC value. Drainage was computed using an exponential function of the excess soil moisture and the value of hydraulic conductivity assigned to each layer. Water lost as drainage from a soil layer was gained by the layer below it as the only moisture input into it. The moisture lost at the bottom of the profile was taken as deep percolation out of the root zone.

d) Computing actual evapotranspiration

This was computed when soil moisture was more than wilting point, else it was set to zero. If the available water was greater than allowed depletion, then ET_a was set equal to ET_m. If it was less, then ET_a was computed as a fraction of ET_m (see section 2.6.3).

EFFECTIVE RAINFALL module

This module was used to evaluate the amount of daily rainfall that was effective in contributing to soil moisture. The method takes into consideration the crop rooting depth and water holding capacity of the soil. It involves a daily water balance of the maximum rooting zone of the crop. The rooting depth was assumed to store against gravity a maximum amount of water equal to the field capacity. If the soil moisture before input (rainfall and runoff) is less than FC, then some input is stored, the amount depending on the magnitude of the difference between soil moisture and FC. If the soil moisture equals or exceeds FC, then all the input is ineffective as it is lost as deep percolation.

CROP YIELD module

This module computes the expected crop yield ratio (%) for the prevailing moisture conditions. The crop yield is computed based on the actual evapotranspiration, ET_A. This is done as outlined in section 2.6.3; equations 2.26 and 2.27 were used for ETA and relative yield, respectively. It also writes a summary of rainfall received, percolation and evapotranspiration losses and runoff as percent of daily rainfall.
The computer programme code is given as Appendix 7.

KEY TO THE COMPUTER PROGRAMME SYMBOLS

Symbol	Meaning	Comment
SMo	initial soil moisture	average of similar plots
CNo	initial curve number	estimated for the mostly bare wet catchments
CN	subsequent curve number	computed daily
R	daily rainfall input	input daily into the top layer of the profile
RI	runoff into cropped area	input daily from the catchment
RO	runoff out of cropped area	generally assumed zero
dP	percolation below root zone	computed daily taking root zone as 105 cm
p	allowable depletion	computed depending on available moisture
SW	soil moisture in the profile	computed daily for each soil layer
FC	field capacity moisture	assumed static but different for each layer
WP	wilting point moisture	as for FC
ETM	maximum evapotranspiration	value corrected from pan evaporation data
ETA	Actual evapotranspiration	value computed daily for each layer depending on ETM and p
K	hydraulic conductivity	different value for each layer
A	catchment area	changed at prompt for each run
B	cropped area	single entry value
Ky	yield response factor	single entry value

4 RESULTS AND DISCUSSIONS

4.1 Moisture Supply in a Growing season

4.1.1 Historical Rainfall and ET for Mutomo

Figures 4.1 and 4.2 shows the average moisture status for "long rains" at Mutomo. The "wet" seasons were for 7 and the "dry" seasons for 17 years.

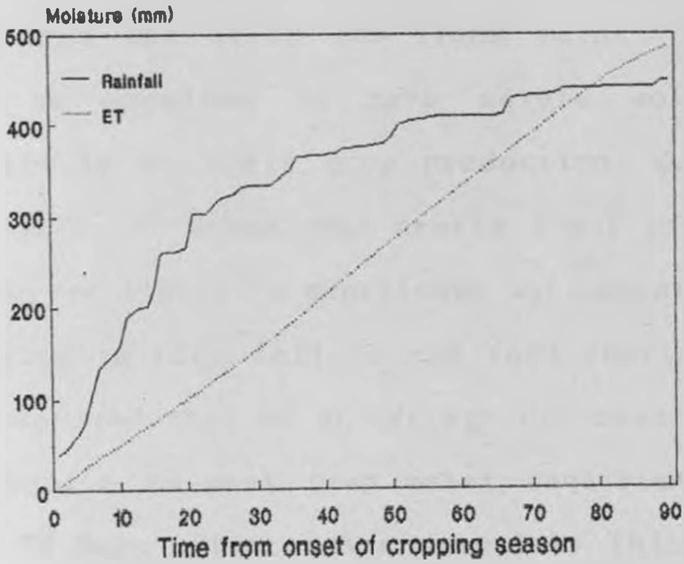


Fig. 4.1 Long rains moisture status of wet seasons

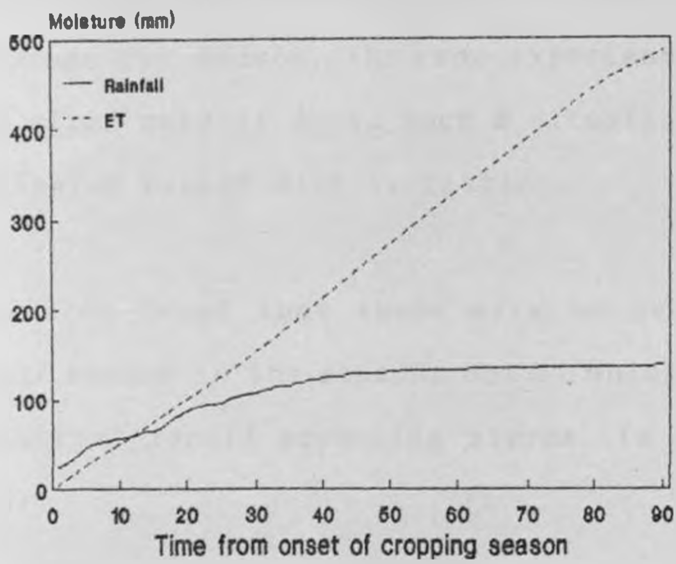


Fig 4.2 Long rains moisture status of dry seasons

4 RESULTS AND DISCUSSIONS

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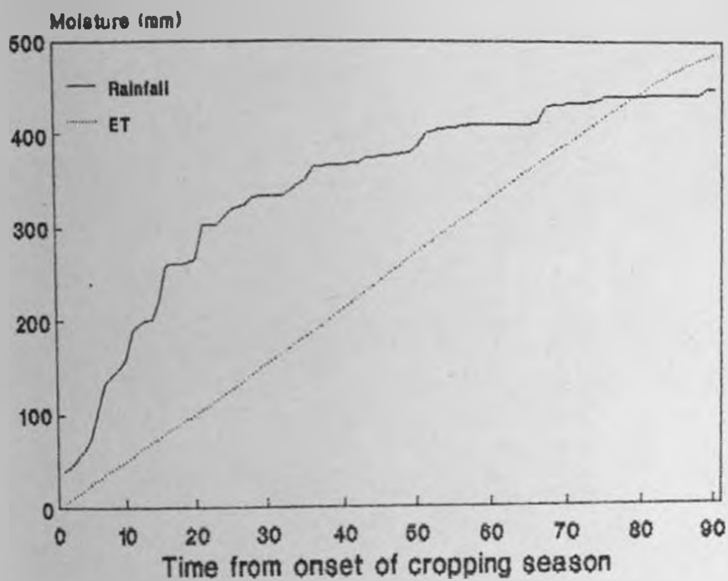

Fig. 4.1 Long rains moisture status of wet seasons

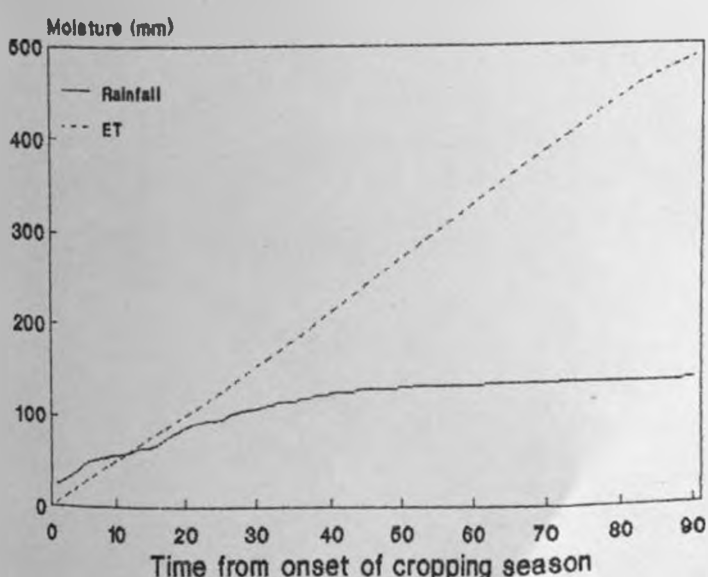

Fig 4.2 Long rains moisture status of dry seasons

Seasonal rainfall data was analysed for the 24 years of daily rainfall record. The lowest seasonal rainfall was 29 mm, the highest 915.2 mm and the average 229 mm. The two figures represent the most likely soil moisture conditions occuring in the 24 year period of record. They reflect possible adequate (wet) and inadequate (dry) probability levels of 29% and 71%. It means that for every 100 "long rains" seasons, 71 would be expected to have severe soil moisture deficits as to limit crop production. On a shorter time-scale, it means that nearly 3 out of every four seasons are likely to experience soil moisture stress, resulting in crop failure and food shortage. It was also observed that on an average wet season, rainfall is adequate to meet crop water requirement for the first 78 days after season onset; by this time fast-growing varieties will experience limited moisture stress as they approach physiological maturity. But on the average dry season, the crop experiences moisture stress after only 11 days. Such a situation could not be mitigated except with irrigation.

It was also found that there were an average of 12 rainfall events in the season, out of which the number of potential runoff producing storms (ie >10 mm) was 7 (58%).

Figures 4.3 and 4.4 show the average moisture status for the "short rains" for the same station. The "wet" were for 10 and the "dry" ones for 13 years. These figures were done for 23 years of daily rainfall within the growing season, with a low of 104.3 mm, a high of 1005 mm and an average of 486 mm. They represent the possible soil moisture conditions in the "wet" and "dry" seasons, and probability levels of 43% and 57% respectively. Therefore 57 of 100 "short rains" (more than half the time) would be expected to be dry, with resulting moisture stress lowering maize yields. There were an average of 18 rainfall events in the season, out of which an average of 12 potentially could produce runoff.

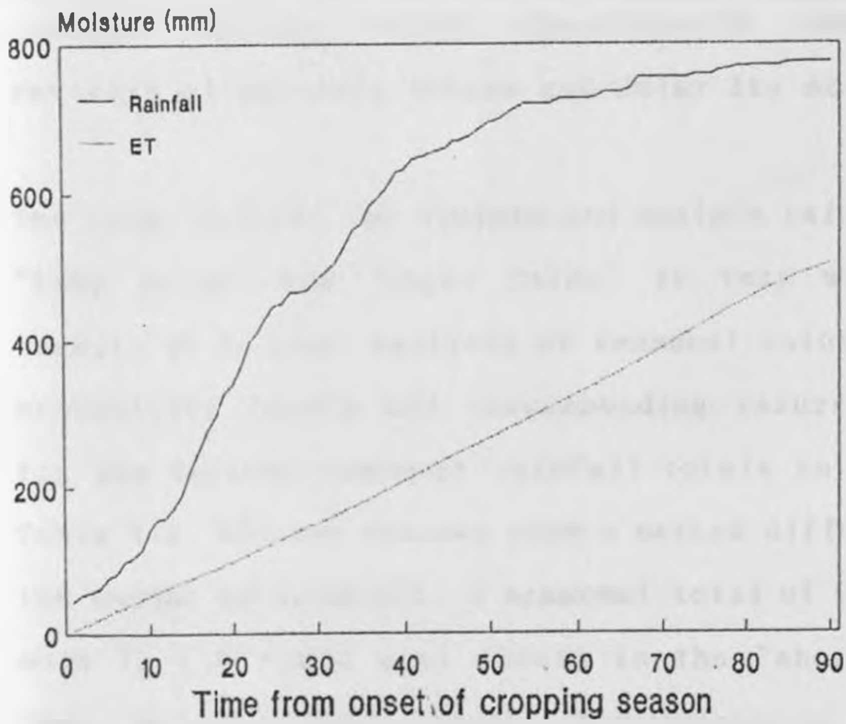

Fig. 4.3 Short rains moisture status of wet seasons

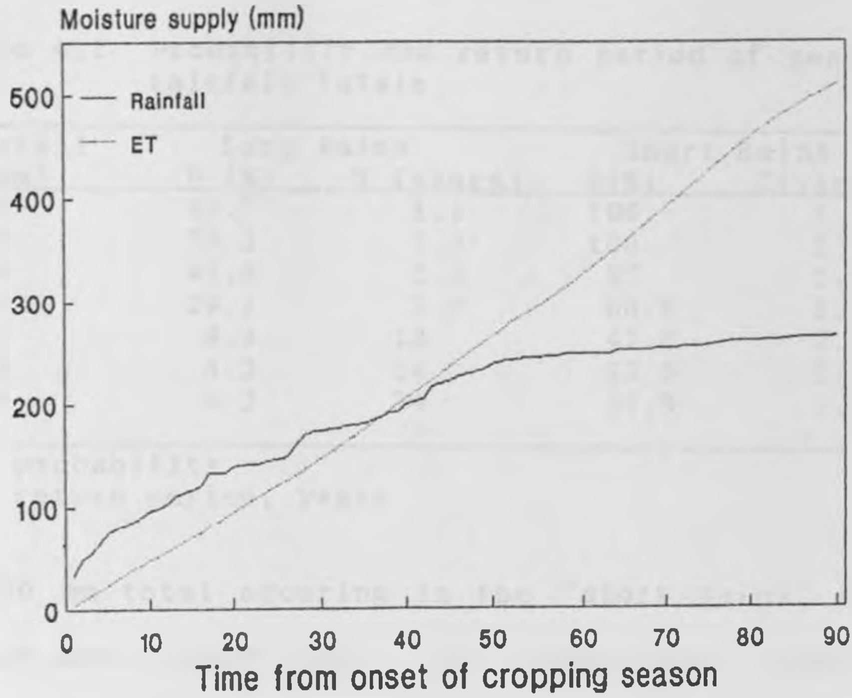

Fig 4.4 Short rains moisture status of dry seasons

The analysis of these seasons did not consider soil moisture storage. A soil which is high in moisture storage capacity would significantly reduce the severity of moisture stress and delay its occurence.

The range between the minimum and maximum rainfall for "long rains" and "short rains" is very wide. The results of further analysis of seasonal rainfall gave probability levels and corresponding return periods for the various seasonal rainfall totals as shown in Table 4.1. The two seasons show a marked difference in the amount of rainfall. A seasonal total of 200 mm or more is 1.9 times more likely in the "short rains" than in the "long rains". The situation is more critical as the amount of expected rainfall increases;

Table 4.1 Probability and return period of seasonal rainfall totals

Rainfall (mm)	Long Rains P (%)	Long Rains T (years)	Short Rains P(%)	Short Rains T(years)
50	91.7	1.1	100	1
100	79.2	1.3	100	1
200	45.8	2.2	87	1.2
300	29.2	3.4	60.9	1.6
400	8.3	12	47.8	2.1
500	4.2	24	43.5	2.3
600	4.2	24	34.8	2.9

P = probability
T = return period, years

a 500 mm total occuring in the "short rains" is 10 times more likely than in the "long rains". Thus the "long rains" are unsuited to crops requiring higher amounts of rainfall, and would be more suited for very fast growing crops of low evapotranspiration demand.

For a food security agricultural system in ASAL, a two year planning period is more appropriate especially because of the high rate of grain deterioration after harvest. This return period corresponds to just under 200 mm and 400 mm for the "long rains" and "short rains" respectively. For a well adapted crop like Katumani maize requiring at least 300 mm, there is a 71% chance that rainfall will be inadequate in the "long rains" season; this is 39% in the "short rains" season. And so on average, out of every 10 years, under normal dryland farming 7 and 4 maize crops will fail in the "long" and "short" rains, respectively. Therefore an intervention is required to avert crop failures and stabilize maize yields over time.

4.1.2 Monthly Rainfall Data

The following were the monthly rainfall totals for 24 years of data.

Table 4.2 Monthly rainfall totals for Mutomo, Kitui (mm)

	LONG	RAINS			SHORT	RAINS			
YEAR	March	Apr	May	TOTAL	Oct	Nov	Dec	Jan	TOTAL
1966	21.9	782.5	118.7	923.1	-	-	37.1	-	37.1
1967	62.7	62.5	49.6	174.8	340.9	659.0	0.0	-	999.9
1968	279.4	142.2	71.2	492.8	33.8	434.7	124.3	-	592.8
1969	67.9	92.0	16.3	176.2	23.7	272.9	39.1	63.8	399.5
1970	149.8	57.8	44.7	252.3	0.0	81.3	14.0	73.9	169.2
1971	1.5	322.2	52.6	376.3	0.0	155.4	106.3	9.0	270.7
1972	9.0	0.0	20.0	29.0	71.7	286.2	138.4	69.1	565.4
1973	0.8	122.1	14.5	137.4	0.0	277.4	41.1	10.7	329.2
1974	97.8	237.6	4.7	340.1	0.0	107.3	7.2	0.0	114.5
1975	7.9	18.2	10.5	36.6	15.1	203.8	1.5	30.0	250.4
1976	0.0	124.4	23.5	147.9	0.0	64.0	128.1	0.5	192.6
1977	43.5	178.6	8.5	230.6	0.0	278.5	199.1	4.5	482.1
1978	99.7	55.3	0.5	155.5	73.0	236.0	337.0	80.0	726.0
1979	-	205.0	144.1	349.1	0.0	126.7	163.8	165.9	456.4
1980	25.0	87.7	-	112.7	0.0	143.2	105.0	0.0	248.2
1981	142.0	120.0	15.0	277.0	17.0	189.2	61.0	31.5	298.7
1982	1.5	222.0	11.5	235.0	66.8	75.0	87.7	0.0	229.5
1983	0.0	42.5	0.0	42.5	0.0	54.4	96.4	22.6	173.4
1984	13.0	42.4	2.0	57.4	210.6	830.0	25.0	23.0	1088.6
1985	0.0	41.0	38.2	79.2	133.0	190.0	207.0	12.0	542.0
1986	78.0	175.5	85.0	338.5	7.0	539.0	141.4	0.0	687.4
1987	0.0	62.0	55.0	117.0	2.0	-	16.0	12.0	30.0
1988	81.5	95.6	0.0	177.1	19.5	389.7	386.0	74.5	869.7
1989	20.0	281.0	8.0	301.0	59.2	722.5	149.0	77.3	1008.0
			Mean =	231.6				Mean =	448.3

Table 4.3 is a summary of rainfall statistics for the Mutomo Station for 24 years of data. The standard deviation of monthly rainfall was between 6.5 mm and 23.1 mm, with the highest being in November and the lowest in May. Coefficients of variation were between 101% to 162%, the extreme cases being for April and

October respectively. The skewness of monthly rainfall was also found to be very high ranging from 4.05 to 7.49 also in April and October. High skewness implies a large number of small rainfall totals. It seems that April, with the least skewness and variability, has the most uniform rainfall, while October has the most non-uniform.

Table 4.3 Computed monthly rainfall statistics for Mutomo, Kitui.

Month	Mean (obs)	Mean (L-N)	50% (LP)	SD	C_s	C_v, %
"Long Rains":						
March	57.3	63.1	27.4	11.1	6.74	150
April	154.0	169.7	112.3	12.5	4.05	101
May	39.5	40.3	24.9	6.5	4.26	105
"Short Rains":						
October	51.7	49.6	19.7	11.4	7.49	162
November	279.5	377.6	189.2	23.1	6.21	141
December	113.8	139.3	69.6	12.9	5.11	121
January	36.9	39.7	19.6	7.4	5.20	123

LP = log-probability plot reading
SD = standard deviation of rainfall
C_s = coefficient of skewness
C_v = coefficient of variation
LN = log-normal computation

November rainfall is dependable, but it seems to have a very wide range between the extremes, hence the high skewness. These statistics are typical of the ASAL areas. The wetter months of April and November had the lowest variability and their data plotted very well on log-normal graph paper (See Appendix 5).

4.2 Soil Properties

4.2.1 Bulk density

Table 4.4 gives a summary of the results of soil bulk densities for samples taken from the profile pit.

Table 4.4 Soil bulk density at various soil depths
Density, kgm^{-3}

Depth, cm	Sample number				Mean
15	1500	1610	1300	1540	1490
30	1530	1580	1430	1560	1520
60	1510	1590	1430	1630	1540
90	1590	1490	-	-	1540

The bulk density was found to increase with depth from 1490 kgm^{-3} at 15 cm to 1540 kgm^{-3} at 60 cm and 90 cm. These high values are typical of mineral soils which are low in organic matter.

4.2.2 Soil Texture

Table 4.5 summarises the results of textural classification of the soil at the experimental site.

Table 4.5 Soil textural classification

Sampling Depth, cm	% Sand	% Silt	% Clay	Textural Class
15	58	5	37	Sandy clay
30	59	2	39	Sandy clay
60	49	4	47	Sandy clay
90	43	3	54	Clay

Based on these constituents and the FAO classification (Jaetzold and Schmidt, 1983), the soil was classified as a sandy clay chromic Luvisol. There was an observed increase in clay content with depth (illuviation), and a corresponding reduction in sand content. The soil was very low in silt content, which did not appear to increase or decrease with depth. The increase in clay content in lower horizons would tend to inhibit water movement through the profile, and also increase water holding capacity of the lower soil layers.

4.2.3 Soil Chemical Properties

Table 4.6 gives a summary of soil chemical analysis for soil samples collected from the same pit.

The pH reactions in water ranged from 6.8 to 7.4 which is favourable for most crops. In addition, no micro- or macro-nutrients are fixed at this pH and therefore the soil has good nutrient availability. The soil organic carbon ranged from 2.05% at 37 cm to 1.20% at 130 cm. Nitrogen content was 0.29% at 37 cm depth. It was observed that carbon, nitrogen and phosphorus tended to decrease with soil depth. The base saturation was 92.4% to 98.3% at 130 cm and 37 cm, respectively. The soil was low in exchangeable sodium, and as such it had no salinity hazard. Phosphorus content ranged between 4 to 17.5 parts per million, which corresponds to 0.0004% and 0.00175% P in the soil.

Table 4.6 Results of soil chemical analysis

	Sampling Depth (cm)					
	37	55	71	100	130	150
pH (water)	6.8	7.3	7.2	7.2	7.2	7.4
pH (CaCl)	6.2	6.3	6.1	6.2	6.1	5.9
% C	2.05	1.92	1.46	1.63	1.20	1.31
% N	0.29	0.18	0.10	0.13	0.20	0.17
me/100g soil:						
K	1.00	1.01	1.00	1.05	0.05	1.05
Na	0.013	0.013	0.013	0.013	0.013	0.013
Ca	14.50	10.60	8.25	10.50	10.50	9.50
Mg	4.25	8.10	4.50	4.00	1.50	2.50
CEC	20.10	20.50	14.45	16.20	13.05	14.00
P (ppm)	17.5	17.5	8.30	4.00	4.00	4.00
BS(%)	98.3	96.2	95.3	96.1	92.4	93.3
ESP(%)	0.06	0.06	0.05	0.08	0.10	0.09

Sanchez (1976) gave the limiting values of macro nutrients for maize as 3%, 0.25% and 1.9% for N, P and K respectively. Therefore this soil was found to be highly deficient in nitrogen and phosphorus. The pH range of 6.8-7.4 was within the recommended range for most crops, although phosphorus tends to be fixed and its availability decreases at pH above 7.0.

