INFLUENCE OF SOIL, CLIMATE AND LAND USE ON SOIL WATER BALANCE IN THE UPPER EWASO NG'IRO BASIN IN KENYA

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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

To all those men and women
from who I learned
and acquired knowledge
to appreciate and embrace
our most precious possession and resource
that most common substance
that we sometimes call 'dirt'
but is in fact the purifying medium
wherein waste is recycled
and productivity regenerated

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ABBREVIATIONS AND SYMBOLS

ACZ	Agroclimatic zone
AEZ	Agroecological zone
ASAL	arid and semi arid lands
AWC	available water capacity (mm m^{-1})
BE	bare enclosed
BO	bare open
C	carbon content (%)
CG	controlled grazing
CT	conventional tillage
D	deep drainage
E	evaporation
EI_{30}	rainfall erosivity index (or EI_{30} for 15 minute intervals)
Ep	pan evaporation (climatic water demand)
ET	evapotranspiration
ETa	actual evapotranspiration
FAO	Food and Agriculture Organisation
FC	field capacity
GL	grazing land
GoK	Government of Kenya
H	hydraulic head (cm)
I	rainfall intensity (cm h^{-1})
ICRISAT	International Crops Research Institute for the Semi Arid Tropics
K	hydraulic conductivity (cm h^{-1})
K_s	saturated hydraulic conductivity (cm h^{-1})
KE	rainfall kinetic energy (J m^{-2})
KMD	Kenya Meteorological Department
LRP	Laikipia Research Programme
LR93	long rains of 1993
LR94	long rains of 1994
LU	livestock unit
MT	mulch tillage
NF	natural forest
NRM^3	Natural Resources Monitoring, Modeling and Management
P	rainfall
PAW	plant available water
PC	potato cropland
PE	perennial enclosed
PO	perennial open
PO	porosity (% volume)
q	water flux (cm h^{-1})
R	runoff
RO	runon
r/E	rainfall to evaporation ratio (mean annual)

SR93/94	short rains of 1993/94
SR94/95	short rains of 1994/95
T	transpiration
t	time
UENB	Upper Ewaso Ng'iro Basin
USDA	United States Department of Agriculture
WP	permanent wilting point
W	water use
z	soil depth taken positive from soil surface
ΔS	change in water content in the soil profile
ρ_b	bulk density ($Mg\ m^{-3}$)
θ	volumetric soil water content
ψ	soil water potential

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ABSTRACT

The influence of soil, climate, and land use on soil water balance was investigated in 3 agroclimatic zones within the Upper Ewaso Ng'iro Basin. Water balance was quantified for various land uses and management systems in each zone. These were natural forest (NF), grazing land (GL) and potato cropland (PC) on a mollic Andosol at Karuri; conventional tillage (CT), mulch tillage (MT), overgrazing (OG) and controlled grazing (CG) on a ferric Luvisol at Kalalu; and perennial grass (PO), enclosed perennial grass (PE), bare ground (BO), enclosed bare ground (BE) and runon (bare ground with a bush and grass at the lower end (RO) sites on a chromic Lixisol at Mukogodo. Soil moisture, runoff and soil cover for each system; and rainfall and evaporation at each site, were monitored for four rainy seasons (September 1993-August 1995). Selected soil physical properties for each system were also measured.

The climatic water balance was negative at all sites as the ratio of mean annual rainfall to mean annual potential evaporation was 0.65, 0.47 and 0.16 for Karuri, Kalalu and Mukogodo, respectively. The annual rainfall means during the monitoring period were similar to available long term records. Total mean runoff as percentage of rainfall in the four seasons at Karuri was 6.6% in PC and 1.6% in GL; at Kalalu it was 6.6, 0.01, 30.0 and 4.0% in CT, MT, OG and CG, respectively; and at Mukogodo it was 25.1, 35.2, 9.9, 51.1 and 47.6% in RO, PO, PE, BO and BE, respectively. Runoff from cropland at Karuri and Kalalu during big storms (>20 mm day^{-1}) was up to 40% of rainfall, and for similar events up to 80% from overgrazed sites at Kalalu and Mukogodo. Bush canopy basal cover (RO) intercepted and infiltrated up to 50% of runoff flowing from bare ground.

Both BO and BE at Mukogodo had similar cover. However, cover in PE increased to about 3 times that in PO. Runoff decreased with increase of cover in all sites and treatments. Calculated minimum (threshold) amount of rainfall required to generate runoff increased with soil cover and ranged from 11-14 mm day^{-1} in cropland and from 6-12 mm day^{-1} in grazing land. Runoff significantly correlated with amount of rainfall in cropland only at Karuri and for cover >30% ($r^2 = 0.71$), but at all sites in grazing land ($r^2 = 0.65$ at Karuri, 0.76-0.94 at Kalalu, and 0.51-0.62 at Mukogodo). Runoff also

significantly correlated with rainfall erosivity at all sites; that in grazing land ($r^2 = 0.88$ at Karuri, 0.56-0.98 at Kalalu, and 0.49-0.68 at Mukogodo) was stronger than in cropland ($r^2 = 0.49$-0.79 at Karuri and 0.77 at Kalalu).

Available soil water stored at Karuri ranged from 140, 130 and 120 mm in the driest period to 230, 205 and 185 mm in the wettest period of the year for NF, GL and PC, respectively, in 160 cm soil depth. On annual average, NF (192 mm) had significantly higher available water than GL (169 mm) and PC (153 mm). Available water stored in Kalalu cropland was 88 and 37 mm in the driest period, and 222 and 176 mm in the wettest period of the year for MT and CT, respectively in 160 cm soil depth. Higher moisture was recorded in MT than CT in both times. In grazing land, CG stored 46% more water (147 mm) than OG (101 mm) in the wettest period, but there was no available water in the driest period in both CG and OG. Moisture recharge in the wet seasons was limited to only 90 cm in OG, but like in cropland, it percolated beyond 120 cm in CG. None of the treatments at Mukogodo had any available water in the dry seasons. Even in the wettest period, only 19, 13, 20, 9 and 7 mm of water was available within a depth of 80 cm in RO, PO, PE, BO and BE, respectively. That in RO and PE were significantly higher ($P<0.05$) than the rest. Moisture percolated to only about 50 cm under good cover and to about 30 cm on bare ground even in the wettest period at Mukogodo.

Water use was higher in PC (4-18%) and GL (7-20%) than NF in the 4 growing seasons, indicating that the forest extracted less water than potato and grass from within the 160 cm soil depth. At Kalalu, MT used more (18-42%) water than CT during the long rains. However, in the short rains, some moisture was conserved and carried over, resulting in lower (10-26%) water use in MT compared to CT. Water use was higher (21-24%) in CG compared to OG in all seasons. At Mukogodo water use was 13-20% and 32-55% lower in PO and BO, respectively, than RO in the 4 growing seasons. In all seasons PE used significantly ($P<0.05$) more water than PO (23-61%) and BO (57-95%). Higher (8-33%) water use by PE than RO was attributed to higher evapotranspiration by grass in the open compared to that under bush canopy. This water balance study indicated that apart from soils and climate, differences in land use and surface soil management also influenced soil water storage and subsequent use within the basin.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Primary productivity of a given environment can be constrained by unfavourable soil water regimes. This may be due to plant water stress if rainfall is inadequate and/or poorly distributed, water logging under poor drainage conditions, or nutrient leaching if there is excessive drainage. Such unfavourable soil water regime may be brought about by natural or man-induced factors such as:

- climatic factors e.g. low, poorly distributed or high intensity rainfall events and high evaporative demands.
- soil factors such e.g. low water holding capacity, surface sealing, restricted water entry and movement in the soil or poor structure.
- vegetation factors e.g. ground cover and/or macropores induced by plant roots and/or high organic matter content.

Much of the rain water received on the soil surface or that applied by irrigation may be lost as runoff, direct evaporation, transpiration from unwanted plants or by deep percolation below the plant root zone. Such losses can deprive the plant of a major portion of limited water supply and might result in crop failure and poor vegetation cover in farming areas with marginal climate. In irrigation farming, such losses reduce the efficiency of irrigation and water use and could contribute to soil salinization. Primary production in the semi-arid tropics is controlled primarily by water availability and hence productivity can be enhanced by developing methods that ensure better use of the rain that falls (McCown, 1973). Wise management of soil moisture in arid and semi-arid regions is a prerequisite to improved productivity and sustainability of soil water and vegetation resources.

The Upper Ewaso Ng'iro basin (UENB) is an highland-lowland system located to the north and northwest of Mount Kenya. The Ewaso Ng'iro river flows north east through the basin. Change in elevation gives rise to a dramatic climatic and ecological gradient, from humid moorlands and forests on the slopes to arid *Acacia* bushlands in the lowlands, with a diverse pattern of land use (Decurtins, 1992). Available data (Liniger and Gichuki, 1994) indicate that the natural resources of this highland-lowland system are under pressure in

a) the highlands (resource rich) due to dynamic land use changes and intensification, resulting in resource degradation and
b) the lowlands (resource poor) due to immigration, accompanied by inappropriate land management practices, and marginalisation of the indigenous communities.

Most of UENB is arid and semiarid land (ASAL). Despite the marginal status, a significant proportion of this area has been subdivided and small scale farming established in the former "White Highlands". Increase in population is estimated to be 7-8% per annum (Kohler, 1987; GoK, 1994a) as a result of natural increase and immigration from the adjacent densely populated areas. Population pressure induces land use changes (Tiffen *et al.*, 1994). These changes are accompanied by a diversity of soil and water management techniques. Most of the UENB has water as the most limiting resource (Flury, 1987; Berger, 1989; Wiesmann, 1992), and the characteristic of intense socio-economic and land use dynamics (Herren, 1990). Due to scarcity of water, crop production and livestock keeping, which are the major land use activities, are greatly constrained. Recurrent crop failure, low biomass production in rangelands, soil erosion and high runoff loss highlight the importance of management of soil, water and vegetation resources (Desaules, 1989; Liniger, 1991a).

Conflicts in the various traditional land use activities have been experienced and the natural ecological balances within the individual locations have been threatened. The changes are in some cases accompanied by environmental degradation, declining primary production and impoverishment. This dynamic and conflicting situation makes management and planning for sustainable use of natural resources extremely difficult. High standards not only have to be met in management and participatory planning approaches, but also in assessment of the dynamics of the natural resources (Liniger and Gichuki, 1994).

One of the Government of Kenya's major long term development plans has been focused on the ASAL areas in order to exploit their productive potential. This is aimed at improving food sufficiency for the increasing population through increased livestock and agricultural production (GoK, 1986; 1994b). In the two policy papers, it is emphasized that research priorities for increased food production in the ASAL should focus on conservation of soil moisture and fertility levels to minimise reliance on chemical fertilisers.

Ecological constraints of the ASAL areas are however numerous. These include low carrying capacity due to low and variable primary production and large variability in rainfall amount and distribution. The inevitable land use changes put pressure on these fragile environments, resulting in problems of how to increase and sustain production, while at the same time conserving the natural resources. Therefore it is complex to manage and predict expected outcomes from such a system. However, experience in more developed countries demonstrates that use of computer simulation models can serve as a powerful tool in assessing effects of development and conservation strategies. This is because the models can integrate the findings of different disciplines and guide and minimise the need for experimental and baseline data (Klemes, 1982). Therefore in order to assess the effect of land use change and conservation practices on soil water dynamics and primary production, superior approaches such as employment of models to simulate soil physical processes and crop performance are recommended (Freebairn *et al.*, 1990).

As in many other developing countries, application of simulation models in investigating the physical environment and agricultural systems in Kenya has not been widespread. This would be explained by lack of skilled manpower, financial resources, and the necessary databases. However, Laikipia Research Programme (LRP), in collaboration with the Universities of Nairobi and Berne (Switzerland) have built capacity and the database necessary to make a start in modelling soil water dynamics, primary production and hydrological processes. Thus, a modelling project, referred to as "Natural Resources Monitoring Modelling and Management (NRM^3) project (Liniger and Gichuki, 1994) was initiated within the upper Ewaso Ng'iro basin in order to:

a) assess the effects of land use changes on primary productivity and on the water and soil resources
b) identify the potential for improved conservation and management practices
c) assist in planning for sustainable and balanced use of the water, soil and vegetation resources within the entire project region.

Environmental and socio-economic conditions in parts of the upper Ewaso Ng'iro basin have been investigated and documented by LRP since the mid-eighties. However, there is still need for more research especially on the development of tools for resource management. As part of NRM^3's major objectives, this study that deals with soil water balance dynamics was initiated to investigate the processes that influence soil water dynamics under different environmental, land use and management conditions experienced in the upper Ewaso Ng'iro basin and develop management guidelines for optimizing use of the scarce rainwater resources. This study is part of the overall NRM^3 objectives which aim at development of aggregated models as management tools for sustainable use of natural resources in Mount Kenya highland-lowland system (Liniger and Gichuki, 1994). The other ongoing complimentary studies cover crop water use and primary production, streamflow and sediment yield, and river water abstraction and allocation.

1.2 RATIONALE FOR THE STUDY

Rainfall is the major factor that determines the space-time characteristics of the soil water status in the tropics. In Kenya, most primary production is by rain fed agriculture. Storage of water in the soil is a primary concern in the management of agriculture in arid and semiarid regions. Through repeated cycles of infiltration and evaporation, much of the water received on the soil surface from rainfall may be lost by runoff (which also entails the hazard of erosion), by direct evaporation or transpiration by weeds, or by internal drainage beyond reach of crop roots. In dry land farming, such losses can deprive the crops to be grown of a major portion of the limited rainwater supply and might result in crop failure. To increase the efficiency of soil and water management, it is necessary to evaluate the balance and storage of soil moisture. A thorough understanding and quantitative knowledge of the dynamics of soil water is a prerequisite to increase the productivity of soil, water and vegetation resources. Knowledge of the amount of water entering the soil and its distribution in the soil profile enables us to:

- evaluate the balance and storage of soil moisture;
- predict quantitatively to what extent they might be amenable to various control measures;

- decide whether and when to plant various crops;
- decide whether and when to provide supplemental irrigation;
- assess the rate of groundwater recharge.

In semiarid areas appropriate water conservation methods are needed to reduce the risk of crop failure. There are various methods that can be used to improve soil moisture storage and availability. However, their effectiveness depends on the climatic and socio-economic characteristics of the area in question and the farmer's needs. Methods developed elsewhere may not be adopted for immediate application without prior testing due to variability in local conditions, specifically climate, soils, social and economic factors (Hudson, 1987).

NRM[3] adopted a three pronged approach in data collection within UENB. Research is carried out at plot, catchment and basin levels (Liniger and Gichuki, 1994). This study concentrated on plot level. So far some investigations on soil water storage and use by plants have been carried out within UENB, and they form the base for the current study. Soil moisture storage and runoff for two soil types within the Laikipia plateau on cropland and grazing land have been investigated by Liniger (1991a). Recently, Njeru (1995) reported water use by various vegetation types along the Naro Moru river profile. In Mukogodo rangelands, studies on infiltration (Kironchi, 1992) and runoff loss (Mutunga, 1995) under various soil cover conditions have been carried out. All these studies indicate that runoff or infiltration of rain water is influenced most by soil cover or soil surface management. It was realised, however, that more data in terms of detail, time and space were required for comprehensive analysis of the processes that affect water entry, movement and storage in the soil and subsequent use by plants. This is because the investigations cited above were limited by one or more of the following:

a) Insufficient data for all key processes of the water balance, especially soil hydraulic properties
b) Insufficient data in terms of time period of collection, especially rainfall
c) Lack of adequate soil moisture data, especially at some critical periods
d) Objectives and scope would not allow broad representation of agroclimatic zones and land uses within the basin.

Therefore there was need to carry out comprehensive investigations at plot level on all the key processes that influence the water balance in various environments under different land use and soil surface conditions. Accrued information would be used to formulate user oriented management guidelines on soil moisture dynamics for various climatic and soil conditions. Also data from this study would be used in further research especially in modelling soil water balance and crop water use. From the latter, quantitative criteria for appraising the possible benefits which might be expected from proposed or alternative soil management methods can be realised.

1.3 STUDY OBJECTIVES AND SCOPE

1.3.1 Objectives

The overall objective of the study was to assess soil water balance under different environmental, land use and management conditions experienced in the Upper Ewaso Ng'iro basin.

To achieve this, the study had the following specific objectives:

a) To characterise climatic and soil physical properties at site level in three agroclimatic zones.

b) To determine rainfall-runoff relationship for different soils, land use and ground cover conditions.

c) To assess soil water dynamics and balance for different soils, land use and management systems.

1.3.2 Scope

Various concepts relevant to this study are defined and elaborated in chapter 2. These include the soil water balance as part of the hydrological cycle, soil water storage and water flow processes of infiltration, percolation and redistribution. The conceptual framework is presented in section 2.3 where the soil water balance concepts are elaborated. This study deals with rainfall water infiltration and runoff and the resultant soil moisture status for three soil types within which a total of four land uses and nine management options are examined. The study area cuts through a gradient of three agroclimatic zones, that is, Mt. Kenya middle-upper sub-humid slopes, semi-humid to semi-arid footslopes and the semi-arid to arid basement area in the Upper Ewaso Ng'iro basin.

The scale of investigation is the field plot and the effective plant rooting depth of the soil profile under non-irrigated prevailing environmental conditions. One site was selected in each of the three zones. Rainfall and evaporation were monitored daily while soil moisture and soil cover were monitored weekly. The thrust of this study is the influence of soil surface conditions in partitioning rainfall into runoff and infiltration water, and in controlling evapotranspiration. Water flow into the soil and its redistribution is assessed using the principles of Richards' equation which describes water flow in both saturated and unsaturated conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 SOIL WATER RESERVOIR

2.1.1 Soil water constants

The capacity of soil to absorb, retain and release water is of prime importance as it determines the amount and dynamics of water available for plant growth. Soil acts as a water reservoir bridging the gap between water use by plants and water supply by rainfall, irrigation or groundwater rise. The total amount of water that can be stored in the soil is determined by the pore space and soil depth. The percentage of water available to plants depends on soil water potential, soil water redistribution and the plants ability to absorb the water. Three water retention constants are defined when the soil medium is considered as a water storage reservoir. These are porosity, field capacity and permanent wilting point.

Porosity, *PO*, is the percentage soil volume occupied by voids, and as such contains the maximum possible soil water storage. At *PO* soil is therefore saturated. The matric potential at saturation is 0 cm pressure head.

Field Capacity, *FC*, is the soil water condition reached when water has been allowed to percolate naturally from the soil until drainage ceases and the water remaining is held by capillary forces that are great enough to resist gravity. *FC* is often described as being the wet limit of the soil water available freely to plants. Also *FC* can be described as the water content below which the hydraulic conductivity is sufficiently small for redistribution of moisture due to hydraulic head to be ignored. According to Gardner (1988), *FC* is the percentage of water remaining in a soil profile 2 to 3 days after having been saturated and after free drainage has practically ceased. A definition in terms of matric potential is difficult owing to the fact that *FC* may vary with texture

(Cassel and Nielsen, 1986), thus it has variously been reported between -100 and -300 cm head (Lal, 1981; Ratliff *et al.*, 1983; Gardner, 1988; Cresswell *et al.*, 1991).

Permanent Wilting Point, WP, is taken as the lower limit of water available to plants. At *WP* the hydraulic conductivity is so low that water cannot move to the roots fast enough, even at short distances, and no water is available for transpiration. A matric potential of -15000 cm is usually taken as an approximation of *WP* for many soils. At such low matric potential, small changes in moisture correspond to large changes in the potential. Hence whilst a potential of -15000 cm may not represent the lowest limit of water available for plant extraction, its corresponding moisture content is not far off the mark (Cassel and Nielsen, 1986; Gardner, 1988).

Plant available water, *PAW*, defined as the difference between upper storage limit and lower storage limit summed over the plant rooting depth, is given as

$$PAW = FC - WP \tag{2.1}$$

The amount of soil water available depends on soil texture, structure and soil depth. Soil water in excess of *WP* value is available to plants for transpiration and hence growth processes. That in excess of *FC* is drainage water. Soil water between *FC* and *WP* may be redistributed upwards or downwards at rates depending on soil water gradients.

2.1.2 Soil water potential

Investigations involving water transport and storage in soils and soil-water-plant relationships require information on the energy status of the soil water. Matric potential is a measure of the energy status of water in the soil and is a component of total soil water potential, which is described as

$$\Psi_t = \psi_g + \psi_p + \psi_o + \ldots \tag{2.2}$$

where Ψ_t is the total potential, ψ_g is the gravitational potential, ψ_p is the matric potential, and ψ_o is the osmotic potential; other types of potential are also possible (Hillel, 1971). The total soil water potential measures the energy of soil water at an elevation ψ_g subject to the suction pressure head ψ_p relative to water at atmospheric pressure located at elevation zero. Energy head is represented by units of length which is equivalent to the amount of energy possessed by a unit weight of water. Since unsaturated soil water pressures are less than atmospheric, the capillary pressure and matric potential are negative numbers.

2.1.3 Relationship between soil water content and potential

The moisture characteristic (Figure 2.1) of the soil describes the soil's ability to store and release water and is defined as the relationship between the soil water content and the soil matric potential. Soil water content and matric potential have a power function relationship. The function relates a *capacity factor*, the water content, to an *intensity factor*, the energy state of the soil. For the purposes of numerical approximation of the relationship between soil water potential and water content, mathematical functions have been developed. Models most frequently used to describe this relationship are those proposed by Brooks and Corey (Klute, 1986), Campbell (1974) and van Genuchten (1980). The model by van Genuchten permits a representation of the total water-retention curve, whereas the other two models describe only the portion of the curve for matric potentials less than the bubbling pressure, or pressure at which air will enter the soil.

The water retention function is primarily dependent upon the texture (Figure 2.1) and the structure (Salter and Williams, 1965; Sharma & Uehara, 1968). Organic matter has a direct effect on the retention function because of its hydrophilic nature, and an indirect effect as it modifies soil structure (Klute, 1986). At low suctions the shape of the curve is largely determined by the soil structure or pore size distribution (Williams *et al.*, 1983). Since soil structure is a function of tillage practices, organic matter content, exchangeable cations and soil solution concentration, this part of the retention curve varies with land use and management (Cresswell *et al.*, 1991).

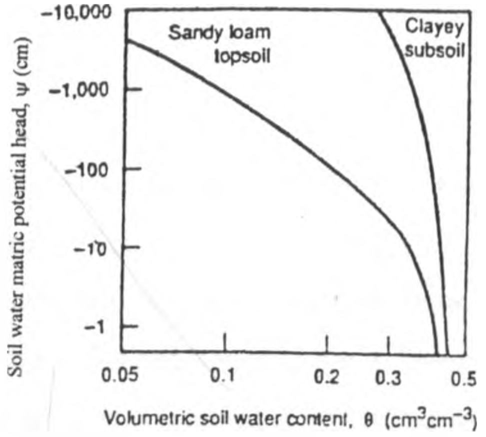


Figure 2.1. The $\psi(\theta)$ relationship of sandy loam and clayey soil horizons.

(Source: Rawls et al., 1993).

The matric potential water content $\psi(\theta)$ relationship is not unique, as it is different for the desorbing (draining) and absorbing (wetting) processes. For the same suction, the drainage process has more water than the wetting process. This phenomenon, termed as hysteresis, is more pronounced for sandy soils that have large pores (Topp, 1969; Pavlakis & Barden, 1972).

2.2 SOIL WATER MOVEMENT

Soil water movement is the process of water flow from one point to another within the soil. The rate of infiltration is controlled by the rate of soil water movement below the surface. Soil water movement also controls redistribution and the supply of water for plant uptake and for evaporation at the soil surface. The soil properties affecting soil water movement are hydraulic conductivity and water-retention characteristics. Flow of soil water can take place under saturated or unsaturated conditions, but it occurs more often in the latter.

2.2.1 Saturated flow

Water flow in saturated soil is governed by Darcy's law which states that flow is directly proportional to the hydraulic gradient but inversely proportional to the length of flow path. For steady state flow this relationship is written as

$$q = -K\frac{\partial H}{\partial z} \tag{2.3}$$

where q is water flux; H is hydraulic head, z is the distance in direction of flow and K is the hydraulic conductivity. Equation 2.3 is written for flow in one dimension, but can be generalised to describe flow in two or three dimensions. Darcy's law applies to a saturated soil which is homogeneous and isotropic. For a layered soil, it can be applied separately for each layer, if each layer is assumed to be homogeneous and isotropic within itself. The value of K and the gradient *dH/dz* vary from layer to layer, but there is a continuity of *H* and *q* across the interfaces between layers (Hanks and Ashcroft, 1980; Rawls *et al.*, 1993).

2.2.2 Unsaturated flow

Soils are seldom completely saturated with water, although saturation may occur at certain depths for brief periods of time. Most of the time water flows in soil under unsaturated conditions; i.e. the soil pore space is occupied by both air and water. Most of the theoretical and experimental developments concerning infiltration and soil water movement are based on the assumption that the air phase is interconnected and continuous, so that air can easily escape as the water moves in, and thus offers negligible resistance to water flow (Rawls *et al.*, 1993). The vapour transport of water in soil is also generally neglected. Under these simplifying assumptions Equation 2.3 is modified to describe unsaturated flow. In unsaturated soil, the hydraulic conductivity *K* is a function of the volumetric soil water content θ, i.e., $K = K(\theta)$, the parameter *K* now referred to as unsaturated hydraulic conductivity. The soil water potential ψ in unsaturated soil is negative, because of the capillary suction forces, since it is a function of θ, $\psi = \psi(\theta)$. The $\psi(\theta)$ is referred to as soil water potential head. For one-dimensional, unsteady vertical flow:

$$q = -K(\theta)\left[\frac{\partial \psi(\theta)}{\partial z} - 1\right] \tag{2.4}$$

where z is the soil depth, taken positive downward. The term $K(\theta)$ can also be written as $K(\psi)$, when θ is assumed to be a unique function of ψ, the matric potential head.

Combining Equation 2.4 with the law of conservation of mass results in an equation of one-dimensional vertical flow in an unsaturated soil:

$$\frac{\partial\theta(z,t)}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta,z)\frac{\partial\psi(\theta,z)}{\partial z}-1\right] \tag{2.5}$$

where t is time and the nomenclature $K(\theta, z)$, $\psi(\theta, z)$ allows for variation of $K(\theta)$ and $\psi(\theta)$ with depth z, as in a layered soil. Equation 2.5 has two dependent variables θ and ψ. Given that θ is a unique function of ψ, we can write $\partial\theta/\partial t$ as $(\partial\theta/\partial\psi)\ \partial\psi/\partial t = C(\psi)(\partial\psi/\partial t)$, and obtain Richards equation which governs water flow in the soil;

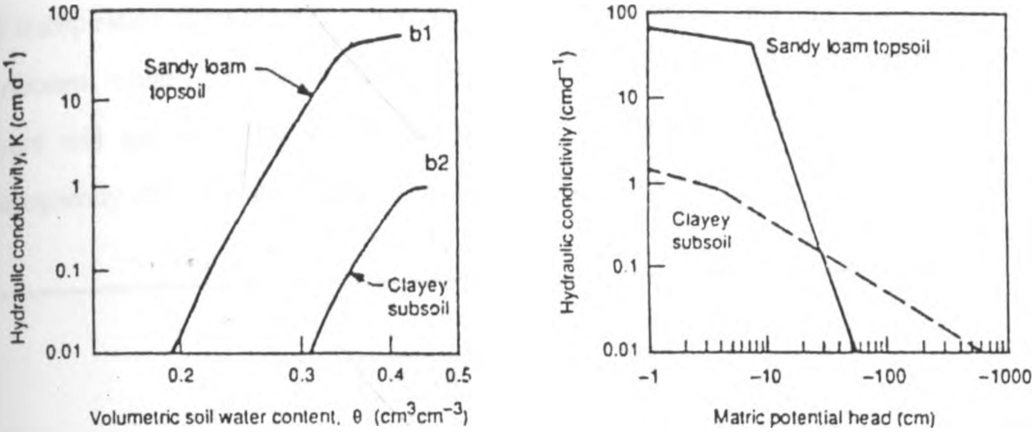
$$C(\psi,z)\frac{\partial\psi(z,t)}{\partial t}=\frac{\partial}{\partial z}\left[K(\psi,z)\frac{\partial\psi(z,t)}{\partial z}-1\right] \tag{2.6}$$

During redistribution or drainage of water between rainfall events, root uptake of water is an important factor. This is added to the equation as a sink term S_w expressing the rate of uptake per unit volume of soil;

$$\partial\theta\frac{(z,t)}{\partial t}+S_w(z,t)=\frac{\partial}{\partial z}\left[K(\theta,z)\frac{\partial\psi(\theta,z)}{\partial z}-1\right] \tag{2.7}$$

2.2.3 Hydraulic conductivity

Hydraulic conductivity K is a measure of the ability of a soil to transmit water and depends upon both the properties of the soil and the fluid (Klute and Dirksen, 1986). Total porosity, pore-size distribution, and pore continuity are the important soil characteristics affecting hydraulic conductivity. Fluid properties affecting hydraulic conductivity are viscosity and density. Since we do not experience temperature extremes in the study area, the effect of fluid properties is considered negligible. The hydraulic conductivity at or above the saturation point ($\psi \geq 0$) is referred to as saturated hydraulic conductivity K_s, and for water contents below saturation ($\psi < 0$), it is called the unsaturated hydraulic conductivity.



(a) (b)

Figure 2.2 (a) The $K(\theta)$ and (b) $K(\psi)$ relationships of sandy loam and clayey soil horizons (*Source: Rawls et al., 1993*).

The hydraulic conductivity is a nonlinear function of volumetric soil water content, and varies with soil texture (Hillel, 1977; Rawls et al., 1993) as shown in Figure 2.2(a) for a sandy loam and a clayey soil. Similarly Figure 2.2(b) presents K as a function of ψ.

2.3 SOIL WATER BALANCE

Water balance is a statement of the law of conservation of matter. It is intimately connected with the energy balance since most water balance processes are driven by energy. The content of water in the soil affects the way the energy fluxes reaching the field are partitioned and utilised, while the energy fluxes affect the state and movement of water. Soil water balance is part of the hydrological cycle. Figure 2.3 presents the key components and processes of the cycle that are relevant to this study. These are processes by which water enters or leaves the soil profile, and can for arbitrary unit of time be written as

$$P - R = ET + D + \Delta S \qquad (2.8)$$

where P is rainfall; R is runoff; ET is evapotranspiration; D is drainage and ΔS is change in water content of the soil profile. ET can be split into evaporation from the soil surface, E, and transpiration from plants, T. Rainfall (P) forms the input component, ΔS the storage component while R, D and ET form the output component. Different land uses or soil covers will influence the various components of the water balance differently, and consequently the soil water regime of a given area.

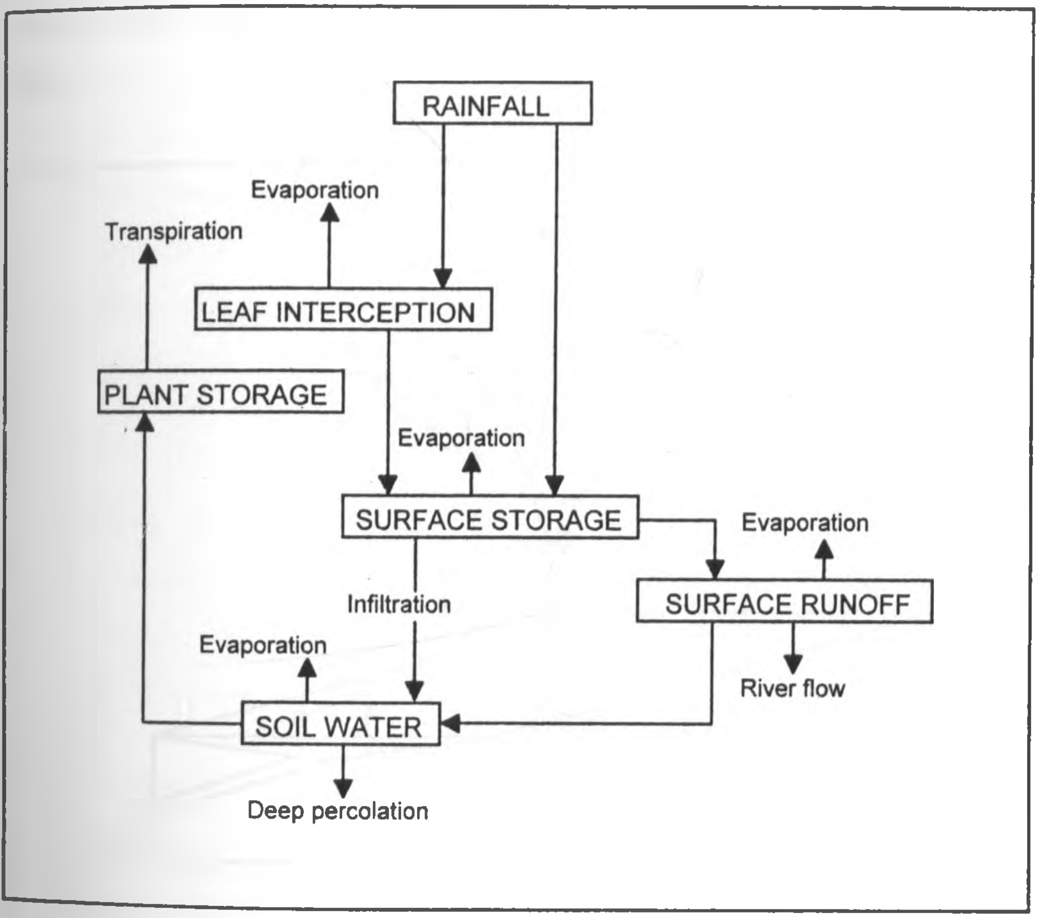


Figure 2.3. Atmosphere-soil-plant water system as part of the hydrological cycle. (*Source: modified from Jackson, 1977*).

A water balance model suggested by Liniger (1991a) and used in soil moisture studies at Kalalu and Matanya within Laikipia plateau is adapted for this study. However, the current model (Figure 2.4) gives an allowance for lateral subsurface flow into or out of the profile and possibility of deep percolation. This is necessary in order to accommodate the sub-humid mountain slopes zone where the two processes are likely to occur.

The model illustrates a non-irrigated system, where rainfall is the water input. Rainfall water either infiltrates or flows away as surface runoff, but with transient surface detention. Surface flow is assumed uniform within the plot site, thus outflow (runoff) equals inflow (run-on), and therefore considered as net runoff. Infiltrated water recharges the soil water store within the rooting depth, the excess deep percolates to recharge ground water. There is no water uptake from the ground water as the water table is very deep.

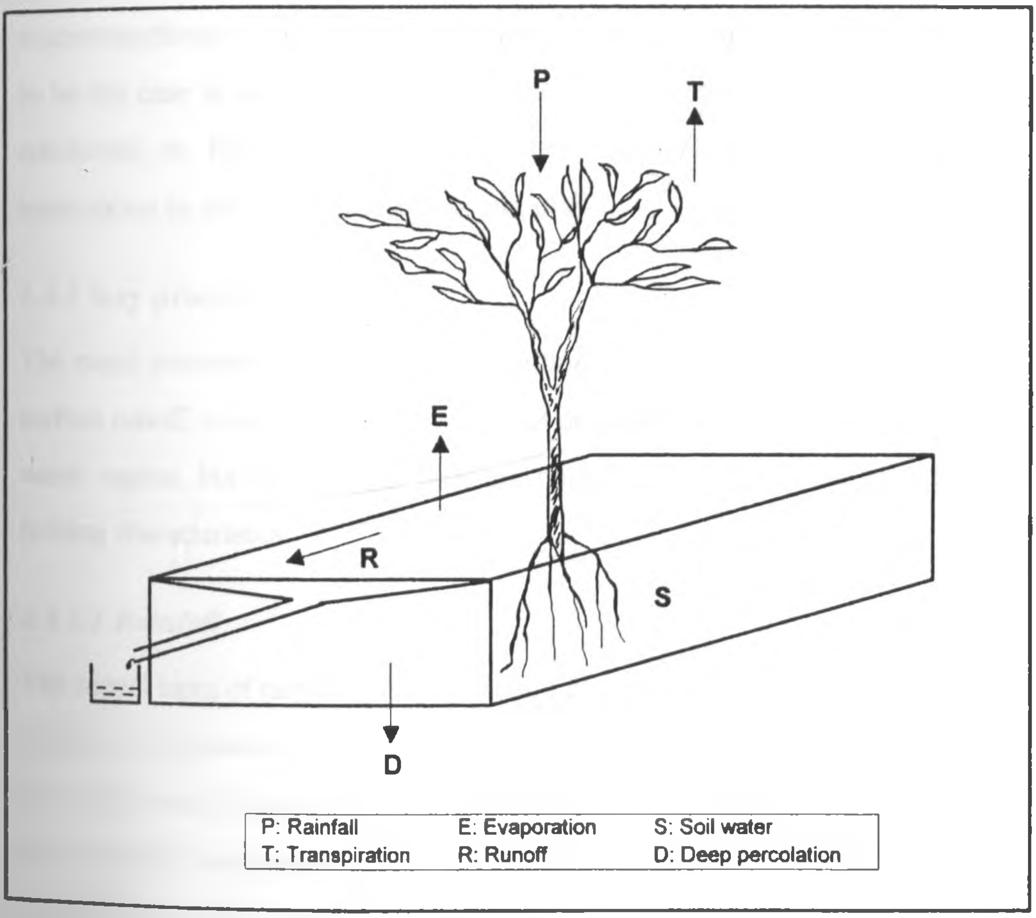


Figure 2.4. Soil water balance control volume.