4.2.4 Infiltration Rate and Hydraulic Conductivity

Cumulative infiltration rates are given in Appendix 3. Estimated basic infiltration rates and saturated hydraulic conductivities of the soil are presented in table 4.7.

Table 4.7 Estimation of saturated hydraulic conductivity from infiltration

Test	a	b	t (h)	I_b, mm/h	K, m/d
B12	4.725	0.565	4.35	14.2	0.3
B13	4.141	0.657	3.43	26.3	0.6
B21	4.325	0.784	2.12	71.4	1.7
B24	2.138	0.897	1.03	75.5	1.8
B31	3.36	0.722	2.78	35.1	0.8
B33	3.376	0.744	2.56	41.5	1.0

Basic infiltration rates were computed from regression equations using a time of four hours. There were wide variations between blocks, particularly between Block 2 and the others. Block 1 had infiltration rates of 26.3 and 14.2 mm/h. Block 2 had 71.4 and 75.5 mm/h, and Block 3 had 35.1 and 41.5 mm/h. These high rates were found to be within the range expected for a sandy loam soil (Landon, 1984). The tests were done in the dry period and pre-wetting did not significantly alter infiltration rates in some of the test sites; other factors like soil structure seemed to be quite dorminant. The apparent presence of micro-organism activity especially in Block 2 also had considerable influence on infiltration, hence the high rates in this block. A soil with high infiltration rate would be expected to absorb most low to moderate rains. From such catchments, high runoff amounts would not be expected. The range of hydraulic conductivity values estimated using final infiltration rate method were consistent for a sandy clay soil and of the same order as those given by Smedema and Rycroft (1983).

4.3 The Water Balance

4.3.1 Measured and Simulated Runoff

In table 4.8 are percent runoff values obtained using the portable rainfall simulator.

Table 4.8 Results of runoff simulation

Plot	% slope	% Runoff collected: test 1	test 2	test 3	mean
1	4.5	56	61	56	57.7
2	5.5	64	68	61	64.3
3	5.9	69	69	73	70.3
5	5.1	58	71	65	64.7
6	4.1	46	54	56	52.0
7	4.1	56	60	46	54.0
9	4.3	55	68	68	63.7
10	5.5	59	59	56	58.0
11	5.7	63	66	61	63.3
Mean	5.0				60.9

The average runoff was found to be 60.9% of the simulated rainfall. This was in dry conditions when the soil has high capacity to absorb water. In wetter conditions in the growing season, runoff would increase for the same catchment conditions. There was no apparent significant influence of slope on runoff. The 360 mm/h rainfall intensity used is too high even for a semi-arid area even if parts of a storm may have such intensities.

The results of computer-generated runoff values computed for the whole season for the largest are also presented in table 4.9 below.

From this table it can be seen that runoff was in general low in the drier periods of early to mid-November and late in December, the highest runoff values obtained being 8.5% and 11.6% of rainfall, respectively. By contrast, more runoff was estimated to occur in the wetter time of the season. For example the 121.7 mm storm falling on 19/11/90 produced 61.2% runoff, hence in the middle of the season more runoff was produced. Figures for the wettest period (early and mid-December) ranged from 0 to 83.9%. The estimated runoff for two 33.5 mm storms occuring on 12/12/90 and 17/12/90 were 70.7 and 83.9%; the second storm, even though of equal magnitude, gave 13.2% more runoff by virtue of the catchment being saturated after an additional 108.8 mm rainfall in subsequent days. Thus antecedent moisture seemed to have a very marked effect on computer generated runoff depth.

The estimated daily effective rainfall was high in dry compared to wet periods of the season. The first four and the last three storms were 100% effective as there was high capacity for moisture storage; effectiveness dropped to as low as 10% in the wettest time, reflecting depletion of soil storage capacity.

Table 4.9 Influence of antecedent moisture on runoff

Date	Rainfall (mm)	CN	Runoff (mm)	% of Rain	R_{Eff} (mm)
15/11	3.9	75.0	0.0	0.0	3.9
16/11	34.1	75.0	2.9	8.5	34.1
17/11	11.5	80.3	0.0	0.0	11.5
18/11	5.9	82.2	0.0	0.0	5.9
19/11	121.7	82.4	74.5	61.2	71.7
20/11	2.2	93.3	0.0	0.0	2.2
24/11	25.9	90.1	8.6	33.2	25.9
26/11	0.6	92.6	0.0	0.0	0.6
27/11	31.0	91.7	14.2	45.8	22.0
28/11	3.5	95.4	0.1	2.9	3.5
29/11	4.0	95.4	0.2	5.0	4.0
1/12	8.8	94.2	1.5	17.0	8.8
2/12	5.0	95.4	0.4	8.0	5.0
3/12	45.5	95.5	33.7	74.1	3.1
4/12	5.0	98.2	1.9	38.0	4.1
5/12	20.5	97.9	14.7	71.7	4.2
6/12	0.3	98.2	0.0	0.0	0.3
8/12	14.4	97.1	7.7	53.5	3.2
11/12	5.8	95.8	0.9	15.5	5.8
12/12	33.5	96.1	23.7	70.7	3.7
13/12	28.5	98.0	23.1	81.1	4.5
14/12	24.7	98.3	20.1	81.4	4.8
15/12	19.0	98.2	14.4	75.8	3.6
16/12	3.1	98.5	0.9	29.0	3.1
17/12	33.5	98.1	28.1	83.9	4.7
18/12	16.2	98.6	12.1	74.7	4.7
19/12	3.1	98.3	0.7	22.6	3.1
30/12	1.4	86.6	0.0	0.0	1.4
31/12	19.0	86.0	2.2	11.6	19.0

Table 4.10 shows the comparison of runoff amounts obtained for the simulated and the computer generated data using the daily rainfall amounts recorded in the season.

The amount of runoff estimated by the simulation technique was higher than the amount obtained using the SCS curve number method. The estimated seasonal runoff values were higher by 8.1%, 5.8% and 4% for the 27.2, 19.6 and 13.6 m^2 catchment areas, respectively.

The differences between the methods were more apparent in the dry periods of the season, when the simulation method overestimated runoff by as much as 7 times. In

Table 4.10 Comparison between simulated and computed runoff (all figures in mm)

		Plot size (m^2)					
		27.2	27.2	19.6	19.6	13.6	13.6
	RAIN	COMP.	SIM.	COMP.	SIM.	COMP.	SIM.
	3.9	0.0	2.4	0.0	1.7	0.0	1.2
	34.1	2.9	21.1	2.1	15.2	1.5	10.6
	11.5	0.0	7.1	0.0	5.1	0.0	3.6
	5.9	0.0	3.7	0.0	2.6	0.0	1.8
	121.7	74.5	75.5	53.6	54.3	37.3	37.7
	2.2	0.0	1.4	0.0	1.0	0.0	0.7
	25.9	8.6	16.1	6.2	11.6	4.3	8.0
	0.6	0.0	0.4	0.0	0.3	0.0	0.2
	31.0	14.2	19.2	10.2	13.8	7.1	9.6
	3.5	0.1	2.2	0.1	1.6	0.1	1.1
	4.0	0.2	2.5	0.1	1.8	0.1	1.2
	8.8	1.5	5.5	1.1	3.9	0.8	2.7
	5.0	0.4	3.1	0.3	2.2	0.2	1.6
	45.5	33.7	28.2	24.3	20.3	16.9	14.1
	5.0	1.9	3.1	1.4	2.2	1.0	1.6
	20.5	14.7	12.7	10.6	9.2	7.4	6.4
	0.3	0.0	0.2	0.0	0.1	0.0	0.1
	14.4	7.7	8.9	5.5	6.4	3.9	4.5
	5.8	0.9	3.6	0.6	2.6	0.5	1.8
	33.5	23.7	20.8	17.1	15.0	11.9	10.4
	28.5	23.1	17.7	16.6	12.7	11.6	8.8
	24.7	20.1	15.3	14.5	11.0	10.1	7.7
	19.0	14.4	11.8	10.4	8.5	7.2	5.9
	3.1	0.9	1.9	0.6	1.4	0.5	1.0
	33.5	28.1	20.8	20.2	15.0	14.1	10.4
	16.2	12.1	10.0	8.7	7.2	6.1	5.0
	3.1	0.7	1.9	0.5	1.4	0.4	1.0
	1.4	0.0	0.9	0.0	0.6	0.0	0.4
	19.0	2.2	11.8	1.6	8.5	1.1	5.9
TOTAL	531.6	286.6	329.6	206	237.3	143.3	164.8
PERCENT		53.9	62.0	38.8	44.6	27.0	31.0

COMP. = computer output SIM. = portable rainfall simulator

the wetter period, the estimates by the two methods were very close. Computer estimates seemed to increase as the amount of rainfall preceding computation date increased. In the SCS method, runoff seems to be highly influenced by antecedent soil moisture. The amount of runoff produced by a 34.1 mm storm earlier in the season was only 2.9 mm, while a 25.9 mm storm in the wetter time produced 8.6 mm. This is not verified by the simulation technique - perhaps because simulation was done in the dry period. Working on similar soils, Chiti (1991) observed an increase in runoff as a result of increasing soil wetness. This was expected; the capacity of a wet soil to absorb moisture is reduced in direct proportion to the increasing amount of moisture it has.

Sharma (1986) showed that over a catchment area range of 0-144 m^2, runoff generally decreased as the area of the catchment increased. Earlier, Sharma et al. (1982) had found that runoff increased with increasing slope and decreasing slope length. In this experiment, limitations due to equipment unavailability could not permit the determination of the effect of catchment size, slope length and the slope on runoff production.

It can also be observed that the amount of runoff obtained by computer and simulation were 54% and 62% of the seasonal rainfall. A one time coefficient of 61% obtained in a dry period was applied on all rainfall events to obtain runoff in the simulation technique. In addition, the simulator used very high uniform rainfall intensity. Thus the SCS curve number method may be expected to be more accurate for estimating daily runoff if all the parameters are accurately determined.

4.3.2 Daily Rainfall and Crop Evapotranspiration

Daily crop evapotranspiration values were estimated from pan evaporation data collected during the crop growing season and converted using crop factors derived from fig. 4.5.

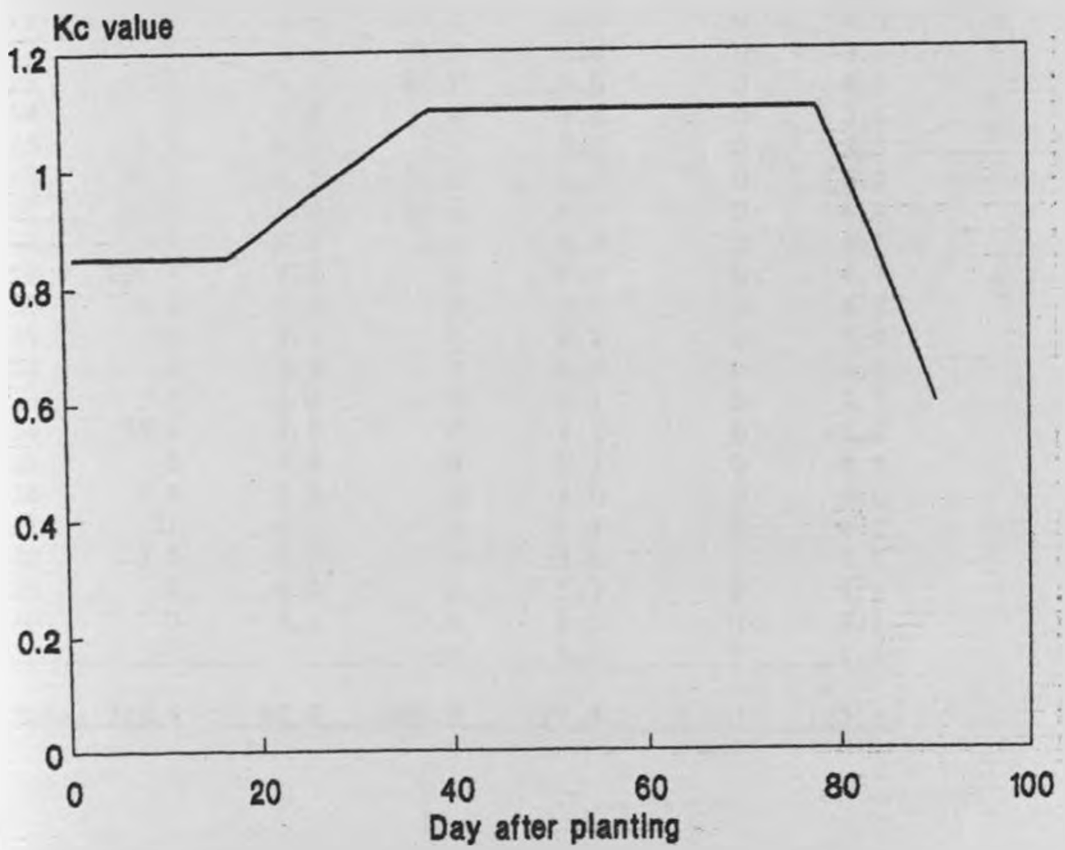

Fig. 4.5. Crop coefficient curve for Katumani Maize.

This data was assumed to be representative for each plot. Daily rainfall was collected using a non-recording gauge placed some 5 m from the evaporation pan. The results are summarised in table 4.11 below.

Table 4.11 Daily rainfall and actual evapotranspiration

	NOVEMBER		DECEMBER		JANUARY	
DAY	Rain	ETA	Rain	ETA	Rain	ETA
1	0	-	8.8	3.4	0	3.8
2	0	-	5	4.2	0	3.4
3	0	-	45.5	3.1	0	4.5
4	14	-	5	4.1	0	4.0
5	0	-	20.1	4.2	0	3.9
6	0	-	0.3	4.0	0	4.0
7	0.5	5.1	14.4	3.2	0	3.5
8	8.4	3.0	0	3.8	0	4.5
9	52.2	4.6	0	3.4	0	4.1
10	0	3.8	5.8	3.9	0	3.4
11	0	3.6	33.5	3.7	0	4.0
12	0	3.8	28.5	4.5	0	3.9
13	0	3.1	24.7	4.8	0	4.3
14	0	4.0	19	3.6	0	3.6
15	3.9	4.2	3.1	3.7	0	3.5
16	34.1	4.3	33.5	3.7	0	4.2
17	11.5	3.0	16.2	4.7	0	4.4
18	5.9	4.7	3.1	4.8	0	4.1
19	121.7	4.0	0	4.3	0	4.7
20	2.2	3.3	0	3.7	0	4.3
21	0	3.7	0	4.1	0	3.9
22	0	3.9	0	4.3	0	4.0
23	0	3.0	0	4.1	0	3.7
24	25.9	4.5	0	4.5	0	3.8
25	0	3.6	0	5.1	0	4.5
26	0.6	3.8	0	5.0	0	3.6
27	31	4.1	0	4.4	0	4.0
28	3.5	3.5	0	3.8	0	3.6
29	4	4.6	0	5.3	0	4.2
30	0	3.1	1.4	4.1	0	3.3
31	-	-	19	3.7	0	3.5
Total	319.4	92.4	286.9	127.4	0	122.1

The table shows the actual evapotranspiration computed for each day. However, during water balance computations, actual evapotranspiration was recomputed again depending on prevailing soil moisture status, and was set equal to computed figure (moisture was adequate) or below these figures (moisture inadequate). The water balance excluded rainfall and evapotranspiration figures between 1/11/90 and 9/11/90 before the crop was planted. A total rainfall of 530.8 mm and evapotranspiration of 341.9 mm were recorded in the cropping season from 10/11/90 to 29/1/91, and 29.2%, 38.7% and 37.1% of seasonal evapo-transpiration were in November, December and January respectively.

4.3.3 Deep Percolation losses

Deep percolation losses were computed on a daily basis once the field capacity was exceeded. The estimated average basic infiltration rate of the soil was used as the saturated hydraulic conductivity of the soil upon which the decaying percolation function was based.

Table 4.12 is a summary of the water balance components of the water balance equation for the whole season for the cropped area of all four treatments. Some observations can be made about these results. First, rainfall is indicated as 530.8 mm whereas the seasonal total was 606.3 mm. This is because the rainfall falling before the planting date was not used

Table 4.12 Water balance of the four treatments

	Component	Catchment area, m^2			
		27.2	19.6	13.6	0.0
1)	Rainfall	530.8	530.8	530.8	530.8
2)	Runoff	287.0	259.7	185.9	0.0
3)	Percolation	368.5	341.9	268.6	84.4
4)	Estimated ET_a	314.1	314.7	314.7	310.7
5)	Last SM	183.1	183.0	182.4	183.6
6)	First SM	47.9	49.2	49.0	47.9
7)	INPUT (1+2)	817.8	790.5	716.7	530.8
8)	LOSS (3+4)	682.6	656.6	583.3	395.1
9)	(5-6)	135.2	133.8	133.4	135.7
10)	(7-8)	135.2	133.9	133.4	135.7

in the water balance computations which started on 10/11/90. Secondly, values for runoff, deep percolation and actual evapotranspiration are those estimated using the computer programme described Chapter 3; values for runoff were scaled down in proportion to the relative size of a catchment area. Initial soil moisture values were actual values as calculated from the first soil moisture analysis for samples collected on 10/11/93. Final soil moisture figures were estimates for each treatment arrived at after running the computer programme.

From these figures, 54.1% of rainfall falling on the 27.2 m^2 catchment became runoff. The figures for actual evapotranspiration and percolation were 37.9% and 45.3% of total moisture, respectively. There were slight variations from one treatment to another, with the figures being 39.3%, 43.3% and 58.6% for evapotranspiration and 43.5%, 38% and 15.5% for percolation. The increasing percentage of ETa with reducing catchment area is because there was less total moisture as the size of thc catchment reduced, while the ETa values remained about the same. Percolation losses were surprisingly high; however, this would be expected from a season where high rainfall was also supplemented with runoff. Percolation was also high because there was no way of establishing how much water was lost when the bunds were breached on 9/11/91 and again on 19/11/91 after heavy rainfall, and thus accounted for run-out as well. Crop evapotranspiration seemed low for a season with so much water from both rainfall and runoff. But elsewhere this rate has been estimated to be possible for Katumani maize.

Table 4.13 gives analysis of variance (ANOVA) values for soil moisture done using randomised block. A summary of gravimetric moisture determination and analysis of variance (ANOVA) computations can be found in Appendices 2 and 3.

There was little difference in soil moisture of the treatments at the beginning of the season, but this changed as the season progressed to reach a maximum of 350, 340, 320 and 315 mm for the largest to the

Table 4.13 Summary of ANOVA for soil moisture

Date	F - Value	Significance (P=0.05)
10/11	0.14	ns
20/11	2.35	ns
30/11	5.49	s
10/12	10.24	s
20/11	7.84	s
30/12	9.24	s
09/01	4.73	s
19/01	5.20	s
29/01	5.04	s

s = significant at P=0.05
ns = not significant

smallest catchments, respectively. The breaching of the soil bunds on 9/11/90 and 19/11/90 caused some problems in the water balance; the amount of runoff could only be estimated, and the runoff and rainfall water lost as run-out could not be seperated from the deep percolation loss from the root zone.

Soil moisture status of the plots were significantly different at P=0.05 in all cases except on 10/11 and 20/11. The first lack of significance (F=0.14) was attributed to the heavy breaching of the soil bunds on 9/11/90. Thus the effect of additional runoff or rainfall was not evident. The second lack of significance was also attributed to a second heavy breaching of the bunds on 19/11/90 after a heavy storm. Subsequent gravimetric sampling every 10 days were significantly different. This shows that there was significant runoff generated by the catchment areas which increased the soil moisture in the root zone of the planted areas.

There was also a mixed crop performance with some of the plots having very poor crop stands. This means that in good stands there was high abstraction of moisture and in poor stands low abstraction of moisture from the soil, again reducing the differences between treatments. Figures 4.6 to 4.9 show the mean gravimetrically determined and computer generated moisture status for all treatments.

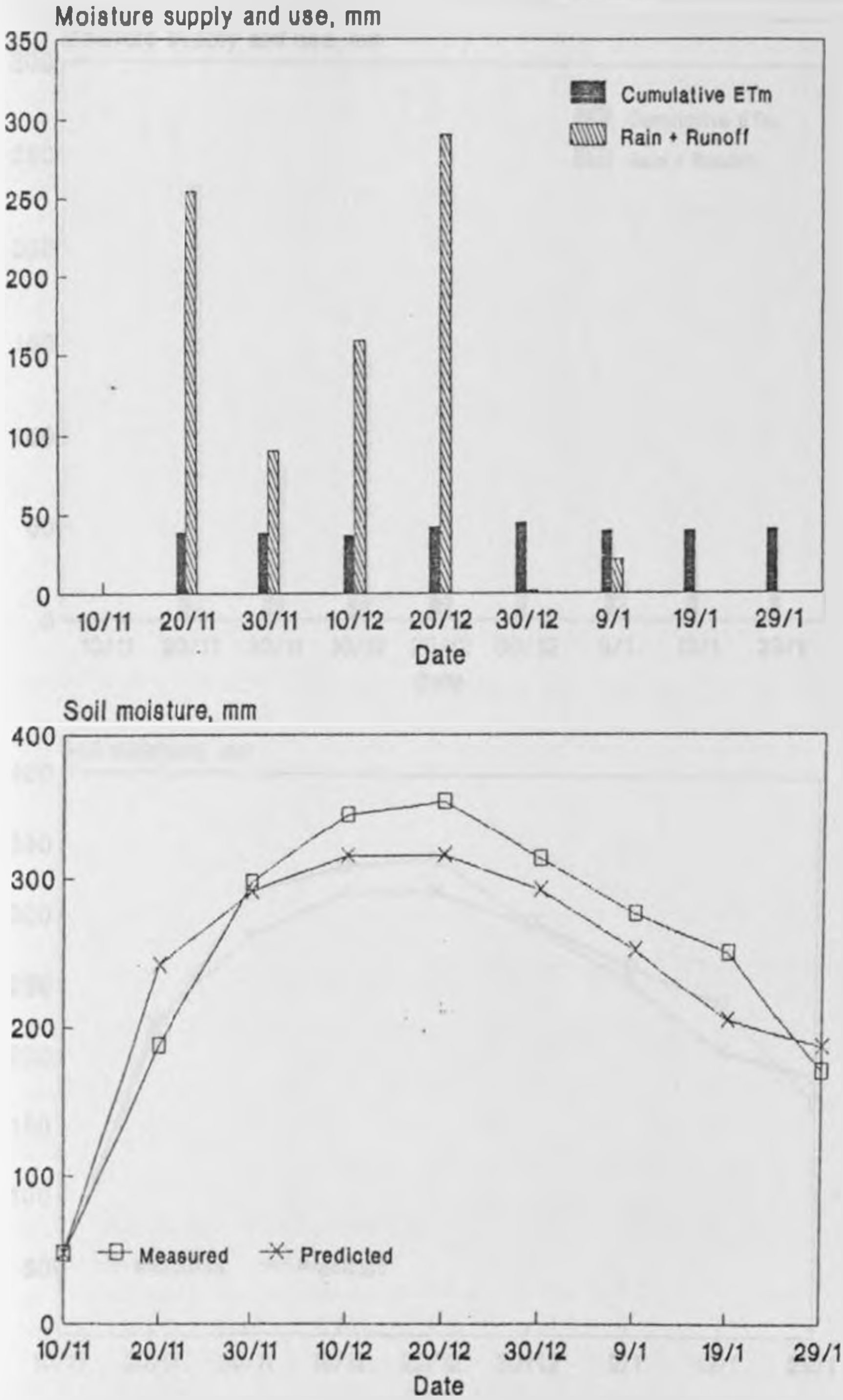

Fig. 4.6 Mean soil moisture for 27.2 m^2 catchment.