Njeru (1995), assessing the vegetation water balance along the Naro Moru river profile, did not measure R nor D. These two components were lumped together as vegetation water use with ET that was calculated from climatic parameters using the modified Penman formula (Doorenbos and Pruit, 1977), that is, from Equation 2.8;

$$P - \Delta S = ET + R + D \qquad (2.9)$$

In situations where there is no water uptake from the ground water, ET and D can be calculated as

$$ET + D = P - R - \Delta S \qquad (2.10)$$

where (ET +D) is referred to as water use and (P-R) as effective rainfall. Rainfall, runoff, and the change in soil water storage are directly measured. The amount of evapotranspiration can be calculated if no deep percolation takes place, which is assumed to be the case in most parts of the study area (semiarid climate), except probably in the sub-humid to humid upper slopes. Another simplifying assumption is that water interception by plants is considered as part of E.

2.3.1 Key processes

The major processes that affect the disposition of water in the soil profile are infiltration, surface runoff, evapotranspiration and deep percolation. Several factors influence the soil water regime, but the principal ones are rainfall, evaporative conditions and soil water holding characteristics.

2.3.1.1 Rainfall

The annual input of rainfall at a site is often taken as an indicator of the water available for plant growth. However, the water that is supplied to the soil surface by rainfall can be lost in several ways. Some of the water is intercepted by the plant canopy and the soil surface, and is directly evaporated. If the water is supplied to the soil surface faster than it can infiltrate, the excess water may be lost to runoff. The fraction of water input which does enter the soil is either held for plant use, or drains beyond the root zone and is lost by deep percolation. Only that stored in the soil, and taken up by the plant roots is useful for producing plant biomass.

Rainfall events are not evenly distributed throughout the growing season to satisfy the crop water requirements. The soil reservoir attempts to bridge the gap between the demand and the supply. Water availability for crop growth is influenced by the climatic factors which determine the supply (rainfall) and evapotranspiration. The climatic data which drives any water balance is the amount and temporal distribution of both rainfall and evaporative demand. Rainfall distribution influences antecedent soil moisture conditions, which in turn influences infiltration and subsequently the resulting soil water regime. Within UENB all the reliable private and Kenya Meteorological Department (KMD) rainfall records have been collected and initial analysis undertaken (Berger, 1989; Liniger and Thomas, 1994). In addition, LRP has set up automatic rainfall recorders from which rainfall intensity can be obtained in representative sites within the basin. The records indicate high variability and very uneven distribution of rainfall. More often than not, storms are of high intensities. Available results indicate that effective rainfall within the footslopes (Liniger, 1991a) and Mukogodo rangelands (Mutunga, 1995), is mainly influenced by soil cover and storms intensities. With more rainfall records and intensities data, plus daily soil moisture monitoring, the current study aims at providing high resolution evaluation of the key factors that influence the partitioning of rainfall into runoff and that which infiltrates.

2.3.1.2 Infiltration

Infiltration is the process of water entry into a soil. Many infiltration models have been used over the years to explain water entry into soil under various conditions. Most models have adopted some form of algebraic equation firmly based on the physical process. Algebraic infiltration equations available number in excess of 100 (Williams *et al*., 1990). Several studies have evaluated existing infiltration equations (Swartzendruber and Young, 1974; Gifford, 1976; and Davidoff and Selim, 1986). Each of these equations has its limitation. All except that of Philip (1957) require the soil parameters to be derived from experimental infiltration data. Most approximate and analytical infiltration equations were developed for idealised situations with specific boundary and initial conditions. These conditions are rarely encountered in the field due to soil heterogeneity. Differences in soil surface conditions, initial soil water content, and natural variation between field plots make approximate infiltration equations difficult to apply under natural situations (Branson *et al.*, 1981).

From the infiltration theory, in recent years, a theme has emerged that strongly favours Richards equation as central to solution of infiltration problems (Williams *et al.*, 1990). Time-dependent rate of infiltration into soil is governed by Richards equation, subject to given antecedent soil moisture conditions in the soil profile, the rate of water application on the soil surface, and the conditions at the bottom of the soil profile. In general, the initial soil water potential will vary with soil depth. The initial conditions ($t = 0$) can be expressed as a profile of matric potential head varying with depth.

The boundary condition at the soil surface will depend upon the rate of water application. For a rainfall event with intensities less than or equal to the saturated hydraulic conductivity of the soil profile, all the rain will infiltrate into the soil without generating any runoff. For higher rainfall intensities, all the rain will infiltrate into the soil during early stages until the soil surface becomes saturated ($\theta = \theta_s$, $\psi \geq 0$, $z = 0$). After this point, the ponding time, the infiltration is less than the rain intensity and runoff begins. These conditions may be expressed as

$$-K(\psi)\frac{\partial \psi}{\partial z} + 1 = R \qquad \theta(0, t) \leq \theta s \qquad t \leq t_p \qquad (2.11)$$

$$\psi = h_0 \qquad \theta(0, t) = \theta_s \qquad t > t_p \qquad (2.12)$$

where R is the rainfall intensity, h_o is a small positive ponding depth on the soil surface, and t_p is the ponding time. These conditions also accommodate time-varying rainfall intensities, as well as when rainfall is smaller than K_s. The lower boundary condition depends upon the depth of the unsaturated profile. For a deep profile, a unit-gradient flux condition is commonly applied at a depth L below the infiltration-wetted zone:

$$q(L, t) = K(\theta, L) \qquad t > 0 \qquad (2.13)$$

For a shallow profile (which does not apply in the current study area), a constant pressure head is assumed at the water table depth L:

$$\psi(L,t) = 0 \qquad t > 0 \qquad (2.14)$$

Richards equation (Equation 2.5) subject to the general conditions described in Equations 2.12 to 2.15 in a layered soil profile does not have any known analytical or closed form solutions for infiltration (Rawls *et al.*, 1993). The solutions can, however, be obtained by using finite-difference or finite-element numerical methods (Whisler *et al.*, 1972; Mein and Larson, 1973; Ross, 1990). Ross (1990) observes that, given the appropriate boundary conditions, the equation predicts water distribution with time precisely.

Factors affecting infiltration rate can be grouped into soil, soil surface, management and natural categories. If any of these factors are important in a given system, their effect should be accounted for in the infiltration model.

Soil factors include the soil physical properties that influence soil structure and soil surface area (texture, bulk density, organic matter content, and clay type), and the soil water properties (hydraulic conductivity and water-retention characteristics) discussed in section 2.2 for soil water movement. The surface factors are those that affect the movement of water through the air-soil interface. Cover materials protect the soil surface. On bare soil, lack of cover leads to the formation of a surface crust under the impact of raindrops (Tackett & Pearson, 1965; Eigel and Moore, 1983). Break down of soil structure, compaction and movement of fine soil particles into pores at or just below the surface leads to crust formation (Morin *et al.*, 1981; Messing, 1993). Surface crusts are characterized by greater density, finer pores and lower saturated conductivity than the underlying soil (McIntyre, 1958). Once formed, a crust impedes infiltration. Changes in soil surface configurations can be caused by natural processes such as erosion or man-made processes such as tillage. Thurow *et al.*, 1986 found that the area around plants maintained higher infiltration compared with the area between plants. Similar results were obtained in Mukogodo (Kironchi, 1992). Freebairn *et al.* (1989) reported that there was a tendency for infiltration steady-state rates to increase with surface roughness generated by tillage

Agricultural management systems involve different types of tillage, vegetation and surface cover. Freebairn *et al.* (1989) obtained higher infiltration for mouldboard plough or chisel plough tillage compared to no till practice. Brakensiek and Rawls (1988) reported that mouldboard ploughing would increase soil porosity from 10 to 20 percent depending on soil texture and would increase infiltration rates over non-tilled soils. Rawls *et al.* (1983) reported that increasing the organic matter of the soil lowers the bulk density, increases porosity, and hence increases the infiltration.

Management practices on rangelands usually change the types of vegetation or the grazing practices. The type of vegetation on rangelands has a significant effect on infiltration. Weltz and Wood (1986) demonstrated the influence of grazing practices on infiltration while Branson *et al.* (1981) have summarised the effects of rangelands management systems on runoff.

Natural factors affecting infiltration include natural processes such as precipitation, seasons and moisture which vary with time and space and interact with other factors in their effect on infiltration. The effect of cumulative antecedent rainfall on exposed and 50 percent residue covered agricultural soil was found to decrease the steady-state infiltration rate with the continued exposure to action of rainfall (Rawls *et al.*, 1993). In the same experiment, a bare soil attained a stable steady-state infiltration rate between planting and midseason, indicating that a stable crust is achieved early in the growing season and maintained thereafter. Increasing steady-state infiltration rate with increase in canopy cover demonstrated the temporal variability in infiltration caused by a growing crop. Also it indicated that canopy cover and residue cover do not cause additive increases in the steady-state infiltration rate.

Increase in rainfall intensity increases surface disturbance caused by the raindrops. On the other hand, the building up of a ponding head can increase the bare soil infiltration. However, for bare soil with canopy cover this intensity effect is dissipated by the canopy of the growing crop. Infiltration process is greatly affected by soil profile heterogeneity. A clay layer impedes flow owing to its low saturated conductivity while a sandy layer retards the wetting front owing to the lower unsaturated conductivity of the sand at equal matrix suction (Hillel, 1980). Flow into a dry sand layer can take place only after the pressure head has built up sufficiently for water to more into and fill the large pores of sand.

Point infiltration measurements are made by applying water at a specific site to a finite area and measuring the intake rate of the soil. The type of infiltrometer used should be that which replicates the system being investigated. For example, sprinkler infiltrometers should be used where the effect of rainfall on surface conditions influences the infiltration rate (Peterson and Bubenzer, 1986), while ponding (e.g. double-ring) infiltrometers are appropriate for making measurements associated with surface ponding (Bouwer, 1986).

2.3.1.3 Runoff

When the rate of water supply by rainfall onto the soil exceeds infiltration rate, water starts to accumulate over the soil surface. The volume of water collected before runoff starts, depends upon the surface roughness and ground slope. Runoff from small fields with little or no rills takes the form of a thin sheet-like flow called overland flow (Morgan, 1986). Overland flow collects into rills and gullies and flows as channel flow. This marks the beginning of stream flow.

The predominant runoff mechanisms in ASAL regions is Hortonian overland flow (Branson et al., 1981). Runoff results when the rate of rainfall exceeds the potential rate of infiltration (Hillel, 1980). Land use and soil cover conditions play a crucial role in partitioning rainfall into runoff and infiltrated water. In agriculture fields runoff is generally undesirable and can be prevented by

a) protecting the soil surface against raindrop splash;
b) increasing infiltration rate and/or surface storage; and
c) obstructing overland flow to prevent it from gathering velocity.

2.3.1.4 Redistribution

After a rainfall event, the infiltrated water is subject to downward redistribution and drainage, as well as plant uptake and evaporation at the soil surface. Soil water moves in response to the hydraulic gradient caused by any of these processes. These changes and losses can be computed by using Equation 2.12 subject to known initial conditions at the cessation of infiltration and boundary conditions at the soil surface (Rawls et al., 1993).

Redistribution of soil water can take place both under saturated or unsaturated conditions (Marshall and Holmes, 1988). Saturated soil water redistribution will take place from an upper to a lower soil horizon or layer, if the top horizon's water content exceeds *FC*. This process will occur through all the horizons within the root zone and subsequently flow below the active root depth as drainage. Unsaturated soil water redistribution downwards can take place slowly from the upper to lower horizons at water content below *FC*, on condition that the upper horizon is relatively wetter than the lower horizon. If the soil water gradient is upward, redistribution may occur as capillary movement due to evaporation from the soil surface.

2.3.1.5 Evaporation from soil surface

The amount of water that evaporates depends on soil properties and environmental conditions. Under some circumstances, most of the rainfall received may be lost by evaporation (Campbell, 1985). During periods of tillage, planting and early growth, evaporation can deplete moisture of the surface soil and thus affect plant development at their most vulnerable stage (Hillel, 1977).

Evaporation from the soil surface can be divided into three stages. A constant-rate stage in which evaporation is controlled by the evaporation demand of the atmosphere; a falling-rate stage in which evaporation is controlled by soil profiles transmission of water to the evaporating zones; and a vapour diffusion stage during which evaporation takes places at a slow relatively constant rate controlled by vapour diffusivity of the dried surface zone (Ritchie, 1972; Hillel, 1977). Studies by Jackson (1973) and Jackson et al. (1973) showed that surface-zone soil moisture content fluctuates as the soil surface dries during daytime and tends to rewet during night time.

In the absence of vegetation, evaporation from the soil surface can be a major cause of water loss (Hillel, 1977). Under annual field crops, soil surface may remain bare throughout periods of tillage, planting, germination and early seedling growth. During this period, evaporation can deplete the moisture particularly from the top layer and thus hamper the growth of young plants during their most vulnerable stage (Doorenbos and Pruitt, 1977; Bradley and Crout, 1993). Liniger (1991a) reported that evaporation loss from the soil surface in the semi-arid areas of UENB under conventional tillage was between 40 and 60% of the rainfall.

Evaporation flux can be modified in the following ways;

a) Controlling energy supply to the evaporation surface, like modifying the albedo through colour or structure of the soil and shading the surface for example by tillage and/or mulching (Ross et al., 1985; Bristow, 1988).

b) Decreasing the conductivity or diffusivity of the profile, for example by tillage and/or mulching (Hillel, 1977).

The actual method used in reducing evaporation depends on whether one wishes to regulate the evaporation demand (effect of meteorological conditions) or the rate of supply (transmitting properties of the profile).

2.3.2 Impact of land use and management on soil water balance

Agricultural production in the tropics is principally controlled by rainfall as temperatures are fairly constant throughout the year. In semi-arid environments seasonal variation in yield is largely determined by the amount of water available for plant growth (Nix and Fitzpatrick, 1969; McCown, 1973). Thus in the semi-arid tropics productivity can be intensified by developing methods for ensuring the best use of rain that falls. Primarily this means ensuring that as much as possible of the rain infiltrates into the soil and the water conserved by adequate and viable management systems (Freebairn *et al.*, 1990; Vogel, 1994). Efforts to achieve these have produced widely varying results due to various complex soil-surface management-climate combinations (Williams *et al.*, 1990).

The type of land use and/or management system that modify soil surface conditions play a key role in partitioning rainfall into infiltration and runoff, and influence evapotranspiration within a given environment. This in turn has a profound effect on the soil water regime. Various land uses found in UENB are mainly attributed to differences in agroecological conditions (Jaetzold and Schmidt, 1983). In this study, the term "land use" refers to both natural vegetation cover and land use (implying anthropogenic influence) through agricultural practices such as crop cultivation and livestock grazing or rangeland reserved for wild life. While "management" refers to a range of land use aspects, such as type of crop grown, tillage method and any soil surface management operations. Intensity and duration of grazing are important attributes for livestock grazing management. The major categories of land uses and management alternatives found in UENB are listed in Table 2.1. Detailed descriptions for the systems that were investigated in this study are given in section 3.2.

Table 2.1. Major land use and management systems in the Upper Ewaso Ng'iro basin.

Land use	Characteristics and management system
Forest land	Natural forest: Indigenous tree species; protected or limited use
	Plantation forest: Exotic tree species; established by *shamba* system; clean felling at maturity (20-30 years)
Crop land	Large scale: Mechanized (conventional and conservation tillage); wheat and barley (rainfed); horticulture (mainly irrigated)
	Small scale: Oxen-drawn plough or hand hoe (conventional tillage, mainly with agroforestry); maize, beans, potatoes (rainfed); horticulture (irrigated)
Grazing land	Large scale: Ranches and wildlife sanctuaries; controlled grazing
	Small scale: Grazing in paddocks within cropland and in unsettled land; mostly overgrazed Communal grazing (pastoralism); limited wildlife; overgrazed

Given the diverse land uses and management systems found in the UENB, several vegetation and land use processes influence the soil water balance dynamics. These may be grouped functionally into

(a) above ground factors concerned with canopy interception losses, water use by plants, shading of the soil thereby separating total evaporation into evaporation from the soil and transpiration from the plants, and protection by the plant or litter cover against direct rain drop impact, and

(b) below ground factors concerned with plant root distribution, root water uptake and soil water redistribution

Activities which disturb the soil surface or vegetative composition and cover have the potential of reducing soil water intake, thereby reducing productivity which in some instances may be minimal at best (Gaither and Buckhouse, 1983). Investigation of soil water processes that easily change with the type of land use or management system does not only identify those areas most susceptible to disturbance but can also quantify the extent of degradation. In the following subsections, relevant literature on the effect of forest clearing, crop cultivation and livestock grazing (which are the main land uses in UENB) on topsoil physical properties and subsequently on the soil water balance is presented.

2.3.2.1 Forest land

Removal of forest cover by land clearing in the humid tropics results in immediate and drastic degradative changes in soil properties (Lal, 1987; Ghuman *et al.*, 1991). This adversely affects subsequent crop production. The soil physical properties that are affected on forest removal include bulk density, total porosity, pore-size distribution, infiltration rate, saturated hydraulic conductivity and available water capacity (van der Weert, 1974; Seubert *et al.*, 1977; Lal and Cummings, 1979; Hulugalle *et al.*, 1984; Ghuman *et al.*, 1991).

Vegetation cover protects the soil from raindrop impact and the leaf litter and root mass reduce the velocity of surface runoff. Infiltration rates are controlled by vegetative, edaphic, climatic, and topographic influences. Of these, vegetation can be most easily manipulated by management (Wood and Blackburn, 1981). This is through cultivation or foraging by livestock. Reduced infiltration rates mean increase of surface runoff which is important because it is the primary force in initiating erosion and transporting away sediment and dissolved nutrients from the soil surface. Erosion affects the productivity of soils by loss of plant nutrients, reduced water infiltration and plant available water capacity through degradation of soil structure and reduction of soil depth (USDA, 1981; Langdale and Shrader, 1982).

Due to high organic matter content, increased microbial and worm activity and reduced disturbance, forest surface soils' porosity consists of a high proportion of macropores (Lal and Cummings, 1979; Ghuman *et al.*, 1991; Alegre *et al.*, 1986). Macroporosity comprises large noncapillary pores or voids in soil, such as fauna holes, decayed root channels, and structural cracks, that are open at the soil surface and capture the free water available at the surface during rainfall or runoff, and conduct it downward very quickly, bypassing most of the soil matrix. Under rainfall, the flow into macropores begins only after the start of surface ponding of the soil matrix (Rawls *et al.*, 1993). The macropore water can be absorbed by the drier soil matrix below the transient wetting front generated by the continuing vertical infiltration into the matrix by radial or lateral infiltration.

Results of runoff studies carried out by Lundgren (1980) in the humid mountain slopes of Usambara, Tanzania, indicated that runoff increased with removal of natural forest for small scale cultivation. Infiltration and soil water storage were reported to decrease after forest clearing for crop production in the south western Nigeria (Hulugalle *et al.*, 1984; Ghuman *et al.*, 1991). However, Alegre *et al.* (1986) reported that tillage and soil management practices adopted after land clearing may be more important than the vegetation removal *per se* with respect to altering soil physical properties important to water infiltration and storage. They concluded that in areas where natural cover has been cleared for crop production, if soil and water conservation techniques are used to manage the soil, production can be optimised.

2.3.2.2 Crop land

Generally, infiltration rate of tropical soils under their natural vegetation cover is high. However, removal of the natural cover and cultivation for crop growth result in disturbance and exposure of soil which causes a rapid decline in the infiltration rate (Wilkinson and Aina, 1976; Lal and Cummings, 1979; Kironchi, 1992). Due to reduced infiltration, less water will be available for storage in the soil, and therefore result in unfavourable soil water balance especially in the marginal cropping areas (Liniger, 1991a; Cresswell *et al.*, 1991). A newly cultivated field may maintain high infiltration as long as the interaggregate pores persist (Hillel, 1980). But this state often is ephemeral because soil structure deteriorates quite rapidly as the soil is subject to destructive forces resulting mainly from raindrop impact. This causes aggregates breakdown, which in turn changes the size distribution of pores at the surface due to sealing or crust formation (McIntyre, 1958; Morin *et al.*, 1981; Eigel and Moore, 1983). On the other hand, Wilkinson and Aina (1976) attribute the reduction of infiltration after cultivation partly to the destruction of the large biotic channels in the topsoil. They argue that further biotic activity is discouraged due to the continuous decrease in organic matter content and negligible litter accumulation which limit food supplies to the microorganisms.

In marginal areas for crop production like the Laikipia Plateau, the negative impacts cited above are aggravated by unreliable rainfall. Risk to crop production in such semiarid areas in the short-term is determined predominantly by seasonal conditions, whereas longer-term risk is associated with degradation of the soil resource (Freebairn *et al.*, 1990). Soil management can reduce the effect of water limitation by creating conditions conducive to water entry and storage. Management systems must be tailored to suit the climate, crops grown, economics, and the social system. Soil management entails manipulation of the soil properties and processes to provide a micro-environment favouring water movement, crop establishment and growth.

The ever increasing demand for food production has kept pushing crop production to areas otherwise unsuitable for arable agriculture. This is mainly in the semiarid tropics and subtropics. In recent years, research has been intensified in these areas to alleviate the constraints and optimize production. Results from various researchers (Ulsaker and Kilewe, 1985; Sivakumar *et al.*, 1987; Freebairn and Gupta, 1990; Hoogmoed and Klaij, 1990; Liniger, 1991a; Cresswell *et al.*, 1991) strongly suggest that the risk to crop production and soil degradation can be reduced through the application of techniques which:

(a) enhance water storage during fallow by killing weeds, modifying soil structure, and using mulches, to maximise infiltration and minimise soil evaporation;

(b) create seedbeds that encourage germination, rapid emergence and favourable growth;

(c) minimise soil erosion by constructing runoff control structures and maintaining surface cover and

(d) apply crop rotations and agroforestry to maximise the efficiency of crop water use

Selection of an appropriate technique will depend on local circumstances and the degree of adequacy anticipated based on experience from elsewhere with similar conditions (Freebairn *et al.*, 1990). Soil surface management which is the use of various techniques to modify topsoil physical processes such as infiltration, evaporation and erosion involves manipulation of surface cover, soil moisture, tillage and/or surface configuration (McCown *et al.*, 1985).

Soil cover: Cultivated bare soils are prone to crust or surface seal formation due to energy from raindrop impact. The resultant decrease in infiltration capacity leads to increased runoff during high intensity rainfall (Figure 2.5).

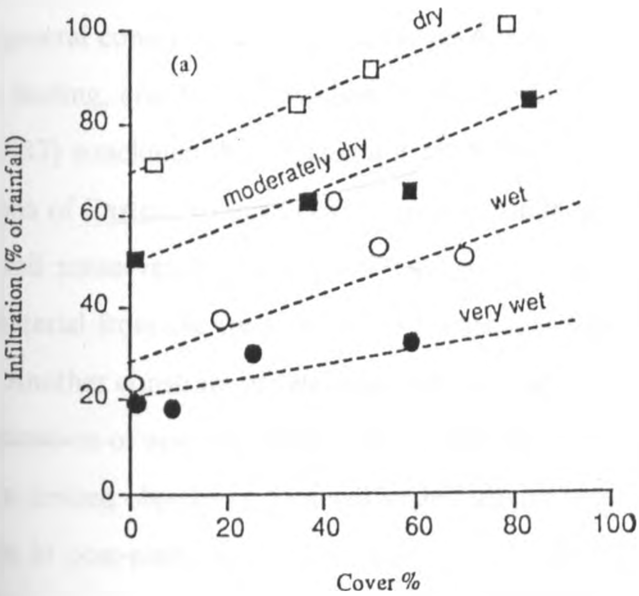


Figure 2.5. Influence of soil cover and antecedent moisture on infiltration of rainfall into a clay soil on contour bay catchments, Queensland, Australia.
(*Source: Freebairn et al., 1990*).

Surface cover, from either crop residue or a growing crop, also reduces soil loss because of decreased runoff generation. However, response to cover is also dependent on other factors like configuration of cover, whether in contact with the soil or not; soil moisture before rainfall, and surface roughness (Unger and McCalla, 1980).

Farming systems using mulches have been tested in many countries. Various investigators (Black, 1973; Mensah-Bonsu and Obeng, 1979; Allmaras and Dowdy, 1986; Lal, 1986, Kilewe and Mbuvi, 1987; Bekele and Thomas, 1989; Freebairn *et al.*, 1990; Liniger, 1991a) have reported that application of crop residues as surface mulch stabilises soil aggregates, reduces runoff and maintains higher infiltration rates. Crop residues also reduce evaporative losses from the soil surface. This is because cover increases albedo and aerodynamic resistance, thus reducing available energy and vapour transfer respectively (Ritchie, 1972). The impact of cover on evaporative loses of water depends on stubble levels, evaporative demand, and the interval between rainfall events (Unger, 1978; Freebairn *et al.*, 1986; Jalota and Prihar, 1990).

There is general consensus that crop residues are in demand for other uses, especially livestock feeding, and are not available for soil protection. For example, Kilewe and Mbuvi (1987) concluded that mulching is not a feasible recommendation for the semi-arid regions of Eastern Kenya because farmers value stover as a stock feed far more than for soil conservation. Liniger (1991a) reports that in agroforesty based systems, pruned material from the tree species or indigenous live fences can supplement crop residue. Another constrain of retaining crop residues on the soil surface is that it may require adoption of special tillage and planting equipment (Vogel, 1994) in order to realise the desired objectives. In small scale farming systems, it may require investing more time in post-planting activities like weeding. From experiences cited above, it would be concluded that cover, either from crop residue or a growing crop, improves infiltration and dramatically reduces runoff, but benefits attributed to reduced evaporation appear to be variable.

Soil moisture: Soil water storage in the profile is controlled by rain water infiltration, soil hydraulic properties, and the rate of plant water use and/or evaporation from the soil surface. In the Laikipia Plateau (altitude ≈ 2000 m) Liniger (1991a) reported high water use by grass early in the growing season compared to a maize-bean intercrop. However, when the crop was fully developed (maize at tasseling stage), it used similar amounts as grass. This is because the established grass resumes full transpiration soon after the onset of rains while water use by the young crop is still low. Njeru (1995) working at Naro Moru profile (altitude ≈ 2500 m), also found that potato crop used less moisture than grass while natural forest vegetation used more moisture than either potato or grass. On the other hand, natural forest used less moisture than planted cypress forest.

Soil moisture content is a major factor determining whether rainfall will result in runoff. In the semiarid tropics and subtropics, seasonal conditions have a strong influence on soil moisture. Data from Queensland, Australia, show that the sequence and number of crops grown have a major effect on timing of soil water deficits during the year, and hence on runoff (Figure 2.5). Results indicate that growing more than one crop each year reduces runoff by increasing the proportion of rainfall used as transpiration (Berndt and White, 1976). Results from experiments on soil moisture management in Australia have led to the conclusion that appropriate soil surface management can increase yield in drier than average years due to better water storage, but has little or no influence on yield in the higher yielding years when water supply is less limiting (Freebairn et al., 1990).

Tillage: Tillage is traditionally used to kill weeds, break crusts and prepare a seedbed. However, tillage can increase evaporation (Linden, 1982) and reduce surface cover by inverting and mixing soil layers. Primary tillage creates a rough and porous surface. This roughness traps water which is detained as depression storage, and subsequently increases infiltration of rainfall (Burwell and Larson, 1969; El-Swaify *et al*., 1985). In most soils, cycles of wetting and drying modify surface roughness. Tillage has a strong influence on infiltration rate, while soil surface roughness maintains higher infiltration rates when soil is protected from raindrop (Freebairn and Gupta, 1990).

Reduced tillage or zero-till fallow systems have been developed which result in less stubble breakdown (Freebairn *et al.*, 1986) and minimise the deleterious features of tillage while maximising water storage (Liniger, 1991a; Vogel, 1994). However, it has been demonstrated by Khatibu *et al.* (1984) that the hydrology of soil profiles may change subtly when the soil surface is not cultivated for extended periods such as under zero-till regime. The response to tillage practices appears to depend on soil type, farming system and climate. Experiments often give contradictory results. In West Africa, Chopart (1989) reported benefits from tillage whereas Lal (1975), Maurya and Lal (1979) reported best results from zero-tillage. However, it can generally be concluded that tillage influences infiltration directly by altering surface configuration and indirectly through destruction of stubble cover. Experience from Australia's semiarid farming areas (Freebairn *et al.*, 1989) advocates that the aim of farming should be to use tillage only when necessary and that any recommendations should reflect knowledge of what tillage is doing to soil hydrologic properties.

From the literature cited above, it is evident that physical and biological responses to soil surface management treatments are often erratic. This apparent unpredictability is often a result of interactions between weather and the physio-biological system (Freebairn *et al.*, 1990). Interpretation of reported results for episodic processes can be strongly influenced by the period and length of measurement. Physically based computer simulation of the important processes is essential to determine the long-term outcome of management on water balance, soil erosion and crop yields (Williams *et al.*, 1990; Liniger and Gichuki, 1994).

2.3.2.3 Grazing land

The term grazing land in this subsection refers to patches of land within small scale crop production areas used for grazing. In most small scale farming systems in East Africa, especially in high potential areas, grazing land reserves in between crop land are a common feature. A similar trend of mixed farming has been adopted in the newly settled semiarid areas like Laikipia Plateau after land subdivision (Flury, 1987; Kohler, 1987). However, due to the ecology of the semiarid areas, their low biomass production potential cannot sustain high livestock grazing intensity like the high potential areas. Therefore overgrazing is increasingly becoming a major problem in the patches of land reserved for grazing in the semiarid areas. High runoff and soil erosion from this grazing land has been reported by Liniger (1991a). Even though most land is gradually being put under crop production, investigations of the soil water balance should not overlook these relatively small parcels of land, as they are key source areas of catchment runoff (Ondieki, 1994). The processes that influence soil water balance on such grazing land are similar to those for rangelands discussed in section 2.3.2.4.

2.3.2.4 Rangeland

Range lands are the semi-arid to arid areas not used for crop production but for extensive livestock grazing and wildlife management (Stoddart *et al.*, 1975). Range lands in East Africa have diverse vegetation cover (Pratt and Gwynne, 1977) that range from grasslands to bushlands. It is well documented that the kind of vegetation and amount of cover may modify soil-water relationship of a site. Infiltration rates and water storage studies consistently report positive correlation with amount of plant cover, and negative correlation with bare ground.

The ecology of ASAL is rather delicate and should vegetation be destroyed by either overgrazing, destruction by man or long dry periods, there can be considerable effects on rainfall-runoff response (Strange, 1980). Livestock grazing alters the natural infiltration-runoff relationships by reducing the protection afforded by vegetation cover, by reducing and scattering the litter, and by compacting the soil through trampling (Stoddard *et al.*, 1975). The magnitude of these changes is determined by the intensity of grazing as well as the soil type, climate, topography, livestock management and vegetation type (Branson *et al.*, 1981). Most studies that have been conducted to evaluate the impact of grazing in range lands on the hydrologic properties of soils have mainly concentrated on measurement of infiltration rates

(McGinty *et al.*, 1979; Wood and Blackburn, 1981; McCalla II *et al.*, 1984; Mbakaya, 1985; Kironchi, 1992). Consistently lower infiltration rates were reported from overgrazed plots and at times, livestock enclosures had similar infiltration rates as some of the controlled grazing systems.

Thomas *et al.* (1981) reported results from test plots under simulated rainfall in Machakos district on grazing land and cultivated land. The results showed that bare grazing land and continuously grazed land produced the highest runoff, with pasture protected from grazing and cultivated land producing about 40% and 75% less runoff respectively. Mutunga (1995) using runoff test plots at Mukogodo in Laikipia, reports that up to 80% of rainfall during big events runs off from bare and crusted soils. This results in a very unfavourable soil water balance, given that the annual potential evaporation is 5 to 6 times higher than the annual total rainfall (Ondieki, 1994).

Lack of cover can be both a cause and a result of degradation in grazing lands. Degradation of grazing land is usually attributed to socio-economic factors such as overgrazing associated with communal land tenure (Pratt and Gywnne, 1977; Herren, 1990), but it may also be due to failure to understand the grazing land ecosystem and, in particular, the role of cover in determining the movement of water within the system (Liniger and Thomas, 1998). Prolonged droughts can lead to death of perennial grasses partly due to the pressure of livestock and wild animals, but also due to the depredation of termites, whose biomass per hectare may equal that of livestock (Leparge, 1977).

Liniger and Thomas (1998) have reviewed research and development activities on semi-arid and arid grazing lands of Eastern Africa. The review concludes that although the importance of grass cover is known and has been widely reported in scientific reports, there has been little success in improving grass cover and primary productivity of grazing lands. The authors propose a search for improved management solutions through an initiative called GRASS (Ground cover for the Restoration of Arid and Semi-arid Soils).

In this chapter of literature review, the basic principles that govern soil hydraulic properties and components of water balance were presented. The importance of land use and top soil management in modifying soil physical properties important to water flow, storage and availability to plants has been highlighted. Research findings on soil surface management strategies to reduce rain water runoff and/or reduce evapotranspiration using viable options were reviewed. Conservation tillage and surface mulch on cropland, and maintenance or increase of grass cover in grazing land were pointed to be viable options for semiarid areas.

Within the UENB, most of which is semi-arid, the problems of high runoff (Liniger, 1991a, Ondieki, 1994; Mutunga, 1995), reduced infiltration (Kironchi, 1992, Liniger, 1992) and high evapotranspiration (Liniger, 1991a; Njeru, 1995) have already been identified on both crop land and grazing land. However, due to lack of a comprehensive data base of agrometeorological and soil data, several questions concerning soil water dynamics still remain unanswered. Also in order to broaden the scope and areal coverage, further investigations are required in representative sites within the basin, especially as more land is being cleared off natural vegetation for crop production. There is need to monitor the water balance with such changes in land use. More research is required in application of soil and water conservation technologies in marginal areas already under cultivation. In grazing land, especially in the communal areas, it has been pointed out that soil cover and top soil conditions play a key role in rain water infiltration. There is need to assess application of simple and viable methods that would increase infiltration, which would in turn result in increased plant biomass production, and therefore provide adequate forage that is in high demand for the pastoralists' livestock. Finally, the data generated from this study will open up scope that would lead to soil water balance and plant water use modelling.

CHAPTER 3

MATERIALS AND METHODS

3.1 DESCRIPTION OF THE STUDY AREA

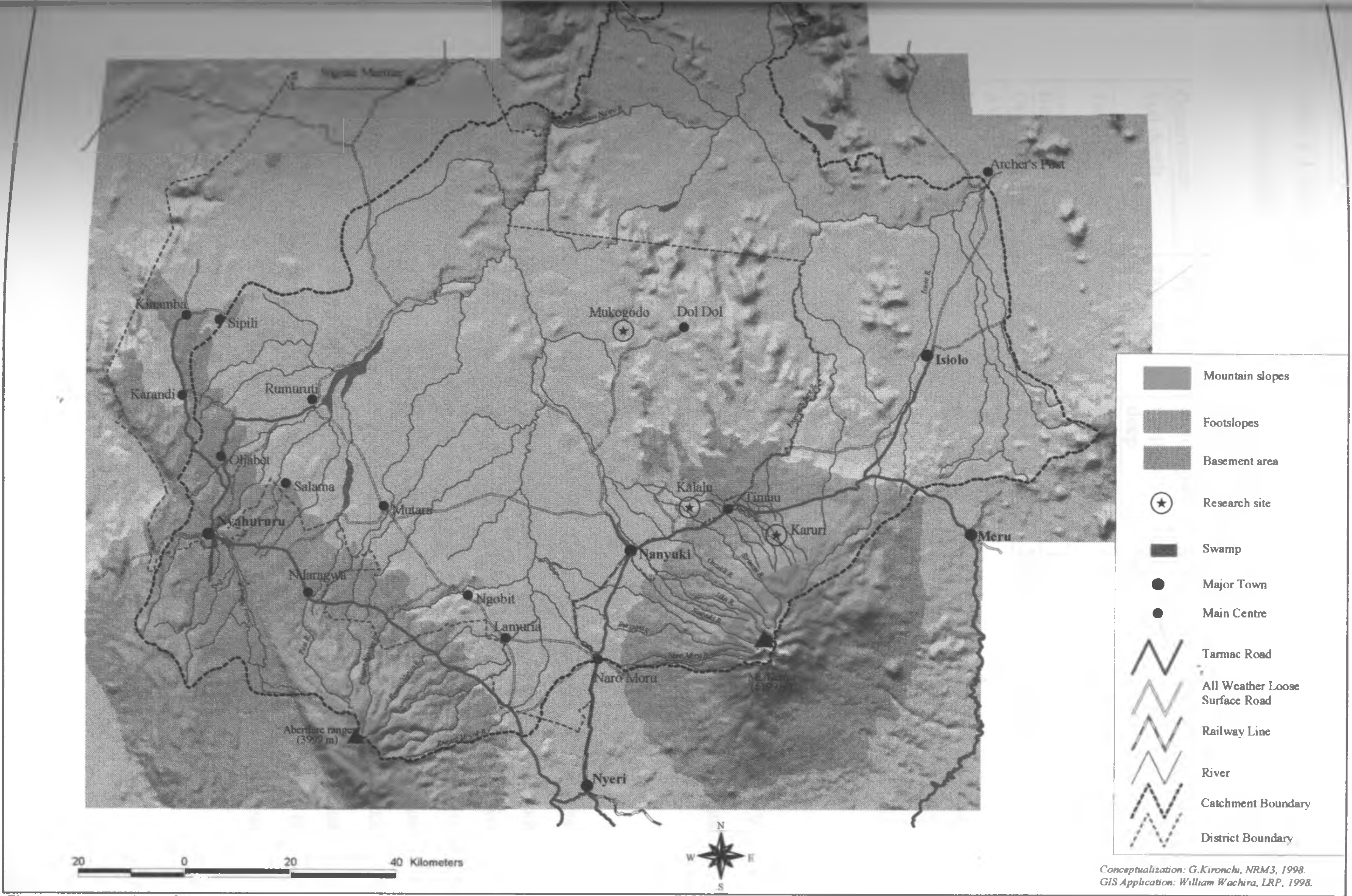
3.1.1 Upper Ewaso Ng'iro basin

The study area lies north to northwest of Mount Kenya in the upper part of the Ewaso Ng'iro river basin (1600-3000 m a.s.l.). The area covered comprises the mountain slopes, footslopes, Laikipia plateau, and the hills and plains in the Basement area (Figure 3.1). The area covers various agroclimatic zones; which delimit climatic land potential zones based on moisture availability (Sombroek et al., 1982). Three investigation sites, each in a different agroclimatic zone (ACZ) were selected. These are Karuri, Kalalu and Mukogodo that are in the semi-humid (ACZ III), semi-humid to semi-arid (ACZ IV) and semi-arid (ACZ V) zones respectively (Sombroek *et al.*, 1982). According to the Farm Management Handbook of Kenya (Jaetzold and Schmidt, 1983), Karuri and Kalalu, represent agroecological zones of medium to low crop production potential in the UENB, while Mukogodo represents areas of low agricultural production potential suitable only for extensive livestock production and wildlife management (rangelands).