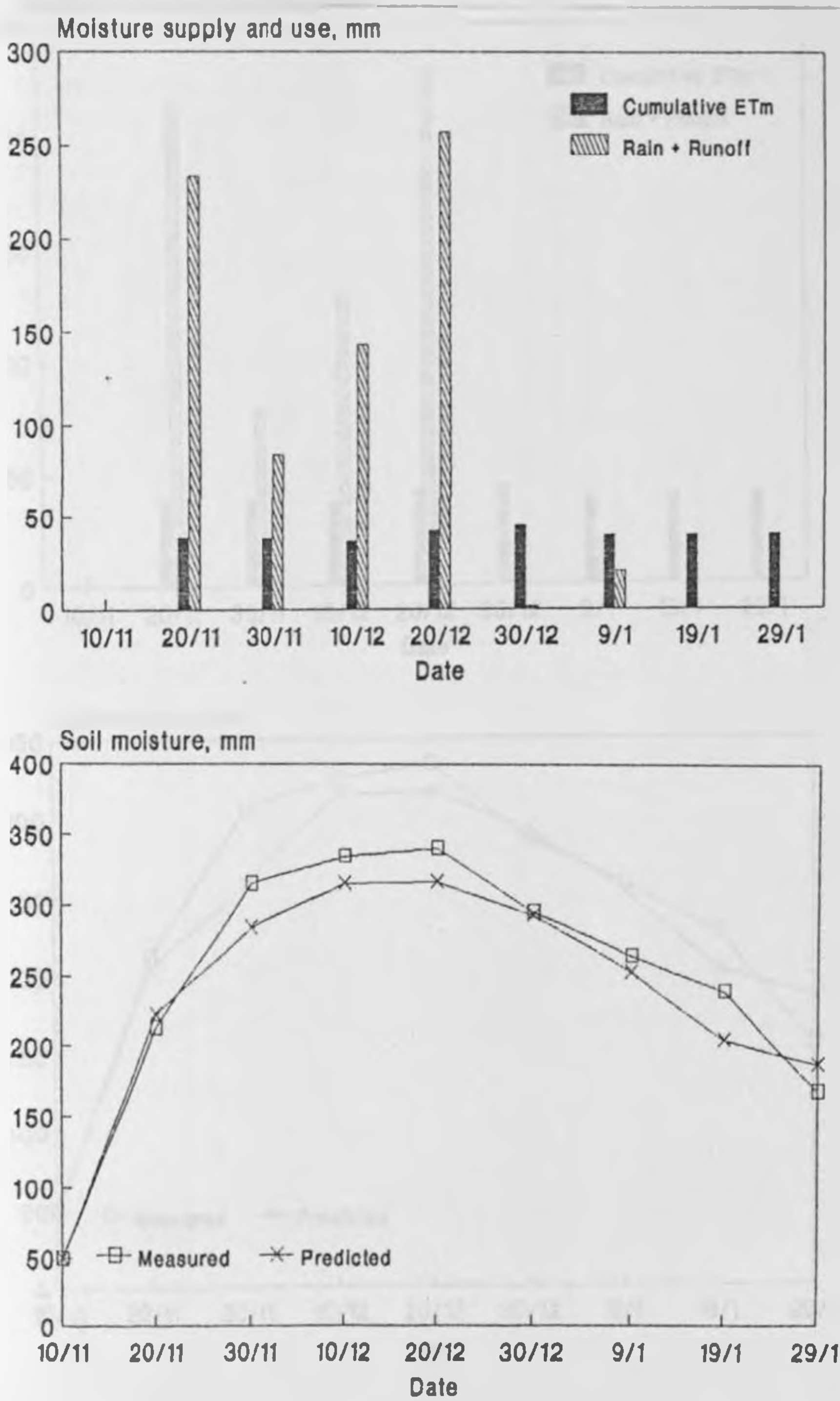

Fig. 4.7 Mean soil moisture for 19.6 m^2 catchment.

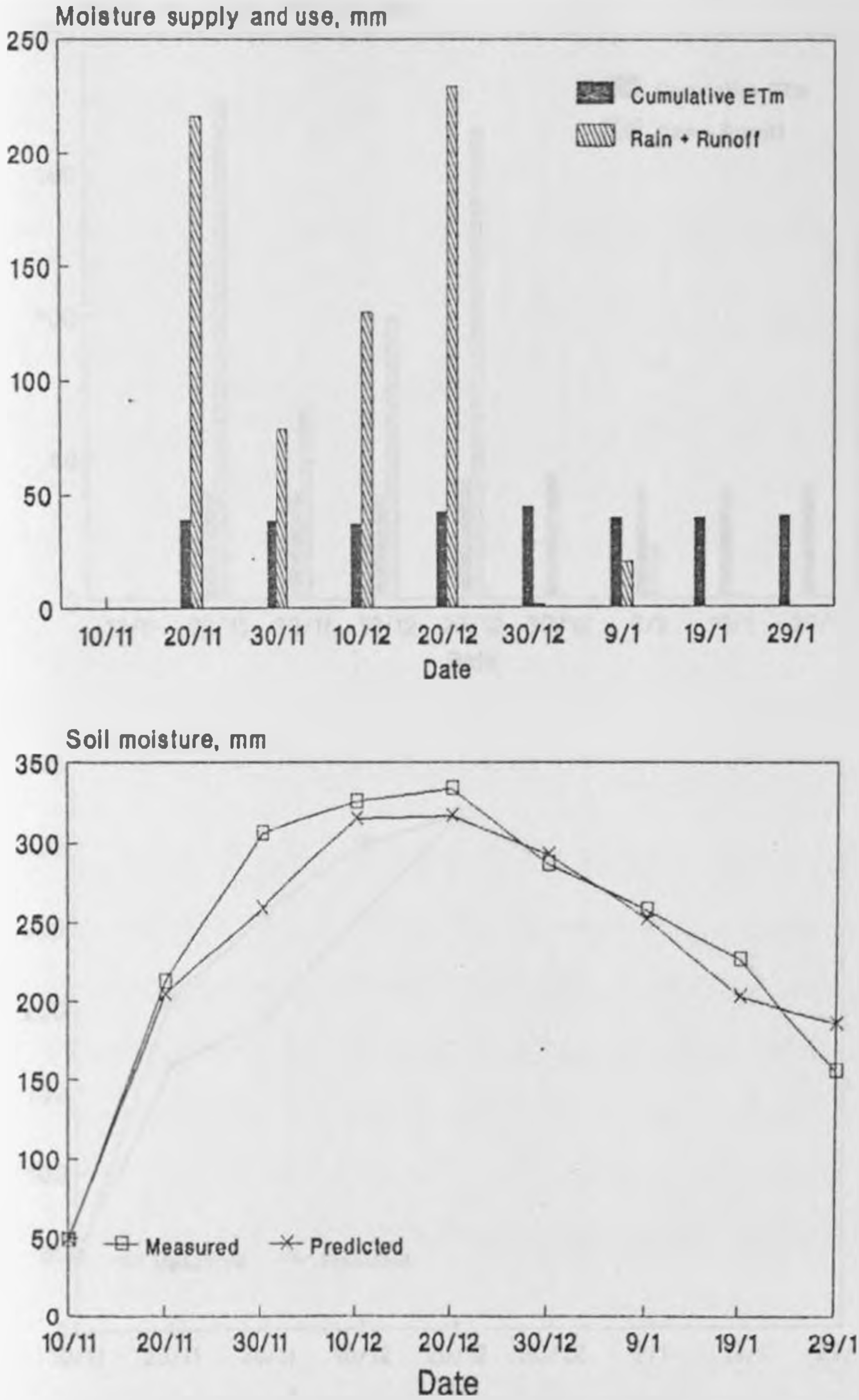

Fig. 4.8 Mean soil moisture for 13.6 m^2 catchment.

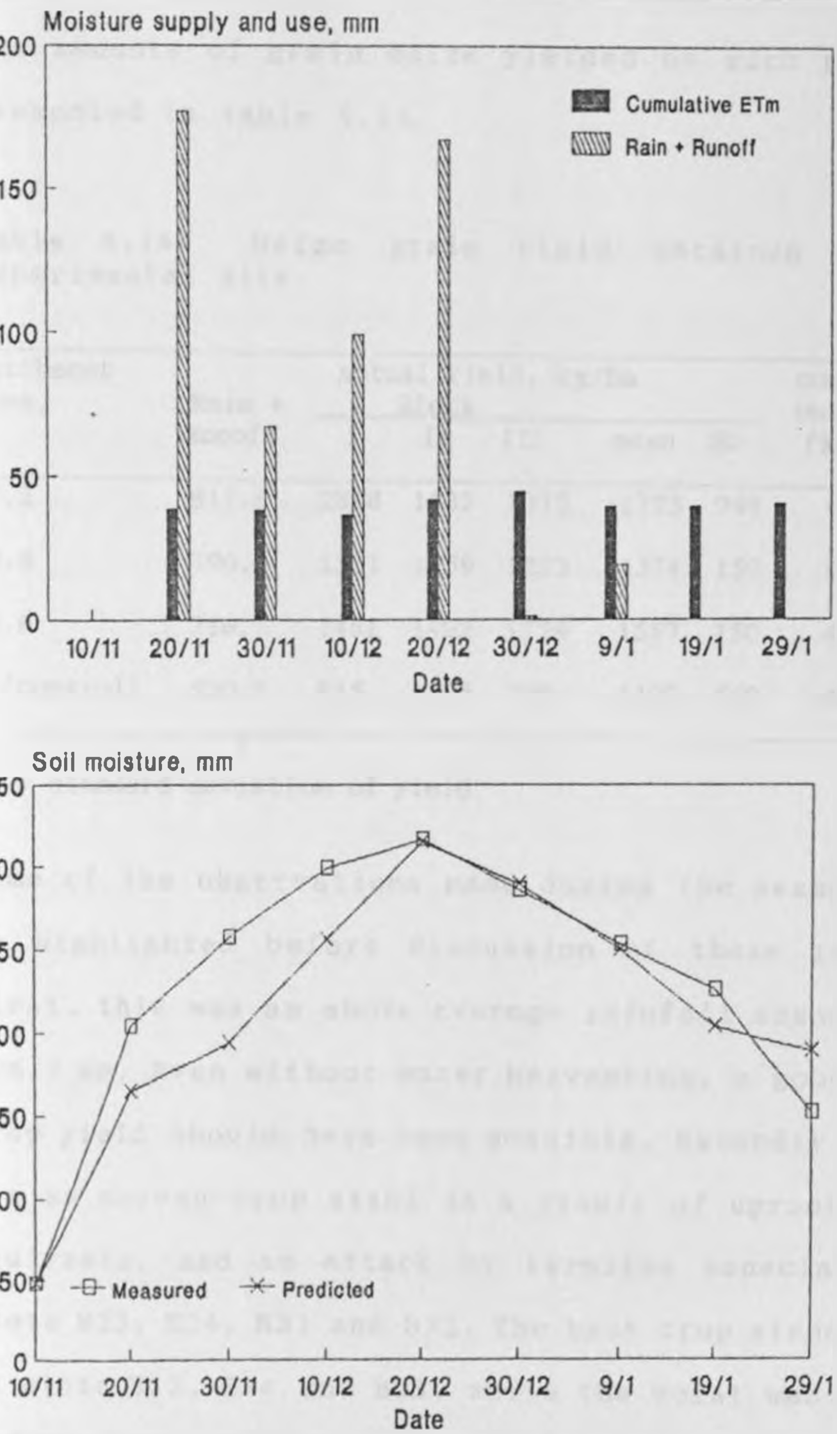

Fig. 4.9 Mean soil moisture for control plot.

4.4 Results of Maize Yields at the Experimental Site

The amounts of grain maize yielded by each plot are presented in table 4.14.

Table 4.14 Maize grain yield obtained at the experimental site

Catchment area, m^2	Rain + Runoff	Actual Yield, kg/ha Block I	II	III	mean	SD	computer output (kg/ha)
27.2	817.8	2868	1435	1075	1793	949	4760
19.6	790.5	1531	1359	1233	1374	150	4770
13.6	716.7	1451	1492	1729	1557	150	4770
0 (Control)	530.8	815	1775	799	1130	559	4690

SD = standard deviation of yield

Some of the observations made during the season will be highlighted before discussion of these results. First, this was an above average rainfall season with 606.3 mm. Even without water harvesting, a good maize crop yield should have been possible. Secondly, there was an uneven crop stand as a result of uprooting by squirrels, and an attack by termites especially on plots B23, B24, B31 and B32. The best crop stands were on plots B13, B14 and B23, while the worst was on B32 and B14. Thirdly, there seemed to be some leaching of nutrients in plot B14; after very good germination, the crop then started yellowing and became stunted, until around the second week of December when the crop gradually changed colour to deep green; this was presumed to be when the crop roots reached a more nutrient-rich soil horizon. By this time the crop was already flowering, but at only 15-20 cm high. Fourth, there was a general water logging effect on the crop especially in plots B13, B21 and B33. The lower half of the plots had a poorer crop due to this effect.

The average crop yields for the treatments were highest for the largest catchment at 1793 kg/ha and smallest for the control plots at 1130 kg/ha. There was a general increase in yield with an increase in catchment size. However, the yields were not significantly different at P=5%. But due to above average seasonal rainfall, these results were not surprising. Thus crop performances could not be attributed to soil moisture availability alone.

The high yield of 2868 kg/ha from plot B13 compares well with yield obtained elsewhere under good management eg Critchley's results in 1984 "short rains" season at UKAI in Kitui (Critchley, 1989). The lower third of the planted area served by larger catchments seemed to have waterlogging effects and crop stands appeared poorer, hence the yiels were also depressed. Under research conditions, Katumani maize planted at 1 plant per hill yielded as high as 5000 kg/ha at Kampi ya Mawe in the "short rains" season of 1978 (Nadar et al., 1984).

There were very small differences in computer yield between treatments. The estimated yields were obtained by multiplying 5000 kg/ha (yield at Kampi ya Mawe which is climatically similar to Mutomo) with the percentage yield obtained from the computer programme. The results were very close with a mean of 4749 kg/ha and a standard deviation of 36 kg/ha. A correction for waterlogging effect in the lower half of the plots would increase the average actual yield of the 27.2 m^2 catchment to 3500 kg/ha. Furthermore, better pest control would give more uniform populations of the treatments and thereby narrow the gap between estimated and the research results.

There were large standard deviations in actual yield; the largest was 949 kg/ha from catchment size 27.2 m^2, and was attributed to the high yield obtained from plot B13 and the low yield from plot B21. The variation in the control plots was also large at 559 kg/ha, and was mostly attributed to the poor stands in plots B14 and B32 and the very good yield obtained from plot B23.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The seasonal rainfall analysis revealed the need for an intervention in the food production system. In the long rains, 71% of the seasons were classified as dry. The highest seasonal rainfall was 32 times the lowest and 400% of the mean. In the average dry season, moisture stress may be experienced only 39 days after seasonal onset, resulting in a crop failure. The seasonal rainfall exceeded on average once in 2 years was 200 mm. In the short rains 57% of the seasons were dry, with the highest rainfall being 6 times the lowest, and 207% of the mean. The average dry season may come just 11 days after seasonal onset. The seasonal rainfall exceeded on average once in 2 years was 400 mm. So the "long rains" season is drier and only suited to fast growing crops of low evapotranspiration demand. In addition, it was found that 58% of rainfall events in the "long rains" and 63% in the "short rains" could produce runoff. There are many areas in Kitui with rainfall patterns much like Mutomo; many more are even drier especially those in agroecological zones LM5 to IL6, covering a total of 1.7 million ha. This land often produces below its capacity due to low soil moisture.

Monthly rainfall was found to best fit a log-normal distribution. There was high rainfall variability in all the months, especially in October. The least variability was in April. Thus April has the most reliable rainfall. November rainfall was better distributed than April (from a comparison of C_v) but large differences between the extremes caused the high variability. Secondly, the mean November rainfall was 212% of the April rainfall, and thus on the strength of the magnitude alone, it has more promise for crop production. The average seasonal coefficient of variation of the "long" and "short" rains were 119% and 137%, and skewness coefficient for the two seasons were 5.0 and 6.0. Thus in both seasons, rainfall was highly unpredictable and the spread between extreme values large.

Potential crop evapotranspiration (PET) was estimated using pan evaporation data for the experimental season. The highest PET was in December (38.7%) as compared to November (24.2%) and January (37.1%). The maximum seasonal evapotranspiration during the experiment was estimated at 327 mm for all the plots, and the actual was 310 mm. The value of ETa was re-estimated and adjusted downwards depending on how dry the soil had become. Katumani maize has been grown with 200 well distributed rainfall, but the yields at such rainfall are low due to moisture stress.

The sandy clay chromic Luvisol was found to have high bulk density ranging from 1490 to 1540 kg/m^{-3}, typical of mineral soils. It was also low in carbon content which was found to decrease with depth. The soil was also very low in silt content with 2-5%. Low clay content of horizons near the surface and high content in lower horizons was due to clay illuviation. The soil had a pH of 6.8-7.4. was low in macro-nutrients N, P and K, and had no salinity or sodicity hazard.

The basic infiltration rate obtained by double-ring infiltrometer method was 14.2 to 75.5 mmh^{-1}. High infiltration rates in some of the plots was attributed to macro-organism activity in the profile. These rates were typical of such kind of soil. Under normal circumstances such a soil would have very low runoff as most of the rain would infiltrate. In this particular case, surface sealing would quickly reduce infiltration; the potential for runoff production from this soil remains high. The range of the estimated saturated hydraulic conductivity of the soil was 0.3-1.8md^{-1}, and the average was 1.05 md^{-1}.

The simulated runoff for the season was 62% and the computer generated runoff value was 54%. Simulated runoff was higher than computer generated runoff in the drier periods, but the two values were very close in the wetter periods of the season. The amount of runoff was dependent on the size of the catchment and also on soil wetness. Computer generated runoff showed a marked sensitivity to initial soil moisture status. High simulated runoff could have been due to both high intensity of storm and surface crusting of the soil. For water harvesting, high runoff production was significant in the determination of potential for crop production. These results were very important. It means that up to 54% of seasonal rainfall falling on crusting soils may become runoff. A water conservation system has to address this moisture loss in unconserved cultivated land. A water harvesting system would greatly improve soil moisture supply by using a catchment area above the cropped area.

The estimated percolation values for the season were 368.5, 341.9, 268.6 and 84.4 mm for the 27.2, 19.6, 13.6 and 0 m^2 plots respectively. These values also accounted for the run-out resulting from the breaching of the soil bunds around the plots on 9/11/90 and 19/11/90 which were unknown. Thus in very wet seasons, up to 45.3% of soil moisture may be lost as deep percolation.

Analysis of variance on gravimetric soil moisture status of the cropped areas found significant difference (P=0.05) in all but 2 occasions, with large catchments having more moisture. The soil moisture evaluated using computer programme closely approximated measured values; discrepancies may be attributed to unaccounted moisture loss by overflow when the soil bunds broke, and by the percolation method used in which soil properties were approximated.

Yield was shown to generally increase with increasing catchment size (increasing moisture supply). The seasonal rainfall was above average and perhaps too high to be the basis of demonstrating the advantages of water harvesting over conventional dryland farming system. Some water logging and pest problems experienced in the experiment seemed to affect crop yields. Therefore based on this experiment, it cannot be concluded that water harvesting has advantage over conventional farming.

5.2 Recommendations

Results of water harvesting experiments are often mixed due to variations of rainfall received in a season with respect to the system design. It is therefore recommended that research is carried on for both "long rains" and "short rains" until adequate data relating evapotranspiration and rainfall to crop yield is collected. This would help designers to safely extrapolate some of the factors when designing. This information is currently limiting especially on locally grown crop varieties.

The heart of a water harvesting research is the water balance of the crop root zone. Due to the limitations placed upon this work by lack of equipment, it is recommended that more work be done on runoff rates, drainage and evapotranspiration. On drainage, such work would be directed at verifying and calibrating the field capacity (FC) model for determining the percolation rate from the crop root zone by using easily measured parameters eg hydraulic conductivity, soil porosity and soil moisture status. Alongside such studies, the complex rainfall-runoff relations should be looked into for several years. This would reveal the influence of slope, soil type, vegetation and antecedent soil moisture on runoff.

Additional studies are also recommended for local calibration and testing of the SCS runoff model for high intensity, low duration tropical storms incedent on ASAL soils, particularly catchments predominated by soils with surface crusting properties. A useful approach to improving this method is suggested by Williams (1990) where soil moisture storage is related to water holding parameters.

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APPENDICES

Appendix 1: Cumulative infiltration data

Time, min.	I_{cum}, mm	Time, min.	I_{cum}, mm	Time, min.	I_{cum}, mm
0.5	4	0.5	3	0.5	3
1	5	1	4	1	4
2	7	2	7	2	8
3	8	3	9	3	10
4	10	4	11	4	12
5	11	5	12	5	14
6	12	6	13	6	17
8	14	7	14	7	19
10	16	8	15	8	21
12	18	10	17	10	26
15	21	12	19	12	31
18	23	14	22	15	36
21	26	16	25	18	42
25	29	20	28	20	45
30	32	25	33	25	54
35	36	30	37	30	62
40	40	35	41	35	69
45	42	40	47	40	77
50	45	45	51	45	87
60	50	50	55	50	96
70	53	55	58	55	103
80	58	60	62	60	109
90	63	70	71	70	114
100	68	80	77	80	134
		90	82	90	149
		100	89	100	164
		110	95	110	177
		120	102	120	191

Appendix 1 (cont.)