3.1.2 Mountain slopes

3.1.2.1 Geology and soils

The geological formation of the area belongs to Ithunguni trachytic tuffs which covers large areas on the lower northern slopes of Mt. Kenya. The trachytes are mainly of olivine type. The major soil types are stony mollic Cambisols and mollic Andosols of medium (50-80 cm) depth in the upper slopes; while in the middle parts are deep mollic Andosols and in the lower parts are deep to very deep humic Alisols. The general soil characteristics in this zone are summarized in Table 3.1.



Conceptualization: G.Kironchi, NRM3, 1998.
GIS Application: William Wachira, LRP, 1998.

Figure 3.1 Location of the study area

Table 3.1 Soil types and their characteristics in the mountain slopes

Characteristics	Soil type			
	mollic Andosols	humic Alisols	humic Acrisols	mollic Cambisols
Occurrence	upper part	middle part	lower part	valleys
Soil depth	moderate-deep	deep-very deep	deep-very deep	shallow-moderate
Texture	clay loam	clay	clay	loam-clay loam
Bulk density	0.7-0.9	1.0-1.3	1.0-1.3	0.7-0.9
Organic matter	3-8%	2-6%	2-5%	3-9%
AWC[1] (mm 100 cm^{-1})	100-150	150-180	150-180	30-50
Drainage class	well drained	well drained	well drained	well drained
Erosion hazard	moderate-high	moderate	moderate	moderate

[1] AWC: Available water capacity

Sources: Speck, 1983; Mainga and Mbuvi, 1994; Kisinyo, 1994; Kironchi, current study

3.1.2.2 Topography

The upper parts have undulating to rolling slopes (5-16%) with deeply incised V-shaped valleys while the lower parts consist of broad ridges dissected by rivers and streams. The elevation ranges from about 2500 to 3000 m.

3.1.2.3 Climatic conditions

This area is located on the leeward side of Mt. Kenya and thus the mountain has profound effect on the climate. The total annual rainfall amounts increase with altitude up to around 3000-3500 m, the lower slopes where the study site is located, receive about 900 mm, while on the western slopes it can reach a maximum of about 1500 mm per year (Dercurtins, 1992). The long rains come between March and May, and the short rains in October/November. The mean annual evaporation ranges from 1000 to 1200 mm. The climate is semi-humid (mean annual rainfall to mean annual evaporation (r/E) ratio of 0.5-0.8) and the area falls in Agroclimatic zone III (Sombroek *et al.*, 1982). The temperature zone is 7-8 (cool-very cool) as mean annual temperature ranges from 10 to16^{0}C.

3.1.2.4 Land use and management

This is the forest zone of the Mt. Kenya slopes. Most of the area is gazetted forest land and to the upper part is designated as a game park. The natural forest is evergreen montane forest of *Juniperous-Podocarpus-Olea* tree species. It is a close stand of trees with one or more storeys, the upper canopy rising at least 10 m high. Ground cover consists of perennial herbs and a thick layer of litter. In the lower parts the natural forest has been cleared and replaced by forest plantations mainly of cypress and pines, large scale barley and wheat farming, and small scale farms mainly growing potatoes and horticultural crops.

3.1.3 Footslopes

3.1.3.1 Geology and soils

The footslopes constitutes the area adjacent to the lower mountain slopes and the immediate Laikipia plateau. The soils of the footslopes and plateau are underlain by phonolites from Mt. Kenya volcanics and their distribution is influenced mainly by landform (Table 3.2). Those on ridges or convex slopes are well drained, deep, dark red to dark brown friable clay (Luvisols and Phaeozems); while those on flat areas or depressions are imperfectly drained, deep grey to black firm clay (Vertisols and Planosols).

3.1.3.2 Topography

The landform consists of gently undulating to undulating plateau and volcanic footridges at an elevation of between 1800 and 2100 m. The slopes range from nearly flat (1-2%) on the ridge tops to 8% in places like minor valleys.

3.1.3.3 Climatic conditions

The total annual rainfall amount for the footzone is very variable, ranging from as low as 300 mm to a maximum of about 1000 mm with the mean at around 700 mm. The region has a trimodal rainfall distribution; the long rains come between March and May, and the short rains in October/November. A partial peak of continental rains occurs in July/August. The mean annual evaporation ranges from 1400 to 1700 mm. The climate is semi-arid to semi-humid (r/E ratio of 0.4-0.5) and the area falls within

Agro-climatic zone IV (Sombroek *et al.*, 1982). The temperature zone is 4-6 (cool to warm temperate) as mean annual temperature range from 16 to 20^{0}C.

Table 3.2 Soil types and their characteristics in the footslopes and plateau.

Characteristics	Soil type			
	ferric Luvisols	luvic/vertic Phaeozems	eutric Vertisols	eutric Planosols
Occurrence	ridges, convex slopes	flat parts	flat, concave slopes	flat parts
Soil depth	deep-very deep	deep-very deep	deep	deep
Texture	clay	clay	clay	sandy clay
Bulk density	1.0-1.4	1.0-1.3	1.0-1.2	1.0-1.3
Organic matter	1-3%	2-4%	2-4%	2-5%
AWC[1] (mm 100 cm^{-1})	180-200	150-180	150-180	140-160
Drainage class	well drained	well drained	imperfectly drained	imperfectly drained
Erosion hazard	low-moderate	low-moderate	low	low

[1] AWC: Available water capacity

Sources: Speck, 1983; Ahn and Geiger, 1987; Liniger, 1991a; Mbuvi and Kironchi, 1994.

3.1.3.4 Land use and management

Most of the area has been subdivided into small plots ranging from 1 to 5 hectares and settled by small scale farmers growing mainly maize and beans as food crops and wheat as a cash crop. In addition, most farmers keep cattle, sheep and goats which are grazed in small patches of uncultivated land or in the cultivated plots after crop harvest. In places where settlement rate is low, the bulk of the grazing consists of forage in the uncultivated plots that belong to people who have not come to settle. A few large scale ranches and wildlife sanctuaries still exist in some places.

3.1.4 Basement area

3.1.4.1 Geology and soils

The area is covered by Basement system metamorphic rocks consisting mainly of gneisesses and migmatites with a few granite outcrops. Soils are well drained to excessively drained, dark reddish brown in colour and range from very shallow to deep. Their texture ranges from gravelly sandy loam to sandy clay. The major soil types are ferric Lixisols, chromic Luvisols, chromic Cambisols and eutric Leptosols (Table 3.3). In most parts water erosion has seriously affected the soils as in some places all or most of the surface horizon has been eroded.

3.1.4.2 Topography

The landform consists of gently undulating to undulating non-dissected and dissected uplands and high level structural plains (Ahn and Geiger, 1987) with slopes ranging from 2 to 8% at an elevation of between 1600 and 1800 m. Some hilly parts which are heavily eroded with rock outcrops (inselbergs) occur in this zone.

Table 3.3 Soil types and their characteristics in the Basement area.

Characteristics	Soil type			
	ferric Lixisols	chromic Luvisols	chromic Cambisols	eutric Leptosols
Occurrence	uplands	uplands	valleys, eroded parts	steep slopes, hills
Soil depth	moderately deep to deep	moderately deep to deep	shallow to moderately deep	very shallow to shallow
Texture	sandy clay	sandy clay	sandy clay loam	loamy sand
Bulk density	1.2-1.4	1.1-1.5	1.1-1.4	1.3-1.4
Organic matter	0.6-2.4	0.5-1.9	0.8-2.3	1.0-4.2
AWC[1] (mm 100 cm^{-1})	70-100	70-100	30-50	5-10
Drainage class	excessive-well drained	well drained	excessive-well drained	well drained
Erosion hazard	moderate-high	moderate	high	high

[1] AWC: Available water capacity

Sources: Wanjogu, 1992; Kironchi, 1992; Mbuvi and Kironchi, 1994

3.1.4.3 Climatic conditions

The total annual rainfall amount in the basement area ranges from about 250 to 600 mm with the mean around 450 mm. The region has a bimodal rainfall distribution; the long rains come between March and May, and the short rains in October and November. The mean annual evaporation ranges from 2000 to 2300 mm. The climate is arid (r/E ratio of 0.15-0.25) and the area falls in Agro-climatic zone V (Sombroek *et al.*, 1982). The temperature zone is 2-3 (warm to fairly hot) as the mean annual temperature is 22-24^{0}C. Rainfall is erratic and usually occurs in high intensities that can cause severe soil erosion.

3.1.4.4 Land use and management

Vegetation consists of open dry thorn bushland dominated by *Acacia tortilis, A. mellifera* and *A. etbaica*. The main grasses are *Pennisetum mezianum, P. straminium* and *Aristida* species. *Cynodon dactylon* is found at the valleys. The area is mainly used for extensive livestock grazing and as a habitat for wild animals. Two main types of livestock grazing management are practised; private large scale ranches and communal grazing by Maasai pastoralists. In the area under pastoral grazing most of the ground is bare due to overgrazing.

3.2 EXPERIMENTAL SITES AND SET UP

Experimental sites were located within the small catchments established and maintained by NRM[3]. The catchments which are instrumented for agrometeorological and hydrological investigations were selected as representative within the region on the basis of physiography, climate, geology and soils, and the fact that they have various land uses and management systems. Table 3.4 summarizes the characteristics of these sites. A major soil type in each area was selected within which the land uses and/or management systems were identified or established for the water balance studies. Each site is identified by the local name of the area it is located in, i.e. Karuri, Kalalu and Mukogodo for the mountain slopes, footzone and basement area respectively. The environmental conditions, experimental site layout and treatments in each site are described in detail in the next three subsections.

3.2.1 Karuri

3.2.1.1 Location and land use

Karuri study site is located on the northwestern slopes of Mt. Kenya at an altitude of 2900 m above sea level. It is in Meru District, approximately 10 km to the south of Timau shopping centre. The site is in Mount Kenya Forest Reserve. The natural vegetation is montane forest with *Juniperous procera*, *Olea africana* and *Podocarpus melanjianus* as the dominant species. Part of the forest reserve has been encroached on by subsistence farmers and the forest cleared for crop production (mainly Irish potato, *Solanum tuberosum*) and livestock (cattle and sheep) grazing.

Table 3.4 Study sites characteristics.

Characteristic	Karuri	Kalalu	Mukogodo
Location	1^{0}05'N/35^{0}44'E	0^{0}05'N/37^{0}10'E	0^{0}23'N/37^{0}04'E
Elevation (m)	2900	2020	1780
Agroclimatic zone[1]	III (sub-humid)	IV (semi-humid to semi-arid	V (semi-arid)
Rainfall (mm/year)[2]	800-900	650-750	300-400
Geology[3]	volcanic rocks: trachytes	volcanic rocks: phonolites	Basement system: gneisses
Soils[4] (FAO/UNESCO)	mollic Andosol	ferric Luvisol	chromo-ferric Lixisol
Slope (%)	varies: 10-14	uniform: 5	varies: 4-7
Vegetation[5]	montane forest: *Juniperous*, *Podocarpus* and *Olea* species	clearing from dry cedar montane sclerophyll forest	*Acacia* bushland: *A. etbica, mellifera* and *tortilis* dominant
Land use	forest reserve, grazing, part cleared for small scale farming: potatoes	small scale mixed farming: maize, beans, potatoes and wheat	communal grazing by Maasai pastoralists

[1]*Sombroek et al. 1982;* [2]*LRP Database;* [3]*Baker 1967, Ahn and Geiger,1987;* [4]*Liniger 1991, Wanjogu 1992, Mainga and Mbuvi 1994;* [5]*Trapnell et al. 1976, Taiti 1992.*

3.2.1.2 Climate

Only four years data are available for Karuri as the meteorological station at this site was put up in May 1992. The rainfall distribution is bimodal with peaks in May and November for the long and short rains respectively. The mean annual rainfall ranges between 800-900 mm while potential evaporation is about 1200 mm.

3.2.1.3 Soils

From a preliminary soil survey (Mainga and Mbuvi, 1994) and a semi-detailed soil survey (Kisinyo, 1994) the soil at Karuri is classified as a mollic Andosol based on the

FAO-UNESCO system (FAO, 1990), equivalent to an Eutrandept in the USDA soil taxonomy system (Soil Survey Staff, 1975). The soil has a dark surface horizon, rich in organic matter and with low bulk density. The soil is well drained, very deep, brownish black to dark brown, friable clay. Topsoil has high silt content, but the clay content increases in the B horizon.

3.2.1.4 Site layout and treatments

The experimental site was selected on the basis of a preliminary soil survey carried out in March 1992 (Mainga and Mbuvi, 1994). A mollic andosol was identified as a representative soil type within the area. Figure 3.2 shows the site layout at Karuri. A farmer whose land is located on a typical slope (11-13%) and practised both crop production and livestock grazing granted permission for use of her land to construct a meteorological station (May 1992), and thereafter, to set up runoff and soil moisture measurement experiments (September 1993). The experiments on both cropland and grazing land were set up based on the on-farm concept, where upon the farmer carries out all the farm activities and management even within the experimental plots.

One site for each land use, herein referred to as a plot was selected. The grass and potato plots (11 and 13% slope, respectively) were 30 m apart while the forest plot (12% slope) was located on an adjacent ridge approximately 300 m away, 150 m from the edge of the forest. Each plot measured about 30 m wide and 50 m along the slope.

The problems identified at Karuri were

- natural vegetation cover removal from sloping land with fragile (very erodible) soils
- continuous tillage without adequate conservation measures which are leading to destruction of soil structure, and
- poor soil cover at beginning of rainy seasons resulting in high runoff and thus soil erosion

Therefore the major study objective at this site was to assess soil water dynamics of the mountain slopes under natural forest, grazing land, and cropland. Thus within this agro-climatic zone, treatments were the three land uses which were referred to as natural forest (NF), grazing land (GL) and potato crop land (PC). Figure 3.3 shows the forest, grass and potato crop treatments.

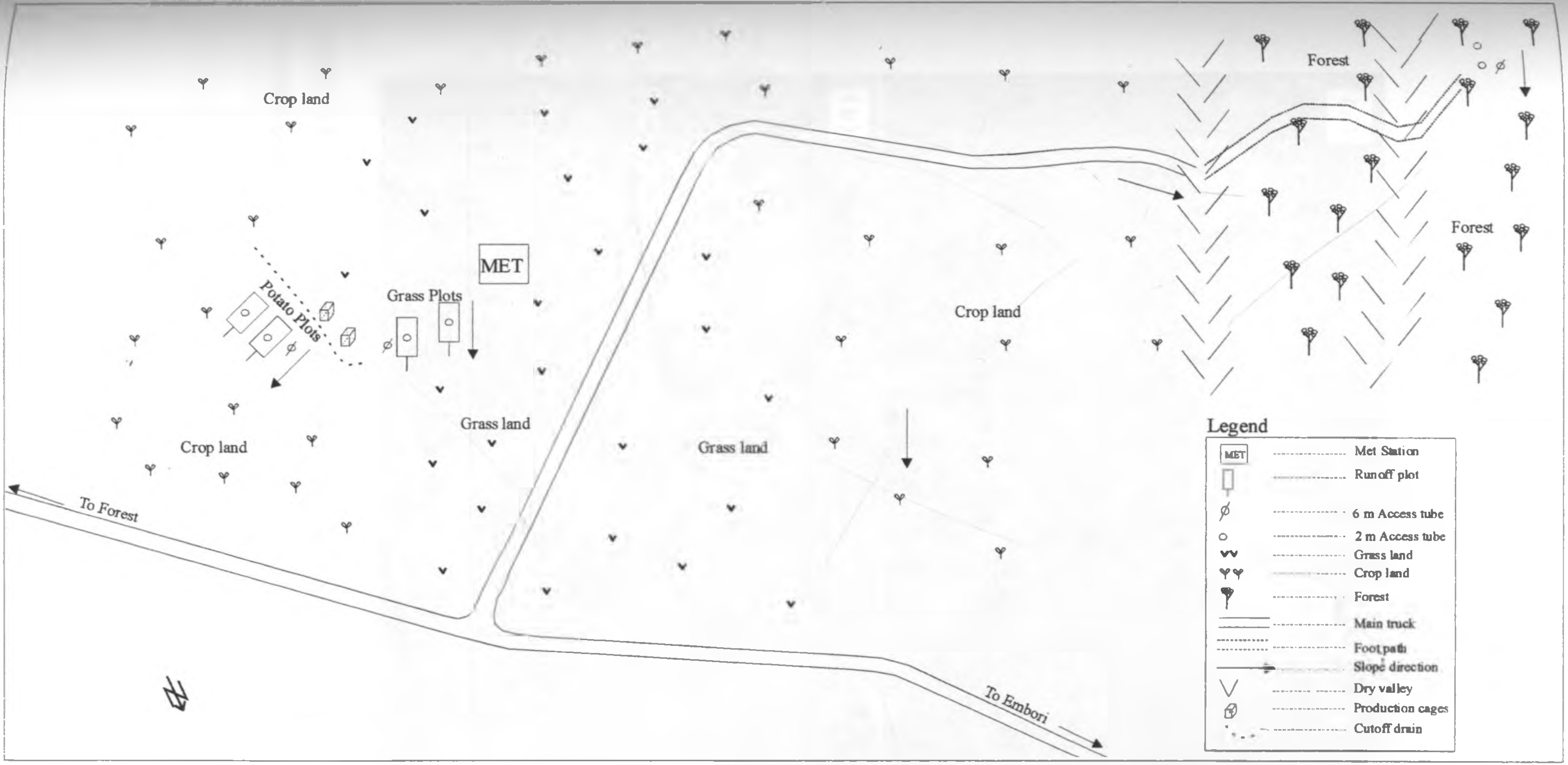


Fig. 3.2 Layout of Karuri research site

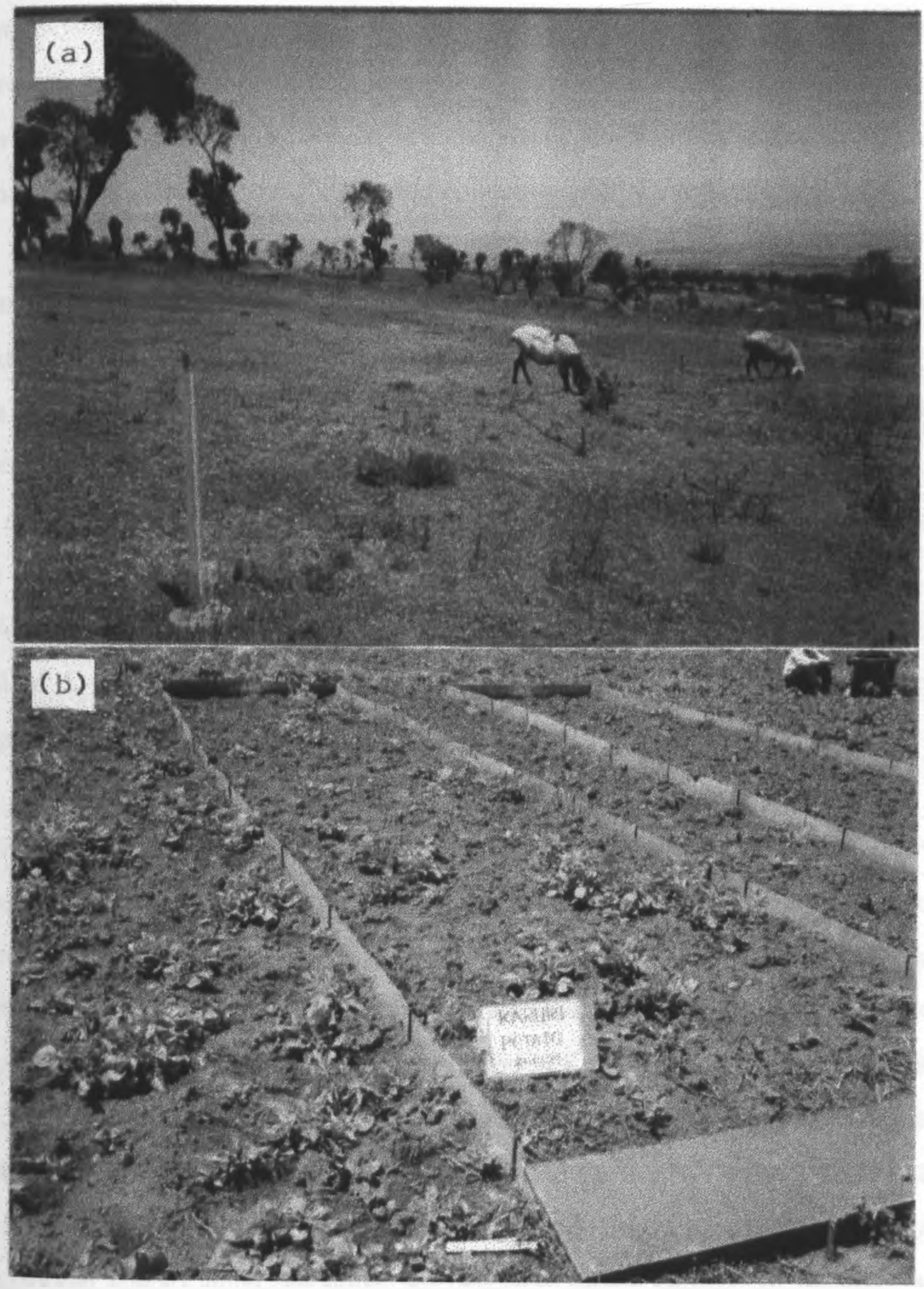


Figure 3.3 Land use at Karuri (a) grazing land with forest edge at the background and (b) potato cropland.

Natural forest (NF): This is evergreen montane forest that consists of mature trees with canopies at least 15 to 20 m high. The undergrowth is very sparse. The main species are *Juniperous procera, Olea africana* and *Podocarpus melanjianus*. A thick layer (5-10 cm) of partly decomposed litter covers the ground and is held in place by perennial grasses and forbs that creep though the litter. Grasses, forbs and litter provide 100% soil cover. However, in some places the litter has been scattered due to human interference in form of fuelwood collection and by livestock grazing.

Grazing land (GL): Grazing land in Karuri exists in form of small patches of land left uncultivated among the potato plots. It covers only about 10% of the area. The grazing sites have short stoloniferous grasses, dominated by *Pennisetum clandestinum* species interspersed with various species of forbs. The maximum height of the vegetation is about 5-7 cm as it is under continuous grazing by mainly sheep and goats throughout the year. The ground cover at all times, both in the rainy and dry seasons ranged between 80 to 90%. The site where experiments are set up has an acreage of approximately 0.1 ha and a total of 5 mature sheep and goats were grazed throughout the year with minimum supplementary feeds.

Potato cropland (PC): In 1986/1987 a section of the forest described above was annexed to settle a group of farmers who were displaced from private land they had encroached on. All forest was cleared except a few scattered trees and most of the land cultivated for crop production. Since then, potato (*Solanum tuberosum*) has been the main crop planted in up to 90% of the cultivated land in Karuri. It is both food and cash crop and is planted twice in a year. The first crop is planted in late March and harvested in July, while the second crop is planted at the beginning of October and harvested in January of the following year. The main land preparation method is conventional tillage using a hand hoe (forked *jembe*) along the slope. An overview survey carried out by LRP in 1994 indicated that more than 90% of the farmers prepare their plots using this method. The rest cultivate across the slope using oxen-drawn ploughs. The top 15-20 cm of the topsoil is inverted, burying under the weeds and previous season crop residue. Small furrows spaced at 40-45 cm apart are dug across the slope to plant potato seed. Soil is scooped and thrown to the lower part of the slope using a *jembe* to create the furrows. The potato seed are manually placed 3-5 cm under the soil in the furrows at a spacing of 15-20 cm apart. After the potato have sprouted, 3-4 weeks later, as the first weeding is carried out, most of the soil is pushed back to fill the furrows. The second weeding was carried out just before flowering whereby soil was heaped around potato plants within a row.

3.2.2 Kalalu

3.2.2.1 Location and land use

Kalalu study site is on the northern footslopes of Mount Kenya at an altitude of 2020 m above sea level, approximately 12 km to the northeast of Nanyuki town. The site is on a gentle uniform slope of 5% in a small scale mixed farming area. Most plots have been settled from the early eighties. Farm sizes range from 0.8 to 2 ha and the main crops grown are maize (*Zea mays*, variety H511), beans (*Phaseolus vulgaris*) and potatoes (*Solanum tuberosum*) as food crops, and wheat (*Triticum* spp); by some farmers, as a cash crop. Many small scale farmers were practicing agroforestry by planting *Grevillia* trees along the plot boundaries. Most farmers keep a few livestock, usually a mixture of cattle, sheep and goats. These are grazed either on small patches of reserved grazing land in between crop land, or herded along road reserves and in fallow land after crop harvest. The natural vegetation of this area was dry cedar montane sclerophyll forest before human settlement for agriculture.

3.2.2.2 Climate

Ten years climatic data are available for Kalalu from a meteorological station at the site which started operating in November 1985 (Liniger, 1991a). The rainfall distribution is trimodal with peaks in April/May, August and November for the long, continental and short rains respectively. Total annual evaporation is more than twice the total annual rainfall, and the monthly evaporation exceeds the amount of monthly rainfall in all months of the year except in April.

3.2.2.3 Soils

The soil at Kalalu is classified as a ferric Luvisol based on the FAO-UNESCO system (FAO, 1990), equivalent to a Ferrustalf in the USDA soil taxonomy system (Soil

Survey Staff, 1975). The soil is well drained, deep, dark reddish brown, friable, clay in texture and the clay content increases with depth. Its structure is moderate, medium subangular blocky. Iron and manganese concretions occur from 90 cm.

3.2.2.4 Site layout and treatments

Kalalu agroecology station where the experimental site is located was started in 1986 by LRP. The layout of the station is presented in Figure 3.4. Several experiments were set up in both cropland and grazing land for soil and water conservation studies (Liniger, 1991b). The practices that were selected are those most prevalent with farmers in the area. Most of the original experiments were maintained in order to collect long term data for modeling purposes; but some were modified either to broaden their scope or to meet the requirements of new studies.

The current study aimed at assessing soil water balance in the footzone areas for cropland and grazing land under different management systems. Four treatments were selected from ongoing experiments. These were on cropland (maize-bean intercrop), two tillage methods: minimum tillage combined with mulching (hereafter referred to as mulch tillage) and conventional tillage; and on grazing land, two grazing management systems: controlled (deferred rotational) grazing and overgrazing.

Mulch tillage (MT): This is a conservation tillage practice where during land preparation for planting and weeding, weeds were chopped by a *jembe* within 5 cm of the topsoil without inverting the surface soil. This is followed by spreading of 3 t ha^{-1} of previous season crop residue (maize stover) as mulch at planting time. The mulch covers 40-50% of soil surface. After harvesting maize, weeds were eliminated by slashing close to the ground.

Conventional tillage (CT): This is the common type of land preparation using a *jembe*. The method is popular among the local farmers. The top 15-20 cm of surface soil layer is inverted, resulting in medium size clods of 10-15 cm average diameter. Previous season's crop residue and weeds are gathered and burned before tillage.

Once in a year, at the on set of the long rains in late March or early April, maize (*Zea mays*, variety H511) and beans (*Phaseolus vulgaris*, variety rosecoco) were planted

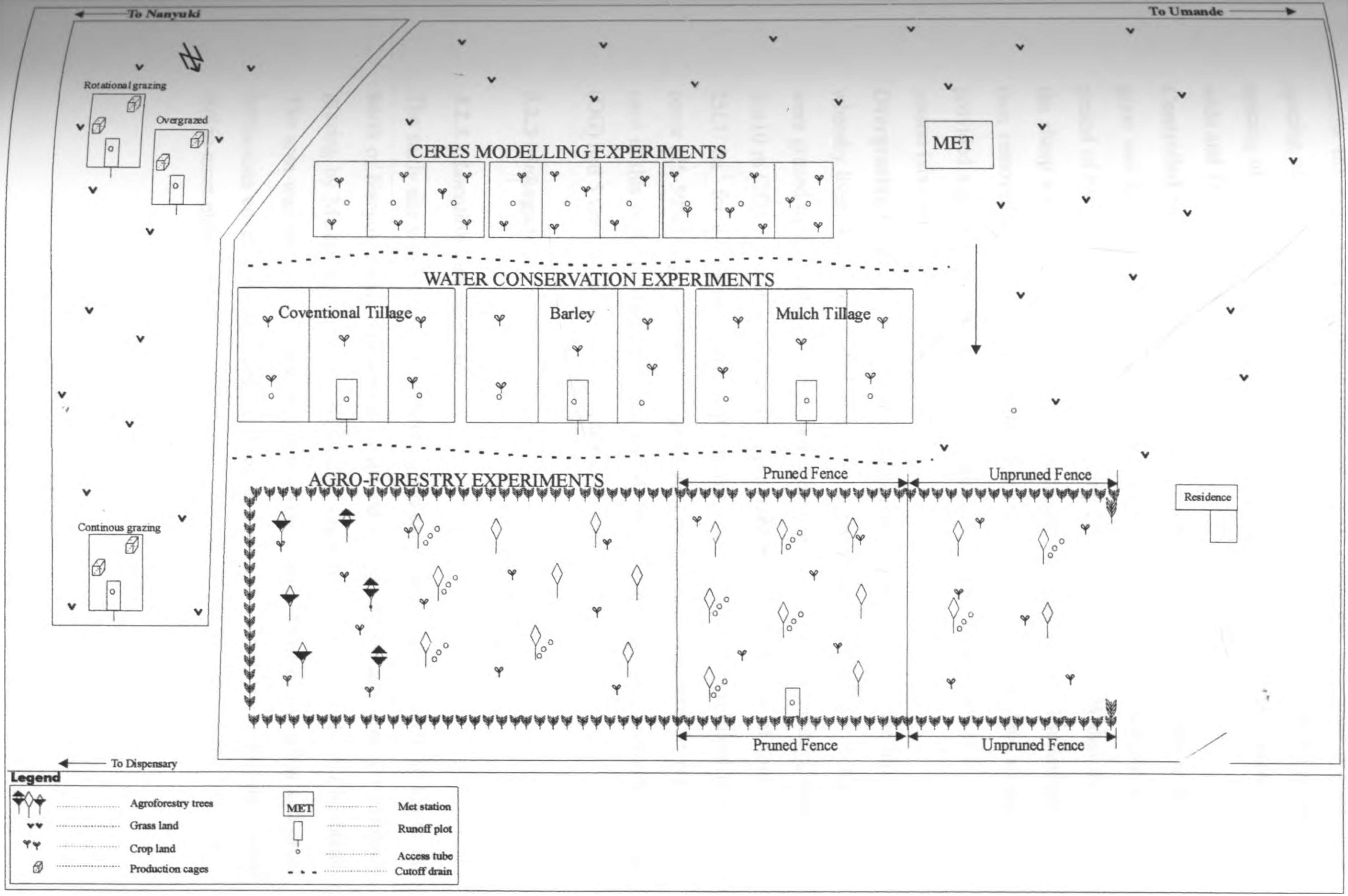


Figure. 3.4 Layout of Kalalu research site

across the slope for each tillage treatment. Two seeds per hole were planted at a spacing of 75x60 cm for maize while beans were planted between the maize rows at spacing of 75x20 cm. Each treatment was replicated 3 times on plots measuring 4 m wide and 11 m along the slope.

Controlled grazing (CG): Grazing was carried out once in each season when the grass was fully grown. Six to eight sheep were grazed for seven hours per day for a period of two weeks in a paddock measuring 20x10 m (200 m^2). Within this period, the sheep would clip grass to an average height of about 10 cm. The animals were then removed from the paddock until after the next rainy season. This arrangement provided a grazing intensity of approximately 25 LU ha^{-1} for a period of 2 weeks per season (six months).

Overgrazing (OG): This represented the common practice among the local farmers, whereby livestock were allowed to graze frequently uncontrolled. Six to eight sheep were grazed for seven hours per day for 3 days in each week in a paddock measuring 20x10 m (200 m^2). This grazing system provided a grazing intensity of approximately 25LU ha^{-1} for a total of 10 weeks per season (six months). This resulted in low soil cover (25-30%) of grass stubs with patches of bare ground. The term 'overgrazing' is used in this study to refer to 'uncontrolled, frequent grazing'. The overgrazed plots (OG) had 5 times more grazing pressure compared to CG.

3.2.3 Mukogodo

3.2.3.1 Location and land use

The study site was located within Mukogodo catchment, approximately 50 km to the north of Nanyuki town. The area is rangeland that is communally used for livestock grazing by Maasai pastoralists. The natural vegetation consists of *Acacia* bushland. The area was severely overgrazed due to overstocking. Most of the grass and other herbacious cover were depleted, resulting in bare and crusted or extensively eroded soil in most places.

3.2.3.2 Climate

Seven years data were available for Mukogodo as the meteorological station at the site was started in late 1988. The distribution of rainfall is bimodal with peaks in April and November for the long and short rains respectively. Mean annual rainfall of the experimental site ranged between 300-400 mm while evaporation is about 2100 mm. Thus evaporation exceeds rainfall by up to six times in a year.

3.2.3.3 Soils

The soil at Mukogodo was classified as a chromic Lixisol based on the FAO-UNESCO system (FAO, 1990), equivalent to a Chromaxeralf in the USDA soil taxonomy system (Soil Survey Staff, 1975). It is well drained, moderately deep, reddish brown to dark reddish brown, friable, sandy clay in texture and weak to moderate, fine to medium subangular blocky structure.

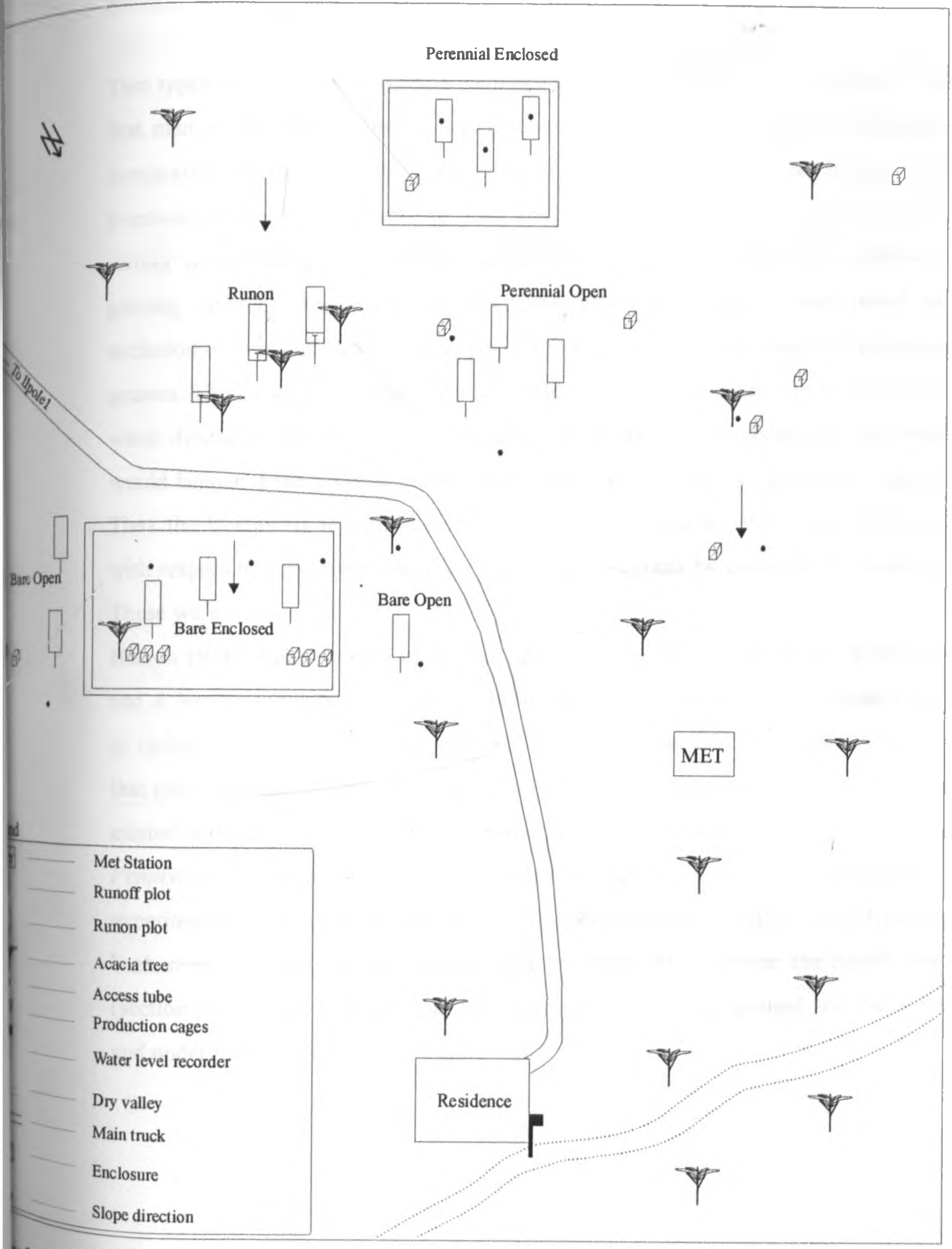
3.2.3.4 Site layout and treatments

Like in Kalalu, the treatments in Mukogodo were selected from ongoing experiments that had either been set up over time at this site to meet the long-term research objectives of NRM^3, or to meet the requirements of single studies i.e. those reported by Kironchi (1992), Mutunga (1995) and Kinyua (1995). Most of the original experiments have been maintained (Figure 3.5) in order to collect long term data for modelling purposes; but some were modified either to broaden their scope or to meet the objectives of the current study.

At this site the objective was to assess soil water balance of different range sites in the degraded communally grazed rangeland. Three distinct soil cover situations were identified as representing the basic condition in the area. These were:

(a) Bush with perennial grasses and forbs as basal cover under its canopy.

(b) Grass cover in the open spaces between bushes, consisting of mainly perennial grass species that were intensively grazed. Basal cover was 10-20%. The ground surface in between the patches of grass is sealed.



e 3.5 Layout of Mukogodo research site

(c) Bare ground in the open spaces between bushes. The soil surface was crusted. Perennial grasses were absent and basal cover was less than 5%, consisting of mainly annual grasses or forbs.

Two types of management systems were applied to cover conditions (b) and (c). The first management system applied was that prevailing in the area, that is, continuous overgrazing by the pastoralists. This was termed as an open system because the livestock had free access to the site. This would prevent soil cover recovery or lead to further deterioration. The second management system was controlled (deferred) grazing, whereby land which had been overgrazed and denuded was rested by exclusion of livestock to allow recovery of soil cover and/or regeneration of perennial grasses. This was termed as the enclosed system. Therefore the aim was to assess soil water dynamics in a heavily grazed rangeland under the current conditions; and what would happen if the simplest management technique of closure to grazing is applied. Thus the treatments investigated in Mukogodo portrayed the three site conditions with respect to vegetation cover and grazing management by exclusion of livestock. These were:

Runon (RO): This consisted of *Acacia* bushes dominated by *A. mellifera, A. etbaica* and *A. tortilis* as the major species. A bush was described as either a single-stemmed or clustered shrub at least 2 m tall. Ground cover of about 30% during the dry season that more than doubles soon after the onset of the rains due to rapid growth of forbs existed under the bush canopies. The herbaceous cover consisted mainly of perennial *Pennisetum stramenium* grass. Single *Acacia* bushes were selected and treated as experimental units. Sampling was carried out under the canopy within 1-2 m from the bush stem(s). This treatment was referred to runon (RO) because the runoff plots (section 3.3.5) were laid such that the upper part was in bare ground and the lower end under the bush canopy (see Figure 3.6b).

Perennial open (PO): These were open interspace sites between the *Acacia* bushes with mainly perennial grasses, but which are heavily grazed (Figure 3.6c). Soil cover on sites selected ranged from 10 to 20%. The dominant perennial grass species were *Cynodon dactylon*, *Pennisetum stramenium*, and *Cenchrus ciliaris*; while the annuals included *Tragus beteronianus* and *Eleusine multiflora* (Kinyua, 1995). The sites were open to continuous communal livestock grazing like the rest of the surrounding range.

Perennial enclosed (PE): The sites were initially similar to PO, but were enclosed to keep away livestock (Figure 3.6d). A thorn hedge was erected by piling together cut *Acacia* branches, just like the way pastoralists construct enclosures (*bomas*) to protect livestock at night. Thus in this treatment the effects of livestock grazing, i.e. foraging and trampling were excluded as from October 1993.

Bare open (BO): These were sites where vegetation was depleted due to excessive livestock grazing. The ground had less than 5% soil cover. Perennial grasses were absent and the scarce cover consisted of mainly annual grasses (*Eragrostis tenuifolia* and *Aristida keniensis*) or forbs. The bare soil surface was covered by a firm crust. These sites were open to continuous livestock grazing like the rest of the surrounding range.

Bare enclosed (BE): The sites had similar characteristics to BO, but were enclosed to keep out livestock (Figure 3.6a). Like for PE, a thorn hedge was erected by piling together cut *Acacia* branches. Inaccessibility to livestock therefore excluded both grazing and trampling.

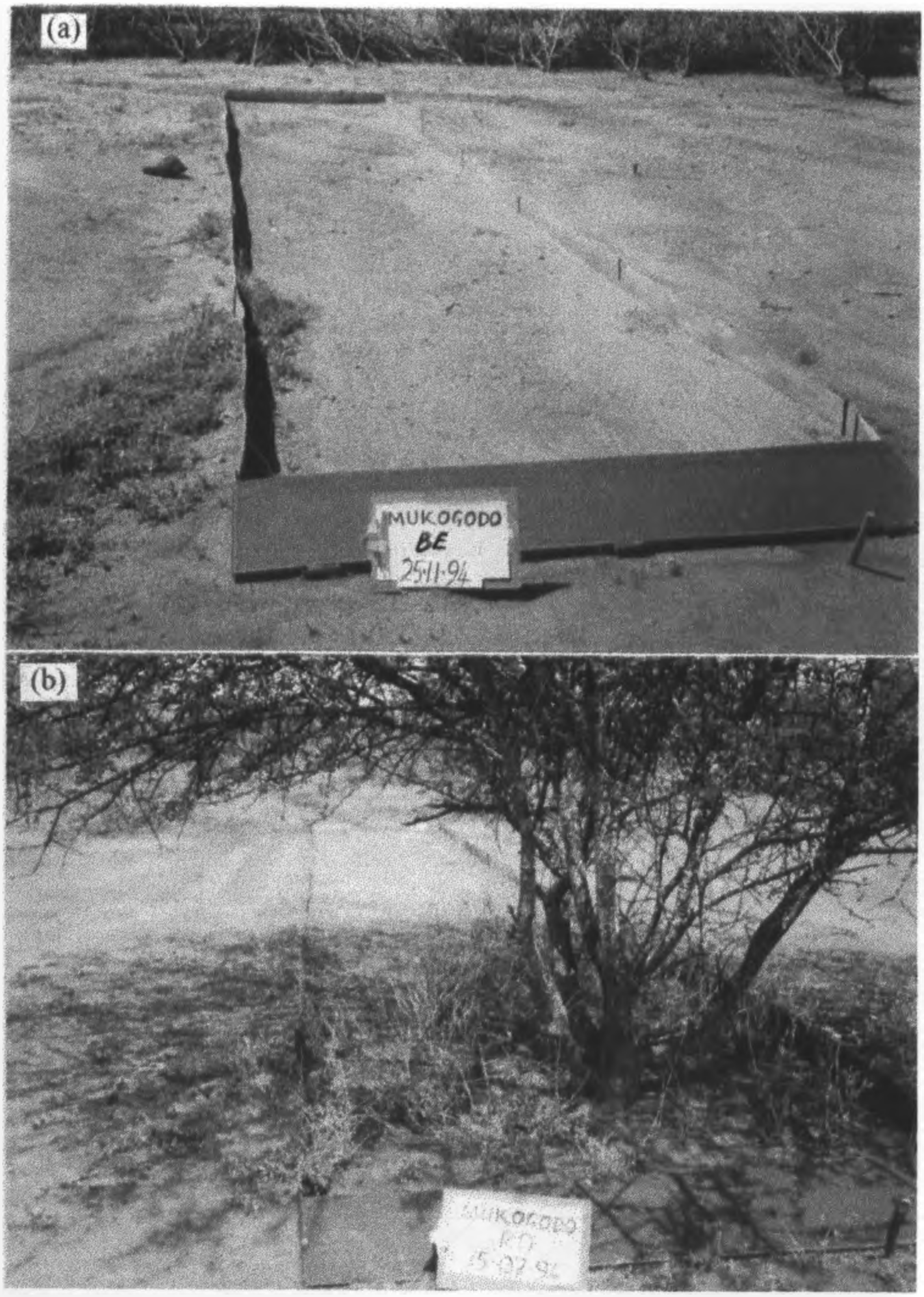


Figure 3.6 Soil cover conditions at Mukogodo (a) bare enclosed and (b) runon plots

Figure 3.6 (continued) (c) perennial open and (d) perennial enclosed plots

From these treatments, it was therefore possible to compare bush canopy with grass and bare sites; grass under two management systems (continuous grazing verses that enclosed from livestock use); and bare ground under two management systems. All the 5 treatments were set up on the same soil unit and each was replicated three times.

3.3 DATA COLLECTION AND ANALYSIS

3.3.1 Soil characterization

3.3.1.1 Profile description

A soil profile was opened at each site and fully described according to FAO guidelines (FAO, 1977) and the information recorded on the standard Kenya Soil Survey data sheet for profile description. The soil colour was determined using Munsell soil colour charts (Munsell Colour Company, 1971). Each genetic horizon was sampled for chemical and physical laboratory analyses. Soil cores were also sampled using steel cylinders of 5 cm in both height and inner diameter. The cores, replicated 5 times for each horizon, were for determination of saturated hydraulic conductivity, water retention and bulk density. The soil samples were taken to the Department of Soil Science, University of Nairobi, where they were air dried, crushed using a pestle and a mortar before being sieved through a 2-mm sieve. Subsamples for organic carbon and total nitrogen determination were further ground to pass a 0.5-mm sieve. Samples for profiles description were analysed according to procedures adapted by Kenya Soil Survey (Hinga *et al.*, 1980) and the rest of the physical properties as outlined in the monograph of methods of soil analysis (Klute, 1986).

In addition to soil profile description and sampling in each of the three experimental sites, topsoil (0-10 cm) from each of the other land uses/treatments where the profile was not located were sampled. At Karuri the profile was sited on GL, therefore additional topsoil samples were taken from NF and PC sites. At Kalalu the profile was sited adjacent to the cropland, but on a grass reserve similar to that of CG paddock; therefore topsoil from MT, CT and OG was sampled. At Mukogodo, two profiles were opened up; one under a bush canopy and the other on bare ground. Therefore additional topsoil samples were taken from PO, PE and BE plots. These samples were obtained by augering randomly in 5 locations and mixing to obtain a composite sample. Similarly, 5 replicates of core samples were obtained by driving the core sampling cylinders into the soil after clearing the vegetation and litter, if any, from the soil surface.

3.3.1.2 Organic matter, soil texture and bulk density

Organic carbon was determined by the Walkley-Black method (Nelson and Sommers, 1982). The hydrometer method as described by Gee and Bauder (1986) was used for texture analysis, and then texture classes obtained by the USDA textural triangle (USDA, 1975). Soil bulk density was determined by the gravimetric method (Blake and Hartge, 1986).

3.3.1.3 Water retention characteristics

The pressure chamber method (Klute, 1986) was used for characterization of water retention. Soil cores were saturated by capillary wetting for 48 hours. They were weighed and subjected to pressure heads of -100, -300, -500, -1000, -3000, -5000, -10000 and -15000 cm in pressure plate apparatus. Equilibrium was attained after 2 to 4 days for low suction and 6 to 10 days for higher suction. After the -15000 cm equilibrium, the cores were dried in an oven at 105°C for 24 hours. The volumetric water content at each pressure head was calculated as follows:

$$\theta = \frac{\omega_i - \omega_o}{V_t \rho_w} \qquad (3.1)$$

where θ is volumetric water content ($cm^3\ cm^{-3}$), ω_i is weight of soil sample at given suction (g), ω_o is oven dry weight of soil sample (g), V_t is volume of soil sample (cm^3), and ρ_w is the density of water.

3.3.1.4 Infiltration

A double-ring infiltrometer with an initial falling head and after 10 minutes, a constant head (Kironchi *et al.*, 1992) was used in infiltration rate measurement. The procedure was modified from Bouwer (1986). The diameters of the outer and inner rings were

60 and 30 cm, respectively, while the plastic aspirators capacity was 25 litres. Infiltration tests at each site were carried out within 50 m radius from the spot where a soil profile pit had been sampled. Replicates ranged between 3 to 6 for each treatment.

Rings were driven into the soil to approximately 10 cm deep, caution being taken that penetration was uniform and vertical. The fall in height of water in the inner ring was measured at 1 minute intervals for the first 10 minutes. Both rings were topped with water every time the level fell to about 7 cm. After 10 minutes the height of water in the rings was adjusted to 7 cm and a plastic tubing connected to supply water from the aspirator. The aspirator air supply tube was also adjusted to 7 cm in order to maintain a constant head and change in water volume in the graduated aspirator recorded at 12, 14, 16, 18, 20, 25, 30, 35, 40, 45, 50, 55, 60, 75, 90, 105 and 120 minutes from start of the experiment.

3.3.1.5 Saturated hydraulic conductivity

A constant head permeameter as described by Klute and Dirksen (1986) was used to determine saturated hydraulic conductivity (K_s). Soil cores taken in each site during soil profile description (section 3.3.1.1) were used. Five replicates for each sample were trimmed and a nylon cloth fixed at the lower end. The samples were placed in a tray with a shallow depth of water and left to saturate for at least 24 hours before measurement. K_s was calculated as:

$$K_s = \frac{QL}{AtH} \tag{3.2}$$

where Q is the volume of water that flows through the sample of length L and cross section area A in time t, and $H = L + h$ (h is depth of water above core sample).

3.3.2 Climatic data

Rainfall and evaporation data were the climatic variables required for this study. Each of the research sites is located within a radius of 100 m from a meteorological station. The stations were set up according to the specifications of the Meteorological Department of

Kenya and are fully maintained and records taken by NRM[3] (Liniger, 1991b). The three stations were started at different times, i.e. Kalalu in 1986, Mukogodo in 1989 and Karuri in 1992.

3.3.2.1 Rainfall

Rainfall was measured using both manual and automatic recording rain gauges. The manual rain gauge is the standard 12.7 cm diameter funnel. The rainfall is recorded daily (in mm day $^{-1}$) at 9.00am, care being taken to specify the day of rainfall and the day of reading. Rainfall intensity at 15 minute intervals was computed from the automatic recording gauge and rainfall erosivity (EI_{30}) obtained from the Wischmeier and Smith equation (Morgan, 1986) for kinetic energy (KE).

$$KE = 11.87 + 8.73\log_{10} I \qquad 3.3$$

where I is the rainfall intensity (mm h^{-1}).

3.3.2.2 Evaporation

Daily evaporation rate was measured using a Standard Evaporation Pan (Pan A) having a protective wire mesh. The change of water height in the pan recorded daily at 9.00 used to calculate evaporation rates in mm day^{-1}.

3.3.3 Soil moisture

The neutron probe method was used for monitoring soil moisture. To introduce the probe into the soil profile, at each site within the same locations for runoff plots, 5 cm diameter aluminium access tubes were installed in triplicate for each treatment. Access tubes were installed to 2 m depth so as to monitor soil moisture changes within this zone at all sites. Soil moisture was monitored weekly during the rainy seasons and after every two weeks during the dry seasons. In addition to the regular data collection, daily data for periods of 3 to 4 weeks were taken during campaigns at various times at each site. Appendix A1 presents the frequency of soil moisture monitoring at each site.

Two neutron probes, CPN-501 and CPN-503, were used. Neutron probe counts were taken at 15, 30, 60, 90, 120, 150 and 170 cm depths. To convert the neutron probe readings into volumetric soil water content, the two neutron probes were calibrated as described by Liniger (1991b), for the dry and wet conditions using separate access tubes installed close to the experimental tubes (Table 3.5). Both calibrations were done at the end of the dry season in late February 1995. At this time the grass was dry and therefore permanent wilting conditions were assumed. For the wet calibration, the soil had to be ponded artificially for several days till the probe registered high and constant readings for all depths. The ponded sites were covered with polythene sheet and excess water allowed to drain for 2 days at Mukogodo and 3 days at the other two sites. After this free drainage it was assumed that the profile had attained field capacity. Calibration involved taking five probe readings for each depth and sampling five replicates of 100 cm^3 soil cores at the same depths. Twenty standard counts were taken at the beginning and at the end of sampling. The average of five readings from each depth were divided by the average standard count to obtain a neutron ratio for each depth. The neutron ratios for each depth were regressed against their corresponding soil core samples volumetric water content calculated gravimetrically. The regression relationship obtained for each site was used to estimate volumetric soil water content from the routine field neutron probe readings. The calibration data and regression equations developed for each site are given in Table 3.9. At Kalalu two calibration equations were necessary due to occurrence of iron and manganese concretions after 90 cm of soil depth (Liniger, 1991a).

The soil water content upper (*FC*) and lower (*WP*) limits for water availability to plants was estimated from field data based on the method recommended by Ratliff *et al.* (1983). Soil profiles were fully saturated, protected from direct evaporation and allowed to drain freely before the upper limit soil water content was measured after 2 days at Mukogodo and 3 days at Karuri and Kalalu. The wilting point was taken as the volumetric soil water content recorded in the dry period between the months of February and March for Kalalu and Mukogodo when the grass was dry. However, for Karuri, laboratory estimated water content at 15000 cm was used as the lower limit. This is because at Karuri soil moisture at all times remained near the upper limit especially below 50 cm from the soil surface. Gardner (1988) and Liniger (1991a) have reported good results using this method in Australia and Kenya, respectively. Available water for each depth was calculated as the difference between these upper and lower limits. The volumetric available soil water content was expressed as equivalent water depth in mm stored within a given depth of the soil profile.

Table 3.5 Neutron probe calibration.

Site	Date	Neutron probe	Soil depth	Regression equation
Karuri	09/02/95 (dry)	CPN 503	15-170 cm	Y = 22.96X-2.03 (r^2 = 0.87)
	21/02/95 (wet)	CPN 501		Y=41.60X-4.84 (r^2 = 0.83)
Kalalu*	1987 and 1991	CPN 503	15-90 m	Y=33.61X-16.37 (r^2 = 0.89)
			120-170 cm	Y=32.14X-18.58 (r^2 =0.98)
Mukogodo	31/01/95 (dry)	CPN 503	15-90 cm	Y=26.95X-15.93 (r^2 = 0.93)
	03/03/95 (wet)	CPN 501		Y=32.74X-24.84 (r^2 = 0.77)

X = calibration ratio (moisture reading/standard count)
Y = estimated volumetric soil water content
**Calibration by Liniger (1991a) and van Roode (1992) for the same neutron probe*

3.3.4 Ground cover

Ground cover was monitored to assess the extent to which the soil was protected against raindrop impact and from direct evaporation. Both green plants and dry litter were considered. Cover assessment was done within the runoff plots using a line transect and pin method. In every plot, two 2-mm diameter manila strings having knots at 25 cm intervals were stretched, each at a height of about 20 cm from the ground and 50 cm from either plot borders along the slope. Along each string at the predetermined points (knots), a 2-mm metal rod was lowered vertically (with the sharp point downwards) and observed whether it touched a green plant or litter or bare ground. When the maize crop grew above 20 cm and under bush canopy at Kalalu and Mukogodo, respectively, the shade created by the vegetation at around noon was used to assess cover. The observations were recorded as presence or absence of plant or litter cover and then converted to percentages for each with respect to the total sum of points (80 in this case) for both strings. The percentage cover C was determined using the formula:

$$C = \frac{n}{N}100 \tag{3.4}$$

Where n is the number of points where plant or litter cover was present and N is the total number of observation points. The frequency of cover observation was similar to that of soil moisture monitoring as presented in Appendix A1.

3.3.5 Runoff

Surface runoff from rainfall was monitored using runoff test plots 2 m wide and 10 m long down the slope (Figure 3.7). These type of runoff plots are widely used and the procedure of setting them up and sampling are described by Liniger (1991b) and Mutunga (1995). The 20 m^2 area of plot was enclosed using strips of 28 gauge plain galvanized iron sheets, which were 25 cm wide and installed into the soil up to a depth of 12 cm. At the lower end of the plot a collecting trough is installed and covers the entire 2 m width across the plot, with a conveyance pipe at the centre leading into the storage tanks. The storage part consists of a 200 litre oil drum placed inside a 1.15 m^3 corrugated iron sheets tank (0.85 m high and 1.31 m in diameter). Figure 3.8 shows the equipment which is designed to store up to 57.5 mm of runoff. The volume was calculated by assuming a 3-hour storm with an intensity of 20 mm h^{-1} and infiltration rate of 5 mm h^{-1}. To prevent rusting, the inside and outside of the tanks was coated with bitumen paint. The plot boundaries were checked regularly to ensure that there were no leaks out of or into the runoff plot and the conveyance system regularly cleaned to facilitate unobstructed flow of water from the plot to the tanks. Adequate drainage was provided around the plot to keep off runoff generated outside the plot boundaries. Runoff was recorded at 9:00 am the following day after every rainfall event.

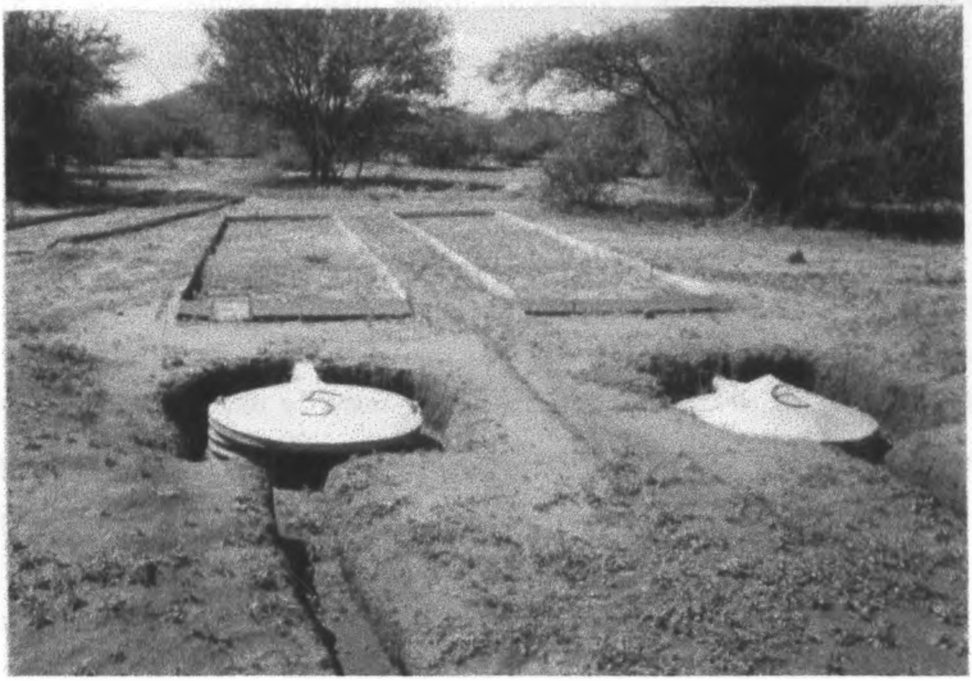


Figure 3.7 Runoff monitoring facilities at Mukogodo

At Mukogodo the runon experiment was/test the extent to which runoff flowing from /to a denuded area into a well vegetated area infiltrates into the ground. Thus plots for this experiment measured 2 by 13 m and had an *Acacia* bush with good basal cover under the canopy at the lower part (about 3 m long); while the upper part (10 m) was bare ground. Ground cover for these plots was recorded like for other plots, but was separated for each section during calculation and analysis. The amount of runoff was determined by measuring the volume of water collected in each tank. Since the tanks were of known diameter, to calculate the volume of runoff only required measurement of depth of water in the tanks, the weight of the sediment and the proportion of water in the sediment. The volume of runoff from each plot per storm was therefore computed in 3 steps:

a) The volume of runoff above the sediment in the inner tank

$$V_1 = \frac{\pi d^2}{4} h \qquad (3.5)$$

where V_1 is the volume of runoff above the sediment in cm^3, d, the diameter of the inner tank in cm, and h, the average water depth to sediment surface in cm.

b) The volume of water in the sediment (sludge) from the inner tank

$$V_2 = \frac{w_1 - w_2}{w_1} W \qquad (3.6)$$

where V_2 is the volume of water in the sediment in cm^3, w_1, is mass of sediment sample in grams, w_2, is dry mass of sediment sample in grams, and W is total mass of sediment.

c) The volume of runoff in the outer tank

$$V_3 = \frac{\pi}{4} H\left(D^2 - d^2\right) \qquad (3.7)$$

where V_3 is the volume of runoff in the outer tank, D and d are, respectively, the diameters of the outer tank and inner tank in cm, and H is the average water depth in the outer tank in cm. Finally, the volume of runoff in cm^3 from the plot for each storm, V, was computed as:

$$V = V_1 + V_2 + V_3 \qquad (3.8)$$

The runoff volume was converted into % runoff, R, using the formula:

$$R = \frac{V_r / A_p}{P} 100 \qquad (3.9)$$

Where V_r is the volume of runoff in litres, A_p, the area of the plot in m^2, and P, the rainfall amount in mm.

3.3.6 Data analysis

Both arithmetic and geometric means were used to describe the central tendency and variation of the data. All statistical analyses were performed using Statistical Analysis System (SAS Institute, 1987). Completely randomized design was used for analysis of variance. Single factor or two factors with replication procedures were applied depending on the design of specific experiments. Simple linear regression was used for correlation analysis. Data were tested for normality before carrying out analysis of variance or regression. Differences among treatments were determined by analysis of variance and means separated by Duncan's multiple range test (Steel and Torrie, 1980).

CHAPTER 4

RESULTS AND DISCUSSION

4.1 SOIL PROPERTIES

4.1.1 Soil profile

Detailed soil profile description for Karuri, Kalalu and Mukogodo are given in Tables 4.1, 4.2 and 4.3, repectively. At Karuri, the profile is well drained, very deep with brownish black topsoil and dark brown subsoil. The texture is clay loam to clay while structure is moderate, very fine to medium subangular blocky. The soil is well drained and deep at Kalalu, with a reddish brown topsoil and dark reddish brown subsoil. The texture is clay throughout while structure is fine to medium subangular blocky. At Mukogodo the soil is well drained, moderately deep to deep with yellowish red to dark reddish brown colour. The topsoil is sandy clay loam in texture while the subsoil is sandy clay. The structure is weak to moderate, fine to medium subangular blocky.

Parent material, climate, relief and the time it has taken for soil formation are the major factors determining soil type. Parent material and climate have by far the greatest influence on the development and properties of soils in the study area (Speck, 1983; Wanjogu, 1992). General soil characteristics for each of the three agroclimatic zones have already been presented in section 3.1. Due to parent material, the soil at Mukogodo has a high sand content compared to that of Karuri and Kalalu. Soils at Kalalu and Karuri are of volcanic origin. However, that of Karuri is less weathered due to a low temperature regime in the higher altitude. Speck (1983) has attributed the high silt content which gives the topsoil at Karuri a loamy texture to low weathering processes. High supply of plant biomass from the forest vegetation and also the low rate of decomposition provide high organic carbon content in Karuri compared to that in the other two sites. The soil profile described at Mukogodo was opened under a bush canopy (Wanjogu, 1992). Most of the open sites have a thin or truncated A horizon due to severe

Table 4.1 Physical and chemical properties of the soil profile at Karuri.

Soil classification		mollic Andosol (FAO/UNESCO) / Eutrandept (USDA)
Surface attributes		Dark surface; rich in organic matter and with low bulk density
General observation		On grazing land with grass cover over 80% throughout the year
Horizon attributes		
A	0-18 cm	Subangular blocky; many medium and few course pores; friable moist, non-sticky and non-plastic wet
AB	18-40 cm	Subangular blocky; many medium pores; friable moist, slightly sticky and slightly plastic wet
Bu_1	40-72 cm	Subangular blocy; many fine and few medium pores, friable moist; sticky and plastic wet
Bu_2	72-112 cm	Subangular blocky; many fine and few medium pores, friable moist; sticky and plastic wet.
Bu_3	112-160 cm	Subangular blocky; many fine and medium pores; friable moist; sticky and plastic wet; 2-5.

Horizon	A	AB	Bu_1	Bu_2	Bu_3
Depth (cm)	0-18	18-40	40-72	72-112	112-160
Sand (%)	28	28	24	20	28
Silt (%)	34	36	32	32	31
Clay (%)	38	36	44	48	41
Textural class	Clay loam	Clay loam	Clay	Clay	Clay
pH H_20	5.8	6.1	6.2	5.9	6.3
C (%)	6.1	5.8	3.9	1.5	1.1
P (mg kg^{-1})	2.25	3.75	2.90	2.10	3.00
N (mg kg^{-1})	0.69	0.45	0.31	0.20	0.20
Ca (cmol kg^{-1})	18.50	18.50	4.00	3.50	5.50
Mg (cmol kg^{-1})	5.67	6.30	1.83	1.68	1.47
K (cmol kg^{-1})	3.25	2.50	1.75	1.25	1.25
Na (cmol kg^{-1})	0.75	0.75	0.50	1.15	1.00
CEC (cmol kg^{-1})	26.0	28.0	20.0	16.0	12.0

Source: Kironchi, current study

Major attributes that contribute to favourable soil water balance for this profile

- Undifferentiated horizons that enhance uniform water flow down the profile
- Favourable particle size distribution throughout the profile
- High amount of C which contribute to good pore distribution throughout the profile
- Very deep, can hold up to145 mm m^{-1} of available water for plant growth

Table 4.2 Physical and chemical properties of the soil profile Kalalu.

Soil classification		ferric Luvisol (FAO/UNESCO) / Ferrustaff (USDA)
Surface attributes		Cultivated land (conventional tillage), maize-bean intercrop
General observation		Termite channels in top soil, small cracks between 20 and 70 cm depth in dry season
		Horizon attributes
Ap	0-20 cm	Subangular blocky; many medium and few coarse pores; loose dry, slightly sticky and slightly plastic wet
Bt1	20-45 cm	Subangular blocky; many medium pores; slightly hard dry, sticky and plastic wet
Bt2	45-70 cm	Subangular blocy: many fine and medium pores, slightly hard dry; sticky and plastic wet
Btcs1	70-100 cm	Subangular blocky; many fine and few medium pores, slightly hard dry; sticky and plastic wet, 2-5 mm Fe/Mg concretions
Btcs2	100-130 cm	Subangular blocky; many fine and few medium pores, slightly hard dry; sticky and plastic wet, 2-10 mm Fe/Mg concretions
BCcs	130-180 cm	Subangular blocky; many fine and few medium pores; hard dry; sticky and plastic wet; 2-10 mm Fe/Mg concrctions

Horizon	Ap	Bt1	Bt2	Btcs1	Btcs2	BCcs
Depth (cm)	0-20	20-45	45-70	70-100	100-130	130-180
Sand (%)	22	18	16	18	20	24
Silt (%)	21	15	11	11	11	21
Clay (%)	57	67	73	71	69	55
Textural class	Clay	Clay	Clay	Clay	Clay	Clay
pH H_2O	6.4	6.2	5.4	5.2	6.6	6.3
C (%)	2.35	0.96	0.69	0.37	0.30	0.35
P (mg kg^{-1})						
N (mg kg^{-1})	0.23	0.23	0.12	0.03	0.06	0.04
Ca (cmol kg^{-1})	6.4	6.8	1.8	1.6	4.8	5.6
Mg (cmol kg^{-1})	5.0	4.0	2.1	1.3	2.9	3.3
K (cmol kg^{-1})	4.51	3.41	1.39	0.58	1.07	1.35
Na (cmol kg^{-1})	0.19	0.18	0.15	0.11	0.34	0.78
CEC (cmol kg^{-1})	28.2	22.6	13.2	10.5	17.6	19.8

Source: Liniger, 1991a

Major attributes that contribute to or hinder favourable soil water balance for this profile

- 0-70 cm Favourable pore distribution
- 70-180 cm Unfavourable pore distribution
- Abrupt change in particle size distribution between 20 and 21 cm which will affect water movement down the profile
- Fe/Mn concretions which reduce the space available for water storage in 70-180 cm depth
- Very deep to hold adequate water (160 mm m^{-1}) for plant growth if there is adequate rainfall

Table 4.3 Physical and chemical properties of the soil profile Mukogodo.

<table>
<tr><td colspan="2">Soil classification</td><td colspan="5">chromic Lixisol (FAO/UNESCO) / Chromaxeralf (USDA)</td></tr>
<tr><td colspan="2">Surface attributes</td><td colspan="5">Perennial grass and forbs; scarce litter</td></tr>
<tr><td colspan="2">General observation</td><td colspan="5">Under the bush canopy; termite channels throughout the profile</td></tr>
<tr><td colspan="7">Horizon attributes</td></tr>
<tr><td>A</td><td>0-11 cm</td><td colspan="5">Subangular blocky; many medium pores; slightly hard dry, sticky and plastic wet</td></tr>
<tr><td>AB</td><td>11-22 cm</td><td colspan="5">Angular blocky; many medium pores; hard dry, sticky and plastic wet</td></tr>
<tr><td>Bt</td><td>22-39 cm</td><td colspan="5">Angular to subangular blocy: many medium pores hard dry; sticky and plastic wet</td></tr>
<tr><td>Btcs</td><td>39-58 cm</td><td colspan="5">Subangular to angular blocky; many medium pores, slightly hard dry; sticky and plastic wet 2-10 mm Fe/Mg concretions</td></tr>
<tr><td>BCcs</td><td>58-85 cm</td><td colspan="5">Angular blocky; many medium pores; slightly hard dry; sticky and plastic wet; 2-5 mm Fe/Mg concretions</td></tr>
<tr><td colspan="2">Horizon</td><td>A</td><td>AB</td><td>Bt</td><td>Btcs</td><td>BC</td></tr>
<tr><td colspan="2">Depth (cm)</td><td>0-11</td><td>11-22</td><td>22-39</td><td>39-58</td><td>58-85</td></tr>
<tr><td colspan="2">Sand (%)</td><td>52</td><td>50</td><td>50</td><td>50</td><td>38</td></tr>
<tr><td colspan="2">Silt (%)</td><td>14</td><td>12</td><td>10</td><td>6</td><td>12</td></tr>
<tr><td colspan="2">Clay (%)</td><td>34</td><td>38</td><td>40</td><td>44</td><td>50</td></tr>
<tr><td colspan="2">Textural class</td><td>Sandy clay loam</td><td>Sandy clay</td><td>Sandy clay</td><td>Sandy clay</td><td>Sandy clay</td></tr>
<tr><td colspan="2">pH H_20</td><td>6.5</td><td>6.8</td><td>7.3</td><td>7.6</td><td>7.6</td></tr>
<tr><td colspan="2">C (%)</td><td>1.86</td><td>0.9</td><td>0.54</td><td>0.45</td><td>0.36</td></tr>
<tr><td colspan="2">P (mg kg^{-1})</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">N (mg kg^{-1})</td><td>0.18</td><td>0.13</td><td>0%</td><td>0.07</td><td>0.07</td></tr>
<tr><td colspan="2">Ca (cmol kg^{-1})</td><td>9.04</td><td>9.52</td><td>10</td><td>13.2</td><td>13.52</td></tr>
<tr><td colspan="2">Mg (cmol kg^{-1})</td><td>3.85</td><td>4.85</td><td>3.35</td><td>4.85</td><td>6.85</td></tr>
<tr><td colspan="2">K (cmol kg^{-1})</td><td>10.14</td><td>8.94</td><td>8.9</td><td>8.54</td><td>7.93</td></tr>
<tr><td colspan="2">Na (cmol kg^{-1})</td><td>2.6</td><td>1.95</td><td>1.25</td><td>1.5</td><td>0.8</td></tr>
<tr><td colspan="2">CEC (cmol kg^{-1})</td><td>31.3</td><td>27.7</td><td>21.7</td><td>28.7</td><td>35</td></tr>
</table>

Source: Wanjogu, 1992 (Profile No 107/1-23)

Major attributes that contribute to/hinder favourable soil water balance for this profile

- Favourable pore distribution
- Thick surface crust which hinders water infiltration
- Fe/Mn concretions reduce the space available for water storage in 39-85 cm depth
- Moderately deep; has medium (115 mm m^{-1}) water storage capacity

erosion (Table 4.4). This has resulted in very shallow soils with reduced effective soil depth for water storage and plant rooting.