Time, min.	I_{cum}, mm	Time, min.	I_{cum}, mm	Time, min.	I_{cum}, mm
0.5	1	0.5	2	0.5	2
1	2	1	4	1	4
2	4	2	6	2	6
3	5	3	7	3	8
4	7	4	9	4	10
5	9	5	10	5	11
6	11	6	12	6	12
7	13	7	13	7	13
8	14	8	14	8	15
10	18	10	17	10	17
12	21	12	19	12	20
14	24	15	22	14	22
16	27	20	30	16	24
20	33	25	35	20	31
25	40	30	40	25	36
30	47	35	44	30	41
35	53	40	49	35	47
40	59	45	54	40	55
45	65	50	59	45	60
50	71	55	62	50	64
55	78	60	66	55	68
60	83	70	73	60	73
70	95	80	79	70	83
82	108	90	88	80	91
90	116			90	99
100	128			100	108
110	138			110	117
120	148				

Appendix 2: Gravimetric calculations of soil moisture

KEY:

W = percent soil moisture (weight basis) BD = bulk density, gcc^{-1}
LT = soil layer thickness, cm H_2O = soil moisture in the layer, mm

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
10/11/90:	B12	7.5	104.1	12.1	0.12	1.49	0.17	7.50	12.99	
		15.0	86.3	12.3	0.14	1.49	0.21	7.50	15.93	
		22.5	74.6	9.1	0.12	1.52	0.19	7.50	13.91	42.8
	B13	7.5	133.7	17.2	0.13	1.49	0.19	7.50	14.38	
		15.0	106.1	15.3	0.14	1.49	0.21	7.50	16.11	
		22.5	88.8	13.6	0.15	1.52	0.23	7.50	17.46	48.0
	B11	7.5	109.6	18.8	0.17	1.49	0.26	7.50	19.17	
		15.0	87.3	13.1	0.15	1.49	0.22	7.50	16.77	
		22.5	91.7	8.1	0.09	1.52	0.13	7.50	10.07	46.0
	B14	7.5	127.4	14.1	0.11	1.49	0.16	7.50	12.37	
		15.0	128.4	15.8	0.12	1.49	0.18	7.50	13.75	
		22.5	102.1	16.6	0.16	1.52	0.25	7.50	18.53	44.7
	B21	7.5	93.2	13.7	0.15	1.49	0.22	7.50	16.43	
		15.0	74.6	12.0	0.16	1.49	0.24	7.50	17.98	
		22.5	73.8	10.4	0.14	1.52	0.21	7.50	16.07	50.5
	B23	7.5	110.3	14.4	0.13	1.49	0.19	7.50	14.59	
		15.0	78.0	12.6	0.16	1.49	0.24	7.50	18.05	
		22.5	68.6	11.1	0.16	1.52	0.25	7.50	18.45	51.1
	B24	7.5	66.9	10.4	0.16	1.49	0.23	7.50	17.37	
		15.0	63.3	9.5	0.15	1.49	0.22	7.50	16.77	
		22.5	67.8	8.8	0.13	1.52	0.20	7.50	14.80	48.9
	B22	7.5	105.5	13.3	0.13	1.49	0.19	7.50	14.09	
		15.0	103.5	14.8	0.14	1.49	0.21	7.50	15.98	
		22.5	91.7	15.1	0.16	1.52	0.25	7.50	18.77	48.8
	B33	7.5	79.9	12.1	0.15	1.49	0.23	7.50	16.92	
		15.0	81.5	10.9	0.13	1.49	0.20	7.50	14.95	
		22.5	73.2	9.7	0.13	1.52	0.20	7.50	15.11	47.0
	B34	7.5	95.5	15.0	0.16	1.49	0.23	7.50	17.55	
		15.0	88.1	13.7	0.16	1.49	0.23	7.50	17.38	
		22.5	93.2	12.4	0.13	1.52	0.20	7.50	15.17	50.1
	B31	7.5	80.8	11.1	0.14	1.49	0.20	7.50	15.35	
		15.0	75.2	11.2	0.15	1.49	0.22	7.50	16.64	
		22.5	72.8	9.7	0.13	1.52	0.20	7.50	15.19	47.2
	B32	7.5	85.9	12.4	0.14	1.49	0.22	7.50	16.13	
		15.0	98.4	18.0	0.18	1.49	0.27	7.50	20.44	
		22.5	84.0	15.0	0.18	1.52	0.27	7.50	20.36	56.9
20/11/90:	B12	7.5	103.9	15.5	0.15	1.49	0.22	15.00	33.34	
		30.0	87.9	15.5	0.18	1.52	0.27	30.00	80.41	
		60.0	78.7	16.0	0.20	1.54	0.31	30.00	93.93	207.7
	B13	7.5	115.2	17.7	0.15	1.49	0.23	15.00	34.34	
		30.0	107.1	21.3	0.20	1.52	0.30	30.00	90.69	
		60.0	73.5	14.3	0.19	1.54	0.30	30.00	89.89	214.9

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
	B11	7.5	50.6	9.8	0.19	1.49	0.29	15.00	43.29	
		30.0	88.8	13.9	0.16	1.52	0.24	30.00	71.38	
		60.0	64.2	11.7	0.18	1.54	0.28	30.00	84.20	198.9
	B14	7.5	124.3	16.2	0.13	1.49	0.19	15.00	29.13	
		30.0	90.9	18.7	0.21	1.52	0.31	30.00	93.81	
		60.0	90.1	15.7	0.17	1.54	0.27	30.00	80.50	203.4
	B21	7.5	74.3	12.0	0.16	1.49	0.24	15.00	36.10	
		30.0	72.4	9.9	0.14	1.52	0.21	30.00	62.35	
		60.0	84.2	14.2	0.17	1.54	0.26	30.00	77.91	176.4
	B23	7.5	100.5	15.1	0.15	1.49	0.22	15.00	33.58	
		30.0	85.7	16.7	0.19	1.52	0.30	30.00	88.86	
		60.0	85.2	18.9	0.22	1.54	0.34	30.00	102.49	224.9
	B24	7.5	96.5	16.6	0.17	1.49	0.26	15.00	38.45	
		30.0	70.5	13.1	0.19	1.52	0.28	30.00	84.73	
		60.0	81.8	11.6	0.14	1.54	0.22	30.00	65.52	188.7
	B22	7.5	118.4	18.3	0.15	1.49	0.23	15.00	34.54	
		30.0	85.5	17.8	0.21	1.52	0.32	30.00	94.93	
		60.0	75.0	14.4	0.19	1.54	0.30	30.00	88.70	218.2
	B33	7.5	73.6	13.5	0.18	1.49	0.27	15.00	41.00	
		30.0	63.2	11.6	0.18	1.52	0.28	30.00	83.70	
		60.0	86.0	13.7	0.16	1.54	0.25	30.00	73.60	198.3
	B34	7.5	90.0	16.7	0.19	1.49	0.28	15.00	41.47	
		30.0	86.6	17.0	0.20	1.52	0.30	30.00	89.52	
		60.0	91.1	17.4	0.19	1.54	0.29	30.00	88.24	219.2
	B31	7.5	89.1	15.4	0.17	1.49	0.26	15.00	38.63	
		30.0	78.3	15.5	0.20	1.52	0.30	30.00	90.27	
		60.0	88.6	11.1	0.13	1.54	0.19	30.00	57.88	186.8
	B32	7.5	87.2	15.9	0.18	1.49	0.27	15.00	40.75	
		30.0	74.3	15.1	0.20	1.52	0.31	30.00	92.67	
		60.0	75.9	13.0	0.17	1.54	0.26	30.00	79.13	212.6
30/11/90:	B12	7.5	93.7	14.6	0.16	1.49	0.23	15.00	34.82	
		30.0	89.5	16.6	0.19	1.52	0.28	30.00	84.58	
		60.0	77.1	14.9	0.19	1.54	0.30	30.00	89.28	
		90.0	83.5	16.4	0.20	1.54	0.30	30.00	90.74	299.4
	B13	7.5	87.3	12.5	0.14	1.49	0.21	15.00	32.00	
		30.0	83.5	15.4	0.18	1.52	0.28	30.00	84.10	
		60.0	66.0	12.3	0.19	1.54	0.29	30.00	86.10	
		90.0	87.3	16.9	0.19	1.54	0.30	30.00	89.44	291.6
	B11	7.5	83.7	16.8	0.20	1.49	0.30	15.00	44.86	
		30.0	74.3	14.1	0.19	1.52	0.29	30.00	86.54	
		60.0	63.6	11.7	0.18	1.54	0.28	30.00	84.99	
		90.0	75.1	14.5	0.19	1.54	0.30	30.00	89.20	305.6
	B14	7.5	105.7	12.5	0.12	1.49	0.18	15.00	26.43	
		30.0	81.0	15.6	0.19	1.52	0.29	30.00	87.82	
		60.0	79.4	14.3	0.18	1.54	0.28	30.00	83.21	
		90.0	100.9	13.6	0.13	1.54	0.21	30.00	62.27	259.7

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
	B21	7.5	79.3	12.3	0.16	1.49	0.23	15.00	34.67	
		30.0	84.0	13.7	0.16	1.52	0.25	30.00	74.37	
		60.0	77.0	14.1	0.18	1.54	0.28	30.00	84.60	
		90.0	88.4	15.4	0.17	1.54	0.27	30.00	80.48	274.1
	B23	7.5	96.9	17.6	0.18	1.49	0.27	15.00	40.59	
		30.0	79.2	15.3	0.19	1.52	0.29	30.00	88.09	
		60.0	81.2	16.8	0.21	1.54	0.32	30.00	95.59	
		90.0	81.7	17.9	0.22	1.54	0.34	30.00	101.22	325.5
	B24	7.5	83.0	9.8	0.12	1.49	0.18	15.00	26.39	
		30.0	74.8	11.6	0.16	1.52	0.24	30.00	70.72	
		60.0	59.1	11.2	0.19	1.54	0.29	30.00	87.55	
		90.0	77.7	10.3	0.13	1.54	0.20	30.00	61.24	245.9
	B22	7.5	102.6	16.8	0.16	1.49	0.24	15.00	36.60	
		30.0	107.3	21.7	0.20	1.52	0.31	30.00	92.22	
		60.0	85.5	17.9	0.21	1.54	0.32	30.00	96.72	
		90.0	84.3	18.6	0.22	1.54	0.34	30.00	101.94	327.5
	B33	7.5	80.0	16.5	0.21	1.49	0.31	15.00	46.10	
		30.0	74.4	15.0	0.20	1.52	0.31	30.00	91.94	
		60.0	65.4	12.9	0.20	1.54	0.30	30.00	91.13	
		90.0	75.8	10.4	0.14	1.54	0.21	30.00	63.39	292.5
	B34	7.5	79.8	11.8	0.15	1.49	0.22	15.00	33.05	
		30.0	77.3	12.7	0.16	1.52	0.25	30.00	74.92	
		60.0	76.5	13.6	0.18	1.54	0.27	30.00	82.13	
		90.0	87.0	14.5	0.17	1.54	0.26	30.00	77.00	267.1
	B31	7.5	97.2	16.8	0.17	1.49	0.26	15.00	38.63	
		30.0	87.5	18.2	0.21	1.52	0.32	30.00	94.85	
		60.0	73.8	15.6	0.21	1.54	0.33	30.00	97.66	
		90.0	85.0	14.6	0.17	1.54	0.26	30.00	79.36	310.5
	B32	7.5	99.9	16.9	0.17	1.49	0.25	15.00	37.81	
		30.0	80.9	16.5	0.20	1.52	0.31	30.00	93.00	
		60.0	85.8	18.0	0.21	1.54	0.32	30.00	96.92	
		90.0	78.7	15.5	0.20	1.54	0.30	30.00	90.99	318.7
10/12/90:	B12	7.5	109.3	16.4	0.15	1.49	0.22	15.00	33.54	
		30.0	97.8	20.7	0.21	1.52	0.32	30.00	96.52	
		60.0	76.9	16.6	0.22	1.54	0.33	30.00	99.73	
		90.0	94.0	20.3	0.22	1.54	0.33	30.00	99.77	329.6
	B13	7.5	102.0	17.2	0.17	1.49	0.25	15.00	37.69	
		30.0	92.9	18.7	0.20	1.52	0.31	30.00	91.79	
		60.0	92.4	18.9	0.20	1.54	0.32	30.00	94.50	
		90.0	93.7	19.6	0.21	1.54	0.32	30.00	96.64	320.6
	B11	7.5	84.7	16.3	0.19	1.49	0.29	15.00	43.01	
		30.0	85.2	18.1	0.21	1.52	0.32	30.00	96.87	
		60.0	79.1	17.3	0.22	1.54	0.34	30.00	101.04	
		90.0	80.9	18.1	0.22	1.54	0.34	30.00	103.36	344.3
	B14	7.5	104.0	15.1	0.15	1.49	0.22	15.00	32.45	
		30.0	91.5	17.3	0.19	1.52	0.29	30.00	86.22	
		60.0	87.1	18.3	0.21	1.54	0.32	30.00	97.07	
		90.0	104.3	21.8	0.21	1.54	0.32	30.00	96.56	312.3

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
	B21	7.5	89.8	16.7	0.19	1.49	0.28	15.00	41.56	
		30.0	85.8	18.1	0.21	1.52	0.32	30.00	96.20	
		60.0	82.7	19.4	0.23	1.54	0.36	30.00	108.38	
		90.0	91.4	20.9	0.23	1.54	0.35	30.00	105.64	351.8
	B23	7.5	103.4	18.1	0.18	1.49	0.26	15.00	39.12	
		30.0	81.5	17.1	0.21	1.52	0.32	30.00	95.68	
		60.0	74.5	16.6	0.22	1.54	0.34	30.00	102.94	
		90.0	108.3	22.9	0.21	1.54	0.33	30.00	97.69	335.4
	B24	7.5	84.6	14.0	0.17	1.49	0.25	15.00	36.99	
		30.0	78.0	14.5	0.19	1.52	0.28	30.00	84.77	
		60.0	78.0	14.3	0.18	1.54	0.28	30.00	84.70	
		90.0	92.5	15.8	0.17	1.54	0.26	30.00	78.91	285.4
	B22	7.5	100.2	17.9	0.18	1.49	0.27	15.00	39.93	
		30.0	91.0	18.7	0.21	1.52	0.31	30.00	93.71	
		60.0	84.4	18.9	0.22	1.54	0.34	30.00	103.46	
		90.0	90.4	20.7	0.23	1.54	0.35	30.00	105.79	342.9
	B33	7.5	99.3	19.5	0.20	1.49	0.29	15.00	43.89	
		30.0	94.9	18.1	0.19	1.52	0.29	30.00	86.97	
		60.0	81.8	18.9	0.23	1.54	0.36	30.00	106.75	
		90.0	99.0	19.6	0.20	1.54	0.30	30.00	91.47	329.1
	B34	7.5	93.6	15.3	0.16	1.49	0.24	15.00	36.53	
		30.0	99.7	18.8	0.19	1.52	0.29	30.00	85.99	
		60.0	80.0	15.8	0.20	1.54	0.30	30.00	91.25	
		90.0	90.6	16.7	0.18	1.54	0.28	30.00	85.16	298.9
	B31	7.5	112.4	20.3	0.18	1.49	0.27	15.00	40.37	
		30.0	94.4	18.1	0.19	1.52	0.29	30.00	87.43	
		60.0	79.5	17.6	0.22	1.54	0.34	30.00	102.28	
		90.0	81.3	18.4	0.23	1.54	0.35	30.00	104.56	334.6
	B32	7.5	104.1	17.1	0.16	1.49	0.24	15.00	36.71	
		30.0	89.8	18.2	0.20	1.52	0.31	30.00	92.42	
		60.0	88.2	20.1	0.23	1.54	0.35	30.00	105.29	
		90.0	81.5	18.2	0.22	1.54	0.34	30.00	103.17	337.6
20/12/90:	B12	7.5	102.2	16.8	0.16	1.49	0.24	15.00	36.74	
		30.0	88.2	18.2	0.21	1.52	0.31	30.00	94.10	
		60.0	72.3	16.3	0.23	1.54	0.35	30.00	104.16	
		90.0	95.4	21.1	0.22	1.54	0.34	30.00	102.18	337.2
	B13	7.5	107.2	18.9	0.18	1.49	0.26	15.00	39.40	
		30.0	96.1	19.8	0.21	1.52	0.31	30.00	93.95	
		60.0	76.9	16.1	0.21	1.54	0.32	30.00	96.73	
		90.0	95.1	20.6	0.22	1.54	0.33	30.00	100.08	330.2
	B11	7.5	97.3	18.7	0.19	1.49	0.29	15.00	42.95	
		30.0	93.0	21.3	0.23	1.52	0.35	30.00	104.44	
		60.0	80.5	17.5	0.22	1.54	0.33	30.00	100.43	
		90.0	88.4	20.2	0.23	1.54	0.35	30.00	105.57	353.4
	B14	7.5	85.9	13.4	0.16	1.49	0.23	15.00	34.86	
		30.0	79.3	16.0	0.20	1.52	0.31	30.00	92.01	
		60.0	82.1	17.6	0.21	1.54	0.33	30.00	99.04	
		90.0	110.4	23.9	0.22	1.54	0.33	30.00	100.02	325.9

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H_2O, mm	
	B21	7.5	65.8	12.3	0.19	1.49	0.28	15.00	41.78	
		30.0	80.3	16.8	0.21	1.52	0.32	30.00	95.40	
		60.0	79.7	15.2	0.19	1.54	0.29	30.00	88.11	
		90.0	108.4	20.3	0.19	1.54	0.29	30.00	86.52	311.8
	B23	7.5	81.5	8.2	0.10	1.49	0.15	15.00	22.49	
		30.0	82.5	15.9	0.19	1.52	0.29	30.00	87.88	
		60.0	83.4	15.8	0.19	1.54	0.29	30.00	87.53	
		90.0	97.7	18.6	0.19	1.54	0.29	30.00	87.95	285.9
	B24	7.5	70.9	10.6	0.15	1.49	0.22	15.00	33.41	
		30.0	78.9	13.6	0.17	1.52	0.26	30.00	78.60	
		60.0	80.2	14.1	0.18	1.54	0.27	30.00	81.22	
		90.0	76.3	12.9	0.17	1.54	0.26	30.00	78.11	271.3
	B22	7.5	90.4	13.6	0.15	1.49	0.22	15.00	33.62	
		30.0	84.6	15.6	0.18	1.52	0.28	30.00	84.09	
		60.0	85.3	17.2	0.20	1.54	0.31	30.00	93.16	
		90.0	99.9	18.7	0.19	1.54	0.29	30.00	86.48	297.3
	B33	7.5	74.3	9.8	0.13	1.49	0.20	15.00	29.48	
		30.0	70.6	12.4	0.18	1.52	0.27	30.00	80.09	
		60.0	74.0	15.1	0.20	1.54	0.31	30.00	94.27	
		90.0	77.9	14.6	0.19	1.54	0.29	30.00	86.59	290.4
	B34	7.5	67.7	9.5	0.14	1.49	0.21	15.00	31.36	
		30.0	71.3	13.9	0.19	1.52	0.30	30.00	88.90	
		60.0	71.5	13.5	0.19	1.54	0.29	30.00	87.23	
		90.0	87.1	15.8	0.18	1.54	0.28	30.00	83.81	291.3
	B31	7.5	64.6	13.5	0.21	1.49	0.31	15.00	46.71	
		30.0	83.5	15.8	0.19	1.52	0.29	30.00	86.29	
		60.0	86.9	16.7	0.19	1.54	0.30	30.00	88.78	
		90.0	93.0	17.5	0.19	1.54	0.29	30.00	86.94	308.7
	B32	7.5	73.8	11.2	0.15	1.49	0.23	15.00	33.92	
		30.0	72.4	11.8	0.16	1.52	0.25	30.00	74.32	
		60.0	76.5	14.8	0.19	1.54	0.30	30.00	89.38	
		90.0	72.9	15.9	0.22	1.54	0.34	30.00	100.77	298.4
9/1/91:	B12	7.5	103.3	13.2	0.13	1.49	0.19	15.00	28.56	
		30.0	96.4	14.1	0.15	1.52	0.22	30.00	66.70	
		60.0	73.9	13.6	0.18	1.54	0.28	30.00	85.02	
		90.0	95.3	18.2	0.19	1.54	0.29	30.00	88.23	268.5
	B13	7.5	118.6	12.2	0.10	1.49	0.15	15.00	22.99	
		30.0	75.1	12.3	0.16	1.52	0.25	30.00	74.68	
		60.0	75.7	12.6	0.17	1.54	0.26	30.00	76.90	
		90.0	89.0	15.2	0.17	1.54	0.26	30.00	78.90	253.5
	B11	7.5	73.0	10.9	0.15	1.49	0.22	15.00	33.37	
		30.0	82.2	14.6	0.18	1.52	0.27	30.00	80.99	
		60.0	69.9	12.2	0.17	1.54	0.27	30.00	80.64	
		90.0	95.4	16.8	0.18	1.54	0.27	30.00	81.36	276.4
	B14	7.5	102.9	10.2	0.10	1.49	0.15	15.00	22.15	
		30.0	80.6	14.3	0.18	1.52	0.27	30.00	80.90	
		60.0	85.9	15.2	0.18	1.54	0.27	30.00	81.75	
		90.0	93.6	16.2	0.17	1.54	0.27	30.00	79.96	264.8

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H20, mm	
	B21	7.5	94.2	17.9	0.19	1.49	0.28	15.00	42.47	
		30.0	82.4	17.9	0.22	1.52	0.33	30.00	99.06	
		60.0	79.2	18.1	0.23	1.54	0.35	30.00	105.58	
		90.0	86.9	19.1	0.22	1.54	0.34	30.00	101.54	348.7
	B23	7.5	94.0	17.1	0.18	1.49	0.27	15.00	40.66	
		30.0	88.6	18.9	0.21	1.52	0.32	30.00	97.27	
		60.0	94.0	21.5	0.23	1.54	0.35	30.00	105.67	
		90.0	107.9	24.5	0.23	1.54	0.35	30.00	104.90	348.5
	B24	7.5	89.9	15.3	0.17	1.49	0.25	15.00	38.04	
		30.0	78.1	15.1	0.19	1.52	0.29	30.00	88.16	
		60.0	90.4	17.1	0.19	1.54	0.29	30.00	87.39	
		90.0	104.3	21.8	0.21	1.54	0.32	30.00	96.56	310.2
	B22	7.5	113.5	20.8	0.18	1.49	0.27	15.00	40.96	
		30.0	90.7	18.9	0.21	1.52	0.32	30.00	95.02	
		60.0	90.0	20.1	0.22	1.54	0.34	30.00	103.18	
		90.0	110.4	24.5	0.22	1.54	0.34	30.00	102.53	341.7
	B33	7.5	91.4	18.2	0.20	1.49	0.30	15.00	44.50	
		30.0	91.1	18.9	0.21	1.52	0.32	30.00	94.60	
		60.0	82.4	19.1	0.23	1.54	0.36	30.00	107.09	
		90.0	98.2	18.4	0.19	1.54	0.29	30.00	86.57	332.8
	B34	7.5	97.7	17.5	0.18	1.49	0.27	15.00	40.03	
		30.0	78.0	15.8	0.20	1.52	0.31	30.00	92.37	
		60.0	72.4	16.2	0.22	1.54	0.34	30.00	103.38	
		90.0	94.8	16.9	0.18	1.54	0.27	30.00	82.36	318.1
	B31	7.5	99.3	18.4	0.19	1.49	0.28	15.00	41.41	
		30.0	78.7	16.2	0.21	1.52	0.31	30.00	93.87	
		60.0	71.3	20.2	0.28	1.54	0.44	30.00	130.89	
		90.0	98.4	15.8	0.16	1.54	0.25	30.00	74.18	340.4
	B32	7.5	95.1	17.4	0.18	1.49	0.27	15.00	40.89	
		30.0	88.3	17.9	0.20	1.52	0.31	30.00	92.44	
		60.0	77.4	17.6	0.23	1.54	0.35	30.00	105.05	
		90.0	86.9	18.6	0.21	1.54	0.33	30.00	98.89	337.3
30/12/90	B12	7.5	78.7	12.6	0.16	1.49	0.24	15.00	35.78	
		30.0	78.5	13.9	0.18	1.52	0.27	30.00	80.74	
		60.0	72.2	14.6	0.20	1.54	0.31	30.00	93.42	
		90.0	80.9	15.2	0.19	1.54	0.29	30.00	86.80	296.8
	B13	7.5	99.5	11.4	0.11	1.49	0.17	15.00	25.61	
		30.0	88.0	14.4	0.16	1.52	0.25	30.00	74.62	
		60.0	69.0	13.4	0.19	1.54	0.30	30.00	89.72	
		90.0	88.9	18.9	0.21	1.54	0.33	30.00	98.22	288.2
	B11	7.5	85.4	13.6	0.16	1.49	0.24	15.00	35.59	
		30.0	79.0	15.8	0.20	1.52	0.30	30.00	91.20	
		60.0	72.4	15.9	0.22	1.54	0.34	30.00	101.46	
		90.0	76.5	14.9	0.19	1.54	0.30	30.00	89.98	318.2
	B14	7.5	105.3	12.8	0.12	1.49	0.18	15.00	27.17	
		30.0	86.3	17.7	0.21	1.52	0.31	30.00	93.52	
		60.0	73.2	15.5	0.21	1.54	0.33	30.00	97.83	
		90.0	98.2	16.8	0.17	1.54	0.26	30.00	79.04	297.6

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
	B21	7.5	81.3	11.6	0.14	1.49	0.21	15.00	31.89	
		30.0	70.3	12.7	0.18	1.52	0.27	30.00	82.38	
		60.0	77.1	13.8	0.18	1.54	0.28	30.00	82.69	
		90.0	113.1	18.8	0.17	1.54	0.26	30.00	76.80	273.8
	B23	7.5	93.1	12.5	0.13	1.49	0.20	15.00	30.01	
		30.0	79.1	14.5	0.18	1.52	0.28	30.00	83.59	
		60.0	75.1	13.9	0.19	1.54	0.29	30.00	85.51	
		90.0	102.4	14.8	0.14	1.54	0.22	30.00	66.77	265.9
	B24	7.5	84.5	8.4	0.10	1.49	0.15	15.00	22.22	
		30.0	92.1	14.9	0.16	1.52	0.25	30.00	73.77	
		60.0	81.5	13.2	0.16	1.54	0.25	30.00	74.83	
		90.0	90.3	14.4	0.16	1.54	0.25	30.00	73.67	244.5
	B22	7.5	92.1	9.8	0.11	1.49	0.16	15.00	23.78	
		30.0	87.8	15.7	0.18	1.52	0.27	30.00	81.54	
		60.0	75.7	14.1	0.19	1.54	0.29	30.00	86.05	
		90.0	102.8	15.7	0.15	1.54	0.24	30.00	70.56	261.9
	B33	7.5	93.1	13.1	0.14	1.49	0.21	15.00	31.45	
		30.0	85.6	14.6	0.17	1.52	0.26	30.00	77.78	
		60.0	76.5	12.8	0.17	1.54	0.26	30.00	77.30	
		90.0	94.7	14.9	0.16	1.54	0.24	30.00	72.69	259.2
	B34	7.5	88.6	9.3	0.10	1.49	0.16	15.00	23.46	
		30.0	85.4	14.4	0.17	1.52	0.26	30.00	76.89	
		60.0	90.4	15.1	0.17	1.54	0.26	30.00	77.17	
		90.0	99.0	15.4	0.16	1.54	0.24	30.00	71.87	249.4
	B31	7.5	99.2	12.4	0.13	1.49	0.19	15.00	27.94	
		30.0	86.4	14.8	0.17	1.52	0.26	30.00	78.11	
		60.0	80.6	14.2	0.18	1.54	0.27	30.00	81.39	
		90.0	74.9	13.4	0.18	1.54	0.28	30.00	82.65	270.1
	B32	7.5	92.4	14.6	0.16	1.49	0.24	15.00	35.31	
		30.0	99.2	15.9	0.16	1.52	0.24	30.00	73.09	
		60.0	94.3	16.8	0.18	1.54	0.27	30.00	82.31	
		90.0	99.1	16.1	0.16	1.54	0.25	30.00	75.06	265.8
19/1/91:	B12	7.5	107.6	11.2	0.10	1.49	0.16	15.00	23.26	
		30.0	89.7	13.6	0.15	1.52	0.23	30.00	69.14	
		60.0	63.9	11.1	0.17	1.54	0.27	30.00	80.25	
		90.0	68.5	11.6	0.17	1.54	0.26	30.00	78.24	250.9
	B13	7.5	97.2	8.8	0.09	1.49	0.13	15.00	20.23	
		30.0	80.1	12.3	0.15	1.52	0.23	30.00	70.02	
		60.0	88.4	13.9	0.16	1.54	0.24	30.00	72.64	
		90.0	79.2	12.3	0.16	1.54	0.24	30.00	71.75	234.7
	B11	7.5	74.9	10.1	0.13	1.49	0.20	15.00	30.14	
		30.0	77.6	11.7	0.15	1.52	0.23	30.00	68.75	
		60.0	81.7	12.8	0.16	1.54	0.24	30.00	72.38	
		90.0	85.1	16.2	0.19	1.54	0.29	30.00	87.95	259.2
	B14	7.5	116.2	10.4	0.09	1.49	0.13	15.00	20.00	
		30.0	90.6	14.6	0.16	1.52	0.24	30.00	73.48	
		60.0	89.2	15.4	0.17	1.54	0.27	30.00	79.76	
		90.0	111.6	16.7	0.15	1.54	0.23	30.00	69.13	242.4

Appendix 2 (cont.)

	Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
	B21	7.5	81.5	10.2	0.13	1.49	0.19	15.00	27.97	
		30.0	86.6	13.1	0.15	1.52	0.23	30.00	68.98	
		60.0	88.6	14.9	0.17	1.54	0.26	30.00	77.70	
		90.0	93.6	14.2	0.15	1.54	0.23	30.00	70.09	244.7
	B23	7.5	102.8	9.9	0.10	1.49	0.14	15.00	21.52	
		30.0	87.1	14.5	0.17	1.52	0.25	30.00	75.91	
		60.0	80.4	11.7	0.15	1.54	0.22	30.00	67.23	
		90.0	78.8	11.6	0.15	1.54	0.23	30.00	68.01	232.7
	B24	7.5	87.4	6.7	0.08	1.49	0.11	15.00	17.13	
		30.0	83.3	12.3	0.15	1.52	0.22	30.00	67.33	
		60.0	89.7	13.8	0.15	1.54	0.24	30.00	71.08	
		90.0	78.6	9.9	0.13	1.54	0.19	30.00	58.19	213.7
	B22	7.5	89.4	8.0	0.09	1.49	0.13	15.00	20.00	
		30.0	82.3	12.7	0.15	1.52	0.23	30.00	70.37	
		60.0	79.3	11.9	0.15	1.54	0.23	30.00	69.33	
		90.0	96.1	15.7	0.16	1.54	0.25	30.00	75.48	235.2
	B33	7.5	93.3	10.1	0.11	1.49	0.16	15.00	24.19	
		30.0	82.3	13.4	0.16	1.52	0.25	30.00	74.25	
		60.0	85.1	13.9	0.16	1.54	0.25	30.00	75.46	
		90.0	91.7	10.3	0.11	1.54	0.17	30.00	51.89	225.8
	B34	7.5	90.6	9.9	0.11	1.49	0.16	15.00	24.42	
		30.0	81.8	12.6	0.15	1.52	0.23	30.00	70.24	
		60.0	88.7	13.2	0.15	1.54	0.23	30.00	68.75	
		90.0	91.0	12.4	0.14	1.54	0.21	30.00	62.95	226.4
	B31	7.5	102.1	13.0	0.13	1.49	0.19	15.00	28.46	
		30.0	92.6	15.2	0.16	1.52	0.25	30.00	74.85	
		60.0	98.7	14.5	0.15	1.54	0.23	30.00	67.87	
		90.0	94.5	13.4	0.14	1.54	0.22	30.00	65.51	236.7
	B32	7.5	100.9	11.4	0.11	1.49	0.17	15.00	25.25	
		30.0	104.1	15.1	0.15	1.52	0.22	30.00	66.14	
		60.0	92.3	14.2	0.15	1.54	0.24	30.00	71.08	
		90.0	95.6	13.9	0.15	1.54	0.22	30.00	67.17	229.6
29/1/91:	B12	7.5	104.7	7.8	0.07	1.49	0.11	15.00	16.65	
		30.0	103.6	15.1	0.15	1.52	0.22	30.00	66.46	
		60.0	88.8	14.7	0.17	1.54	0.25	30.00	76.48	159.6
	B13	7.5	117.5	6.2	0.05	1.49	0.08	15.00	11.79	
		30.0	104.3	16.0	0.15	1.52	0.23	30.00	69.95	
		60.0	82.2	13.1	0.16	1.54	0.25	30.00	73.63	155.4
	B11	7.5	98.4	10.9	0.11	1.49	0.17	15.00	24.76	
		30.0	103.8	15.8	0.15	1.52	0.23	30.00	69.41	
		60.0	93.1	14.7	0.16	1.54	0.24	30.00	72.95	167.1
	B14	7.5	124.0	8.1	0.07	1.49	0.10	15.00	14.60	
		30.0	105.5	17.2	0.16	1.52	0.25	30.00	74.34	
		60.0	99.2	12.8	0.13	1.54	0.20	30.00	59.61	148.6

Appendix 2 (cont.)

Plot	Depth	Soil(g)	Water(g)	W (g/g)	BD	W*BD	LT, cm	H2O, mm	
B21	7.5	94.2	8.7	0.09	1.49	0.14	15.00	20.64	
	30.0	88.3	13.2	0.15	1.52	0.23	30.00	68.17	
	60.0	88.2	13.8	0.16	1.54	0.24	30.00	72.29	161.1
B23	7.5	108.5	7.2	0.07	1.49	0.10	15.00	14.83	
	30.0	89.9	12.6	0.14	1.52	0.21	30.00	63.91	
	60.0	93.0	15.8	0.17	1.54	0.26	30.00	78.49	157.2
B24	7.5	93.1	9.3	0.10	1.49	0.15	15.00	22.33	
	30.0	91.6	12.0	0.13	1.52	0.20	30.00	59.74	
	60.0	89.3	13.4	0.15	1.54	0.23	30.00	69.33	151.4
B22	7.5	101.4	7.8	0.08	1.49	0.11	15.00	17.19	
	30.0	88.9	13.5	0.15	1.52	0.23	30.00	69.25	
	60.0	87.0	13.9	0.16	1.54	0.25	30.00	73.81	160.3
B33	7.5	96.2	8.8	0.09	1.49	0.14	15.00	20.44	
	30.0	87.7	10.4	0.12	1.52	0.18	30.00	54.08	
	60.0	89.7	15.3	0.17	1.54	0.26	30.00	78.80	153.3
B34	7.5	87.6	8.3	0.09	1.49	0.14	15.00	21.18	
	30.0	96.9	13.3	0.14	1.52	0.21	30.00	62.59	
	60.0	94.9	14.3	0.15	1.54	0.23	30.00	69.62	153.4
B31	7.5	97.3	11.8	0.12	1.49	0.18	15.00	27.10	
	30.0	100.6	16.2	0.16	1.52	0.24	30.00	73.43	
	60.0	83.7	15.1	0.18	1.54	0.28	30.00	83.35	183.9
B32	7.5	102.3	9.4	0.09	1.49	0.14	15.00	20.54	
	30.0	98.4	15.2	0.15	1.52	0.23	30.00	70.44	
	60.0	91.4	17.8	0.19	1.54	0.30	30.00	89.97	180.9

Appendix 3: Analysis of Variance on soil moisture.

Key:
Treatments 1 for 27.2, 2 for 19.6, 3 for 13.6 and 4 for 0 sq m catchment.

Date: 10/11/90

Block	Treatment 1	2	3	4			
1	46	42.8	48	44.7	181.5	32942.25	8249.93
2	50.5	48.8	51.1	48.9	199.3	39720.49	9934.11
3	47.2	56.9	47	50.1	201.2	40481.44	10184.46
	143.7	148.5	146.1	143.7	582	28232.28	
	20649.69	22052.25	21345.21	20649.69	28286.05	28227.00	141.50

Variation	df	SS	MS	F
Trt	3	5.28	1.76	0.14
Blk	2	59.05	29.52	2.30
Error	6	77.17	12.86	
Total	11	141.50		

Date: 20/11/90

Block	Treatment 1	2	3	4			
1	198.9	207.7	214.9	203.4	824.9	6.80E+05	1.70E+05
2	176.4	218.2	224.9	188.8	808.3	6.53E+05	1.65E+05
3	186.8	212.6	198.3	219.2	816.9	6.67E+05	1.67E+05
	562.1	638.5	638.1	611.4	2450.1	501540.0	
	315956.4	407682.2	407171.6	373809.9	5.00E+05	5.00E+05	2423.08

Variation	df	SS	MS	F
Trt	3	1290.91	430.30	2.35
Error	6	1097.71	182.95	0.09
Blk	2	34.46	17.23	
Total	11	2423.08		

Date: 30/11/90

Block	Treatment 1	2	3	4			
1	305.6	299.4	291.6	259.7	1156.3	1.34E+06	3.36E+05
2	274.1	327.5	325.5	245.9	1173	1.38E+06	3.49E+05
3	310.5	318.7	292.5	267.1	1188.8	1.41E+06	3.55E+05
	890.2	945.6	909.6	772.7	3518.1	1037017.	
	792456.0	894159.3	827372.1	597065.2	1.03E+06	1.03E+06	7770.12

Variation	df	SS	MS	F
Trt	3	5598.65	1866.22	5.49
Blk	2	132.06	66.03	0.19
Error	6	2039.41	339.90	
Total	11	7770.12		

Date: 10/12/90

Block	Treatment 1	2	3	4			
1	344.3	329.6	320.6	312.3	1306.8	1.71E+06	4.27E+05
2	351.8	342.9	335.4	285.4	1315.5	1.73E+06	4.35E+05
3	334.6	337.6	329.1	298.9	1300.2	1.69E+06	4.24E+05
	1030.7	1010.1	985.1	896.6	3922.5	1285652.	
	1062342.	1020302.	970422.0	803891.5	1.28E+06	1.28E+06	4196.02

Variation	df	SS	MS	F
Trt	3	3485.50	1161.83	10.24
Blk	2	29.45	14.72	0.13
Error	6	681.08	113.51	
Total	11	4196.02		

Date: 20/12/90

Block	Treatment 1	2	3	4			
1	353.4	337.2	330.4	325.9	1346.9	1.81E+06	4.54E+05
2	348.7	341.7	348.5	310.2	1349.1	1.82E+06	4.56E+05
3	340.4	337.3	332.8	318.1	1328.6	1.77E+06	4.42E+05
	1042.5	1016.2	1011.7	954.2	4024.6	1351167.	
	1086806.	1032662.	1023536.	910497.6	1.35E+06	1.35E+06	1800.38

Variation	df	SS	MS	F
Trt	3	1383.98	461.33	7.84
Blk	2	63.33	31.67	0.54
Error	6	353.07	58.84	
Total	11	1800.38		

Date: 30/12/90

Block	Treatment 1	2	3	4			
1	318.2	296.8	288.2	297.6	1200.8	1.44E+06	3.61E+05
2	311.8	297.3	285.9	271.3	1166.3	1.36E+06	3.41E+05
3	308.7	298.4	290.4	291.3	1188.8	1.41E+06	3.54E+05
	938.7	892.5	864.5	860.2	3555.9	8055006.	
	881157.6	796556.2	747360.2	739944.0	1.05E+06	1.05E+06	1739.54

Variation	df	SS	MS	F
Trt	3	1304.01	434.67	9.24
Blk	2	153.37	76.69	1.63
Error	6	282.16	47.03	
Total	11	1739.54		

Date: 9/1/91

Block	Treatment 1	2	3	4			
1	276.4	268.5	253.5	264.8	1063.2	1.13E+06	2.83E+05
2	273.8	261.9	265.9	244.5	1046.1	1.09E+06	2.74E+05
3	270.1	265.8	259.2	249.4	1044.5	1.09E+06	2.73E+05
	820.3	796.2	778.6	758.7	3153.8	829556.7	
	672892.0	633934.4	606217.9	575625.6	8.29E+05	8.29E+05	1029.06

Variation	df	SS	MS	F
Trt	3	685.52	228.51	4.73
Blk	2	53.72	26.86	0.56
Error	6	289.81	48.30	
Total	11	1029.06		

Date: 19/1/91

Block	Treatment 1	2	3	4			
1	259.2	250.9	234.7	242.4	987.2	9.75E+05	2.44E+05
2	244.7	235.2	232.7	213.6	926.2	8.58E+05	2.15E+05
3	236.7	229.6	225.8	226.4	918.5	8.44E+05	2.11E+05
	740.6	715.7	693.2	682.4	2831.9	668970.2	
	548488.3	512226.4	480526.2	465669.7	6.69E+05	6.68E+05	1629.53

Variation	df	SS	MS	F
Trt	3	665.48	221.83	5.20
Blk	2	708.33	354.17	8.31
Error	6	255.72	42.62	
Total	11	1629.53		

Date: 29/1/91

Block	Treatment 1	2	3	4			
1	167.1	159.6	155.4	148.5	630.6	3.98E+05	9.96E+04
2	161.1	160.3	157.3	151.4	630.1	3.97E+05	9.93E+04
3	183.9	180.9	153.4	153.3	671.5	4.51E+05	1.14E+05
	512.1	500.8	466.1	453.2	1932.2	311895.5	
	262246.4	250800.6	217249.2	205390.2	3.11E+05	3.11E+05	1370.60

Variation	df	SS	MS	F
Trt	3	779.10	259.70	5.04
Blk	2	282.25	141.13	2.74
Error	6	309.25	51.54	
Total	11	1370.60		

Appendix 4: Graphs of infiltration rates

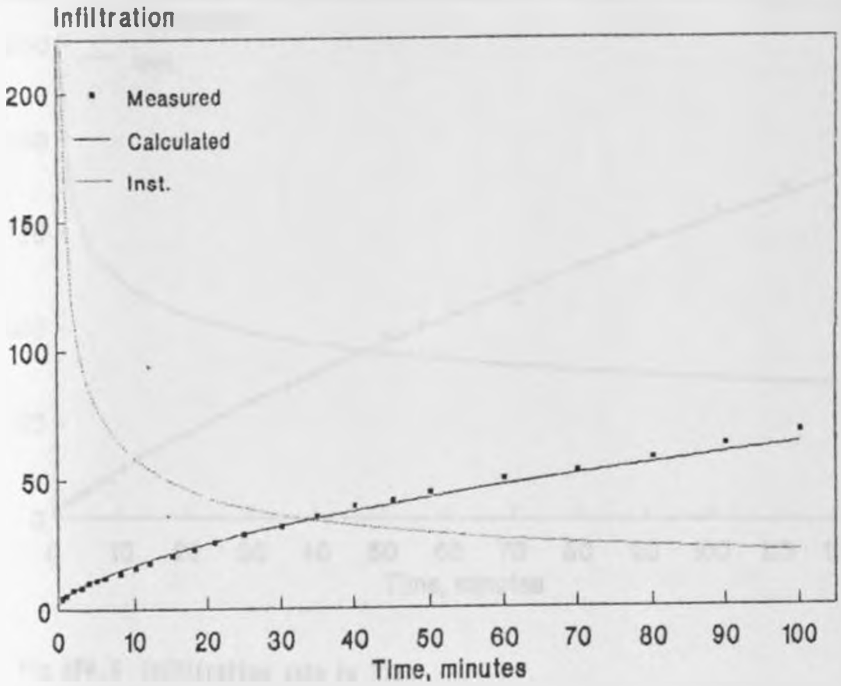


Fig AP4.1 Infiltration rate in B12.