Table 4.4 Topsoil thickness and organic carbon content under bush and on bare ground at Mukogodo.

Profile No	Bush canopy		Bare ground	
	Thickness (cm)	C %	Thickness (cm)	C %
107/1-2	15	1.24	5	0.70
107/1-8	15	1.10	7	0.86
107/1-18	12	1.53	9	0.28
107/1-23	11	1.86	6	0.55
107/1-24	12	0.67	4	0.38

Source: Wanjogu, 1992

4.1.2. Soil texture and structure

Particle size distribution, bulk density and organic carbon content of a soil influence its structure. Structure in turn influences the soil's total porosity and pore-size distribution, both of which affect water movement and storage. Tables 4.5 to 4.7 present the attributes of three soil layers for various topsoil conditions in the three sites.

4.1.2.1 Particle size distribution

Soil texture variation with profile depth for each site is illustrated in Figure 4.1. At Karuri the topsoil was loam to clay loam while the subsoil was clay. The Andosol had a high silt content (>30%), thus a high silt/clay ratio which suggest that the soil is highly susceptible to erosion if organic matter decreases and/or bulk density increases (Morgan, 1986). This is likely to be the case with removal of forest and cultivation. The topsoil in GL and PC is clay loam while that of NF is loam (Table 4.5). This would be either due to topsoil removal by erosion or mixing from ploughing. The latter would have also occurred in GL because the site was under cultivation for at least two years before it was converted to grazing land. The course texture of topsoil in the forest may be attributed to downward migration of finer clay particles by percolating water, given the high infiltration rate (Ghuman *et al.*, 1991) as discussed in section 4.1.4.1.

Table 4.5 Soil physical properties for three land uses at Karuri

Land use	NF			GL			PC		
Depth (cm)	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50
Sand (%)	30	25	26	28	21	23	27	22	20
Silt (%)	46	40	32	34	38	32	40	39	32
Clay (%)	24	35	42	38	41	44	33	39	48
Textural class	L	CL	C	CL	C	C	CL	CL	C
Carbon (%)	14.1	7.57	1.42	8.42	6.93	3.90	5.61	5.59	1.54
Bulk density ($Mg\ m^{-3}$)	0.73	0.78	1.02	0.88	0.83	0.97	0.89	0.92	0.98

NF Natural forest, GL Grazing land, PC Potato cropland
Bulk density is arithmetic mean of 5 replicates
Texture and carbon content are arithmetic means of 3 composite replicates

Table 4.6 Soil physical properties for four management systems at Kalalu.

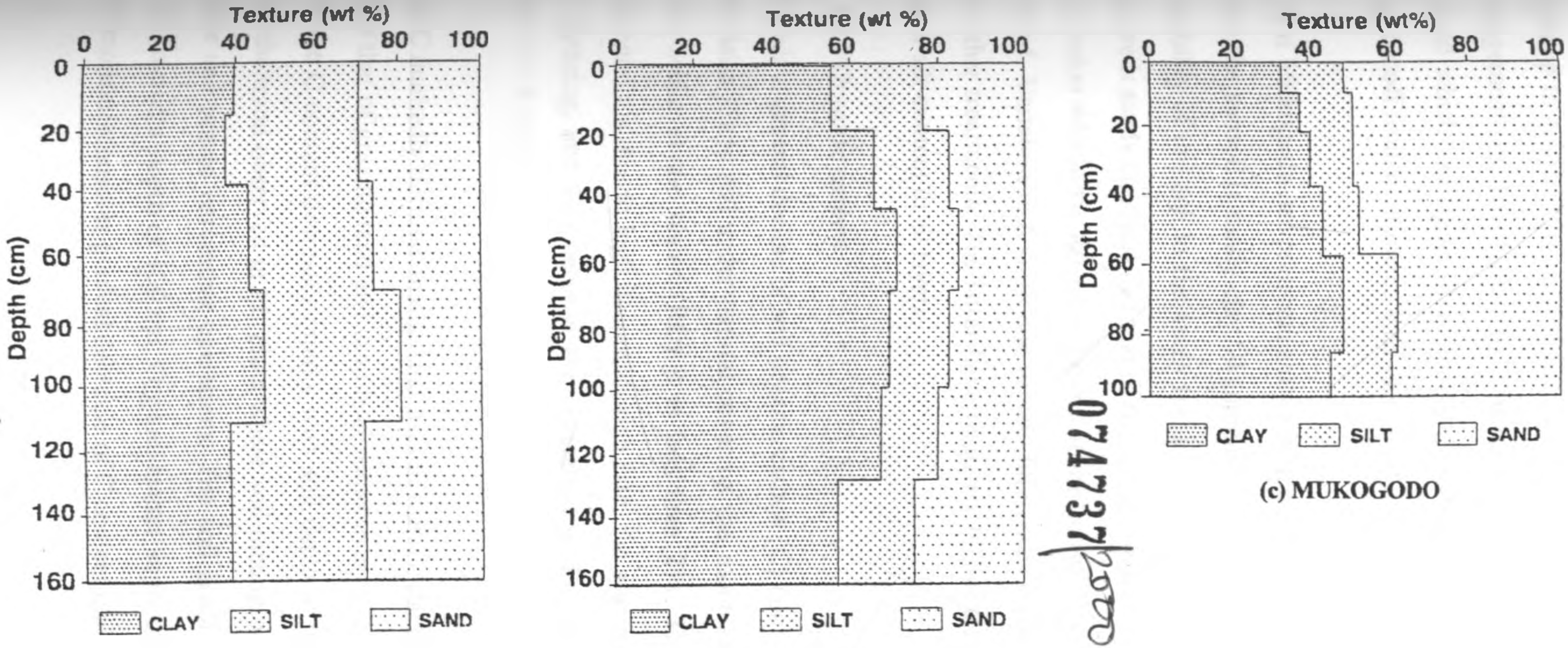
Land use	CT			MT			OG			CG		
Depth (cm)	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50
Sand (%)	23	22	19	25	24	17	21	17	17	26	20	18
Silt (%)	21	17	16	21	18	16	19	17	12	20	17	13
Clay (%)	56	61	65	54	58	67	60	66	71	54	63	69
Textural class	C	C	C	C	C	C	C	C	C	C	C	C
Carbon (%)	2.19	0.87	0.64	3.13	1.07	0.59	0.91	0.86	0.57	2.93	1.20	0.54
Bulk density ($Mg\ m^{-3}$)	1.14	1.18	1.20	1.01	1.15	1.23	1.21	1.20	1.22	1.17	1.19	1.23

CT Conventional tillage, MT Minimum and mulch tillage, OG Overgrazing, CG Controlled grazing
Bulk density is arithmetic mean of 5 replicates
Texture and carbon content are arithmetic means of 3 composite replicates

Table 4.7 Soil physical properties of five soil cover conditions at Mukogodo

Land use	RO			PO			PE			BO			BE		
Depth (cm)	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50	0-10	20-30	40-50
Sand (%)	55	52	49	54	53	46	59	56	54	51	47	40	47	45	42
Silt (%)	16	15	12	22	20	16	23	27	23	12	9	11	12	10	8
Clay (%)	29	33	39	24	27	38	18	17	23	37	44	49	41	45	50
Textural class	SCL	SCL	SC	SCL	SCL	SC	SL	SL	SCL	SC	SC	C	SC	SC	C
Carbon (%)	1.64	0.86	0.54	0.94	0.70	0.49	1.33	0.66	0.37	0.43	0.44	0.29	0.38	0.31	0.24
Bulk density (Mg m^{-3})	1.32	1.48	1.56	1.46	1.51	1.53	1.43	1.49	1.54	1.49	1.54	1.52	1.51	1.55	1.56

RO Run on, PO Perennial open, PE Perennial enclosed, BO Bare open, BE Bare enclosed
Bulk density is arithmetic mean of 5 replicates
Texture and carbon content are arithmetic means of 3 composite replicates



(a) KARURI

(b) KALALU

(c) MUKOGODO

Figure 4.1 Soil texture variation with profile depth.
(Source of soil profile data for Kalalu and Mukogodo from Liniger (1991a) and Wanjogu (1992) respectively)

Kalalu soil has a clay texture throughout the profile. The clay content increases with depth up to around 120 cm. Topsoil clay content in OG is higher compared to the other 3 management systems (Table 4.6). This would be due to topsoil removal and gradually the subsoil which has higher clay content is getting exposed at the soil surface because of high runoff from overgrazed land (section 4.3.1).

Soil at Mukogodo has predominantly a high sand content. The topsoil is sandy clay loam, while the subsoil is sandy clay. Wanjogu (1992) attributed the weak structure and high erodibility of this soil to the sandy texture. Table 4.7 indicates that the bare sites topsoil texture is sandy clay, just like that of the subsoil under vegetated sites. This would be due to erosion which has led to exposure of the subsoil on the surface in most of the bare ground. Variation in texture due to site differences is noted between PE and the rest of the other treatments. The latter have relatively higher clay content while the former has higher silt content in all layers.

4.1.2.2 Organic carbon

There is a general decline of soil organic carbon (C) content from the mountain slopes to the plains. Sites still under natural cover on the mountain slopes (NF) have more than 10%, while in the plains (RO) it is less than 2%. The generally low C content in Mukogodo is due to high decomposition rate, the scarcity of vegetative material due to overgrazing, and also because the vegetation is dominated with *Acacia* bushes which have low foliage biomass.

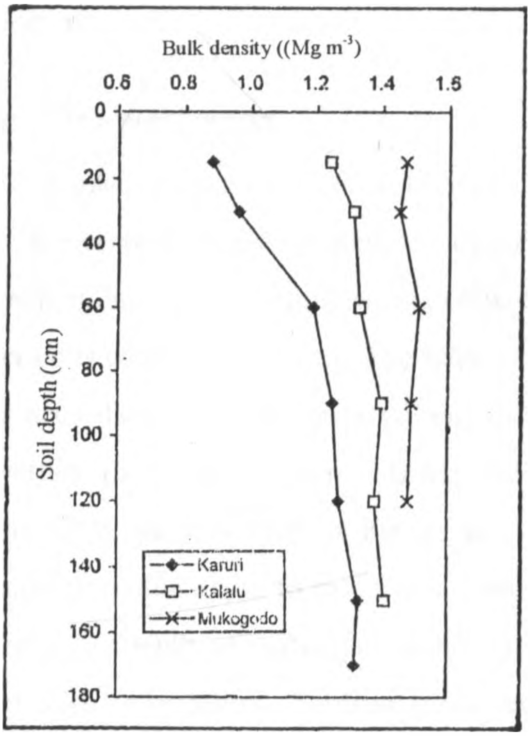
Soil C markedly differed among land uses at Karuri; the forest topsoil had almost 2 and 3 times that of grazing land and crop land respectively (Table 4.5). It is interesting to note that the C content decreases rapidly with soil depth in the forest. This contrasts greatly with the trend observed in PC plots where soil mixing occurs up to 30 cm depth during tillage and potato harvesting operations. The soil profile on grass had many fine roots even beyond a depth of 100 cm. Organic matter supplied by the grass roots biomass on decomposition ensures gradual decrease of C content under grass.

At Kalalu, reduced cultivation and mulching (3.1%) has kept organic C significantly higher compared to conventional tillage (2.2%). Controlled grazing which ensures retention of grass litter, has maintained high organic matter in topsoil, which is up to 3 times that obtained in overgrazed plots (Table 4.6). Both conservation methods (MT and CG) have comparable amounts of carbon content on the topsoil. As expected in Mukogodo, topsoil under bush had the highest amount of organic C content (1.64%), but it is not significantly higher ($P<0.05$) than that in PE (1.33%). Comparison of topsoil values for PO and PE, reveals that an increase of 40% has occurred after enclosure of sites which had perennial grass. This contrasts with the bare eroded sites where no significant change occurred between BO (0.43%) and BE (0.38%) during the experiment period (Table 4.7).

4.1.2.3 Bulk density

Soil bulk density is generally low at Karuri, intermediate at Kalalu and high at Mukogodo. This can be attributed to differences in soil type and parent material the soils have formed from. Figure 4.2 illustrates the variation of bulk density with depth for the three sites. There is a general trend of increasing bulk density with soil depth at Karuri and Kalalu. However, it remains almost constant throughout the profile at Mukogodo. Rapid increase up to 60 cm depth at Karuri would be due to sudden change in texture and reduction in C content within this part of the profile.

Tables 4.5 to 4.7 show the variation of bulk density among land uses and management systems for 3 soil layers. Forest removal for either grazing or cultivation had resulted in significant ($p>0.05$) and similar (20.5 and 21.9% respectively) increase in surface soils bulk density at Karuri. The increase is reflected in decreased total- and macro-porosities (section 4.1.3.3). At Kalalu, conservation tillage has resulted in significant decrease (11.4%) in surface soil bulk density, but this is not the case on grazing land where controlled grazing has only marginally decreased compaction (3.3%). Bush canopy ground (RO) at Mukogodo has 10.6 and 12.9% lower bulk density compared to overgrazed grass site (PO) and bare eroded ground (BO) respectively. Similar magnitudes of change in bulk density for alfisols in Nigeria were reported by Lal *et al.* (1979) on naturally eroded soil and by Mbagwu et al. (1984) on artificially desurfaced soils. The mulch tillage results at Kalalu agree with those of Black (1973) where significant reductions in soil bulk density were reported with continued use of surface mulch. However, the findings at Mukogodo differ from what was reported by Gachene (1995) for a Nitisol at Kabete. In the latter, topsoil removal by erosion of soil with stable structure did not result in increased bulk density.



Bulk density is mean of 5 replicates. Sampled in GL at Karuri, CG at Kalalu and BO at Mukogodo.

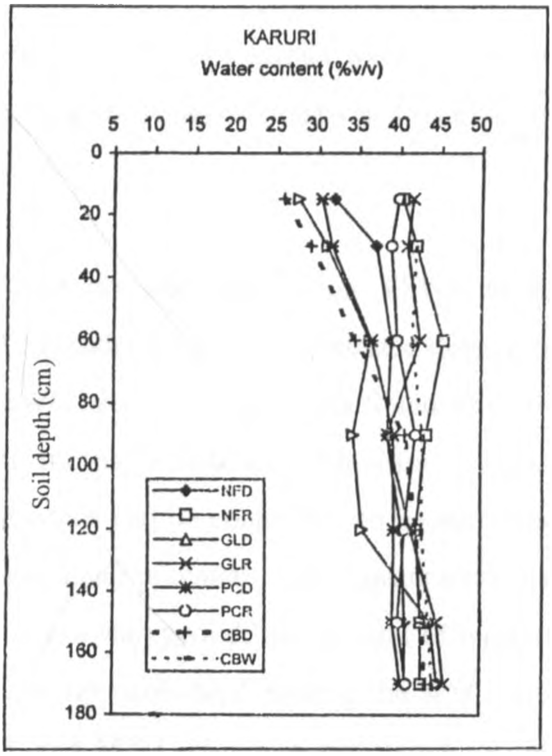
Figure 4.2 Bulk density variation with soil depth

Data in Table 4.7 further indicate that despite exclusion of livestock grazing at Mukogodo, topsoil bulk density has not significantly decreased in both PE and BE even after 4 years. From the above results on soil texture, C content and bulk density, it is observed that parent material, the levels of organic matter supply and the degree of disturbance (of topsoil) are key factors influencing soil structure in the study area. The amount of organic matter and degree of compaction or sealing of topsoil will determine the surface soils' porosity, and thus its infiltration capacity. The bulk densities reported for each site are reflected in the soil pore space as illustrated in Figure 4.6. It is indicated that Karuri and Kalalu topsoils have high porosity (≈ 60%) while that of Mukogodo is relatively low (<40%). Also, porosity gradually decreases down the profile in the former, while that in the latter remains almost constant. Porosity reflects soil structure, especially pore-size distribution, which has major influence on water movement and storage.

4.1.3 Soil water storage

4.1.3.1 Soil profile water content

In this section volumetric soil water content (VSWC) at different soil depths in a dry and a rainy season are presented. In all 3 areas the driest period occurs in February to early March (dry calibration of neutron probes was carried out during such a period!); while the wettest period is usually in late May. The selection of the time points of soil moisture extremes was according to rainfall received and moisture recorded at each site in the driest and wettest parts of the year. During the time of study, this occurred in February/March 1995 and May 1994 for the dry and wet period respectively. The VSWC was plotted against profile depth to examine soil moisture distribution in the entire soil profile (Figure 4.3). Depth of water percolation and plant extraction pattern can be revealed from such information. Neutron probe calibration data that were used to estimate the upper and lower limits of water that would be available to plants were included for comparison. The distribution of available water in the profile at extreme moisture conditions under different land uses or management systems can be illustrated from this information. To assess the dynamics, water content variation with soil depth can be plotted at various times. A series of such graphs can be used to examine profile recharge trend or the pattern of moisture extraction by plants in a more detailed study such as in modelling.



NFD is natural forest dry, NFR is natural forest rainy, GLD is grazing land dry, GLR is grazing land rainy, PCD is potato cropland dry and PCR is potato cropland rainy. The terms dry and rainy represent dry and rainy season. CBD and CBW are, respectively, soil water contents during dry and wet neutron probe calibrations.

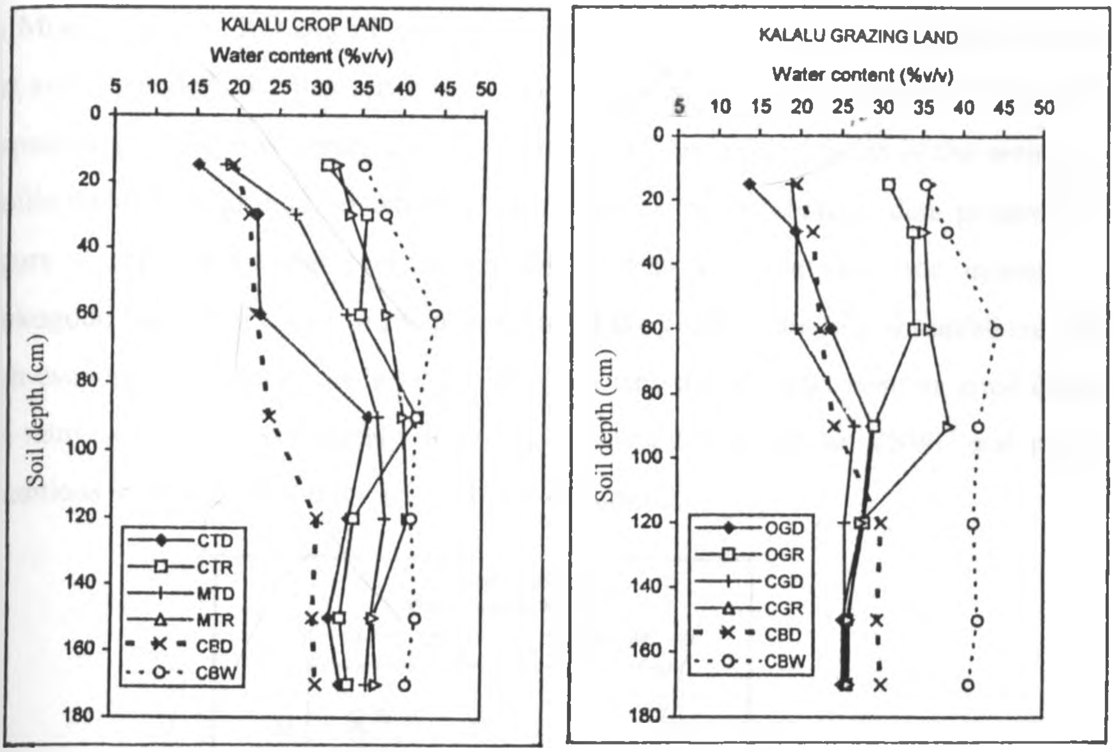
Figure 4.3(a) Soil water content variation with soil depth in a dry (9/2/95) and a wet (25/5/94) period at Karuri.

At Karuri the water content was significantly different between the wet and dry season from the surface to 60 cm, 90 cm and 120 cm for PC, NF and GL respectively. As expected the differences are much larger in the topsoil with that of GL being more pronounced (up to 50%). There was no difference in water content between the seasons below 60 cm and 120 cm in cropland and grazing land respectively. However, in the forest a difference of about 5% is recorded up to 170 cm, indicating extraction of moisture by the deep rooted forest vegetation. The percentage moisture difference for GL was almost twice that of NF and PC in topsoil. Figure 4.3a shows a distinct moisture extraction pattern for grass. The extraction is almost uniform between 40 to 120 cm. When these field measured data are compared with laboratory estimated lower limit, it is revealed that plants at Karuri do not extract water to the lower limit even in the driest part of the year. Therefore this suggests that water availability is not a limiting factor for plant growth at Karuri.

The difference between dry and wet season VSWC at Kalalu indicates that water percolated up to 90 cm under CT, but it penetrated deeper, up to 120 cm under MT. A difference of 4% VSWC between seasons was found to be the threshold for statistically significant value. This translates to 40 mm of moisture within 1 m soil depth. Incidentally this is at a threshold which can be considered to be agronomically significant at Kalalu. Given that the average daily potential evapotranspiration is about 3.5 mm (Njeru, per. com.) during the crop growing period, this amount of moisture can adequately meet the evaporative demand of up to10 days. During the wet period, the difference in water content between CT and MT (<2%) was not significant up to 90 cm depth; but the difference was significant for the rest of the profile below this depth (as it ranges between 3.5 and 6.6%).

Therefore the upper part of the profile got recharged to a similar extent for both systems. However, due to reduced surface runoff and the initial high residual moisture, MT afforded higher storage deeper into the lower part of the profile. It would be concluded that conservation of moisture up to 90 cm was very significant, but also substantial in the rest of the profile under mulch tillage system. Therefore under MT, the extra moisture conserved in the upper part of the profile can be available to the planted crops. That stored below 100 cm is of little agronomic value to crops like beans and potatoes with shallow roots since it would not be extracted by such crops. However, it can be reached by deep rooted plants like trees. Therefore agroforestry becomes very favourable under such conditions.

On grazing land at Kalalu, VSWC in the rainy period (25/5/94) was almost twice that recorded in the dry period (8/2/95) up to at least 60 cm depth for both grazing systems (Figure 4.3(b)). Moisture recharge in the wet season was limited to only 90 cm in OG,



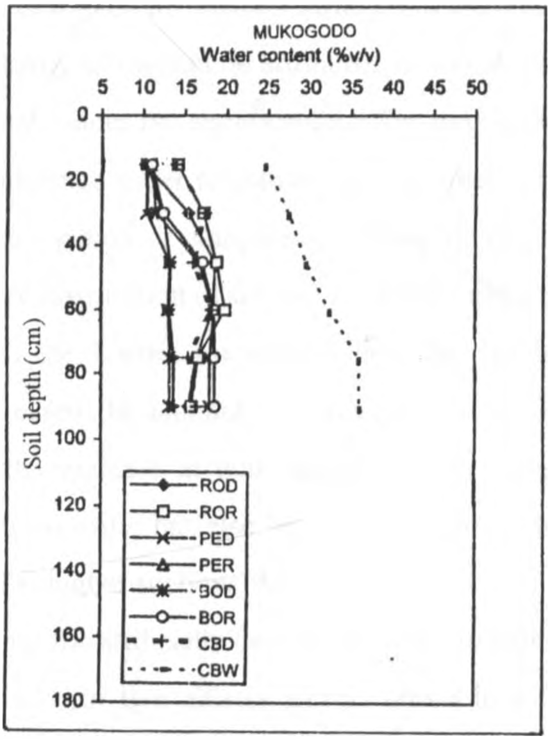
CTD is conventional tillage dry, CTR is conventional tillage rainy, MTD is mulch tillage dry, MTR is mulch tillage rainy, OGD is overgrazing dry, OGR is overgrazing rainy, CGD is controlled grazing dry and CGR is controlled grazing rainy. The terms dry and rainy represent dry and rainy season. CBD and CBW are, respectively, soil water contents during dry and wet neutron probe calibrations.

Figure 4.3(b) Soil water content variation with soil depth in a dry (8/2/95) and a wet (25/5/94) period at Kalalu.

but it penetrated up to 120 cm in CG. This difference in water percolation and storage would be attributed to high surface runoff water loss from OG (section 4.3.1).

Due to high utilization of moisture by the grass, both profiles were depleted to similar levels of VSWC in the dry season. More water infiltrated under controlled grazing and the moisture stored was utilized to produce more forage. This qualifies CG as a viable system for livestock production because the extra grass can be reserved to be used latter in the dry season. Therefore if farmers could defer grazing within their plots during the rainy seasons and graze the livestock elsewhere like along the road reserves or use planted fodder like napier grass, production of grass in paddocks would be increased.

At Mukogodo only RO and PE plots had significant differences in VSWC between the wet and dry period. But this was limited to only 30 cm and 45 cm depth for RO and PE respectively. There was hardly any change in VSWC between seasons in the entire soil profile under bare ground conditions. Neutron probe wet calibration data presented in Figure 4.3(c) indicate that even in the wettest period of the year, soil moisture at Mukogodo hardly got closer to *FC* in any part of the profile. Due to low rainfall but very high evaporative demand, the little moisture that was stored under bush or grass during the rainy season was completely depleted. This resulted in similar VSWC soil profile conditions in the dry season for all soil cover conditions.



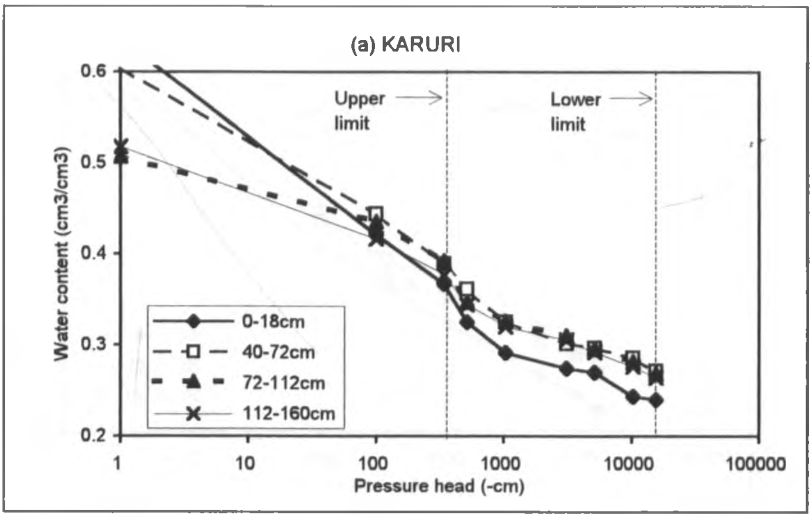
ROD is runon dry, ROR is runon rainy, PED is perennial enclosed dry, PER is perennial enclosed rainy, BOD is bare ground dry and BOR is bare ground rainy. The terms dry and rainy represent dry and rainy season. CBD and CBW are, respectively, soil water contents during dry and wet neutron probe calibrations.

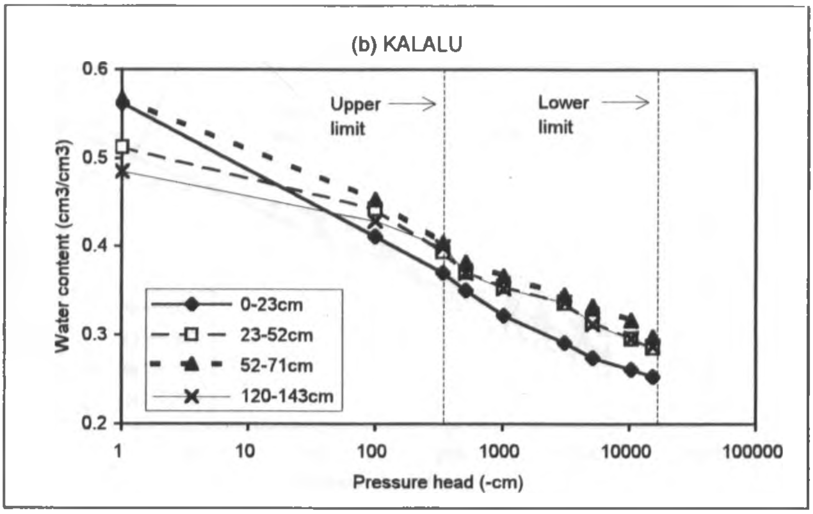
Figure 4.3(c) Soil water content variation with soil depth in a dry (2/3/95) and a wet (24/5/94) period at Mukogodo.

4.1.3.2 Soil water retention

Soil profile water retention characteristics are illustrated by curves of four distinct horizons for each site (Figure 4.4). Karuri and Kalalu profiles have similar water retention characteristics. They retain more water at all pressure heads compared to Mukogodo. This would be attributed to texture and total porosity. Mukogodo soil has lower clay content and higher bulk density. Variations in water retention among horizons in each profile were more notable between saturation and -100 cm pressure head. Water retention pattern for the surface horizon in each site was also distinct from the other horizons. This was due to differences in pore-size distribution which influence the amount of water released especially at low pressure heads. Figure 4.5 present water retention curves of topsoil for various surface soil conditions. The shapes of the curves at Kalalu and Mukogodo would be attributed to soil structure rather than texture since at each site the latter does not significantly differ among the topsoil of various land uses in each site to influence water retention characteristics. Therefore it can be argued that the degree of aggregation or compaction, which are manifested in bulk density (Table 4.5) and pore-size distribution (Table 4.11), determined the trend of water release from topsoil. From all the 3 sites, the graphs illustrate that both conventional tillage and overgrazing increased the amount of water held from -300 to -1500 cm. This is an indication that the increase in bulk density (compaction) does not only result in a decrease of total porosity, but also increases the proportion of finer pores which can hold water even at higher suctions. Mbagwu *et al.* (1984) reported that water retention at -100 cm suction for artificially desurfaced soils (to simulate erosion) was lower than for undisturbed soil for two alfisols and an ultisol in southern Nigeria. Reduction of total porosity was suggested to be the main cause rather than change in the distribution of various pore sizes.

All the 3 land uses at Karuri had high (60-65%) water content at saturation due to high total porosity (Table 4.11). The thick layer of litter and high organic matter content in the forest topsoil maintains a crumb granular structure which was reflected in low bulk density. On the other hand, cultivation (PC) and grazing (GL) have resulted in a decrease of 11% of topsoil total porosity.





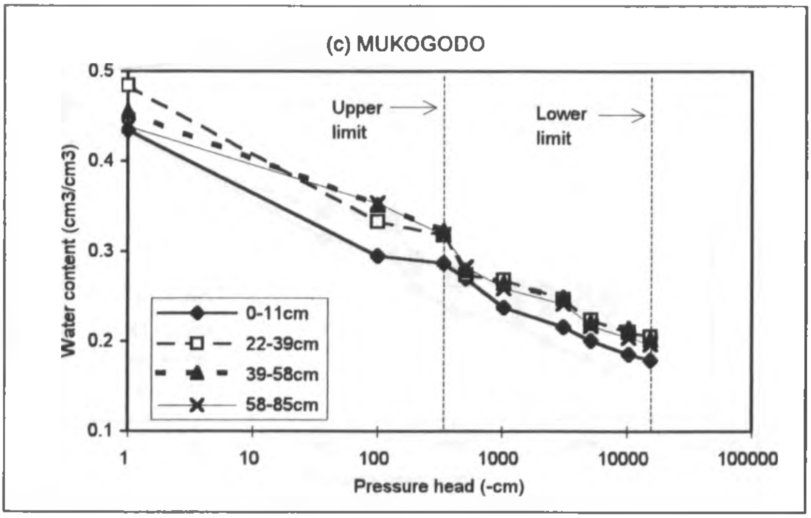
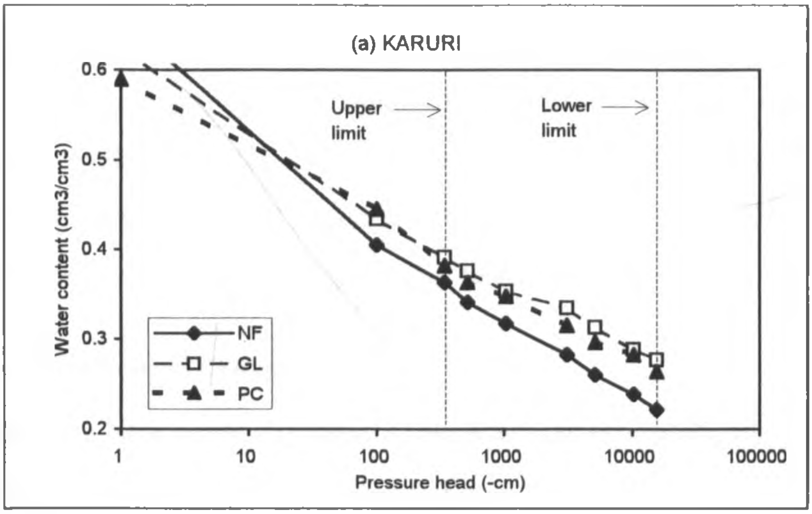
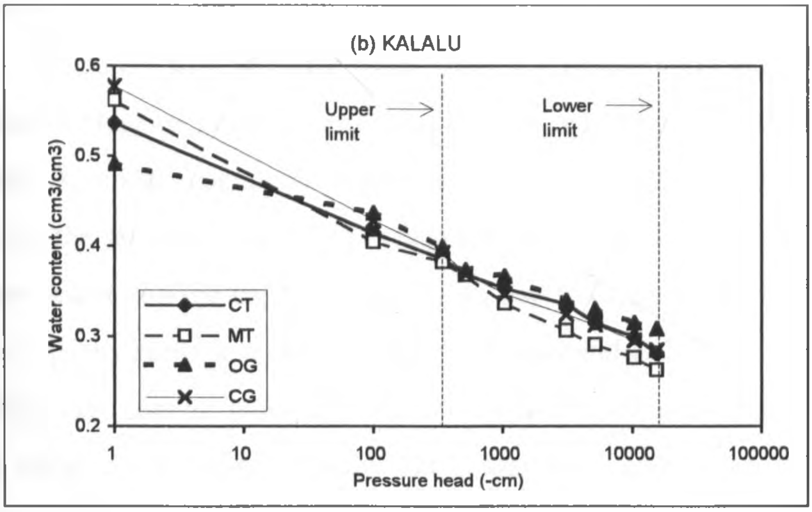


Figure 4.4 Soil profile horizons water retention characteristics. In each area a profile was opened on a site with good soil cover (a) Karuri (grass land) (b) Kalalu (grass land) and (c)Mukogodo (bush canopy).





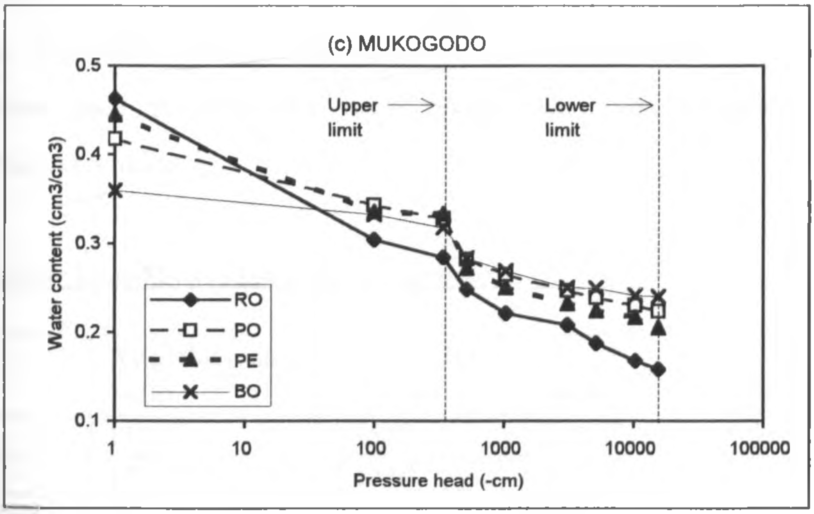


Figure 4.5 Topsoil (0-10 cm) water retention for different land uses at (a) Karuri (b) Kalalu and (c) Mukogodo.

Conservation tillage only marginally (4%) improved porosity at Kalalu. However, on grazing land, controlled grazing significantly increased (18%) total porosity. As was expected at Mukogodo, the bush canopy (RO) had the highest porosity while bare ground (BO) had the least. Comparing PO and PE values indicates that total surface porosity of grass sites is improving after protection from grazing.

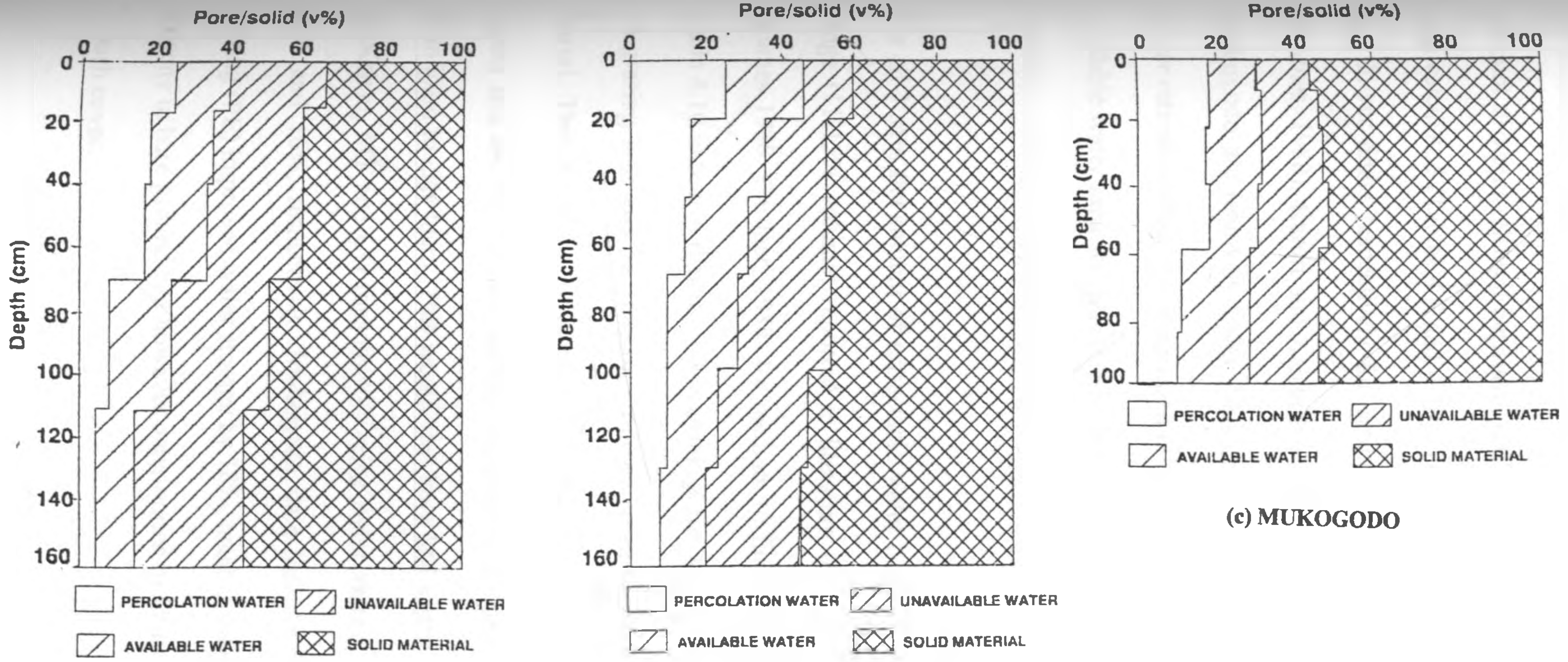
4.1.3.3 Available water capacity

Soil profile available water capacity (Table 4.8) was estimated using data obtained by a neutron probe (field measurement) for the upper limit and small cores (laboratory measurement) for the lower limit. A profile of 160 cm was considered for Karuri and Kalalu, while 80 cm was taken for Mukogodo due to limitation in soil depth. Kalalu soil profile had the highest potential for water storage, which was up to 271 mm for 160 cm soil depth. A similar magnitude of storage capacity (263 mm) was obtained by Liniger (1991a) for the same site. Figure 4.6 which was drawn based on these field measurements show how water storage capacity varies with depth for each soil. More than half of the moisture capacity is not available to plants at Karuri and Kalalu. This would be explained by the high clay content which favour formation of a structure with predominantly fine pores in which water is held strongly. The soil at Mukogodo has medium texture, thus a large proportion of water can be released to plants despite the relatively lower total porosity. High water storage capacity of soils at Karuri and Kalalu indicates that the two areas have high potential for crop production given adequate rain and proper conservation techniques.

Table 4.8 Soil profile available water capacity.

Site	Available water capacity (mm)[1]		
	0-80cm	81-160cm	Total
Karuri	116.2^b	96.0^a	212.2^b
Kalalu	150.8^a	120.0^a	270.8^a
Mukogodo	109.3^b	n.a.	109.3^c

[1] Each value is an arithmetic mean of 5 replicates. Means with the same letter superscript within each column are not significantly different at $p<.05$ using Duncan's Multiple Range Test.
n.a : not available due to limited soil depth



(a) KARURI

(b) KALALU

(c) MUKOGODO

Available water capacity for each profile horizon depth was estimated using data obtained by field measurement using a neutron probe for the upper limit and that obtained from small cores in the laboratory for the lower limit.

Figure 4.6 Water storage capacity variation with soil profile depth.
(Source of soil profile data for Kalalu and Mukogodo from Liniger (1991a) and Wanjogu (1992) respectively)

In evaluation of the capacity of the soil water reservoir using small core samples, the amount of water released between -300 and -15000 cm pressure heads for each horizon was calculated (Tables 4.9 and 4 10). These pressure heads are referred to as the upper and lower limits respectively for medium to fine textured soils (Ratliff et al., 1983; Gardner, 1988). Karuri and Kalalu have similar upper and lower limits, while those of Mukogodo are relatively lower. This can be explained by the textural differences. The water retention difference (expressed in mm) between the two limits, which indicates the available water capacity, was referred to as potential extractable water and is presented in the last columns of Tables 4.9 and 4.10.

For all 3 sites the amount of extractable water from each profile horizon was within the range (11-15% volume) reported in literature (e.g. Ratliff et al., 1983; Marshall and Holmes 1988; Gardner, 1988) for medium to fine textured soils. The data presented in Table 4.10 indicates that topsoil available water storage capacity had decreased by 19% on grazing land and by 16% on cropland when compared to that of natural forest at Karuri. This would be attributed to changes in structure due to reduction of organic matter and increase of bulk density. As already discussed, topsoil texture had changed from loam to clay loam. This would also have had appreciable effect on available water. At Kalalu, MT and CG topsoils had more water storage capacity than CT and OG by 12% and 16%, respectively. Mukogodo data indicate that protection of grass from grazing (PE) improved water storage by 18%, making it similar to that in bush cover. The capacity in bare ground had however deteriorated by almost 40% when compared to that in bush cover.

Table 4.9 The upper and lower limits of soil water availability in different horizons of soil profiles at Karuri, Kalalu and Mukogodo.

Site	Depth (cm)	Water content (cm^3cm^{-3})		Potential extractable water (mm 10 cm^{-1})[2]
		Upper limit (-300 cm)	Lower limit (-15000 cm)	
Karuri	0-18	0.3674[1]	0.2397	13.77
	18-72	0.3892	0.2716	11.76
	72-112	0.3924	0.2683	12.41
	112-160	0.3774	0.2641	11.33
Kalalu	0-23	0.3704	0.2533	11.71
	23-52	0.3935	0.2855	10.80
	52-71	0.4038	0.2979	10.59
	120-143	0.3995	0.2874	11.21
Mukogodo	0-11	0.2865	0.1789	10.76
	11-39	0.3178	0.2049	11.29
	39-58	0.3225	0.2019	12.06
	58-85	0.3181	0.1966	12.15

[1] Each value is an arithmetic mean of 5 replicates

[2] Calculated as difference in water content (expressed in mm 10cm^{-1}) between -300 and -15000 cm pressure heads from data obtained using soil cores of 100 cm^3 volume.

Table 4.10 The upper and lower limits of soil water availability in the topsoil (0-10 cm) for various land uses.

Site	Land use	Water content (cm^3cm^{-3})		Potential extractable water (mm 10 cm^{-1})[2]
		Upper limit (-300 cm)	Lower limit (-15000 cm)	
Karuri	NF	0.3633 [1]	0.2219	14.14^{a}
	GL	0.3917	0.2768	11.49^{b}
	PC	0.3827	0.2641	11.86^{b}
Kalalu	CT	0.3863	0.2813	10.50^{b}
	MT	0.3824	0.2627	11.97^{a}
	OG	0.3991	0.3082	9.09^{c}
	CG	0.3932	0.2846	10.86^{b}
Mukogodo	RO	0.2845	0.1581	12.64^{a}
	PO	0.3278	0.2233	10.45^{b}
	PE	0.3335	0.2048	12.87^{a}
	BO	0.3182	0.2396	7.86^{c}

[1] Each value is an arithmetic mean of 5 replicates.

[2] Calculated as difference in water content (expressed in mm 10^{-1} cm) between -300 and -15000 cm pressure heads from data obtained using soil cores of 100 cm^3 volume. Within each site, means with the same letter superscript are not significantly different at $p<0.05$ using Duncan's Multiple Range Test.

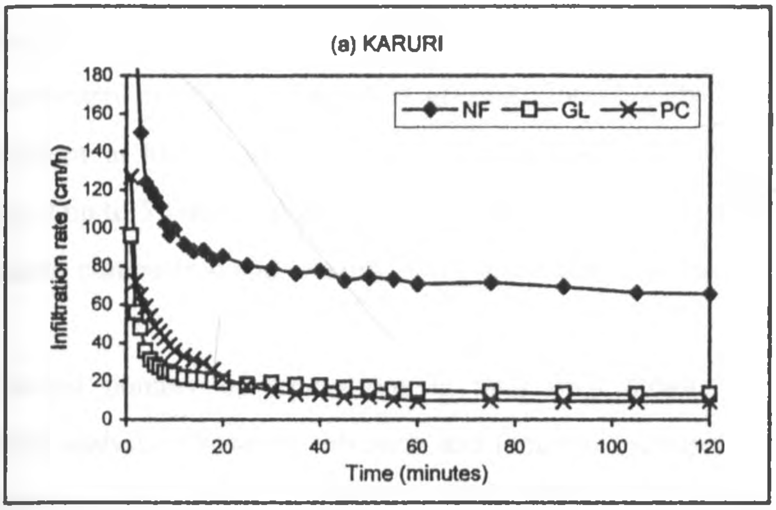
Analysis from a large sample of soils by Ratliff *et al.* (1983) indicated no significant difference between field measured (neutron probe) and laboratory estimated (small cores) potential extractable soil water for fine textured soils. However, the core method has disadvantages; there are high chances of obtaining unrepresentative cores during sampling, and there are inherent errors while processing. Therefore field measured data are usually preferred as a more accurate alternative if they are available (Ritchie, 1981; Ratliff *et al.*, 1983).

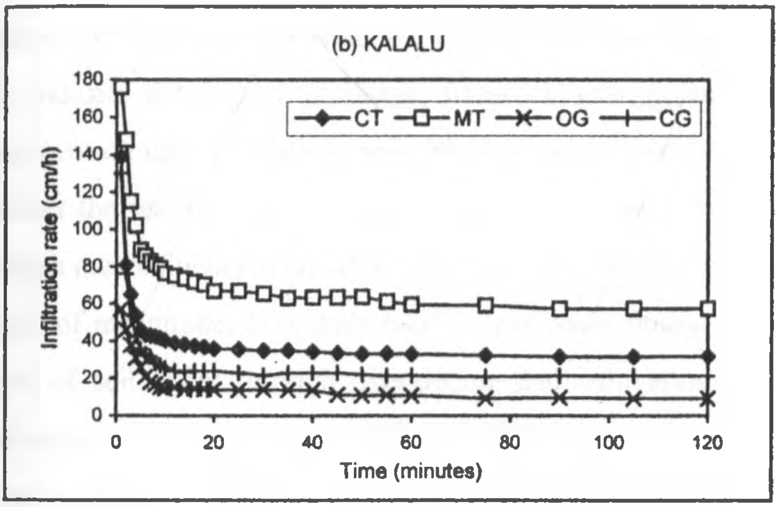
4.1.4 Soil water movement

4.1.4.1 Infiltration

Dry season infiltration rates measured using standard sets of double-ring infiltrometers (Bouwer, 1986) are presented in Figure 4.7. Infiltration tests were limited to 3 or 4 replicates per treatment due to logistics and requirement of a lot of water. Infiltration experiments were run for at least 2 hours, but in most cases infiltration tended to steady state within 30 to 60 minutes. Intake was extremely high at Karuri in the forest. Initial infiltration rates as high as 250 cm h^{-1} and final infiltration rates as high as 60 cm h^{-1} were obtained. Both cultivation and grazing after forest removal significantly reduced infiltration. Despite the good grass cover, intake was quite low in GL even at initial stages due to continuous livestock grazing and trampling. Initial intake was relatively high in PC, but it gradually decreased and became quite low at steady state stage. This is because tillage opens up the surface soil and lets water in freely at first, but the structure of bare soil is vulnerable as aggregates breakdown and sealing of the immediate surface occurs with marked reduction in the potential infiltration rate (Alegre *et al.*, 1986).

Infiltration rates at Kalalu were higher in MT than in CT. This indicates that the mulch cover protected topsoil from raindrop impact. Combined with reduced tillage, mulch cover maintained the structure of topsoil, thus the macroporosity that facilitates high water intake. In a study by Lal (1975) where higher infiltration rates were obtained under mulch compared to unmulched plots, the results were attributed to increased soil fauna





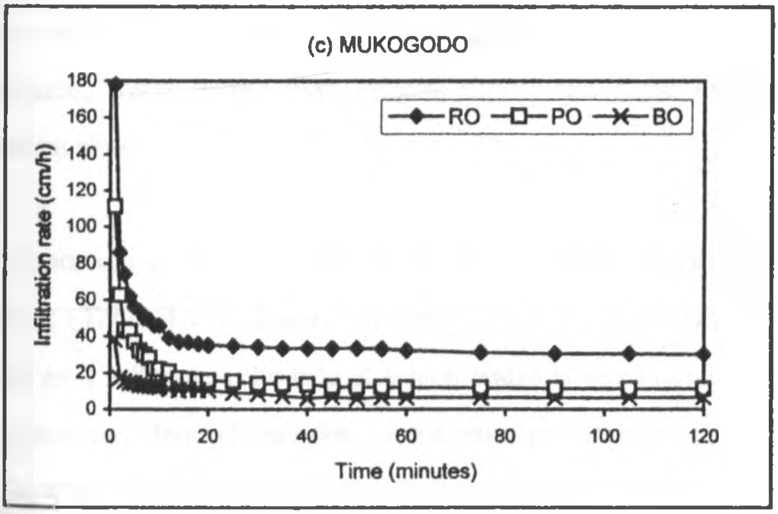


Figure 4.7 Infiltration rates using a double-ring infiltrometer.

activity due to surface mulch. As expected, lower intake rate was recorded in overgrazed plots compared to that in controlled grazing plots. Steady state infiltration rate under bush canopy at Mukogodo was about 3 times that measured on overgrazed grass site (PO), and up to 5 times that obtained on bare ground. This large decrease in water intake was due to compaction and crusting of topsoil in the latter two soil cover conditions.

The limited number of replications in infiltration measurements did not allow for statistical analysis. Thus only the mean and range of the steady state infiltration rates for each treatment are given in Table 4.11. Nevertheless, going by the order of magnitude of the numerical differences among the various land uses and management systems, the results indicate the impact of tillage, livestock grazing and topsoil or surface cover management on final infiltration rates. Measurements carried out using a double-ring may not reflect the real situation as during rain storms where the effects of raindrop impact and splash may influence infiltration. This not withstanding, the results give an indication, by order of magnitude, how soils take in rain water during a storm. Depletion or total removal of soil cover through overgrazing and cultivation had adverse effect on soil water intake. This would reduce plant available water due to increased surface runoff. A bare soil surface is prone to compaction and destruction of topsoil aggregates which greatly reduce water intake, whereas sites with adequate cover or minimum surface soil disturbance, water intake may remain almost the same as that obtained by ponding infiltration experiments.

The proportion of porosity that freely drains after saturation was computed for each treatment (Table 4.11). Topsoil drainable pore space plays a key role in the infiltration process as it influences the rate at which water is conducted from the surface. Drainable pore space can also indicate the contribution of macropores to total porosity. The term macropores is not used consistently in literature (Bouma, 1981a). However, according to Watson and Luxmoore (1986) and Messing (1993), macropores are functionally defined as those pores >0.5 mm diameter and transport water at potentials <-10 cm. At Mukogodo, for example, bush canopy topsoil had up to four times (43%) drainable pore space compared to that of bare ground (11%); while on sites excluded from livestock grazing it improved from 24 to 34%. Mulch tillage at Kalalu also increased macroporosity. Similar observations were reported by Cresswell *et al.* (1991) at Canberra, Australia; where low intensity tillage resulted in high volume of macropores. Regression analysis of data in Table 4.11 indicate significant relationship between drainable pore space and initial (r^2=0.80) and steady state (r^2=0.56) infiltration rates. The stronger correlation between initial infiltration rate and drainable pore space shows the importance of the latter and the bigger role it plays in the early stages of infiltration process. Also since most of the drainable pore space is constituted of macropores, then the former can be used as an index to reflect the macroporosity of a given soil.

Raindrops were intercepted by the trees' canopy and underground litter in Karuri forest. The protected soil maintained high infiltration because of high porosity and dominance of macropores in the topsoil. Since the forest topsoil had high infiltration capacity, most of the rainwater infiltrated to replenish soil water and subsequently recharge ground water.

Table 4.11 Porosity of topsoil (0-10 cm) and infiltration rates for various land uses.

Site	Land use	Total porosity (cm^3/cm^3)[1]	Drainable pore space, *DS* (cm^3/cm^3)[2]	Proportion of *DS* (%)	Initial infiltration rate (cm/h)[3]	Steady state infiltration rate (cm/h)[3]
Karuri	NF	0.66	0.25	38	252 (119-406)	65.7 (44.2-81.6)
	GL	0.59	0.16	27	96 (78-115)	13.4 (7.3-18.4)
	PC	0.59	0.11	19	127 (103-144)	9.7 (4.6-16.0)
Kalalu	CT	0.54	0.12	22	139 (93-162)	31.9 (26.5-41.4)
	MT	0.56	0.16	29	176 (121-212)	57.3 (30.1-62.6)
	OG	0.49	0.07	14	57 (37-70)	9.3 (5.6-13.3)
	CG	0.58	0.18	31	130 (84-173)	21.3 (14.4-30.9)
Mukogodo	RO	0.46	0.20	43	178 (132-294)	29.8 (17.8-42.0)
	PO	0.42	0.10	24	111 (66-184)	10.8 (6.5-16.2)
	PE	0.44	0.15	34	n.a.	n.a.
	BO	0.36	0.04	11	38 (26-48)	6.3 (2.7-9.4)

[1] Total pore space calculated from bulk and particle densities. Each value is arithmetic mean of 5 replicates.

[2] Total porosity minus volumetric water content at pressure head of –100 cm (100 cm^3 core samples)

[3] Double ring infiltrometer, size of 30 cm and 60 cm for inner and outer ring, respectively. Means of 3 to 4 replicates and values in brackets are the range. No tests were carried out in PE because it would have interfered with soil moisture monitoring within the limited plot size.

Results from Karuri PC indicate that cultivation reduced infiltration compared to that in forest. But the amount of water infiltrating into soil can be increased by ponding on the surface as was demonstrated by newly cultivated plots in PC which had rough surface. Depressions provided temporary storage of water during rainstorms. On the other hand, mulch tillage at Kalalu, by reducing water flow provided opportunity for infiltration just like the rough surface at Karuri.

4.1.4.2 Saturated hydraulic conductivity

Once the upper layer of the soil attains moisture above *FC*, downward transport begins and from this time it is no longer the infiltration capacity which dominates, but the rate at which the water is moved away (conducted) from the surface layer. Saturated hydraulic conductivities, K_s, measured in the laboratory using small soil cores were highly variable within treatments (Table 4.12). This was not unique as K_s is a parameter reported to have high variation (Warrick and Nielsen, 1980). At Karuri, conductivity in the forest decreased rapidly down the profile. In contrast, that in grazing land and cropland had similar values in the second and third layers. Water flow through the surface layer has decreased by 3 to 5 times after forest removal for livestock grazing or crop production.

Table 4.12 Saturated hydraulic conductivity of three soil layers under various land uses.

Site	Land use	Saturated hydraulic conductivity (cm h^{-1})[1]		
		0-10 cm	20-30 cm	40-50 cm
Karuri	NF	19.03 (7.92-47.44)[2]	6.00 (2.19-13.45)	2.69 (0.86-7.10)
	GL	4.57 (1.46-17.27)	2.50 (0.69-7.07)	2.24 (0.17-8.91)
	PC	7.23 (2.61-13.72)	2.05 (0.57-8.00)	1.70 (0.26-11.96)
Kalalu	CT	2.27 (1.08-3.59)	0.95 (0.07-6.18)	1.48 (0.95-6.16)
	MT	4.87 (2.21-11.05)	1.79 (0.08-10.56)	1.82 (1.09-5.33)
	OG	1.35 (0.47-5.12)	2.65 (0.77-9.81)	1.11 (0.04-7.37)
	CG	9.93 (5.07-22.56)	2.75 (0.74-8.33)	2.16 (0.53-11.17)
Mukogodo	RO	11.59 (5.66-37.63)	5.11 (1.72-12.06)	2.50 (0.59-11.43)
	PO	5.24 (1.39-11.26)	2.63 (0.78-7.34)	1.84 (0.38-7.14)
	PE	9.31 (4.48-16.37)	3.08 (1.19-8.35)	2.36 (0.56-8.09)
	BO	0.60 (0.18-1.20)	1.55 (0.48-6.41)	1.73 (0.69-4.22)

[1] Measurements on soil cores of 100 cm^3 volume

[2] Each value is geometric mean from 5 replicates and values in brackets are the range

Conductivity was significantly higher ($P<0.05$) in the surface layers of MT and CG compared with that of CT and OG. Water flow in mulch tillage was about twice that of conventional tillage; while on grazing land, controlled use had resulted in up to 7 times more water flow compared to overgrazing. In CT treatment, water flow through the second layer was much slower compared to that of the third layer. This would be due to formation of a compacted section within the depth of the second layer. Occurrence of a compacted section just below the plough layer is expected after several years of cultivation (Cresswell *et al.*, 1991; Messing and Jarvis, 1993). However, on grazing land compaction takes place on the surface layer due to continuous livestock trampling. Therefore water flow was much slower through OG surface layer. This explains why high runoff is generated from the overgrazed plots.

Though the conductivity values in Table 4.9 for Mukogodo were obtained from one soil unit according to Wanjogu (1992), they are closely similar to those that were sampled from several soil units in the entire catchment (Kironchi, 1992). Basically, the difference in water flow among the 4 treatments was in the surface layer. The values indicate that water movement through the surface layer with some vegetation cover was 10 to 20 times more compared to that of bare ground. After exclusion from grazing (PE) for 4 rainy seasons conductivity has almost doubled. Conductivity in PE increased to a value comparable to that obtained under the bush canopy. Due to improvement in water flow, it was expected that runoff generated from this treatment would decrease. Results presented in section 4.2.4 show that runoff decreased by up to 4 times when compared to that generated from PO. In this rangeland obvious signs of degradation were crusting and reduction of soil depth due to erosion. However, on protection from heavy grazing, soil exposure was reduced as vegetation cover increased and macroporosity improved. Numerous termite channels in the topsoil under good vegetation cover were clear evidence. Therefore, apart from the protection against rainfall energy, soil cover and management system improve soil structure, which in turn enhances water intake and movement.

Statistical analysis for all 3 sites indicate that the treatments with high saturated hydraulic conductivity had also much higher variance. This was also true for the surface layer values. Given that most water flow occurs through macropores as discussed in section 4.1.3.1, it indicates that most of this variation was contributed by the high variation in occurrence and distribution of the macropores. *K* is a parameter for which appropriate values are difficult to obtain with accuracy due to its extreme sensitivity to variability in the large pore system (Germann and Beven, 1981) and due to constraints such as air entrapment and sealing of pores during the course of the experiment (Messing, 1993). The water conducting pore space which characterizes individual soil horizons, such as termite channels and textural pores vary in space. A question is whether the small cores (100 cm^3) used to obtain the data above can adequately represent this spatial variation. It would be assumed that the smaller pores in the soils were appropriately represented in the 'standard' small cores with the 5 replicates. However, macropores which are critical for rapid redistribution of water in soil during rainfall may occur less frequently and may be less well represented leading to underestimation of K_s. On the other hand, if present in the core sample, macropores may contribute more to the flow than they actually do in the field due to truncation of otherwise dead-end large pores (Bouma, 1981b). Therefore the size of cores should be larger in order to account for the totality of the macropore system.

Comparing K_s of small cores with those of large monoliths, Messing (1993) found that small core data were correlated with the intact monolith data although the small cores had smaller values. It was also observed that small cores can satisfactorily predict hydraulic properties for a natural soil at pressure heads smaller than –5 cm, but they may be in error, especially in soils with macropores, in the pressure head range –5 cm to saturation. However, Messing (1993) concluded that K_s measured on small cores may well be treated in a relative manner to describe differences in soil structure between soil types and alternative land management systems, but may be in error in absolute terms.

4.2 RAINFALL AND EVAPORATION

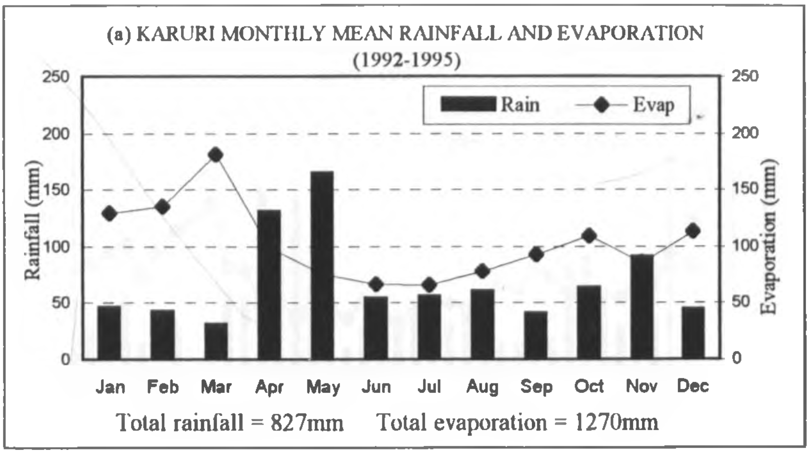
4.2.1 Rainfall characteristics

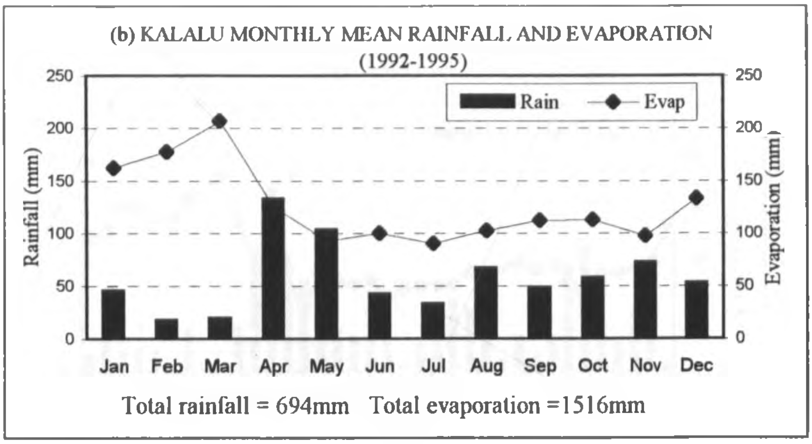
Rainfall and evaporation characteristics presented in this study are from records of 4 years, that is from 1992 to 1995. The climatic seasons were divided into six month intervals, each covering a rainy season; the long rains (LR) from March to August and short rains (SR) from September to February of the following year. Therefore within the study period six rainy seasons, 3 each for LR and SR were sampled.

4.2.1.1 Variability in amount

Figure 4.8 presents the amount and distribution of rainfall for the 3 sites during the period of study. The mean annual rainfall was 827, 694 and 335 mm for Karuri, Kalalu and Mukogodo respectively. Unlike Karuri, Kalalu and Mukogodo stations which were started earlier have more than four years of records. The 10 and 7 years means available for Kalalu (736 mm) and Mukogodo (359 mm) respectively were close to the study period means. All the 3 areas have two main peaks in annual rainfall distribution in April/May and October/November. Kalalu has a third distinct peak in August due to continental rains. Monthly and annual totals presented in Appendix A7 indicate that rainfall is very variable in all sites.

Examining the long rains and short rains seasons data in Table 4.13, it is clear that the amount of rainfall received in the LR is slightly higher than that received in the SR season at all sites. From means of 3 seasons each, the LR contribute 61, 63 and 56% of the total annual rainfall at Karuri, Kalalu and Mukogodo respectively. Variation in amount of rainfall within seasons is higher in SR than in LR at all sites. This suggests that the LR are relatively more reliable. In all sites approximately 20% of the total annual rainfall is received in the wettest month of the year while about a third (29-36%) of this rainfall comes in the months of April and May (Table 4.14). At least 50% of the rain, even in Kalalu where a third rainy season exists, is received in the 4 wettest months.





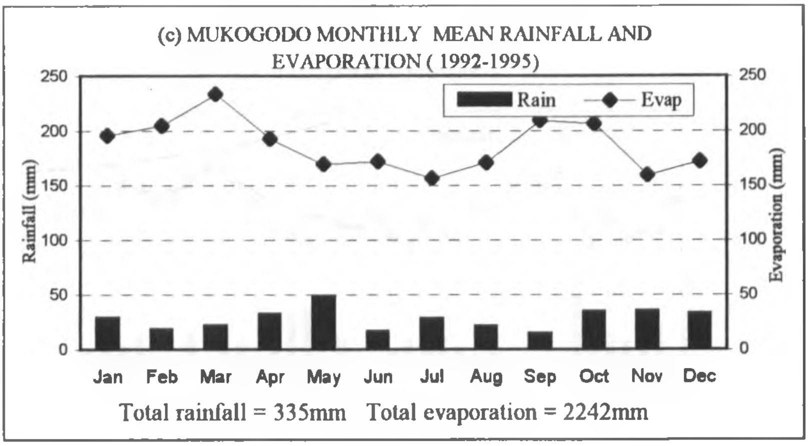
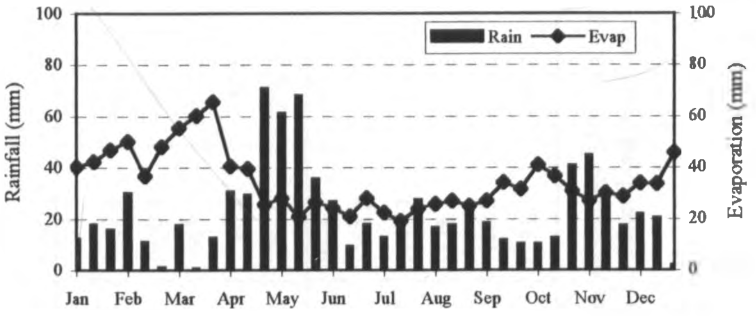
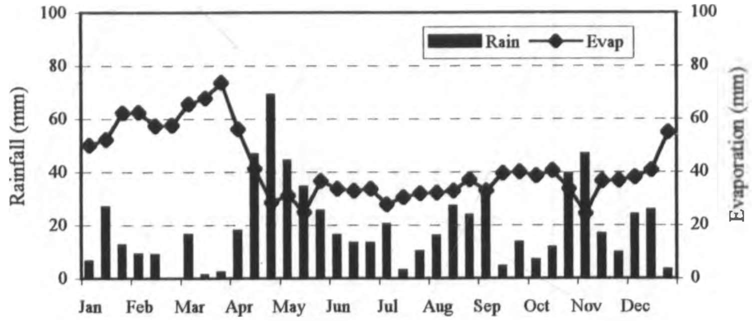


Figure 4.8 Mean monthly rainfall and pan evaporation.


(a) KARURI DECADE MEAN RAINFALL AND EVAPORATION (1992-1995)


(b) KALALU DECADE MEAN RAINFALL AND EVAPORATION (1992-1995)

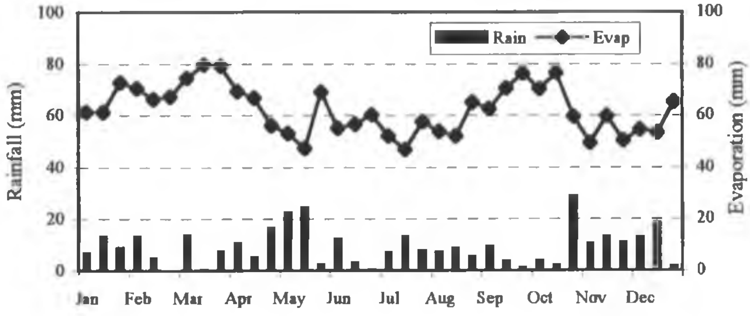

(c) MUKOGODO DECADE MEAN RAINFALL AND EVAPORATION (1992-1995)

Figure 4.9 Mean decade rainfall and pan evaporation

Table 4.13 Seasonal amount of rainfall and pan evaporation (1992-1995).

Season	Period	Karuri			Kalalu			Mukogodo		
		Rain, P (mm)	Evap., E (mm)	P-E (mm)	Rain, P (mm)	Evap., E (mm)	P-E (mm)	Rain, P (mm)	Evap., E (mm)	P-E (mm)
LR1	Mar93-Aug93	384.3	614.6	-230.3	290.0	711.0	-420.4	136.8	1053.6	-916.8
LR2	Mar94-Aug94	652.7	595.7	57.0	489.2	701.0	-211.8	224.1	1087.1	-863.0
LR3	Mar95-Aug95	466.0	602.1	-136.1	537.4	638.9	-101.5	205.6	1050.3	-844.7
LR Mean	1992-95	501.0	604.1	-103.1	439.1	683.6	-244.6	188.8	1063.7	-874.9
LR SD	1992-95	137.6	9.6	146.5	130.8	39.1	162.0	146.0	20.4	37.5
LT Mean	*	n.a	n.a	n.a	461.6	724.7	-263.1	186.5	1084.9	-898.4
SR1	Sep92-Feb93	371.9	585.5	-213.6	388.6	673.5	-284.9	251.1	1012.9	-761.8
SR2	Sep93-Feb94	196.4	737.7	-541.3	204.7	873.6	-668.9	56.1	1253.2	-1197.1
SR3	Sep94-Feb95	375.4	672.4	-297.0	282.7	769.3	-486.6	193.3	1148.3	-955.0
SR Mean	1992-95	314.6	665.2	-350.4	292.0	772.1	-480.1	166.8	1138.1	-971.3
SR SD	1992-95	102.4	76.4	170.5	92.3	100.0	192.1	100.2	120.5	218.1
LT Mean	*	n.a.	n.a	n.a	275.8	851.4	-575.6	136.3	1131.0	-994.7

LR1, LR2 and LR3: First, second and third long rains season; LR Mean and LR SD are long rains mean and standard deviation respectively. SR1, SR2 and SR3: First, second and third short rains season; SR Mean and SR SD are short rains mean and standard deviation respectively. LT Mean: Long term mean, Kalalu *(1986-95) and Mukogodo *(1989-95), n.a : no long term records available

Table 4.14 Rainfall and evaporation characteristics at Karuri, Kalalu and Mukogodo.

Characteristic	Karuri	Kalalu	Mukogodo
Max. monthly rainfall/annual rainfall	0.20	0.19	0.18
Apr/May rainfall/annual rainfall (a)	0.36	0.32	0.29
Oct/Nov rainfall/annual rainfall (b)	0.19	0.18	0.25
a + b	0.55	0.50	0.54
Number of months rainfall exceeds evaporation	3	2	0
Number of months rainfall exceeds 80% evaporation	5	2	0
Number of months rainfall exceeds 50% evaporation	7	6	0
Annual rainfall/annual evaporation	0.65	0.47	0.16

Figure 4.9 illustrates decades mean rainfall amounts. The distribution pattern is very similar to that of monthly means. It requires a plot of single storms to get a true picture of the magnitude and spread of rainfall within a given period as illustrated by the daily data presented in Figures 4.24-4.26. The bulk of the 50-60% rainfall which is received in the 4 wettest months of the year falls in a few heavy storms in these months. Concentration of rainfall in short periods, typical of East Africa (Jackson, 1977) is therefore apparent in the study area. Thus averages *per se* are of little value, especially for crop production where such poor distribution in the season may have big impact on yield.

4.2.1.2 Variability in intensity

The marked seasonality of rainfall discussed above exerts an overall control on water availability whilst the variability imposes uncertainty. The characteristics of individual rainstorms often get overlooked, but, they are equally important. These include intensity, duration and frequency of occurrence. From two LR and two SR seasons, covering the period September 1993 to August 1995 rainfall intensities were analysed at 15 minutes intervals (I_{15}). Results presented in Figure 4.10 indicate that generally a large proportion of rainfall in all sites occur in storms of low intensity.