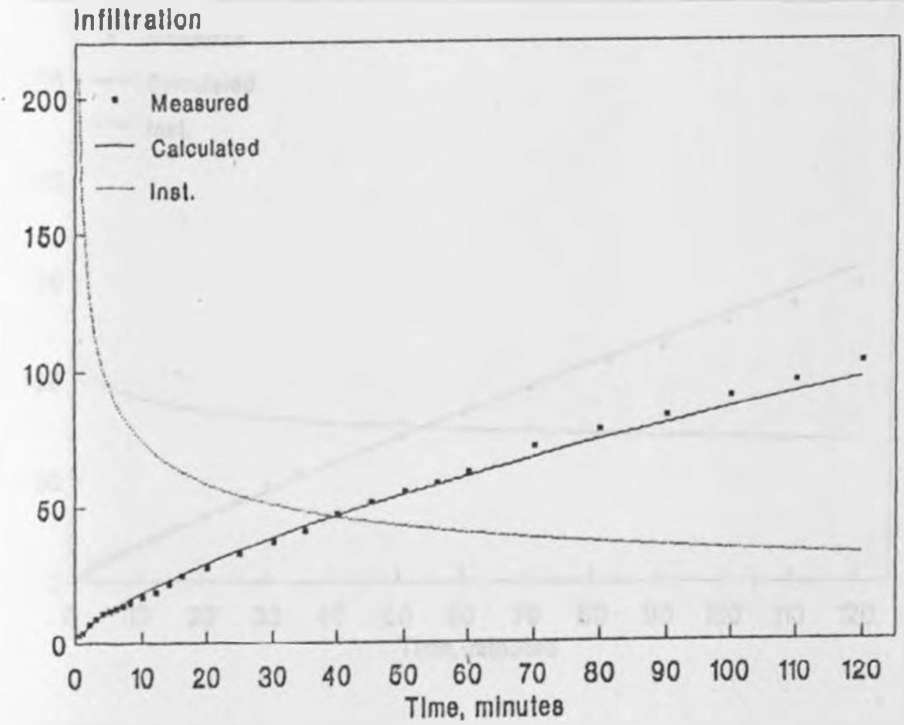


Fig AP4.2 Infiltration rate in B13.

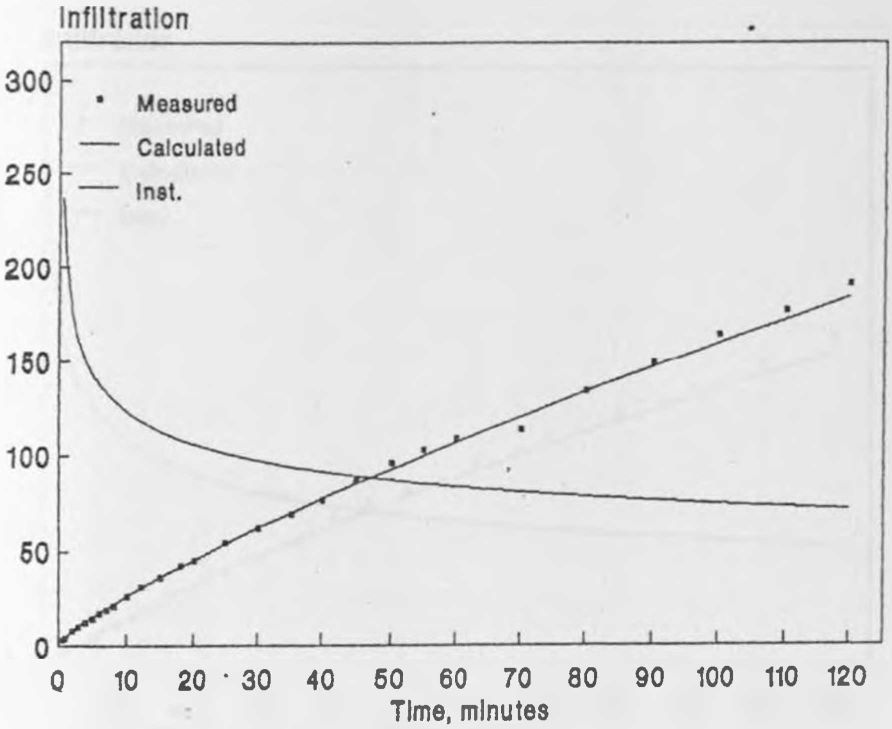


Fig AP4.3 Infiltration rate in B21.

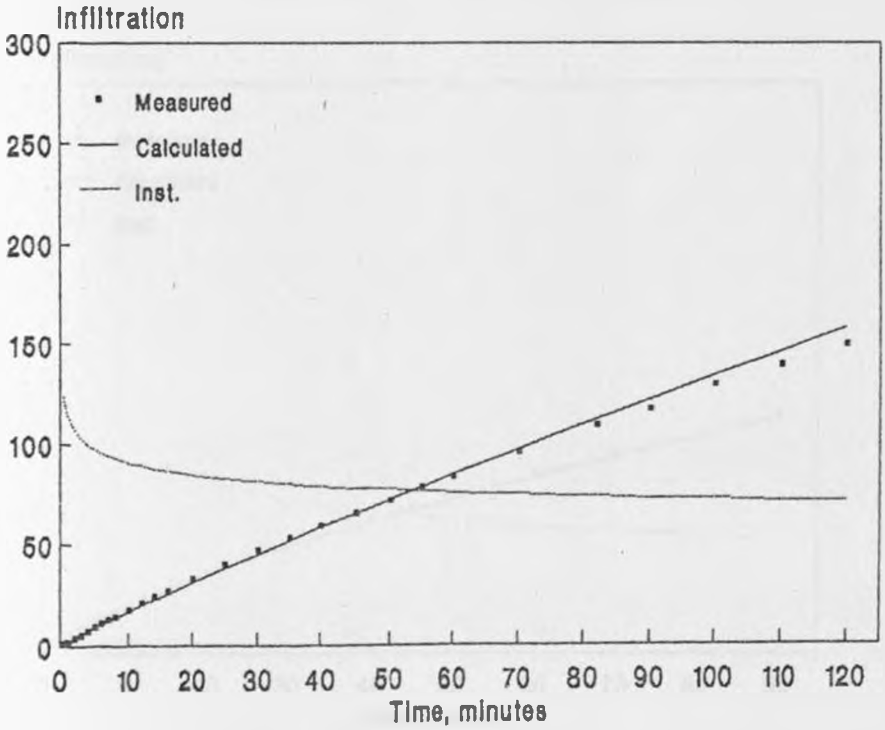


Fig AP4.4 Infiltration rate in B24.

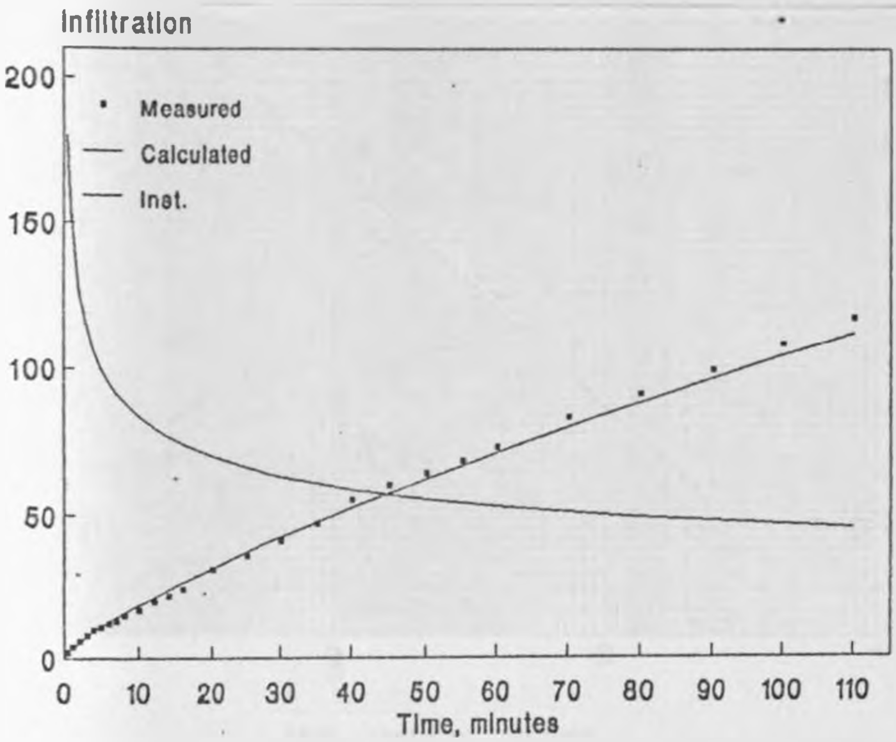


Fig AP4.5 Infiltration rate in B31.

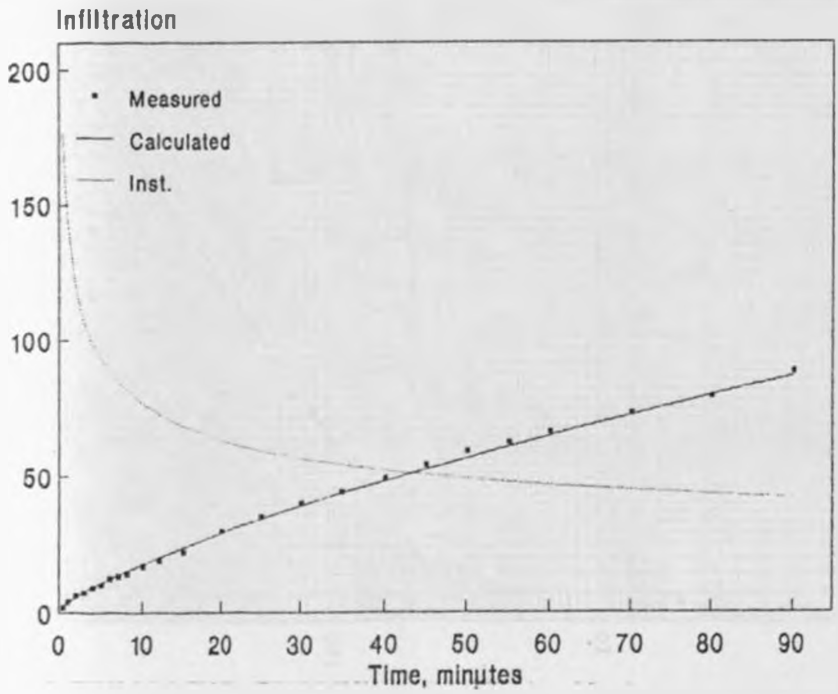


Fig AP4.6 Infiltration rate in B34.

Appendix 5: Plots of probability of monthly rainfall

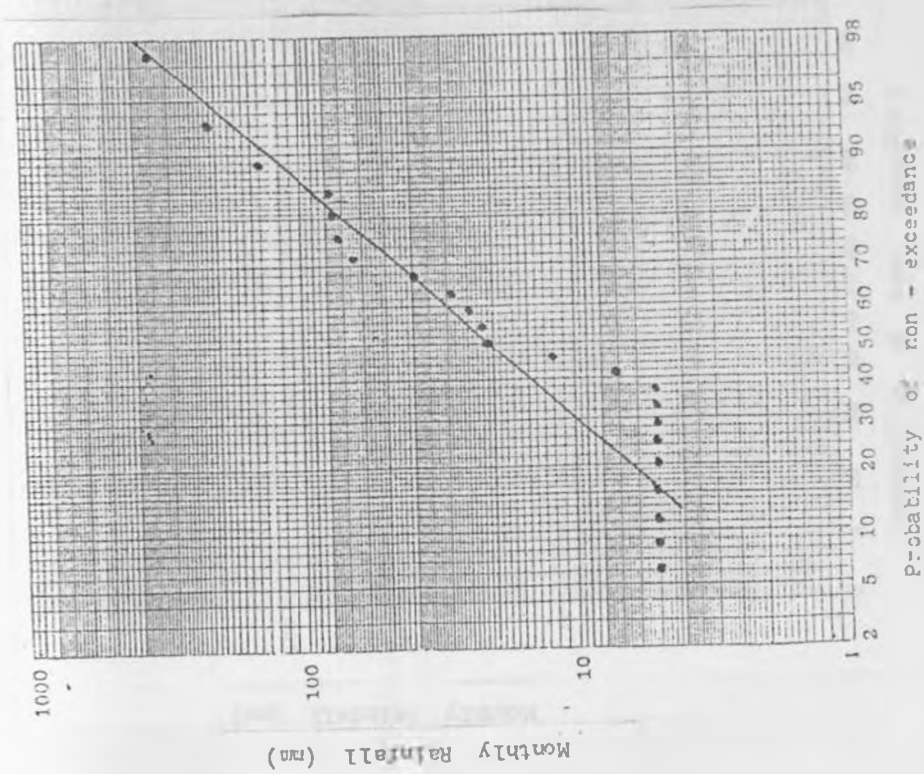


Fig. AP5.1 Log-probability plot for October.

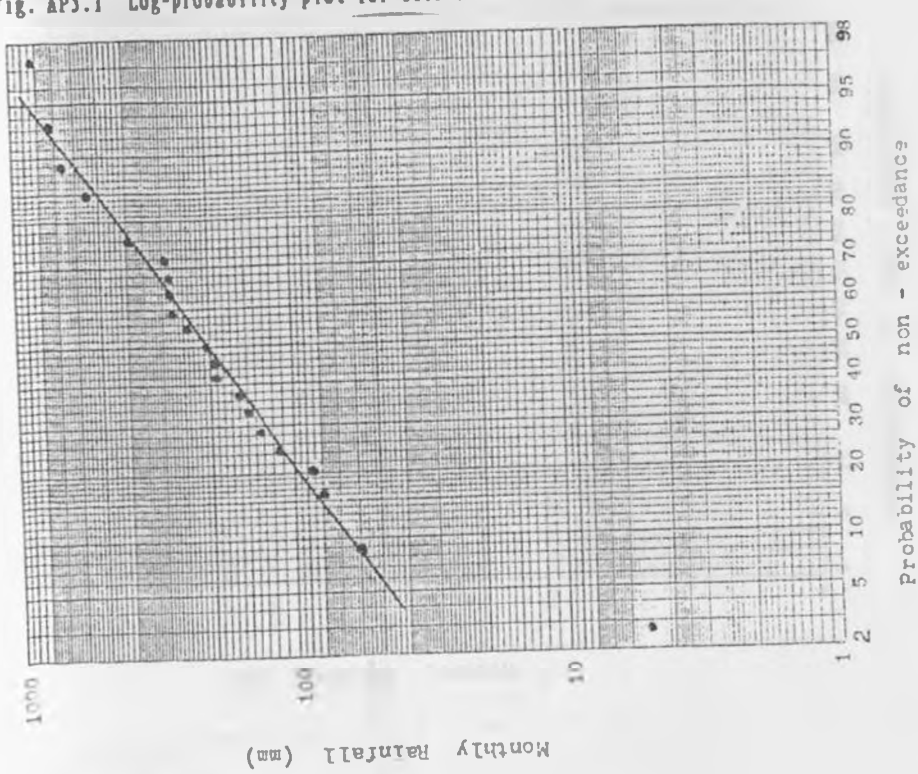


Fig. AP5.2 Log-probability plot for November.

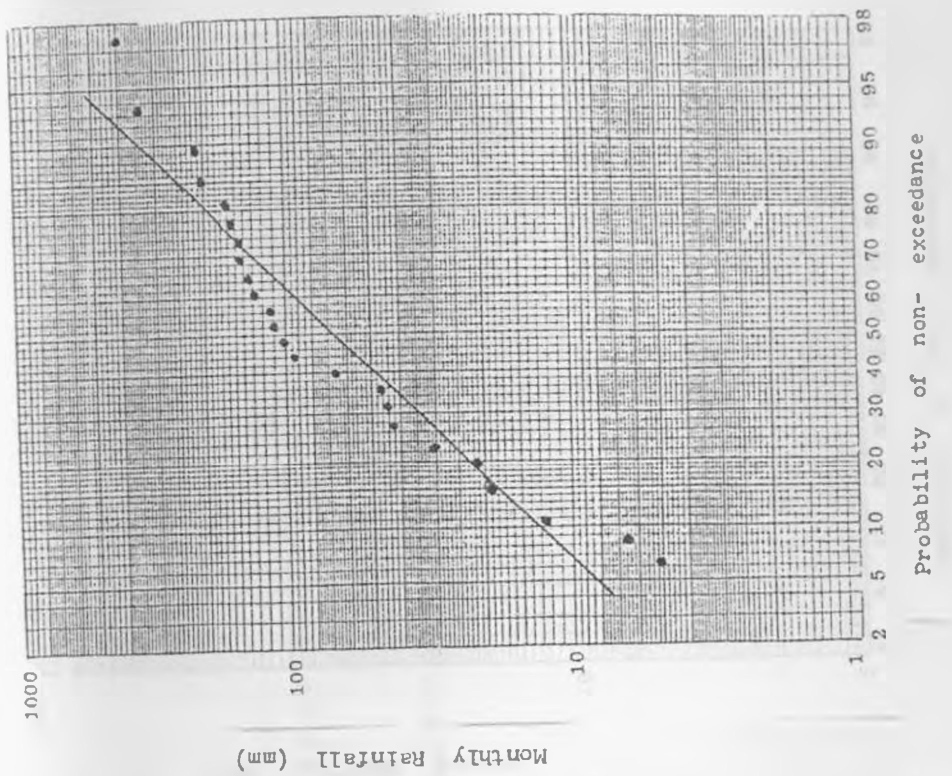


Fig. APS.3 Log-probability plot for December.

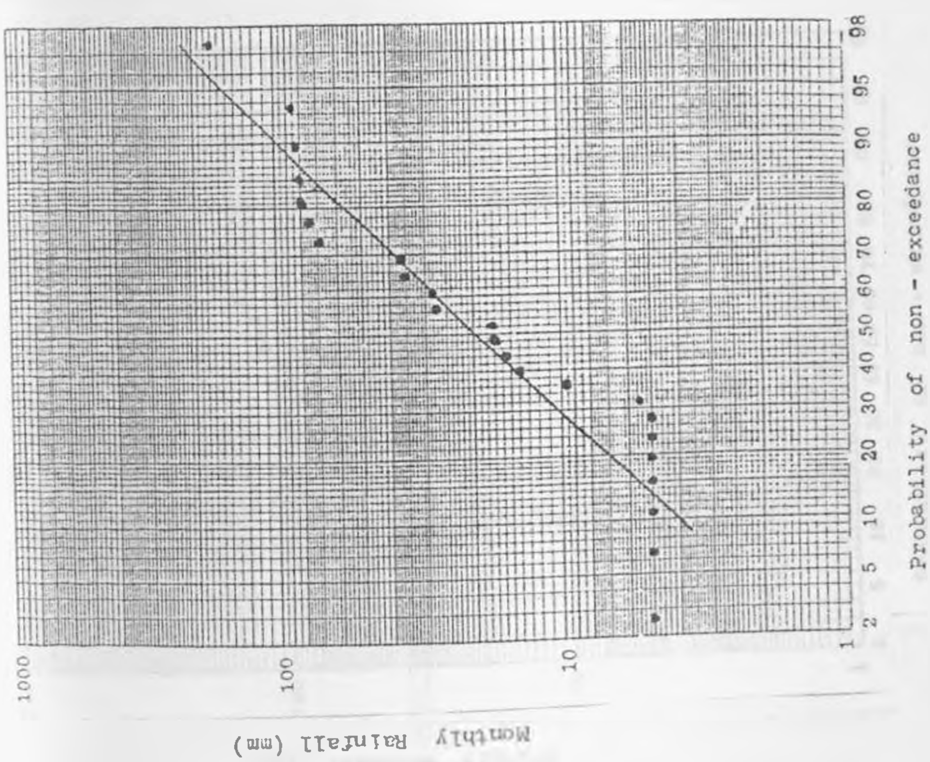


Fig. APS.4 Log-probability plot for January.

Fig. APS.5 Log-probability plot for March.

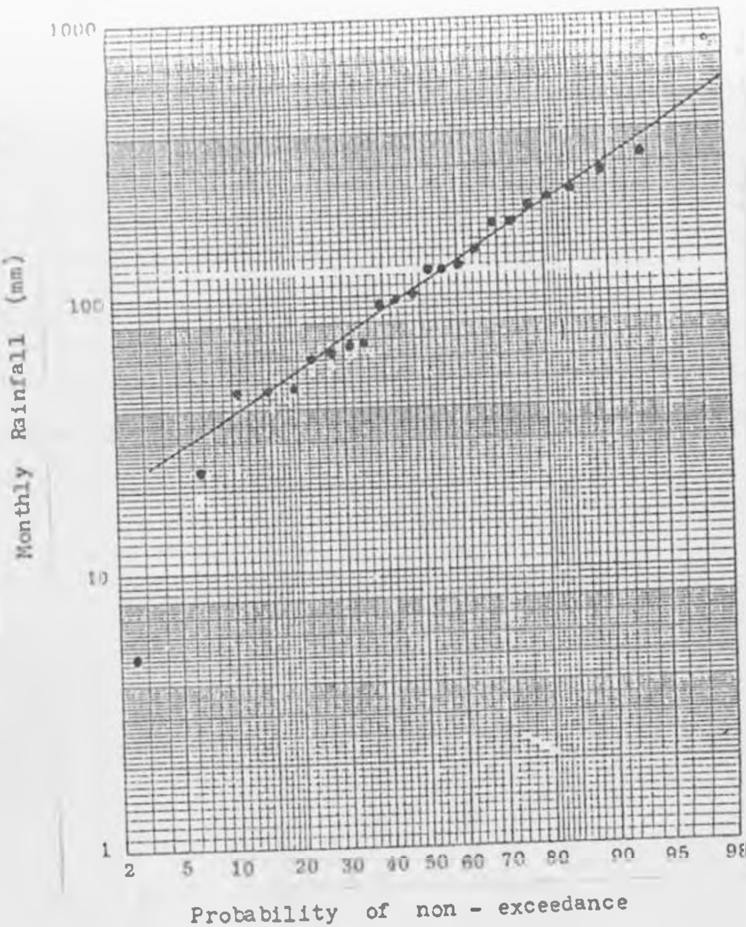


Fig. APS.6 Log-probability plot for April.