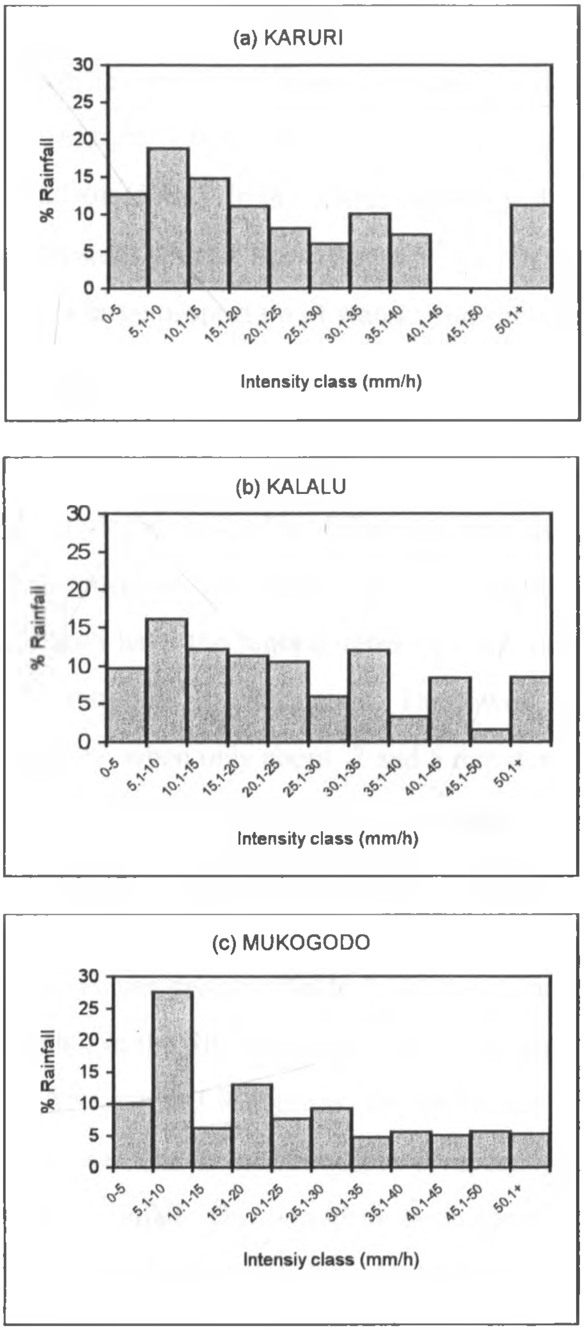


Figure 4.10 Proportion of rainfall in various intensity (I_{15}) classes.

At Karuri, Kalalu and Mukogodo, respectively, 35, 40 and 36% of the rainfall occurs at intensities of at least 25 mm h^{-1}, a figure considered a threshold level at which rainfall becomes erosive (Hudson, 1981). These compare well with a figure of 40 % for the tropics given by Hudson (1981). In the 3 sites within the 4 rainy seasons, 5 to 11% of the rainfall fell with intensities greater than 50 mm h^{-1}. Given that most large storms come in high intensities then a large proportion of water from such storms may be lost as runoff.

4.2.2 Potential evaporation

The mean monthly evaporation for a period of 4 years is presented together with rainfall in Figure 4.8. Although there is a big difference between the 3 sites in terms of total annual amount of evaporation, they have a similar trend throughout the year. The months of February and March have the highest rates of evaporation, which range from 6 mm day^{-1} at Karuri to 8 mm day^{-1} at Mukogodo. The lowest evaporation is recorded in the months of June and July, when only about 2 and 5 mm day^{-1} of water is lost at Karuri and Mukogodo respectively. Computing annual averages from all data available, evaporation of 3.5, 4.3 and 6.2 mm day^{-1} are obtained for Karuri, Kalalu and Mukogodo respectively.

Seasonal evaporation values given in Table 4.13 show that evaporation from each of the 3 sites is slightly higher in the SR than in the LR. It can also be observed the evaporation is more variable in SR than in LR seasons. Decade mean daily evaporation (Figure 4.9) values give a similar trend like the monthly data. Evaporation is much more constant from season to season than rainfall. This would be because of the small variation in the key factors influencing it, such as solar radiation. Nevertheless, the variations recorded reflect variations in temperature, humidity, wind speed and cloud cover in the 3 areas.

In plant water use, the driving force for root water extraction is the evaporative demand exerted by the atmosphere to the plant canopy. Most crop models use the concept of potential evapotranspiration (*ET*) as a measure of evaporative demand. This demand is satisfied by both soil and canopy evaporation. Estimation techniques, for example the Penman method, use daily meteorological variables (i.e. air temperature, wind speed, relative humidity and sunshine duration). The accuracy and precision with which potential evaporation can be determined using assumptions and approximations inherent in this technique, given that data is available, is one of the more unsatisfactory aspects of estimating crop water use (McCown and Williams, 1989). Ritchie (1991) discusses the relative merits and drawbacks of estimating evaporative demand, and argue that pan evaporation, with all its problems appears to be no less reliable than some of the meteorological equations which have, in common with pan estimates, a requirement for local calibration.

It is worth noting that some current models such as NTRM (Shaffer and Larson, 1987) and PARCH (Bradley and Crout, 1993) use pan evaporation as their empirical measure of evaporative demand. In this study pan evaporation is used as an estimate of evaporative demand. Some stations within the study area have all the data required to compute *ET*. Therefore it is worthwhile to compare the calculated *ET* with pan data (*Ep*) to find out how they relate in the study area. Table 4.15 presents *ET/Ep* ratios for 2 stations. From graphs drawn, it was observed that for each area, the year can be divided into two distinct periods. However, overall average annual values indicate that *Ep* is very similar to *ET*. Njeru (1995) computed *ET/Ep* ratios for Gate and Munyaka stations along the Naro Moru profile. Higher values were obtained during the rainy season (1.4 and 1.1) compared to the dry season (1.0 and 0.8) for the lower forest (Gate) and footzone (Munyaka) respectively. Based on the above findings, it can be concluded that *Ep* gives similar values as *ET* in the study area, therefore the former can be satisfactorily used as an estimate of evaporative demand.

Table 4.15 Ratios of Penman potential evapotranspiration (*ET*) to pan evaporation (*Ep*).

Site	Period	*ET/Ep*
Embori	November-June	0.89
	July-October	1.15
	January-December	0.98
Kalalu	November-April	0.94
	May-October	1.20
	January-December	1.07

Source: NRM^3 Database

4.2.3 Water deficit and water surplus

4.2.3.1 Annual and seasonal status

The climatic water balance is calculated as the difference between water input (rainfall) and output (potential evaporation). The ratios of total annual rainfall to total annual evaporation given in Table 4.14 indicate that evaporation is approximately 1½ times more than rainfall at Karuri, 2 times more at Kalalu and 6 times more at Mukogodo. This implies that at Kalalu, atmosheric water demand is about twice that which the rainfall can supply while at Mukogodo it is more than six times. Seasonal rainfall and evaporation data presented in Table 4.13 show that all sites in both LR and SR have a negative water balance. In all cases the SR have a larger deficit than the LR. For example, looking at mean values, Karuri SR deficit is approximately 3 times that in the LR while for Kalalu SR is more than twice that in the LR. It should also be noted that the study period deficits at Kalalu and Mukogodo were similar to those of the long term records.

4.2.3.2 Monthly and decadal status

The seasonal nature of rainfall means that at certain times of the year water supply may be adequate, but not at others. Figure 4.8 shows that rainfall is less than evaporation in all months of the year except in April, May and November at Karuri, and only April and May at Kalalu. Evaporation exceeds rainfall throughout the year at Mukogodo. The decade values give a similar trend as monthly values (Figure 4.9). This is because the decades that have a positive balance are those within the months which have also a favourable balance.

4.2.3.3 Daily status

Examination of daily rainfall data reveals amount and distribution of single storms while evaporation data presents the atmospheric demand for moisture and how it varies with time. Even in rainy seasons, considerable day-to-day variations occur as illustrated by Figures 4.24, 4.25 and 4.26 for Karuri, Kalalu, and Mukogodo respectively. The pattern is irregular with marked surplus or deficit depending on the size of storms, their frequency and distribution. Dry spells do occur even in the rainy months and wet spells are found in the relatively dry months. Much of the rain is however concentrated in short periods with a few days of heavy storms. In days when rainfall events occur, evaporation is drastically reduced.

Evaporation gives an estimate of plant water requirement while rainfall provides an estimate of plant water availability. Therefore variability on a day-to-day basis and for periods less than a month is critical to plant growth, particularly in the early part of the rainy season before soil moisture reserves have been built up. When rainfall exceeds actual evaporation, soil moisture reserves are recharged and this is especially important for cropland. At Karuri there is surplus rainfall for reasonable periods within the rainy seasons owing to low evaporation. With several days in the months of April and May having water surplus, soil moisture gets recharged to capacity (section 4.1.3.1) and at this time drainage beyond the rooting zone is possible.

At Kalalu, the short rainy seasons provide 1-2 months when rainfall exceeds potential evaporation, allowing some soil moisture recharge followed by utilisation in succeeding months when, however, the deficit is still marked. Concentration of rainfall in such short seasons in the growing period is a major constrain as at least rains spread in 4 months are required to mature a maize crop. Cultivation technologies or management systems that would facilitate storage in surplus times to be used at deficit times are therefore recommended in Kalalu.

At Mukogodo rainfall at all times, except a few days in the rainy seasons, is less than the potential evaporation. Because of high evaporative demand, light showers are ineffective as they wet only the surface layer of the soil and evaporate quickly, contributing little to soil moisture build up or plant growth. On the other hand, most water from heavy storms is lost as runoff due to limited infiltration. The key to water conservation in this area is that adequate soil cover should be established and maintained to enhance infiltration (Liniger and Thomas, 1998).

The onset and end of rainy season as well as the rainfall characteristics (intensity, duration and frequency) are of great importance for agriculture. Effective rainfall in agricultural terms is that entering the soil and remaining within the root zone. Large storms of high intensity result in considerable loss as surface runoff (Kalalu and Mukogodo) and as drainage beyond the root zone (Karuri). The few heavy storms that supply most of the rainfall are significant not only because much of their total can be ineffective, but also because they are few in number, there are time intervals when the soil dries out and plants suffer water stress (Kalalu and Mukogodo).

High intensity rainfall results in water excess of the soil infiltration capacity. This leads to surface runoff and soil erosion. At the beginning of the rainy season, the soil is bare on crop land. Rain drops break soil aggregates, degrade structure and cause surface sealing and crusting, thus reducing infiltration and subsequently little build up of soil moisture. However, it is also the relation between rainfall and evaporative demand which is important in these semi-arid areas. Like at Kalalu, most rainfall is received in early part of growing season, but higher crop water requirements come later in the season. As shown by Liniger (1991a), this makes water the most limiting factor in production as shortage at critical stages like tasseling and grain filling may lead to total crop failure.

Climatic factors create an evaporative demand of the atmosphere, but the actual evaporation is influenced by the nature of the evaporating surface as well as the availability of water. Therefore in arid and semi arid areas (like the study area), actual evaporation (water use) is often considerably less than the potential value because water is not always available. Also, it is not the rainfall as such which supplies the needs of the plants but soil water. The complexities of this supply system have already been discussed in section 4.1.3.3. Due to the complexity of the atmosphere-soil-plant water system, from agricultural point of view, comparison of rainfall and evaporation is therefore only a crude indication of the potential of an area.

Soil surface conditions play a big role not only in partitioning rainfall into infiltration and runoff; but also in determining how much is lost as direct evaporation or used in transpiration. The latter depends on vegetative cover. Using a lysimeter at Muguga to assess soil water storage, Mugah and Stewart (1986) found that on bare fallow evaporation responds more readily to rainfall, rising markedly when the soil is wetted and dropping sharply after cessation of the rainy season or interval. The proportion of rainfall that went into evaporation varied markedly with the previous soil moisture status. It was higher when the soil was initially dry and lower when the soil was initially wet. This was so because when the soil is dry, a higher proportion of rainfall would be retained in the upper soil layers from where it evaporates more readily. For a wet soil, a higher proportion would infiltrate deeper into the soil (as the capacity of the upper soil to hold more water would be reduced) from where it would not readily evaporate. Therefore there would be scope in water conservation using mulch and minimum tillage at Kalalu if any moisture stored during the short rains when the plots are under fallow is preserved by application of surface cover and cutting the weeds to reduce transpiration.

4.3 SURFACE RUNOFF

4.3.1 Runoff water loss

Runoff water loss reported here for the 3 sites is from data collected for two long rains (LR) and two short rains (SR) seasons. The period covered is from the start of SR in 1993/94 to the end of LR in 1995, that is, September 1993 up to August 1995. Most of the runoff generating storms were concentrated in the months of April/May and October/ November. Total and percent runoff for this period is presented for each season in Tables 4.16 to 4.18 for Karuri, Kalalu and Mukogodo respectively. The amount of runoff varied from season to season over the study period depending on the amount of rainfall.

Even though the total mean runoff from cropland was about 4 times that produced from grazing land at Karuri (Figure 4.11), both land uses produced low runoff (i.e. less than 10% of the rainfall) than expected. On cropland this was due to surface configuration. The small furrows that are cut across the slope for potato seed placement at planting time

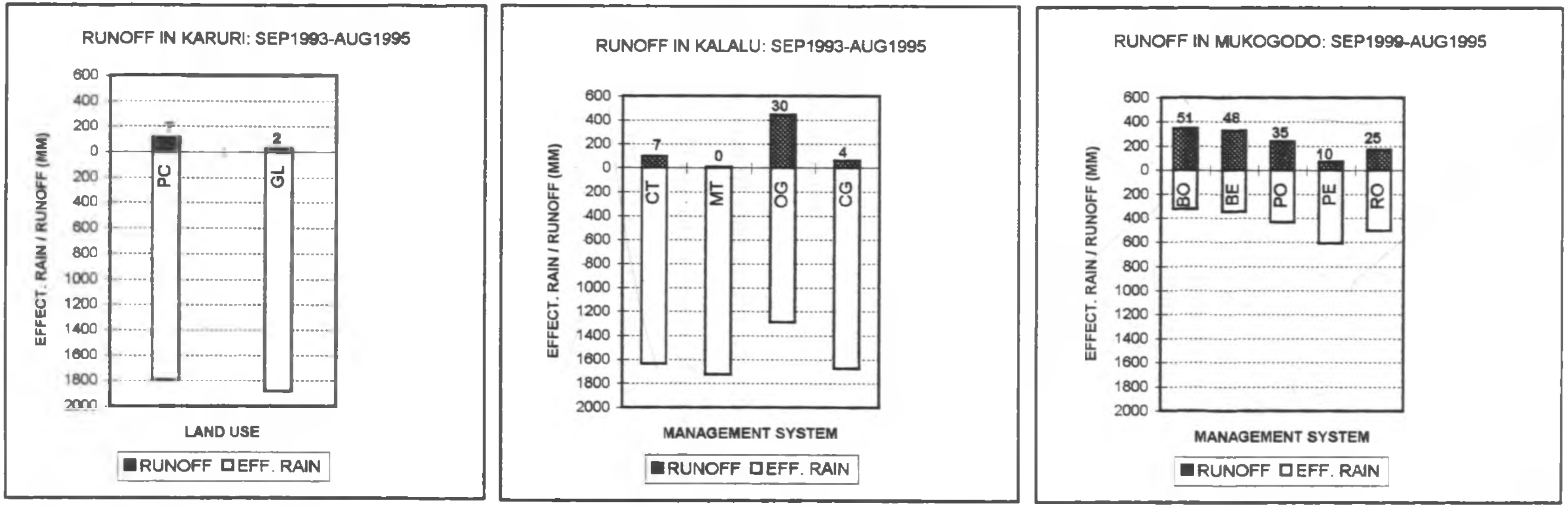


Figure 4.11 Runoff and effective rainfall from various land uses and management systems over a period of four rain seasons (September 1993-August 1995)

Table 4.16 Runoff from two land uses at Karuri over a period of four rainy seasons between September 1993 and August 1995.

Season	Rainfall (mm)	Parameter	PC	GL
SR 1993/94 (Sep93-Feb94)	196.4[1]	No. of storms[2] Runoff (mm) Runoff (% rain)	5 6.9 3.5	4 3.4 1.7
LR 1994 (Mar94-Aug94)	652.7	No. of storms Runoff (mm) Runoff (% rain)	20 76.6 11.7	19 14.8 2.3
TOTAL (Sep93-Aug94)	849.1	No. of storms Runoff (mm) Runoff (% rain)	25 83.5 15.2	23 18.2 4.0
SR 1994/95 (Sep94-Feb95)	375.4	No. of storms Runoff (mm) Runoff (% rain)	8 2.2 0.006	5 1.1 0.003
LR 1995 (Mar95-Aug95)	466.0	No. of storms Runoff (mm) Runoff (% rain)	13 26.6 5.7	11 7.3 1.6
TOTAL (Sep94-Aug95)	841.4	No. of storms Runoff (mm) Runoff (% rain)	21 28.8 5.71	16 8.4 1.6
TOTAL (Sep93-Aug95)	1690.5	No. of storms Runoff (mm) Runoff (% rain)	46 112.3 6.6	39 26.5 1.6

[1] Total rainfall for storms ≥5 mm
[2] Number of storms producing runoff

intercept most of the runoff that could have been generated by the storms in the early part of a rainy season. Therefore most of the rainfall, even from storms ≥ 20 mm day^{-1}, was able to infiltrate. Despite continuous grazing in GL, the grass cover was over 80% throughout the year. This provided favourable conditions for high infiltration.

For the 4 rainy seasons at Kalalu mean runoff from CT was less than 10% while it was negligible from MT plots (Table 4.17 and Figure 4.11). At Kumasi, Ghana, Mensa-Bonsuh and Obeng (1979), comparing bare fallow and mulched plots, found that mulching reduced runoff by between 11 and 35 times. Close examination of records reveal that runoff was higher from CT at onset of rains when cover was still low. At such times single storms would produce up to 30% runoff. It is nevertheless evident that overall runoff from cropland is relatively low. This would be attributed to the gentle slope of the land. Within the same locality, Liniger (1991a) reported that runoff from conventionally tilled land was 6 and 10% of the rainfall for 5 and 20% slope, respectively,

Table 4.17 Runoff from four management systems at Kalalu over a period of four rainy seasons between September 1993 and August 1995.

Season	Rainfall (mm)	Parameter	CT	MT	OG	CG
SR 1993/94 (Sep93-Feb94)	204.7[1]	No. of storms[2]	2	0	7	0
		Runoff (mm)	6.3	0	32.7	0
		Runoff (% rain)	3.1	0	16.0	0
LR 1994 (Mar94-Aug94)	489.2	No. of storms	9	2	22	11
		Runoff (mm)	20.9	3.0	178.0	24.2
		Runoff (% rain)	4.3	0.6	36.4	5.0
TOTAL (Sep93-Aug94)	693.9	No. of storms	11	2	29	11
		Runoff (mm)	27.2	3.0	210.7	24.2
		Runoff (% rain)	7.4	0.6	52.4	5.0
SR 1994/95 (Sep94-Feb95)	282.7	No. of storms	4	1	8	3
		Runoff (mm)	12.9	0.7	57.8	9.0
		Runoff (% rain)	4.5	0.2	20.4	3.2
LR 1995 (Mar95-Aug95)	537.4	No. of storms	9	2	16	6
		Runoff (mm)	59.4	4.2	185.2	27.0
		Runoff (% rain)	11.1	0.8	34.5	0.05
TOTAL (Sep94-Aug95)	820.1	No. of storms	13	3	24	9
		Runoff (mm)	72.3	4.9	243.0	36.0
		Runoff (% rain)	15.6	1.0	54.9	3.25
TOTAL (Sep93-Aug95)	1514.0	No. of storms	24	5	53	20
		Runoff (mm)	99.5	7.9	454.7	60.1
		Runoff (% rain)	6.6	0.01	30.0	4.0

[1] Total rainfall for storms ≥5 mm

[2] Number of storms producing runoff

in the LR of 1988. After a series of experiments on an alfisol in Western Nigeria, Lal (1975) reported that mulching with straw effectively prevented runoff on slopes ranging from 1 to15%.

In the current study, up to one third of rain water was lost as runoff from overgrazed plots (OG), but only about 5% was lost from control grazed plots (CG). In both grazing systems soil cover was at its lowest at the end of the dry season; that is, 30-35% in OG and about twice as much (65-70%) in CG. With such cover reduction in OG the topsoil was exposed to raindrop impact. In addition to this, the soil was also subjected to continuous livestock trampling. These had resulted to compaction and sealing which were manifested in increased bulk density and decreased porosity and infiltration as already discussed.

Table 4.18 Runoff from five soil cover conditions at Mukogodo over a period of four rainy seasons between September 1993 and August 1995.

Season	Rainfall (mm)	Parameter	PO	PE	BO	BE	RO
SR 1993/94 (Sep93-Feb94)	56.1[1]	No. of storms[2]	3	0	7	7	3
		Runoff (mm)	5.1	0	17.0	12.7	1.6
		Runoff (% rain)	9.1	0	30.3	22.6	2.9
LR 1994 (Mar94-Aug94)	224.1	No. of storms	15	9	18	8	15
		Runoff (mm)	73.0	30.7	102.9	95.2	54.8
		Runoff (% rain)	32.6	13.7	45.9	42.5	24.5
TOTAL (Sep93-Aug94)	280.2	No. of storms	18	9	25	15	18
		Runoff (mm)	78.1	30.7	119.9	107.9	56.4
		Runoff (% rain)	41.7	13.7	76.2	69.1	27.4
SR 1994/95 (Sep94-Feb95)	193.3	No. of storms	16	13	18	18	16
		Runoff (mm)	71.0	21.3	105.4	94.4	43.5
		Runoff (% rain)	36.7	11.0	54.5	48.8	22.5
LR 1995 (Mar95-Aug95)	205.6	No. of storms	17	9	17	17	15
		Runoff (mm)	89.8	15.2	112.0	120.9	70.7
		Runoff (% rain)	43.7	7.4	54.5	58.8	34.4
TOTAL (Sep94-Aug95)	398.9	No. of storms	33	22	35	35	31
		Runoff (mm)	160.8	36.5	217.4	215.3	114.2
		Runoff (% rain)	80.4	18.4	109.0	107.6	56.9
TOTAL (Sep93-Aug95)	679.1	No. of storms	51	31	60	60	49
		Runoff (mm)	238.9	67.2	347.2	323.2	170.7
		Runoff (% rain)	35.2	9.9	51.1	47.6	25.1

[1] Total rainfall for storms ≥5 mm

[2] Number of storms producing runoff

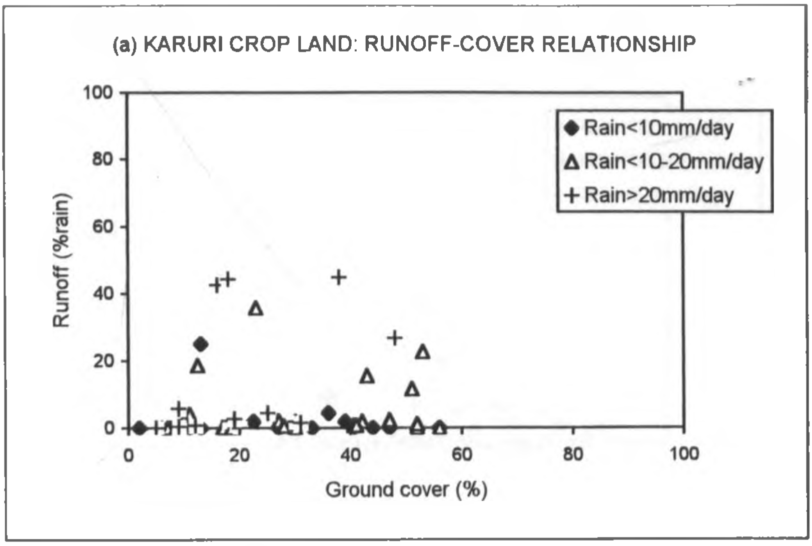
Bare (BO) and overgrazed grass (PO) sites lost up to a half (51%) and about a third (35%) respectively of the rainfall as runoff at Mukogodo (Table 4.18). It is interesting to note that seasonal total runoff percentages are very consistent and very close to the means in all seasons except SR 1993/94 when very low rainfall was received. Runoff did not decrease in the enclosed bare plots even after protection from grazing for 6 growing seasons. However, closure of plots that had some perennial grass (PE) for the same period, significantly decreased runoff from 35% to only about 10%. Soil cover remained almost the same (≈ 5) on bare ground, but it substantially increased on overgrazed grass plots from less than 20% to about 50% after enclosure. Pereira (1973) reported similar results in northern Uganda where sites with some few perennials were able to recover by only enclosing. The role which bush canopy with basal cover plays in arresting runoff was clearly demonstrated by the RO plots. About a half of the runoff that flowed from the bare section through under bush was trapped and had opportunity to infiltrate (RO = 25% and BO = 51%).

4.3.1.1 Influence of cover

Before relating soil cover with the percentage of rainfall generated as runoff, rainfall events were separated into 3 categories according to amounts (<10 mm, 10-20 mm and >30 mm day^{-1}). Observations from all 3 sites show that despite the land use, runoff decreases with increase of cover. However, statistically there was no significant ($P<0.05$) correlation between runoff and cover in any of the conditions. This suggests that apart from cover, other factors were significantly contributing to runoff.

Cropland soil cover was very dynamic at Karuri (Figure 4.24). It ranged from less than 10% after land preparation for planting, to a maximum of about 60% when the potato crop cover was fully established. The cover in grazing land remained fairly constant (80-90%) throughout the year. Figure 4.12 illustrates that only storms over 20 mm are likely to produce runoff of ≥5% of the rainfall on grazing land. However, on cropland even storms of 10 mm generated ≥10% runoff. It was also observed that chances are very small for runoff to occur on cropland once the soil cover approached 60%.

Despite the marked differences in topsoil conditions on crop land and grazing land at Kalalu, both land uses have similar points scatter in the runoff/cover relationship as illustrated in Figure 4.13. This would be explained by the similar spread of amount of cover (ranges between 25 and 90%), especially during the period when most storms are received. MT and CG had fairly high soil cover (>60%) throughout, but CT and OG plots have low (<35%) cover at the beginning of the rains (Figure 4.25). Grazing land had however a large number of runoff events recorded because most storms of at least 10 mm generated substantial runoff from OG plots.



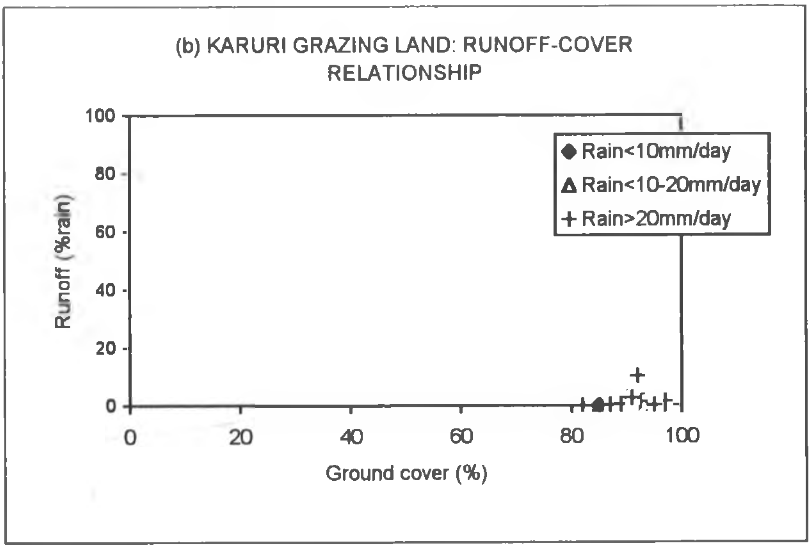
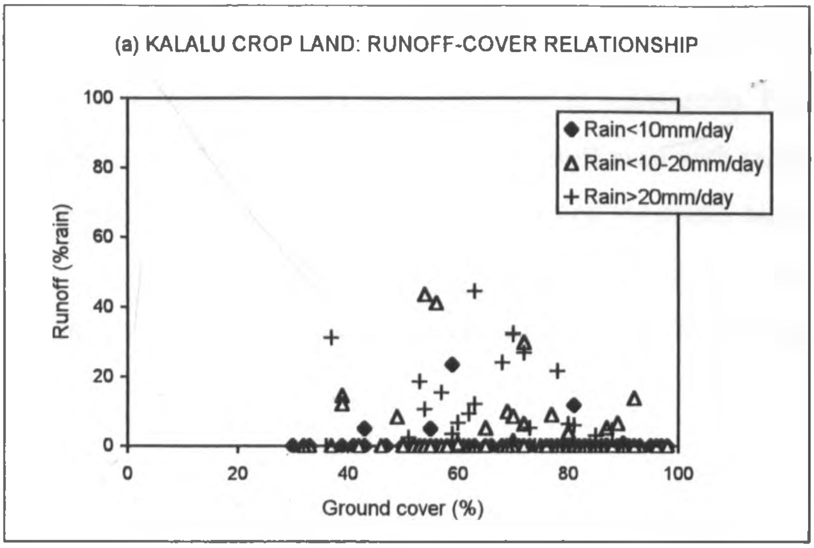


Figure 4.12 Runoff and soil cover relationship at Karuri (September 1993-August 1995).



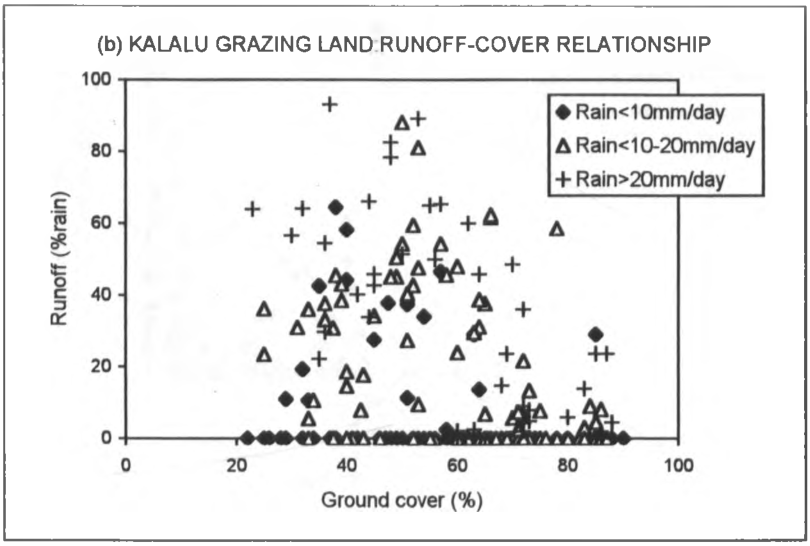


Figure 4.13 Runoff and soil cover relationship at Kalalu (September 1993-August 1995)

Bare and eroded grazing land, which is the most common situation at Mukogodo, has very high percentage of runoff even for small rainfall events. However, very few storms produce runoff events from sites with adequate cover at Mukogodo. Figure 4.14 shows that if the cover is around 40%, there is virtually no runoff even with rainfall of more than 20 mm. Also the scatter is more with high rainfall, which illustrates high variability with higher rainfall. This is true because at high rainfall other factors like intensity and antecedent moisture may predominate the cover conditions in influencing generation of runoff.

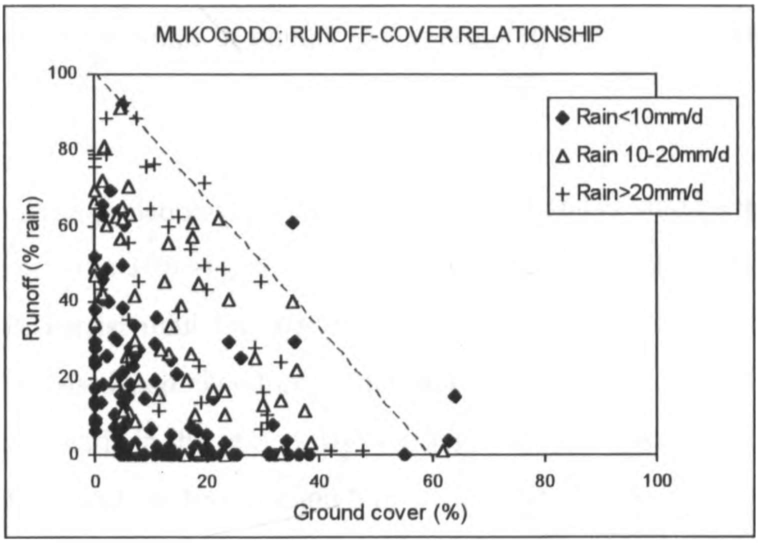


Figure 4.14 Runoff and soil cover relationship at Mukogodo (September 1993 to August 1995).

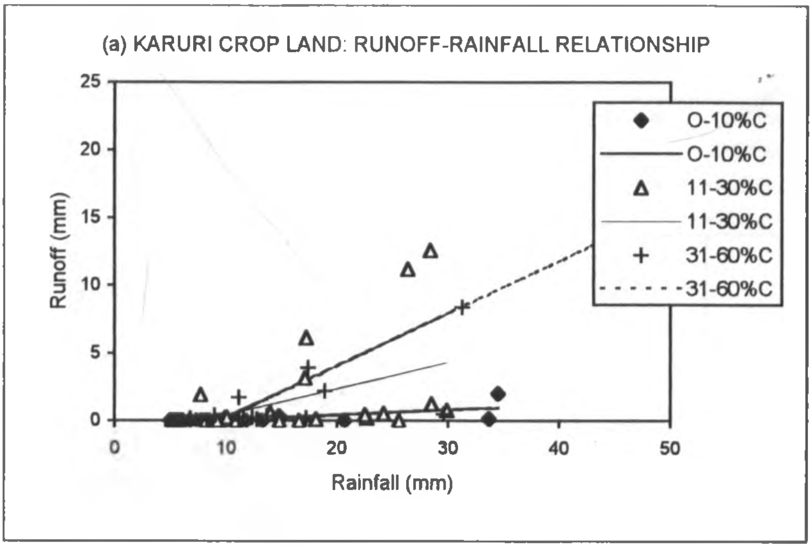
4.3.1.2 Influence of rainfall amount and intensity

The proportion of water reaching the ground surface that infiltrates into the soil depends to a large extent upon the relation between rainfall intensity and the infiltration capacity of the soil. Runoff occurs when rainfall intensity exceeds the infiltration rate. Therefore intense rain storms will result in water flowing over the soil surface whenever the infiltration capacity of the soil is less than the rate at which the rain is falling.

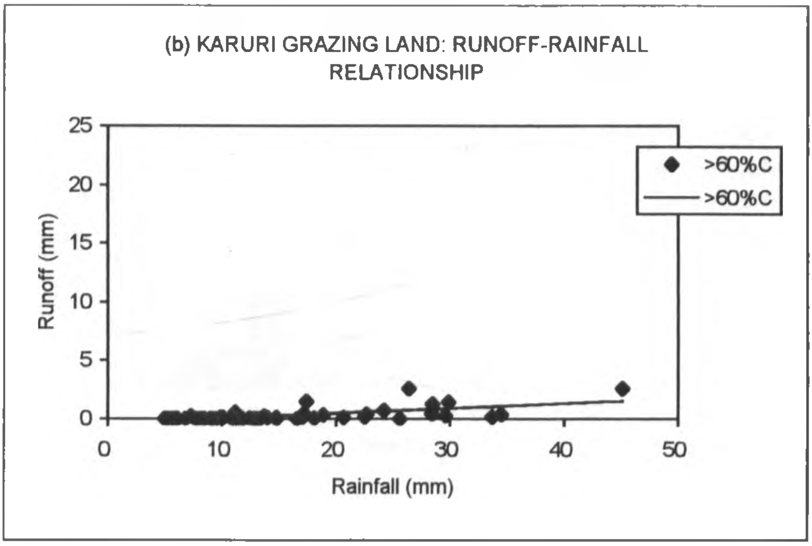
In the analysis of influence of rainfall amount and intensity on runoff, soil cover was partitioned into four categories (0-10, 11-30, 31-60 and >60% cover). This was necessary in order to block the effect of cover on runoff. The cover categories were selected by running a trial analysis which indicated the cover ranges where response became significant. Data was also separated into crop land and grazing land since the two land uses have different topsoil conditions. Regression equations for runoff verses amount of rainfall are presented in a format which the constant gives the cut-off value which represents the amount of rainfall that is required to initiate runoff within a given soil cover.

There was no strong relationship between runoff and rainfall amount at Karuri on crop land for cover of up to 30% (Figure 4.15). The small furrows that are prepared for potato seed placement persist until the first weeding. Due to high surface roughness, water detention is increased and therefore opportunity to infiltrate most of the water from storms that occur early in the season. By weeding time soil cover was already over 30%; but weeding destroyed the furrows and thus surface roughness. The effect of this would be large storms generating runoff unlike immediately after planting. Such a situation distorts the relationship between runoff and rainfall, and it has clearly come out by the equations which indicate that a higher amount of rainfall (14 mm) was required to initiate runoff on low cover (11-30%) than that required (11 mm) for higher cover (31-60%) conditions.

A weak but significant ($p<0.05$) relationship exists between runoff produced on grazing land and amount of rainfall at Karuri. The influence of rainfall on runoff yield was probably masked in this case because of the presence of high cover (80-90%) throughout the year. The high cover intercepts most of storms, thus only a few yield runoff.