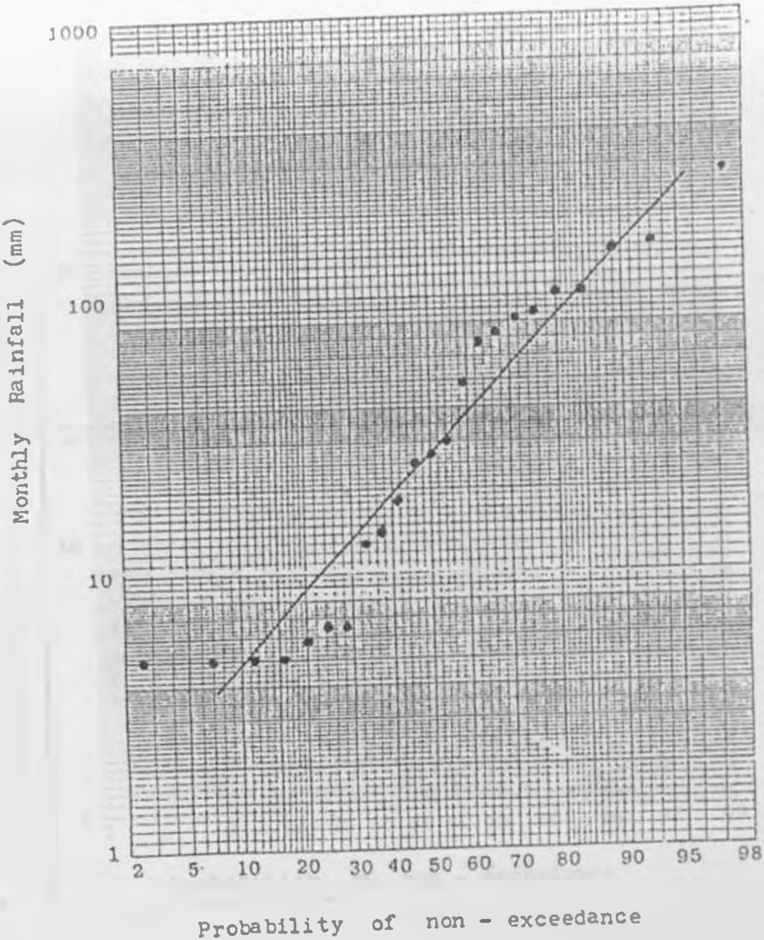
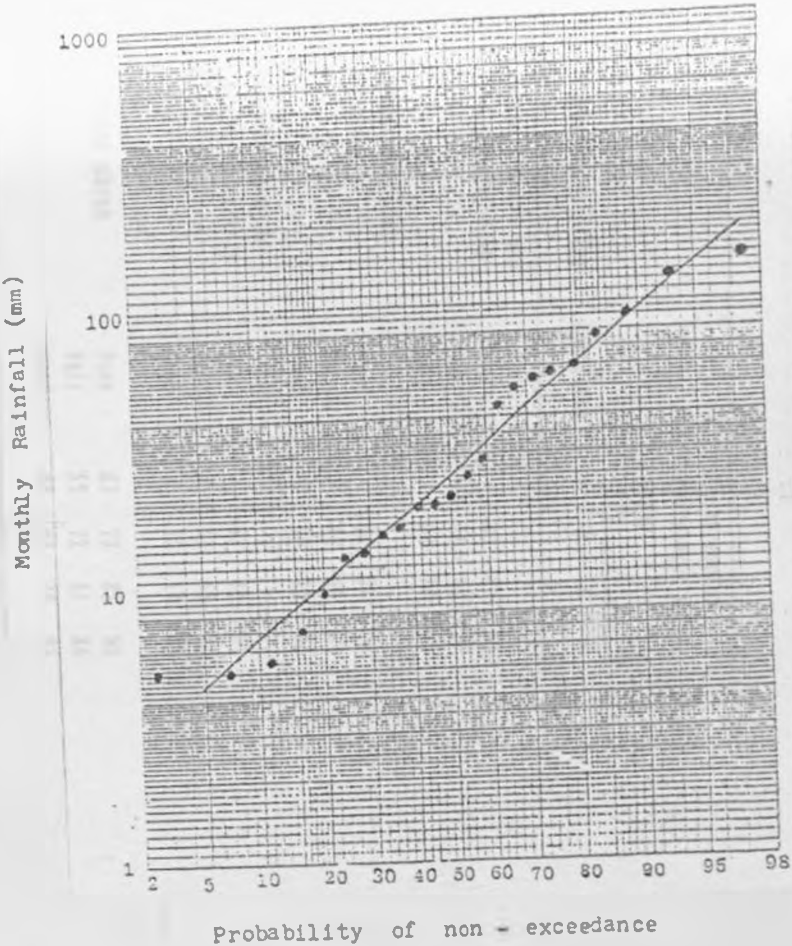

1000
100
10
1
Monthly Rainfall (mm)
2
5
10
20
30
40
50
60
70
80
90
95
98
Probability of non - exceedance

Fig. AP5.7 Log-probability plot for May.


1000
100
10
1
Monthly Rainfall (mm)
2
5
10
20
30
40
50
60
70
80
90
95
98
Probability of non - exceedance

Appendix 6: Runoff curve numbers for arid and semi-arid rangelands

Cover description	Condition	Curve number for hydrologic soil group			
		A	B	C	D
Grass + weeds and low growing bush	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Mountain brush mixture	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Sagebrush with grass understory	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

Conditions:

$I_a = 0.2S$

Poor: 30% cover Fair: 30-70% cover Good: 70% cover

Soil group	Description
A	Lowest runoff potential. High infiltration rates in deep sands with little silt and clay.
B	Moderately low runoff potential. Above average infiltration after thorough wetting. Mostly sandy soils shallower than A.
C	Moderately high runoff potential. Below average infiltration. Shallow and clayey soils.
D	Highest runoff potential. Mostly swelling clays, shallow soil with nearly impermeable sub-horizon.

Source: *Hromadka and Whitley (1989)*

Appendix 7: Computer programme code

```
DECLARE SUB Extraction1 (ETa!, ETm!, SaD1!, TP!)
DECLARE SUB Extraction2 (ETa!, ETm!, SaD2, TP!)
DECLARE SUB Extraction3 (ETa!, ETm!, SaD3!, TP!)
DECLARE SUB Extraction4 (ETa!, ETm!, SaD4!, TP!)
DECLARE SUB Depletion (P!, ETm!)
DECLARE SUB Root (D(), Dy!)
CLS
DIM i(90), ETm(90), SW(90, 4), Q(90), R(90), tdw(90, 4), swi(90), D(90)
DIM DD(90, 4), A$(20, 120), m(15), N(15), ET(90), RO(90), CN(90), S(90), RI(90)
DIM ETMAX(90), ROUT(90), AW1(90, 4), AW2(90, 4), AW3(90, 4), AW4(90, 4), ETAC(90)
DIM dp1(90, 4), dp2(90, 4), dp3(90, 4), dp4(90, 4), dp5(90, 4), dp6(90, 4)
DIM dp7(90, 4), dp8(90, 4), swa1(90, 4), swa2(90, 4), swb1(90, 4), swb2(90, 4)
DIM sw1(90, 4), sw2(90, 4), sw3(90, 4), sw4(90, 4), SWT(90, 4), TP(90), DR(90)
DIM swc1(90, 4), swc2(90, 4), swd1(90, 4), swd2(90, 4), inputs(90), RE(90)
DIM AWA(90), AWB(90), AWC(90), AWD(90), TP1(90), TP2(90), TP3(90), TP4(90)
DIM TPD1(90), TPD2(90), TPD3(90), TPD4(90), StD1(90), StD2(90), StD3(90)
DIM StD4(90), SaD1(90), SaD2(90), SaD3(90), SaD4(90), ETa1(90), ETa2(90)
DIM ETa3(90), ETa4(90), beta1(90), beta2(90), beta3(90), beta4(90), ROFF(90)

WHILE choice < 1 OR choice > 3
    BEEP
    LOCATE 20, 20: PRINT SPC(40);
    LOCATE 20, 20: INPUT "Please enter 1, 2 or 3: ", choice
WEND
IF choice = 1 THEN GOSUB 100 ELSE 200
200 IF choice = 2 THEN GOSUB 400 ELSE 500
100
CLS
          '=============================================================
          '                    READING DATA FROM FILE
          '=============================================================
PRINT
CN1 = 78              ' Curvenumber, function of driness, catchment char.
TotalPercent = 0: Totrain = 0
ROC = 0               ' Cumulative runoff into the plot
TotNum = 0:
TPerc = 0             ' Total percolation below the root zone
DR = 0:   ETMAX = 0:  ETT = 0:   ETIN = 0
TP = 0                ' Value of P*SaD/ETm
TPD = 0               ' Accumulation of TP
FOR i = 1 TO 82
     READ ETm, Rain
     ET(i) = ETm
     R(i) = Rain

          '=======================================================
          '                RUNOFF GENERATING MODULE
          '=======================================================

IF i = 1 AND R(i) = 0 THEN
                CN(i) = CN1
                RI(i) = 0: ROUT(i) = 0: PERCENT = 0: inputs(i) = 0
ELSEIF i = 1 AND R(i) > 0 THEN
```

```
               CN(i) = CN1
                S(i) = 25400 / CN(i) - 254
                 Num = R(i) - .2 * S(i)
             IF Num <= 0 THEN
                  RI(i) = 0: PERCENT = 0: inputs(i) = R(i)
             ELSE
                     N = Num ^ 2
                     D = R(i) + .8 * S(i)
                 RI(i) = (N / D) * 27.2 / 27.2
               PERCENT = 100 * RI(i) / R(i)
                   ROC = ROC + RI(i)
               ROUT(i) = 0
             inputs(i) = R(i) + RI(i)
             END IF
END IF
IF i > 1 AND R(i) = 0 THEN
    CN(i) = 30480 / ((30480 / CN(i - 1)) - R(i - 1) + RI(i - 1) + ET(i - 1))
        IF CN(i) < 75 THEN
                CN(i) = 75
                 S(i) = 25400 / CN(i) - 254
            IF S(i) < 0 THEN
                   S(i) = 0: RI(i) = 0: PERCENT = 0: inputs(i) = 0
            END IF
        ELSEIF CN(i) > 75 AND CN(i) <= 100 THEN
                 S(i) = 25400 / CN(i) - 254
                RI(i) = 0: PERCENT = 0: inputs(i) = 0
        END IF
ELSEIF i > 1 AND R(i) > 0 THEN
    CN(i) = 30480 / ((30480 / CN(i - 1)) - R(i - 1) + RI(i - 1) + ET(i - 1))
        IF CN(i) > 100 THEN
                 CN(i) = 100
        ELSEIF CN(i) < 75 THEN
                 CN(i) = 75
        END IF
                  S(i) = 25400 / CN(i) - 254
           IF S(i) < 0 THEN
                  S(i) = 0
           END IF
                    Num = R(i) - .2 * S(i)
               IF Num <= 0 THEN
                      RI(i) = 0: PERCENT = 0: ROUT(i) = 0
                 inputs(i) = R(i)
               ELSE
                       N = Num ^ 2
                       D = R(i) + .8 * S(i)
                   RI(i) = (N / D) * 27.2 / 27.2
                 PERCENT = 100 * RI(i) / R(i)
                     ROC = ROC + RI(i)
                 inputs(i) = R(i) + RI(i)
               END IF
END IF
ROFF = RI(i)
IF bb = 0 AND cc = 0 AND ee = 0 THEN
ROFF$ = " ##     ###.#     ###.#     ##.#     ###.#     ##.#"
PRINT USING ROFF$; i, R(i), CN(i), S(i), RI(i), PERCENT
END IF
```

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'===============================================================
'                        COMPUTING DRAINAGE
'===============================================================

'********** INITIAL SOIL MOISTURE, FC AND WP VALUES. **********

T = 24                  ' hours in a day

            ' Initial soil moisture for layers 1, 2, 3, 4 (mm):

ism1 = 36: ism2 =8: ism3 = 3: ism4 = 3

            ' Field capacity for layers 1,2, 3, 4 (mm):

fc1 = 40.6:  fc2 = 78.9:  fc3 = 89.6:  fc4 = 116.4

            ' Wilting points for layers 1, 2, 3, 4:

wp1 = 18.9:  wp2 = 46.7:   wp3 = 51.6:   wp4 = 70.6

            ' Hydraulic conductivity for layers 1, 2, 3, 4 (m/d):

k(1) = 2.5:  k(2) -= 2.5:  k(3) = 2.5: k(4) = 1.5

            ' Bottom Depth of layers 1, 2, 3, 4 (mm):

d1 = 150:  d2 = 450:  d3 = 750:  d4 = 1050

            ' Available soil moisture per layer (FC-WP, mm):

AW1 = fc1 - wp1:  AW2 = fc2 - wp2
AW3 = fc3 - wp3:  AW4 = fc4 - wp4

            ' Unit available soil moisture (mm):

Delta1 = AW1 / d1:          Delta2 = AW2 / (d2 - d1)
Delta3 = AW3 / (d3 - d2):   Delta4 = AW4 / (d4 - d3)

            ' Unit soil moisture held at PWP, mm:

beta1 = wp1 / d1:              beta2 = wp2 / (d2 - d1)
beta3 = wp3 / (d3 - d2):       beta4 = wp4 / (d4 - d3)

            ' unit soil moisture of initial soil condition (%):

alf1 = ism1 / d1:          alf2 = ism2 / (d2 - d1)
alf3 = ism3 / (d3 - d2):   alf4 = ism4 / (d4 - d3)


FOR h = 1 TO 4
IF i = 1 AND h = 1 THEN
   Root D(), i
              F1 = fc1 * D(i) / d1
              F2 = fc1 * (d1 - D(i)) / d1
        AW1(i, h) = Delta1 * D(i)
            SaD1 = AW1(i, h)
```

```
swa1(i, h) = alf1 * D(i) + inputs(i)
swa2(i, h) = alf1 * (d1 - D(i))
IF swa1(i, h) <= F1 THEN
    tdw(i, h) = 0:  dp1(i, h) = 0
ELSEIF swa1(i, h) > F1 THEN
    tdw(i, h) = swa1(i, h) - F1
    dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
   swa1(i, h) = swa1(i, h) - dp1(i, h)
END IF
Depletion P, ETm
   IF swa1(i, h) > beta1 * D(i) THEN
            StD1 = swa1(i, h) - beta1 * (D(i))
             AWA = (1 - P) * SaD1
      IF StD1 >= AWA THEN
            ETa1 = ETm
      ELSEIF StD1 <= AWA THEN
             TP1 = P * SaD1 / ETm
Extraction1 ETa, ETm, SaD1, TP1
             ETa1 = ETa
      END IF
         swa1(i, h) = swa1(i, h) - ETa1
   ELSEIF swa1(i, h) <= beta * D(i) THEN
              ETa1 = 0
          swa1(i, h) = swa1(i, h)
   END IF
          swa2(i, h) = swa2(i, h) + dp1(i, h)
      IF swa2(i, h) <= F2 THEN
            tdw(i, h) = 0:  dp2(i, h) = 0
      ELSEIF swa2(i, h) > F2 THEN
            tdw(i, h) = swa2(i, h) - F2
            dp2(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
           swa2(i, h) = swa2(i, h) - dp2(i, h)
      END IF
END IF
IF i = 1 AND h = 2 THEN
   Root D(), i
              F3 = 0:   F4 = fc2
        AW2(i, h) = 0:  swb1(i, h) = 0
       swb2(i, h) = ism2 + dp2(i, h - 1)
             SaD2 = 0:   ETa2 = 0
    IF swb2(i, h) > F4 THEN
        tdw(i, h) = swb2(i, h) - F4
        dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(2) / tdw(i, h)))
       swb2(i, h) = swb2(i, h) - dp3(i, h)
        dp4(i, h) = dp3(i, h)
    END IF
END IF
IF i = 1 AND h = 3 THEN
   Root D(), i
              F5 = 0:   F6 = fc3
        AW3(i, h) = 0:   swc1(i, h) = 0
       swc2(i, h) = ism3 + dp4(i, h - 1)
             SaD3 = 0:  ETa3 = 0
    IF swc2(i, h) > F6 THEN
        tdw(i, h) = swc2(i, h) - F6
        dp5(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(4) / tdw(i, h)))
```

```
        swc2(i, h) = swc2(i, h) + dp5(i, h)
         dp6(i, h) = dp5(i, h)
    END IF
END IF
IF i = 1 AND h = 4 THEN
   Root D(), i
                 F7 = 0:   F8 = fc4
          AW4(i, h) = 0:   swd1(i, h) = 0
         swd2(i, h) = ism4 + dp6(i, h - 1)
               SaD4 = 0:   ETa4 = 0
     IF swd2(i, h) > F8 THEN
                tdw(i, h) = swd2(i, h) - F8
                dp7(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(4) / tdw(i, h)))
               swd2(i, h) = swd2(i, h) - dph(i, 7)
                       dp = dp7(i, h)
                       DR = DR + dp
     END IF
 END IF
 IF i > 1 AND h = 1 THEN
     Root D(), i
     DD(i, h) = D(i) - D(i - 1)
    IF D(i) < d1 THEN
              F1 = fc1 * D(i) / d1
              F2 = fc1 * (d1 - D(i)) / d1
        AW2(i, h) = 0: AW3(i, h) = 0: AW4(i, h) = 0
        AW1(i, h) = Delta1 * D(i)
             SaD1 = AW1(i, h)
              swi = swa2(i - 1, h) * DD(i, h) / (d1 - D(i - 1))
       swa1(i, h) = swa1(i - 1, h) + inputs(i) + swi
       swa2(i, h) = swa2(i - 1, h) - swi
        IF swa1(i, h) <= F1 THEN
           tdw(i, h) = 0:  dp1(i, h) = 0
        ELSEIF swa1(i, h) > F1 THEN
                 tdw(i, h) = swa1(i, h) - F1
                 dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
                swa1(i, h) = swa1(i, h) - dp1(i, h)
                swa2(i, h) = swa2(i, h) + dp1(i, h)
        END IF
  Depletion P, ETm
              IF swa1(i, h) > beta1 * D(i) THEN
                     StD1 = swa1(i, h) - beta1 * (D(i))
                      AWA = (1 - P) * SaD1
                     IF StD1 >= AWA THEN
                            ETa1 = ETm
                     ELSEIF StD1 <= AWA THEN
                            TP1 = P * SaD1 / ETm
   Extraction1 ETa, ETm, SaD1, TP1
                            ETa1 = ETa
                     END IF
                       swa1(i, h) = swa1(i, h) - ETa1
              ELSEIF swa1(i, h) < beta1 * D(i) THEN
                            ETa1 = 0
                       swa1(i, h) = swa1(i, h)
              END IF
           IF swa2(i, h) <= F2 THEN
                tdw(i, h) = 0:   dp2(i, h) = 0
```

```
        ELSEIF swa2(i, h) > F2 THEN
              tdw(i, h) = swa2(i, h) - F2
              dp2(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
             swa2(i, h) = swa2(i, h) - dp2(i, h)
        END IF
END IF
   IF D(i) = d1 THEN
                F1 = fc1:     F2 = 0
        swa2(i, h) = 0
             SaD1 = AW1
              swi = swa2(i - 1, h)
        swa1(i, h) = swa1(i - 1, h) + inputs(i) + swi
      IF swa1(i, h) <= F1 THEN
          dp1(i, h) = 0
      ELSEIF swa1(i, h) > F1 THEN
          tdw(i, h) = swa1(i, h) - F1
          dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
         swa1(i, h) = swa1(i, h) - dp1(i, h)
          dp2(i, h) = dp1(i, h)
      END IF
 Depletion P, ETm
                   IF swa1(i, h) > beta1 * d1 THEN
                                  StD1 = swa1(i, h) - beta1 * d1
                                   AWA = (1 - P) * SaD1
                         IF StD1 >= AWA THEN
                                  ETa1 = ETm
                         ELSEIF StD1 <= AWA THEN
                                   TP1 = P * SaD1 / ETm
 Extraction1 ETa, ETm, SaD1, TP1
                                  ETa1 = ETa
                         END IF
                           swa1(i, h) = swa1(i, h) - ETa1

                   ELSEIF swa1(i, h) < beta1 * d1 THEN
                                  ETa1 = 0
                           swa1(i, h) = swa1(i, h)
                   END IF
    ELSEIF D(i) > d1 AND D(i) <= d2 THEN
             AW1(i, h) = AW1
                  SaD1 = AW1(i, h)
            swa2(i, h) = 0
            swa1(i, h) = swa1(i - 1, h) + inputs(i)
                    F1 = fc1:    F2 = 0
            IF swa1(i, h) <= F1 THEN
                  tdw(i, h) = 0:   dp1(i, h) = 0
            ELSEIF swa1(i, h) > F1 THEN
                  tdw(i, h) = swa1(i, h) - F1
                  dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
                 swa1(i, h) = swa1(i, h) - dp1(i, h)
                  dp2(i, h) = dp1(i, h)
            END IF
  Depletion P, ETm
                   IF swa1(i, h) > beta1 * d1 THEN
                                  StD1 = swa1(i, h) - beta1 * d1
                                   AWA = (1 - P) * SaD1
                                  IF StD1 >= AWA THEN
```

```
                                          ETa1 = ETm / 2
                                     ELSEIF StD1 <= AWA THEN
                                               TP1 = P * SaD1 / ETm
Extraction1 ETa, ETm, SaD1, TP1
                                              ETa1 = ETa / 2
                                     END IF
                                       swa1(i, h) = swa1(i, h) - ETa1
                       ELSEIF swa1(i, h) < beta1 * d1 THEN
                                              ETa1 = 0
                                       swa1(i, h) = swa1(i, h)
                       END IF
   ELSEIF D(i) > d2 AND D(i) <= d3 THEN
            AW1(i, h) = AW1
                 SaD1 = AW1(i, h)
           swa2(i, h) = 0
           swa1(i, h) = swa1(i - 1, h) + inputs(i)
                   F1 = fc1:    F2 = 0
           IF swa1(i, h) <= F1 THEN
                 tdw(i, h) = 0:  dp1(i, h) = 0
           ELSEIF swa1(i, h) > F1 THEN
                 tdw(i, h) = swa1(i, h) - F1
                 dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
                swa1(i, h) = swa1(i, h) - dp1(i, h)
                 dp2(i, h) = dp1(i, h)
           END IF
Depletion P, ETm
                        IF swa1(i, h) > beta1 * d1 THEN
                                    StD1 = swa1(i, h) - beta1 * d1
                                     AWA = (1 - P) * SaD1
                                 IF StD1 >= AWA THEN
                                       ETa1 = ETm / 3
                                 ELSEIF StD1 <= AWA THEN
                                          TP1 = P * SaD1 / ETm
Extraction1 ETa, ETm, SaD1, TP1
                                       ETa1 = ETa / 3
                                 END IF
                                 swa1(i, h) = swa1(i, h) - ETa1

                        ELSEIF swa1(i, h) < beta1 * d1 THEN
                                       ETa1 = 0
                                 swa1(i, h) = swa1(i, h)
                        END IF
   ELSEIF D(i) > d3 AND D(i) <= d4 THEN
            AW1(i, h) = AW1
                 SaD1 = AW1(i, h)
           swa2(i, h) = 0
           swa1(i, h) = swa1(i - 1, h) + inputs(i)
                   F1 = fc1:   F2 = 0
             IF swa1(i, h) <= F1 THEN
                   tdw(i, h) = 0:  dp1(i, h) = 0
             ELSEIF swa1(i, h) > F1 THEN
                   tdw(i, h) = swa1(i, h) - F1
                   dp1(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
                  swa1(i, h) = swa1(i, h) - dp1(i, h)
                   dp2(i, h) = dp1(i, h)
             END IF
```

```
Depletion P, ETm
                IF swal(i, h) > beta1 * d1 THEN
                           StD1 = swal(i, h) - beta1 * d1
                            AWA = (1 - P) * SaD1
                      IF StD1 >= AWA THEN
                            ETa1 = ETm / 4
                      ELSEIF StD1 <= AWA THEN
                             TP1 = P * SaD1 / ETm
Extraction1 ETa, ETm, SaD1, TP1
                            ETa1 = ETa / 4
                      END IF
                       swa1(i, h) = swa1(i, h) - ETa1
                ELSEIF swa1(i, h) < beta1 * d1 THEN
                            ETa1 = 0
                       swa1(i, h) = swa1(i, h)
                END IF
  END IF
END IF
IF i > 1 AND h = 2 THEN
   Root D(), i
       DD(i, h) = D(i) - D(i - 1)
 IF D(i) <= d1 THEN
      AW2(i, h) = 0:   swb1(i, h) = 0
     swb2(i, h) = swb2(i - 1, h) + dp2(i, h - 1)
           F3 = 0:   F4 = fc2
    IF swb2(i, h) > F4 THEN
         tdw(i, h) = swb2(i, h) - F4
         dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
        swb2(i, h) = swb2(i, h) - dp3(i, h)
         dp4(i, h) = dp3(i, h)
            SaD2 = 0:  ETa2 = 0
    END IF
 ELSEIF D(i) > d1 AND D(i) < d2 THEN
            F3 = fc2 * (D(i) - d1) / (d2 - d1)
            F4 = fc2 * (d2 - D(i)) / (d2 - d1)
      AW2(i, h) = Delta2 * (D(i) - d1)
           SaD2 = AW2(i, h)
            swi = swb2(i - 1, h) * DD(i, h) / (d2 - D(i))
      swb1(i, h) = swb1(i - 1, h) + dp2(i, h - 1) + swi
      swb2(i, h) = swb2(i - 1, h) - swi
    IF swb1(i, h) <= F3 THEN
         dp3(i, h) = 0
    ELSEIF swb1(i, h) > F3 THEN
          tdw(i, h) = swb1(i, h) - F3
          dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
         swb1(i, h) = swb1(i, h) - dp3(i, h)
         swb2(i, h) = swb2(i, h) + dp3(i, h)
           IF swb2(i, h) > F4 THEN
                tdw(i, h) = swb2(i, h) - F4
                dp4(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
               swb2(i, h) = swb2(i, h) - dp4(i, h)
           END IF
    END IF
Depletion P, ETm
              IF swb1(i, h) > beta2 * (D(i) - d1) THEN
                           StD2 = swb1(i, h) - beta2 * (D(i) - d1)
```

```
                              AWB = (1 - P) * SaD2
                          IF StD2 >= AWB THEN
                              ETa2 = ETm / 2
                          ELSEIF StD2 <= AWB THEN
                              TP2 = P * SaD2 / ETm
Extraction2 ETa, ETm, SaD2, TP2
                              ETa2 = ETa / 2
                          END IF
                        swb1(i, h) = swb1(i, h) - ETa2
               ELSE
                              ETa2 = 0
                        swb1(i, h) = swb1(i, h)
               END IF
    ELSEIF D(i) = d2 THEN
            swi = swb2(i - 1, h)
      swb1(i, h) = swb1(i - 1, h) + dp2(i, h - 1) + swi
      swb2(i, h) = 0
             F3 = fc2: F4 = 0
       AW2(i, h) = AW2
           SaD2 = AW2(i, h)
        IF swb1(i, h) > F3 THEN
             tdw(i, h) = swb1(i, h) - F3
             dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swb1(i, h) = swb1(i, h) - dp3(i, h)
             dp4(i, h) = dp3(i, h)
        END IF
Depletion P, ETm
                IF swb1(i, h) > beta2 * (d2 - d1) THEN
                              StD2 = swb1(i, h) - beta2 * (d2 - d1)
                               AWB = (1 - P) * SaD2
                           IF StD2 >= AWB THEN
                               ETa2 = ETm / 2
                           ELSEIF StD2 <= AWB THEN
                               TP2 = P * SaD2 / ETm
Extraction2 ETa, ETm, SaD2, TP2
                               ETa2 = ETa / 2
                           END IF
                         swb1(i, h) = swb1(i, h) - ETa2
                ELSE
                               ETa2 = 0
                         swb1(i, h) = swb1(i, h)
                END IF
  ELSEIF D(i) > d2 AND D(i) <= d3 THEN
         swb1(i, h) = swb1(i - 1, h) + dp2(i, h - 1)
         swb2(i, h) = 0
                F4 = 0:  F3 = fc2
          AW2(i, h) = AW2
              SaD2 = AW2(i, h)
         IF swb1(i, h) > F3 THEN
                tdw(i, h) = swb1(i, h) - F3
                dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
               swb1(i, h) = swb1(i, h) - dp3(i, h)
                dp4(i, h) = dp3(i, h)
         END IF
Depletion P, ETm
                IF swb1(i, h) > beta2 * (d2 - d1) THEN
```

```
                                StD2 = swb1(i, h) - beta2 * (d2 - d1)
                                 AWB = (1 - P) * SaD2
                        IF StD2 >= AWB THEN
                                ETa2 = ETm / 3
                        ELSEIF StD2 <= AWB THEN
                                 TP2 = P * SaD2 / ETm
Extraction2 ETa, ETm, SaD2, TP2
                                ETa2 = ETa / 3
                        END IF
                        swb1(i, h) = swb1(i, h) - ETa2
              ELSE
                                ETa2 = 0
                        swb1(i, h) = swb1(i, h)
              END IF
  ELSEIF D(i) > d3 AND D(i) <= d4 THEN
         swb1(i, h) = swb1(i - 1, h) + dp2(i, h - 1)
         swb2(i, h) = 0
              F4 = 0:   F3 = fc2
          AW2(i, h) = AW2
             SaD2 = AW2(i, h)
           IF swb1(i, h) > F3 THEN
             tdw(i, h) = swb1(i, h) - F3
             dp3(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swb1(i, h) = swb1(i, h) - dp3(i, h)
             dp4(i, h) = dp3(i, h)
           END IF
Depletion P, ETm
               IF swb1(i, h) > beta2 * (d2 - d1) THEN
                                StD2 = swb1(i, h) - beta2 * (d2 - d1)
                                 AWB = (1 - P) * SaD2
                        IF StD2 >= AWB THEN
                                ETa2 = ETm / 4
                        ELSEIF StD2 <= AWB THEN
                                 TP2 = P * SaD2 / ETm
Extraction2 ETa, ETm, SaD2, TP2
                                ETa2 = ETa / 4
                        END IF
                        swb1(i, h) = swb1(i, h) - ETa2
               ELSE
                                ETa2 = 0
                        swb1(i, h) = swb1(i, h)
               END IF
  END IF
END IF
IF i > 1 AND h = 3 THEN
    Root D(), i
         DD(i, h) = D(i) - D(i - 1)
   IF D(i) <= d2 THEN
       AW3(i, h) = 0:  swc1(i, h) = 0
      swc2(i, h) = swc2(i - 1, h) + dp4(i, h - 1)
            ETa3 = 0:  F5 = 0:   F6 = fc3
          IF swc2(i, h) > F6 THEN
             tdw(i, h) = swc2(i, h) - F6
             dp5(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swc2(i, h) = swc2(i, h) - dp5(i, h)
             dp6(i, h) = dp5(i, h)
```

```
        END IF
  ELSEIF D(i) > d2 AND D(i) < d3 THEN
         F5 = fc3 * (D(i) - d2) / (d3 - d2)
         F6 = fc3 * (d3 - D(i)) / (d3 - d2)
        swi = swc2(i - 1, h) * DD(i, h) / (d3 - D(i))
   AW3(i, h) = Delta3 * (D(i) - d2)
       SaD3 = AW3(i, h)
  swc1(i, h) = swc1(i - 1, h) + dp4(i, h - 1) + swi
  swc2(i, h) = swc2(i - 1, h) - swi
          IF swc1(i, h) <= F5 THEN
             tdw(i, h) = 0:  dp5(i, h) = 0
          ELSEIF swc1(i, h) > F5 THEN
             tdw(i, h) = swc1(i, h) - F5
             dp5(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swc1(i, h) = swc1(i, h) - dp5(i, h)
            swc2(i, h) = swc2(i, h) + dp5(i, h)
              IF swc2(i, h) > F6 THEN
                 tdw(i, h) = swc2(i, h) - F6
                 dp6(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
                swc2(i, h) = swc2(i, h) - dp6(i, h)
              END IF
          END IF
Depletion P, ETm
                IF swc1(i, h) > beta3 * (D(i) - d2) THEN
                              StD3 = swc1(i, h) - beta3 * (D(i) - d2)
                                AW = (1 - P) * SaD3
                        IF StD3 >= AW THEN
                           ETa3 = ETm / 3
                        ELSEIF StD3 <= AW THEN
                            TP3 = P * SaD3 / ETm
Extraction3 ETa, ETm, SaD3, TP3
                                    ETa3 = ETa / 3
                        END IF
                                swc1(i, h) = swc1(i, h) - ETa3
                ELSE
                                    ETa3 = 0
                                swc1(i, h) = swc1(i, h)
                END IF
   ELSEIF D(i) = d3 THEN
       swi = swc2(i - 1, h)
       swc1(i, h) = swc1(i - 1, h) + dp4(i, h - 1) + swi
       swc2(i, h) = swc2(i - 1, h) - swi
           F5 = fc3:   F6 = 0
        AW3(i, h) = AW3
            SaD3 = AW3(i, h)
      IF swc1(i, h) > F5 THEN
         tdw(i, h) = swc1(i, h) - F5
         dp5(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
        swc1(i, h) = swc1(i, h) - dp5(i, h)
         dp6(i, h) = dp5(i, h)
        swc2(i, h) = 0
      END IF
 Depletion P, ETm
                  IF swc1(i, h) > beta3 * (d3 - d2) THEN
                              StD3 = swc1(i, h) - beta3 * (d3 - d2)
                                AW = (1 - P) * SaD3
```

```
                                    IF StD3 >= AW THEN
                                           ETa3 = ETm / 3
                                    ELSEIF StD3 <= AW THEN
                                            TP3 = P * SaD3 / ETm
Extraction3 ETa, ETm, SaD3, TP3
                                           ETa3 = ETa / 3
                                    END IF
                                      swc1(i, h) = swc1(i, h) - ETa3
                          ELSE
                                           ETa3 = 0
                                      swc1(i, h) = swc1(i, h)
                          END IF
   ELSEIF D(i) > d3 AND D(i) <= d4 THEN
        swc1(i, h) = swc1(i - 1, h) + dp4(i, h - 1)
               F5 = fc3:   F6 = 0
         AW3(i, h) = AW3
              SaD3 = AW3(i, h)
         IF swc1(i, h) > F5 THEN
             tdw(i, h) = swc1(i, h) - F5
             dp5(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swc1(i, h) = swc1(i, h) - dp5(i, h)
             dp6(i, h) = dp5(i, h)
            swc2(i, h) = 0
         END IF
Depletion P, ETm
                             IF swc1(i, h) > beta3 * (d3 - d2) THEN
                                        StD3 = swc1(i, h) - beta3 * (d3 - d2)
                                          AW = (1 - P) * SaD3
                                    IF StD3 >= AW THEN
                                           ETa3 = ETm / 4
                                    ELSEIF StD3 <= AW THEN
                                            TP3 = P * SaD3 / ETm
Extraction3 ETa, ETm, SaD3, TP3
                                           ETa3 = ETa / 4
                                    END IF
                                      swc1(i, h) = swc1(i, h) - ETa3
                             ELSE
                                           ETa3 = 0
                                      swc1(i, h) = swc1(i, h)
                             END IF
   END IF
END IF
IF i > 1 AND h = 4 THEN
     Root D(), i
             DD(i, h) = D(i) - D(i - 1)
  IF D(i) <= d3 THEN
            AW4(i, h) = 0:  swd1(i, h) = 0
          swd2(i, h) = swd2(i - 1, h) + dp6(i, h - 1)
                 SaD4 = 0:  ETa4 = 0:   F7 = 0:   F8 = fc4
       IF swd2(i, h) > F8 THEN
             tdw(i, h) = swd2(i, h) - F8
             dp7(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
            swd2(i, h) = swd2(i, h) - dp7(i, h)
       END IF
                    dp = dp7(i, h)
                    DR = DR + dp
```

```
  ELSEIF D(i) > d3 AND D(i) < d4 THEN
                F7 = fc4 * (D(i) - d3) / (d4 - d3)
                F8 = fc4 * (d4 - D(i)) / (d4 - d3)
         AW4(i, h) = Delta4 * (D(i) - d3)
              SaD4 = AW4(i, h)
               swi = swd2(i - 1, h) * DD(i, h) / (d4 - D(i))
         swd1(i, h) = swd1(i - 1, h) + dp6(i, h - 1) + swi
         swd2(i, h) = swd2(i - 1, h) - swi
      IF swd1(i, h) <= F7 THEN
          tdw(i, h) = 0:  dp7(i, h) = 0
      ELSEIF swd1(i, h) > F7 THEN
           tdw(i, h) = swd1(i, h) - F7
           dp7(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
          swd1(i, h) = swd1(i, h) - dp7(i, h)
          swd2(i, h) = swd2(i, h) + dp7(i, h)
        IF swd2(i, h) > F8 THEN
               tdw(i, h) = swd2(i, h) - F8
               dp8(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
              swd2(i, h) = swd2(i, h) - dp8(i, h)
        END IF
                      dp = dp8(i, h)
                      DR = DR + dp8(i, h)
      END IF
Depletion P, ETm
                    IF swd1(i, h) > beta4 * (D(i) - d3) THEN
                            StD4 = swd1(i, h) - beta4 * (D(i) - d3)
                              AW = (1 - P) * SaD4
                           IF StD4 >= AW THEN
                                   ETa4 = ETm / 4
                           ELSEIF StD4 <= AW THEN
                                    TP4 = P * SaD4 / ETm
Extraction4 ETa, ETm, SaD4, TP4
                                   ETa4 = ETa / 4
                           END IF
                             swd1(i, h) = swd1(i, h) - ETa4
                    ELSE
                                   ETa4 = 0
                             swd1(i, h) = swd1(i, h)
                    END IF
  ELSEIF D(i) = d4 THEN
              swi = swd2(i - 1, h)
        swd1(i, h) = swd1(i - 1, h) + dp6(i, h - 1) + swi
                F7 = fc4:   F8 = 0
         AW4(i, h) = AW4
              SaD4 = AW4(i, h)
        IF swd1(i, h) > F7 THEN
           tdw(i, h) = swd1(i, h) - F7
           dp7(i, h) = tdw(i, h) * (1 - EXP(-1000 * k(h) / tdw(i, h)))
          swd1(i, h) = swd1(i, h) - dp7(i, h)
          swd2(i, h) = 0
        END IF
                  dp = dp7(i, h)
                  DR = DR + dp
Depletion P, ETm
                    IF swd1(i, h) > beta4 * (d4 - d3) THEN
                              StD4 = swd1(i, h) - beta4 * (d4 - d3)
```

```
                                        AW = (1 - P) * SaD4
                                IF StD4 >= AW THEN
                                        ETa4 = ETm / 4
                                ELSEIF StD4 <= AW THEN
                                        TP4 = P * SaD4 / ETm
Extraction4 ETa, ETm, SaD4, TP4
                                        ETa4 = ETa / 4
                                END IF
                                 swd1(i, h) = swd1(i, h) - ETa4
                    ELSE
                                        ETa4 = 0
                                 swd1(i, h) = swd1(i, h)
                    END IF
  END IF
END IF
   sw1 = swa1(i, 1) + swa2(i, 1)
   sw2 = swb1(i, 2) + swb2(i, 2)
   sw3 = swc1(i, 3) + swc2(i, 3)
   sw4 = swd1(i, 4) + swd2(i, 4)
   SWT = sw1 + sw2 + sw3 + sw4
FRMT$ = " ##     #       ###.#      ###.#      ###.#       ###.#"
SWF1$ = "##   ###.#   ###.#   ###.#   ###.#   ###.#   ###.#   ###.#   ###.#"
IF aa = 0 AND bb = 3 AND cc = 0 AND ee = 0 THEN
'PRINT USING SWF1$; i; D(i) / 10; R(i); RO(i); DR; ET; RE; SWT
END IF
YLD$ = " ##   ###.#   #.#   #.#   #.#   #.#   ##.#   ###.#   ###.#   ###.#   ###.#"
IF aa = 0 AND bb = 0 AND cc = 4 AND ee = 0 THEN
'PRINT USING YLD$; i; D(i) / 10; ETa1; ETa2; ETa3; ETa4; sw1; sw2; sw3; sw4; SWT
END IF
RDT = D(i)
NEXT h
FOR xy = 1 TO 500: NEXT xy
ETMAX = ETMAX + ETm                              ' Accumulating maximum ET
ETT = ETT + ETa1 + ETa2 + ETa3 + ETa4            ' Accumulating actual ET
ETAC = ETa1 + ETa2 + ETa3 + ETa4
PRINT

           ' ================================================
           '        COMPUTING  EFFECTIVE  RAINFALL
           ' ================================================

   FC = fc1 + fc2 + fc3 + fc4
   IF i = 1 AND SWT < FC THEN
         SMAX = FC - SWT               ' Max. soil storage, mm.
           IF Rain >= SMAX THEN
               RE = SMAX
           ELSEIF Rain < SMAX THEN
               RE = Rain
           END IF
   ELSEIF i = 1 AND SWT >= FC THEN
         SMAX = 0
           RE = 0
   END IF
          RET = RET + RE
   IF i > 1 AND SWT < FC THEN
         SMAX = FC - SWT               ' Max. soil storage, mm.
```

```
          IF Rain >= SMAX THEN
              RE = SMAX
          ELSEIF Rain < SMAX THEN
              RE = Rain
          END IF
   ELSEIF i > 1 AND SWT >= FC THEN
         SMAX = 0
          RE = 0
   END IF
         RET = RET + RE
fmtt$ = " ##      ###.#    ###.#    ###.#    ###.#    ###.#    ###.#    ###.#"
PRINT USING fmtt$; i; RDT / 10; Rain; ROFF; dp; ETAC; RE; SWT
CLS

          '==========================================
          '           SUMMARY MODULE
          '==========================================

YRatio = 100 * (1 - 1.25 * (1 - ETT / ETMAX))
PRINT
PRINT USING "   The Yield Ratio is ###.# %"; YRatio
PRINT
PRINT USING "   Total rainfall in the season = ###.#"; Totrain
PRINT
PRINT USING "   Cumulative runoff = ###.#"; ROC; : PRINT "mm."
PRINT
PRINT USING "   Seasonal percolation loss = ###.# "; DR; : PRINT "mm"
PRINT
PRINT USING "   Total seasonal INPUT ET = ###.#"; ETMAX; : PRINT "mm"
PRINT
PRINT USING "   Total Abstracted ET = ###.#"; ETT; : PRINT "mm"
IF TotNum = 0 THEN
          TotalPercent = 0
      ELSEIF TotNum > 0 THEN
PRINT USING "   Percentage of rain that ran off = ##.# "; 100 * ROC / Totrain
END IF

DATA 3.8,0,3.6,0,3.8,0,3.1,0,4.0,0,4.2,3.9,4.3,34.1,3.0,11.5,4.7,5.9,4.0,121.7
DATA 3.3,2.2,3.7,0,3.9,0,3.0,0,4.5,25.9,3.6,0,3.8,0.6,4.1,31,3.5,3.5,4.6,4
DATA 3.1,0,3.4,8.8,4.2,5,3.1,45.5,4.1,5,4.2,20.1,4.0,0.3,3.2,14,3.8,0,3.4,0
DATA 3.9,5.8,3.7,33.5,4.5,28.5,4.8,24.7,3.6,19,3.7,3.1,3.7,33.5,4.7,16.2
DATA 4.8,3.1,4.3,0,3.7,0,4.1,0,4.3,0,4.1,0,4.5,0,5.1,0,5.0,0,4.4,0,3.8,1.4
DATA 5.3,19,4.1,0,3.7,0,3.8,0,3.4,0,4.5,0,4.0,0,3.9,0,4,0,3.5,0,4.5,0,4.0,0
DATA 3.9,0,4.0,0,3.5,0,4.5,0,4.1,0,3.4,0,4.0,0,3.9,0,4.3,0,3.6,0,3.5,0,4.2,0
DATA 4.4,0,4.1,0,4.7,0,4.3,0,3.9,0,4.0,0,3.7,0,3.8,0,4.5,0
400
500       '==========================================
          '        ENDING THE PROGRAMME
          '==========================================
END

SUB Depletion (P, ETm)

'    ==================================================
'         This data is from Doorenbos and Kassam (1979)
'    ==================================================
```

```
    IF ETm < 2 THEN
       P = .875
       END IF
    IF ETm > 2 AND ETm <= 3 THEN
       P = .8
       END IF
    IF ETm > 3 AND ETm <= 4 THEN
       P = .7
       END IF
    IF ETm > 4 AND ETm <= 5 THEN
       P = .6
       END IF
    IF ETm > 5 AND ETm <= 6 THEN
       P = .55
       END IF
    IF ETm > 6 THEN
       P = .5
       END IF
END SUB

SUB Extraction1 (ETa, ETm, SaD1, TP1) STATIC
Depletion P, ETm
    IF TP1 > 0 THEN
            A = ETm * TP1
            F = 1 - P
            B = F * SaD1
            C = P / F
         ETa = SaD1 / TP1 * (1 - (1 - P) * EXP(-(A / B + C)))
    END IF
END SUB

SUB Extraction2 (ETa, ETm, SaD2, TP2) STATIC
Depletion P, ETm
    IF TP2 > 0 THEN
            A = ETm * TP2
            F = 1 - P
            B = F * SaD2
            C = P / F
            ETa = SaD2 / TP2 * (1 - (1 - P) * EXP(-(A / B + C)))
    END IF
END SUB

SUB Extraction3 (ETa, ETm, SaD3, TP3) STATIC
Depletion P, ETm
    IF TP3 > 0 THEN
            A = ETm * TP3
            F = 1 - P
            B = F * SaD3
            C = P / F
         ETa = SaD3 / TP3 * (1 - (1 - P) * EXP(-(A / B + C)))
    END IF
END SUB

SUB Extraction4 (ETa, ETm, SaD4, TP4) STATIC
Depletion P, ETm
    IF TP4 > 0 THEN
```

```
            A = ETm * TP4
            F = 1 - P
            B = F * SaD4
            C = P / F
          ETa = SaD4 / TP4 * (1 - (1 - P) * EXP(-(A / B + C)))
    END IF
END SUB

SUB Root (D(), i)
    IF i <= 60 THEN
         D(i) = i * 100 / 6 + 50
    ELSEIF i > 60 THEN
         D(i) = 1050
    END IF
END SUB
```