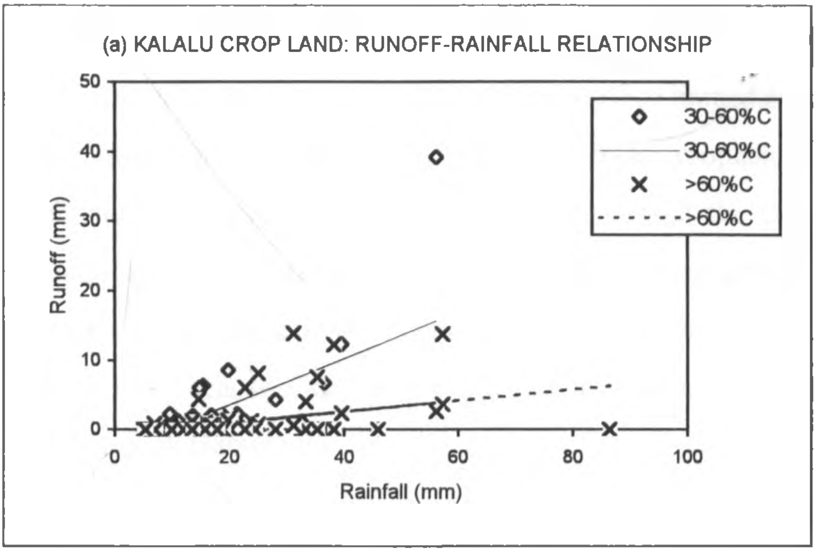


0-10% Cover: RO = 0.0828(P - 11.6506) R^2 = 0.46
11-30% Cover: RO = 0.9126(P - 14.1661) R^2 = 0.21
31-60% Cover: RO = 0.5455(P - 10.7759) R^2 = 0.71

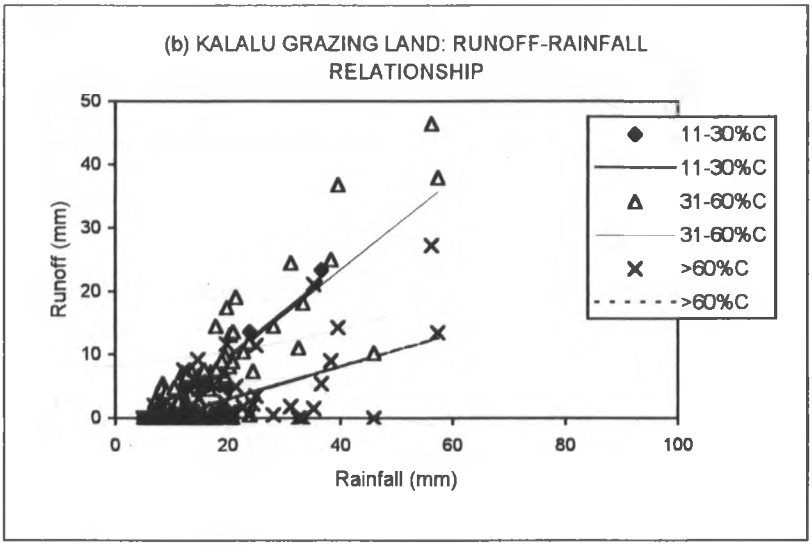


>60% Cover: RO = 0.0941(P - 11.7889) R^2 = 0.65

Figure 4.15 Runoff and rainfall amount relationship at Karuri (September 1993 to August 1995).



31-60% Cover: RO = 0.7615(P -11.4808) $R^2 = 0.44$
>60% Cover: RO = 0.3863(P - 12.8683) $R^2 = 0.21$



11-30% Cover: RO = 0.7819(P - 7.4736) $R^2 = 0.94$
31-60% Cover: RO = 0.9350(P - 8.6568) $R^2 = 0.76$
>60% Cover: RO = 0.6022(P - 11.3336) $R^2 = 0.43$

Figure 4.16 Runoff and rainfall amount relationship at Kalalu (September 1993 to August 1995).

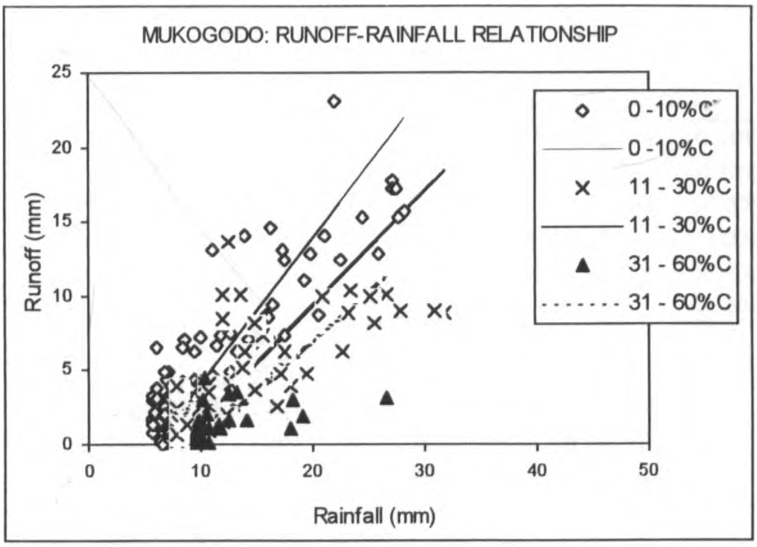
Figure 4.16 indicates that runoff and rainfall amount have no significant relationship in crop land at Kalalu. This would be attributed to the gentle slope (4-5%) of the land. Also most of the early storms infiltrate due to the rough soil surface immediately after tillage in CT, and due to adequate soil cover in MT system. Unlike cropland, the relationship between runoff and rainfall in grazing land was strong for all the categories of grass cover. The equations indicate that successively more rainfall is required to initiate runoff with increase of soil cover. Despite the gentle slope, most storms of at least 10 mm and above produce runoff because OG soil surface has low grass cover, compacted and smoothened by livestock trampling.

Runoff production was strongly related to rainfall amount under the range land conditions at Mukogodo (Figure 4.17). The trend was similar to that in Kalalu grazing land. But storms as low as 6 mm generated up to 50% runoff on bare ground at Mukogodo. The chart clearly indicates that only about 6 mm of rainfall was required to initiate runoff on bare ground. Almost twice as much rainfall (10 mm) was required to produce runoff from soils with cover of at least 30% and above (Table 4.19).

Table 4.19 Threshold amount of rainfall (mm) required to produce runoff under various soil cover conditions.

Cover (%)	Crop land		Grazing land		
	Karuri[1]	Kalalu[2]	Karuri	Kalalu	Mukogodo
0-10	11.7	n.a	n.a	n.a	5.8
11-30	14.2	n.a	n.a	7.5	7.9
31-60	10.8	11.5	n.a	8.7	9.7
>60	n.a	12.9	11.8	11.3	n.a

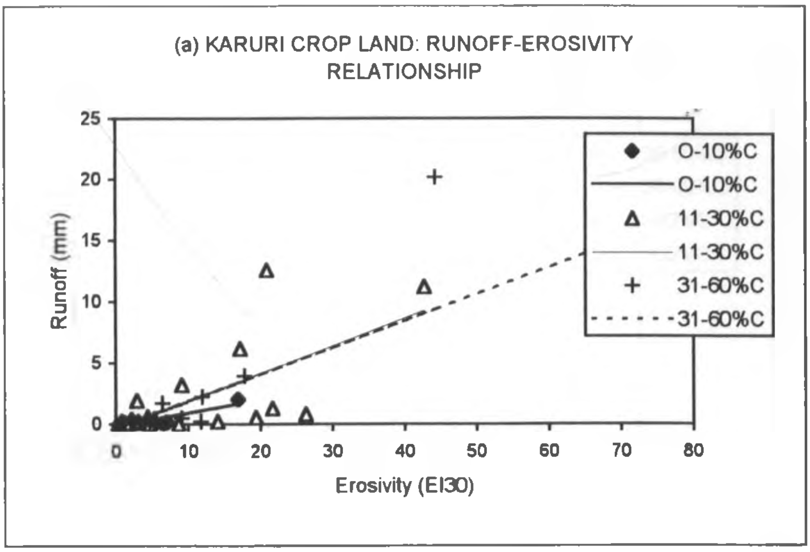
[1] Ridged potato
[2] Maize-bean intercrop
n.a: Not applicable during the data collection period



0-10% Cover: Ro = 0.9787(P - 5.7884) $R^2 = 0.62$
11-30% Cover: Ro = 0.7727(P - 7.8507) $R^2 = 0.54$
31-60% Cover: Ro = 0.6641(P - 9.7003) $R^2 = 0.51$

Figure 4.17 Runoff and rainfall amount relationship at Mukogodo (September 1993 to August 1995).

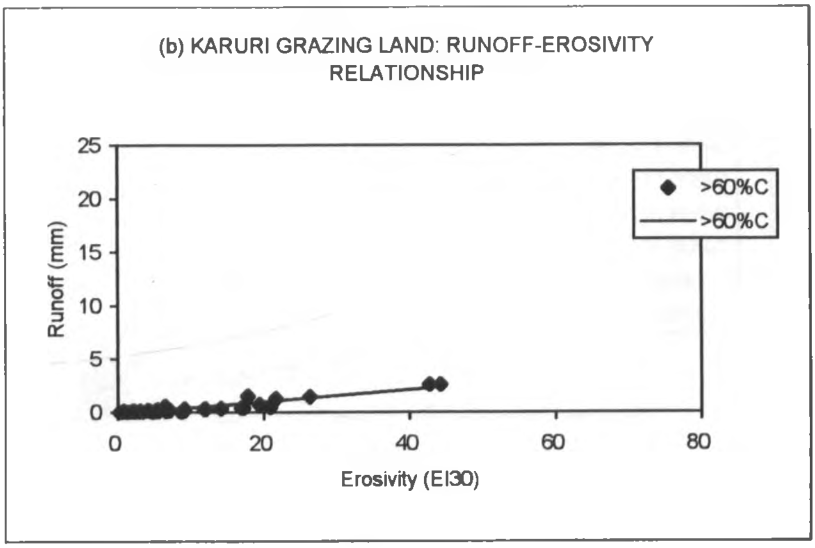
Rainfall intensity strongly influenced the amount of runoff produced in all sites and land uses (Figures 4.18-4.20). However, the influence became less significant as soil cover increased on both crop land and grazing land. Analysis shows that if 60% of the soil surface is covered on cropland at Kalalu, then rainfall intensity becomes a less significant factor in generation of runoff on gentle slope. Therefore given adequate soil cover like mulch on cropland, the soil surface is likely to maintain a good structure, reducing excess of infiltration to a minimum, a feat which is not easily met by even good grass cover under regular grazing at Kalalu.



0-10% Cover: RO = 0.1083E - 0.1871 $R^2 = 0.79$

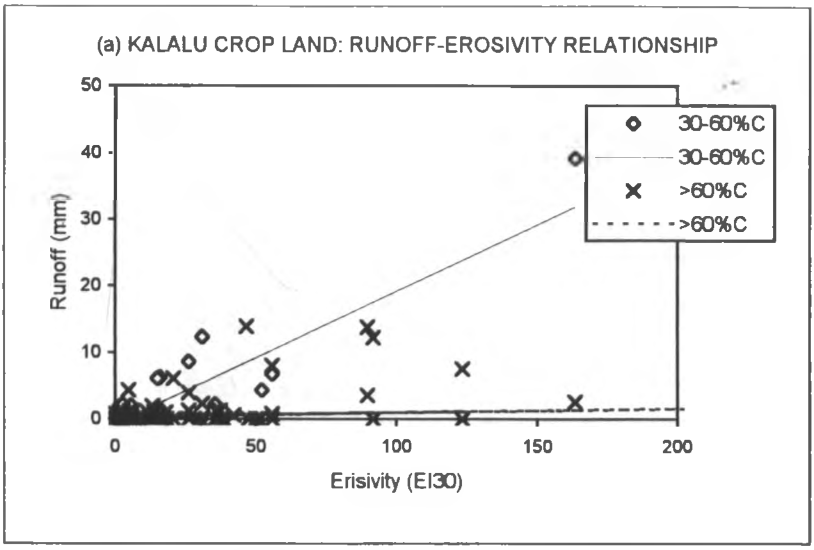
11-30% Cover: RO = 0.2256E - 0.3886 $R^2 = 0.49$

31-60% Cover: RO = 0.2199E - 0.3494 $R^2 = 0.62$

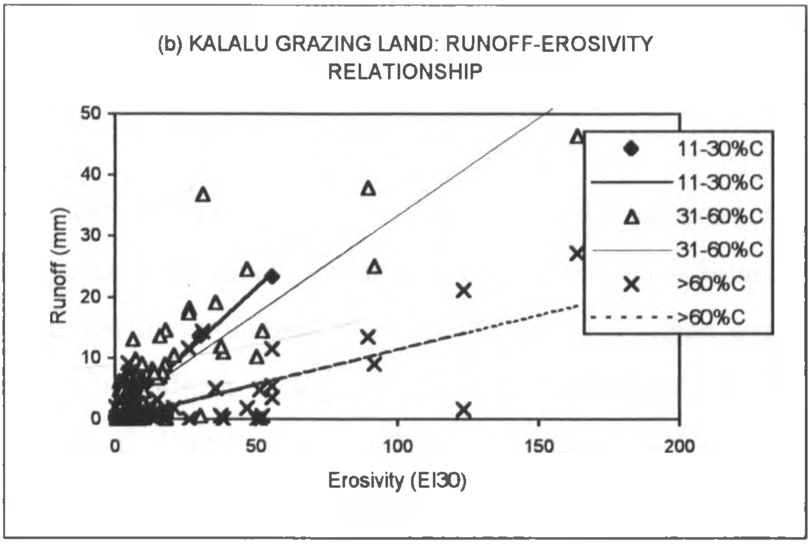


>60% Cover: RO = 0.0557E - 0.1265 $R^2 = 0.88$

Figure 4.18 Runoff and rainfall erosivity relationship at Karuri (September 1993 to August 1995).

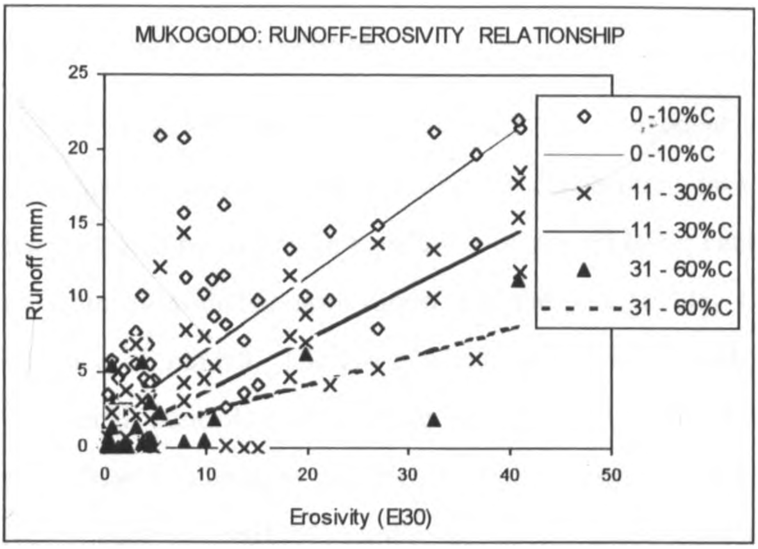


31-60% Cover: RO = 0.1989E - 0.7267 $R^2 = 0.77$
>60% Cover: RO = 0.0062E + 0.3745 $R^2 = 0.04$



11-30% Cover: RO = 0.4282E + 0.0721 $R^2 = 0.98$
31-60% Cover: RO = 0.3216E +1.2504 $R^2 = 0.72$
>60% Cover: RO = 0.1150E - 0.0856 $R^2 = 0.56$

Figure 4.19 Runoff and rainfall erosivity relationship at Kalalu (September 1993 to August 1995).



0-10% Cover: RO = 0.4875E + 1.6735 $R^2 = 0.65$
11-30% Cover: RO = 0.3480 + 0.3148 $R^2 = 0.68$
31-60% Cover: RO = 0.1896 + 0.3904 $R^2 = 0.49$

Figure 4.20 Runoff and rainfall erosivity relationship at Mukogodo (September 1993 to August 1995).

Hudson (1981) and Morgan (1986) point out that runoff appears to be related to two types of rainfall events; the short-lived intense storm where the infiltration capacity of the soil is exceeded and the prolonged storm of low intensity which saturates the soil. In many instances it is difficult to separate the effects of these two types of events in accounting for runoff. However, for sites like Karuri forest, runoff is very unlikely to occur due to infiltration excess as steady state infiltration rate was over 60 cm h^{-1} (section 4.1.4.1), while the highest rainfall intensity (I_{15}) recorded so far during the study period was 70 mm h^{-1}. But with cultivation and grazing, topsoil structure gets degraded, and in such conditions infiltration excess is likely to occur. It is very unlikely that soil saturation will occur in Mukogodo. This implies that most runoff that occurred in this area would be accounted for as infiltration excess.

4.3.1.3 *Influence of antecedent soil moisture*

The amount of runoff generated may be determined by antecedent soil moisture conditions. The importance of rainfall events occurring in consecutive days in generation of runoff can be demonstrated by data from Kalalu in overgrazed land (Table 4.20). In all the times presented, a storm produced more runoff than the previous day's event despite the amount or intensity of rainfall. Therefore when rains are concentrated in short seasons, antecedent rainfall controls soil moisture and hence the proportion of a storm which will infiltrate. These results give credence to observations made in Queensland, Australia, that given similar soil surface conditions, soil moisture content is the most important factor in determining whether rainfall will result in runoff (Freebairn *et al.*, 1989).

Table 4.20 Influence of consecutive rainfall events on runoff in grazing land at Kalalu.

Date	Rainfall (mm)	Erosivity (EI30)	Runoff (% of rain)
17 Apr 1994	5.5	1.0	0.0
18 Apr 1994	23.9	30.3	46.5
19 Apr 1994	8.6	6.3	64.1
20 Aug 1994	18.0	16.8	42.7
21 Aug 1994	20.9	15.9	65.0
30 Oct 1994	16.0	8.7	0.0
31 Oct 1994	14.8	6.2	25.0
29 Apr 1995	17.5	5.1	29.5
30 Apr 1995	12.7	51.2	37.7
01 May 1995	14.7	4.7	62.4

Similar results were obtained from overgrazed grass sites (PO) at Mukogodo (Table 4.21). But the same was not true for bare ground conditions (BO). In the latter, similar percentage of runoff was generated from successive events. This indicates that surface soil conditions which influence infiltration capacity, in this case, crusting, may override the antecedent soil moisture conditions in generation of runoff.

Table 4.21 Influence of consecutive rainfall events on runoff for two soil cover conditions at Mukogodo.

Date	Rainfall (mm)	Erosivity (EI30)	PO runoff (% of rain)	BO runoff (% of rain)
17 Jan 1993	5.0	1.0	1.9	23.8
18 Jan 1993	8.0	1.3	5.1	48.2
19 Jan 1993	8.2	1.9	10.8	49.0
30 Oct 1993	8.8	1.3	0.0	26.0
31 Oct 1993	5.3	2.8	26.1	69.4
01 Nov 1993	8.2	3.1	34.1	64.0
08 Feb 1995	23.4	32.5	49.9	79.0
09 Feb 1995	24.8	40.7	71.6	88.6
10 Jul 1995	6.7	1.0	5.0	18.2
11 Jul 1995	6.9	2.0	10.2	21.3

4.3.1.4 Influence of land use and management

The forested mountain slopes in Karuri have little overland flow because water rapidly infiltrates into the soil that is protected by adequate cover. This reduces the peak flow from storms. It is then less likely that soil erosion or flooding in the lower parts would occur. With forest removal, surface runoff is likely to increase, but data from the current study indicated minimum negative impact (only 5-10% of seasonal rainfall was recorded as runoff in PC). Close spacing of potato and quick cover development helps to protect soil against raindrop impact on crop land. High runoff events were mainly recorded when large (>20 mm day^{-1}) and frequent storms were received (e.g. April/May 1994). The major factor contributing to high runoff at this time would be soil moisture. As already discussed above, rainfall amount and intensity are also significant contributors to generation of runoff.. Therefore, it can be concluded from the observations made that rainfall amount, frequency and intensity influence runoff generation more than soil cover within such a period.

Forest cover removal and subsequent cultivation has resulted in some of the rainfall being lost through surface runoff at Karuri. This may gradually lower dry season river flow as less water would be available for deep percolation. Even though currently potato cultivation gave high water infiltration, it is possible that gradual soil degradation will occur as the organic matter decreases in subsequent cultivations. Thus a question of sustainability and feasibility of soil conservation measures arise. Similar results were reported at Mbeya in Tanzania (EAAFRO, 1971), where runoff was found to be only 1% and 3% for forest and cultivated catchment respectively. These very low values were attributed to the high infiltration rate of the volcanic ash-derived soil. However, such a condition does not exist in many areas, hence it should be pointed out that each system may have its peculiar attributes and complexity. Generally forest canopy and ground cover protects soil against raindrop impact, enhances infiltration and reduces surface flow and soil erosion. Control of storm flow afforded by forest depends on free movement of water through the soil profile to maintain high infiltration rates and a large soil moisture storage capacity. Forest cover particularly in mountainous, steep-sided, high rainfall areas form an excellent protective vegetation. By encouraging infiltration they reduce storm flow, increase stream flow during dry periods and also conserve soils. Jackson (1971) cautions that since forest areas exist in a wide variety of hydrological situations, slopes, soils and human pressures; then the question of alternative land use must be carefully considered in each case.

For storms of similar characteristics received early in the season at Kalalu, the first few produced relatively low runoff from CT (despite the low cover) compared to the subsequent storms. This would be attributed to a progressive destruction of soil structure at the soil surface, caused by processes such as raindrop impact, soil aggregate breakdown and infilling of conducting pores by mobilized clay particles. Mulching provided cover that protected the soil early in the season when most intense storms are received. Therefore virtually no runoff is produced because the soil maintains high infiltration due to existence of good structure.

Overgrazing has resulted in reduction of soil cover, compaction of the soil surface due to trampling and lack of protection against rain drops, and subsequently destruction of soil structure. This has decreased infiltration capacity and most water runs off thus reduced replenishment of soil moisture reserves that would be used by plants in dry periods or recharge ground water supplies. Destruction of topsoil structure at Mukogodo has made the soil more susceptible to erosion, decreasing its water holding capacity and ability to maintain vegetation.

Half of the rainfall received is lost as runoff from bare ground at Mukogodo. Despite protection from grazing, the bare sites have not shown any recovery. On the other hand, sites that were overgrazed but had some perennial grasses are resilient as shown by the substantial gain in cover and tremendous reduction in runoff after protection from grazing. The role played by bush in reducing runoff is clearly demonstrated as up to a half of the runoff from bare ground was trapped and got opportunity to infiltrate. Results from Mukogodo can be compared with those obtained by Pereira (1973) in Karamoja, northern Uganda. It is reported that at least one third of the rain became runoff on grazed and trampled sites and penetration of rain was shallow in many cases to less than 50 cm. But on an adjacent site where controlled grazing was carried out (by fence protection) after one season, penetration of rain into the soil increased from 50 to 125 cm, peak flows were reduced and a rich flora of grasses developed. Thus on less severely degraded range land, application of a simple pasture management technique can simultaneously improve water infiltration and grazing conditions. On the other hand, it requires more than closure to regenerate cover on severely degraded land.

4.4 SOIL WATER DYNAMICS

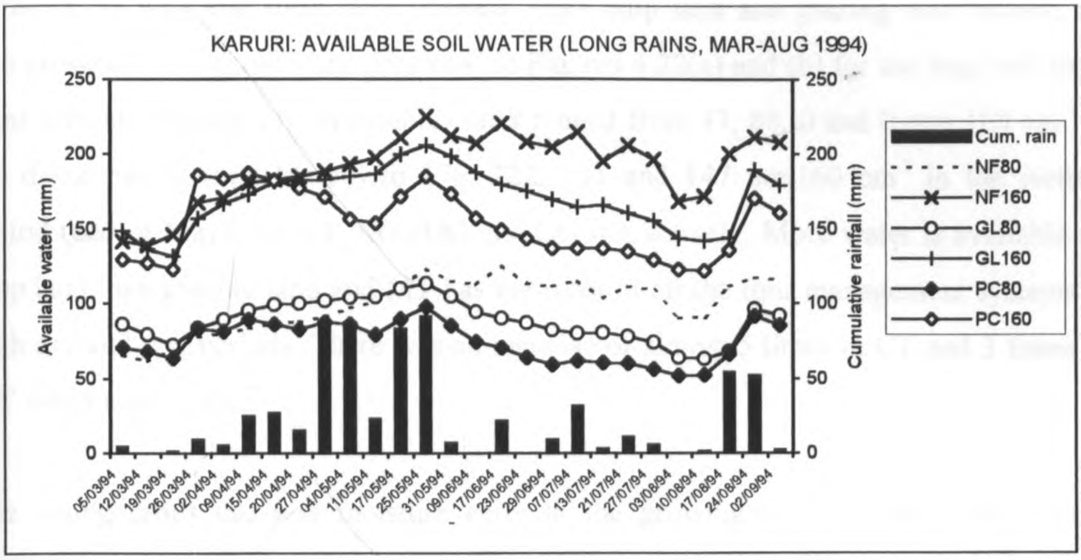
4.4.1 Available soil water

The soil's potential in each site to store water that can be available to plants has been discussed in section 4.1.3.3. In this section the actual amount of water and its temporal variation as measured in each site are presented. The data used covers a period of one year and illustrates the dynamics for two representative growing seasons; that is, the long rains (March to August 1994) and the short rains (September 1994 to February 1995).

Available soil water at Karuri was similar within the land uses in both seasons, therefore only results for the long rains season are shown in Figure 4.21 as the trend was similar even for the short rains season. Available water ranged from 140, 130 and 120 mm160 cm^{-1} in the dry season (mid-March) to 230, 205 and 185 mm 160 cm^{-1} in the wettest season (end of May), for NF, GL and PC respectively. Thus for the three land uses, the forest had the highest available water in both dry and rainy seasons. In terms of increase between the dry and wet period these was 64, 58 and 54% for NF, GL and PC respectively.

When the amount of water for each land use was averaged for a whole year (March 94-February 95), means of 192, 169 and 153 mm 160 cm^{-1} for NF, GL and PC, respectively were obtained. That in the forest was significantly ($P<0.05$) higher than the other two. This indicated that forest removal for farming has resulted in a reduction of available water at Karuri. Figure 4.21 shows that the available water was evenly distributed within the profile in both dry and wet seasons as approximately half of the total available water was found in the upper 80 cm of the profile. The results also indicate that even in the driest part of the year, moisture contained in the soil profile at Karuri was about two thirds of its available water capacity.

During the rainy season water storage constantly increased under forest and grass cover reaching a peak late in May. However, the trend was slightly different on cropland. This would be probably due to high water use by the rapidly growing potato crop leading to a depression in water storage build up in May. This observation is interesting as it contradicts what Njeru (1995) found at Naro Moru (2500 m a.s.l., on the northwestern slopes of Mount Kenya) that grass and forest, which had higher vegetative cover, had higher water use. High water use by grass and potato from the upper part of the profile towards the end of the rains in June led to faster moisture decrease compared to that in



NF: Natural forest, GL: Grazing land and PC: Potato crop land
80: Soil depth up to 80 cm , 160: soil depth up to 160 cm

Figure 4.21 Available soil water at Karuri during the long rains of March to August 1994.

forest. This would be attributed to reduced direct evaporation in the forest because of shading by the trees canopy and thick layer of litter on the ground. The forest may also be using much water but from deeper layers (than the part of soil profile assessed in this study).

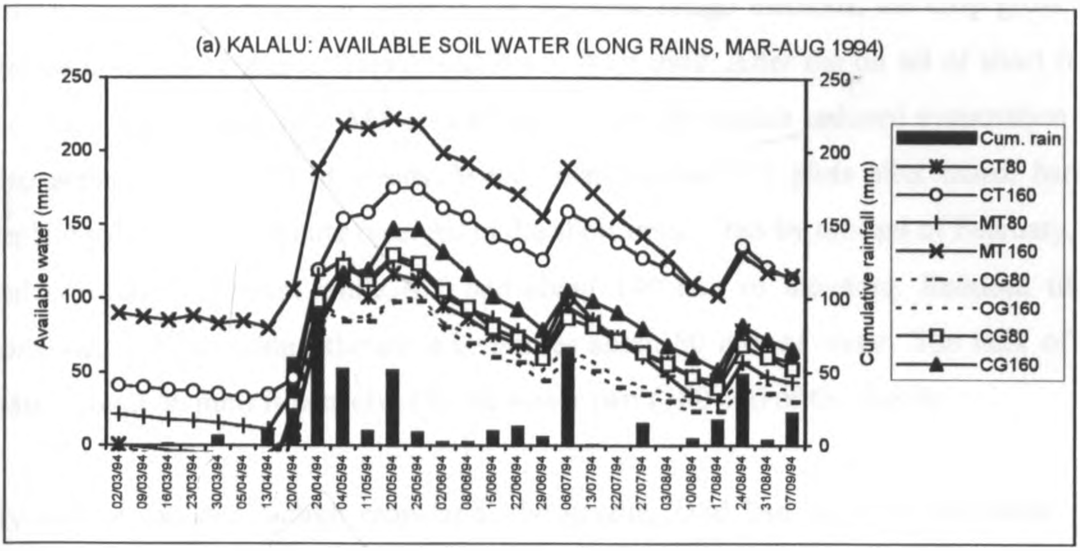
The way available water results are presented here does not indicate in detail how moisture was distributed within the profile for each land use. Results presented by Njeru (1995) for Naro Moru forest zone, however, indicate that vegetation type had marked influence on distribution of available water in the profile. Based on various proportion classes of available water, Njeru (1995) reported that the natural forest had two water extraction depths (0-60 cm and below 90 cm). This pattern was attributed to different rooting depths for the mixed (grass/bamboo/tree) vegetation system. On the other hand, uniform vegetation of grass and potato covers, had each only a single extraction depth. These were 0 to 90 cm and 0 to 30 cm, for grass and potato, respectively.

Unlike Karuri, available water at Kalalu especially on crop land, was quite different between the long and short rains seasons. Both crop land and grazing land results, for two growing periods each, are presented in Figures 4.22(a) and (b) for the long and short rains seasons respectively. Available water ranged from 37, 88, 0 and 0 mm 160 cm^{-1} in the driest period (mid-March) to 176, 222, 101 and 147 mm160 cm^{-1} in the wettest period (end of May), for CT, MT, OG and CG respectively. More water is available on crop land than grazing land and MT has the most of all the four management systems in both dry and wet periods. There was an increase of almost 5 times in CT and 3 times in MT when rains came.

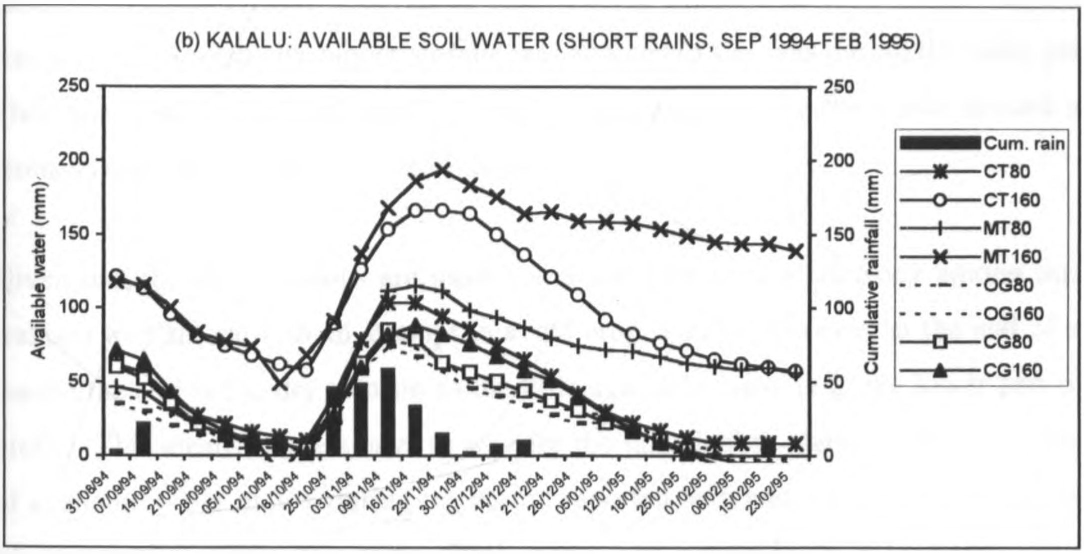
The young crops use less moisture early in the growing season. This would allow gradual build up of moisture reserves. Virtually there was no available water under grass cover in the dry season; it only started to build up after the onset of rains and reached a maximum towards the end of May.

The relatively lower water storage on grazing land compared to crop land would be attributed to the high runoff from OG and also to high water use by grass cover (Liniger, 1991a). This is also why water percolation in the profile is limited to 90-120 cm on grazing land, while that in crop land was detected even beyond 150 cm during the wettest period of a rainy season. Relatively more water was available in the upper than in the lower part of the profile during wet seasons in all systems. The reverse was true in dry seasons. This distribution would be explained by the fact that the upper layers readily get recharged when rains come, and it is from the same layers where most water is extracted from by plants or by direct evaporation.

Averaging moisture for a whole year (March 94-February 95), gives means of 105, 140, 36 and 46 mm 160 cm^{-1} for CT, MT, OG and CG respectively. That in MT and CG was significantly ($p<0.05$) more than that in CT and OG. Maximum storage which was attained in mid-May was, however, far below the full storage potential for the profile. During this wettest period of the year, MT contained about 50 mm (26%) more water than CT and CG had 46 mm (46%) more than OG.



(a) KALALU: AVAILABLE SOIL WATER (LONG RAINS, MAR-AUG 1994)



(b) KALALU: AVAILABLE SOIL WATER (SHORT RAINS, SEP 1994-FEB 1995)

CT: Conventional tillage, MT: Mulch tillage, OG: Overgrazing and CG: Controlled grazing
80: Soil depth up to 80cm , 160: soil depth up to 160cm

Figure 4.22 Available soil water at Kalalu during (a) the long rains of March to August 1994 and (b) short rains of September 1994 to February 1995

From August until harvesting of maize in October/November, both tillage methods had similar amounts of moisture. Despite the different tillage methods, the crop grow was the same, therefore similar amounts of water were used. After the on set of short rains, the water that infiltrated in MT was stored because the mulch reduced evaporation and also suppressed growth of weeds. Weeds that infested CT plots after maize harvest deplete most of the moisture received in the short rains. Thus by the end of February, CT had only about 60 mm while MT had about 140 mm of moisture. Reduced tillage combined with mulching therefore conserves about 80 mm of water. The bulk of this water (about 50 mm) is conserved in the lower part (>80 cm) of the profile.

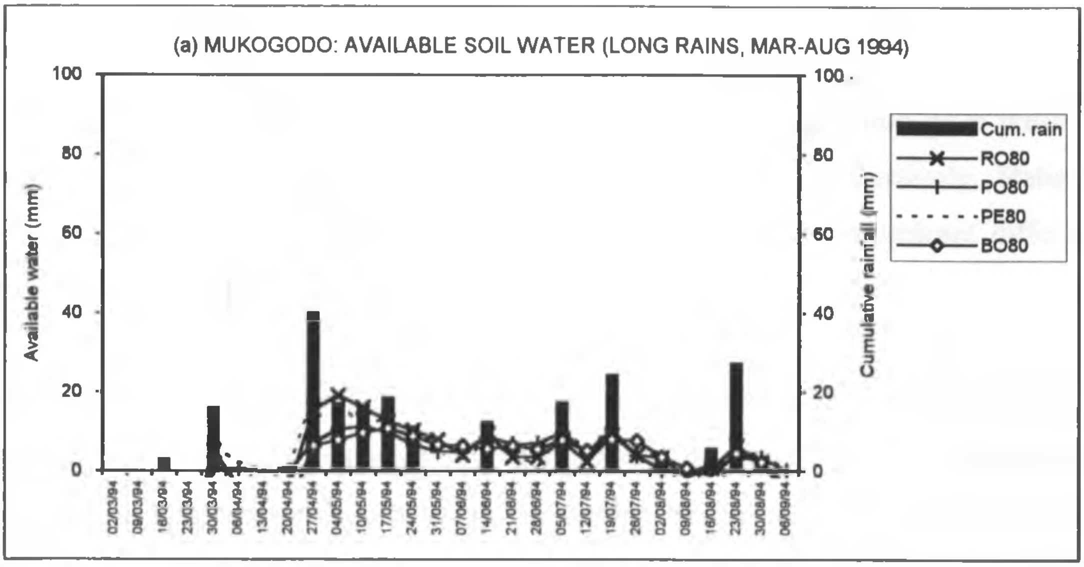
By end of January, unlike crop land, the grazing land had no available water. The moisture was completely used up in both grazing systems as soon as the dry season started, though relatively higher storage was attained in CG was during the rainy period. Therefore complete depletion of available water explains why the above ground grass biomass dried up during this time of the year.

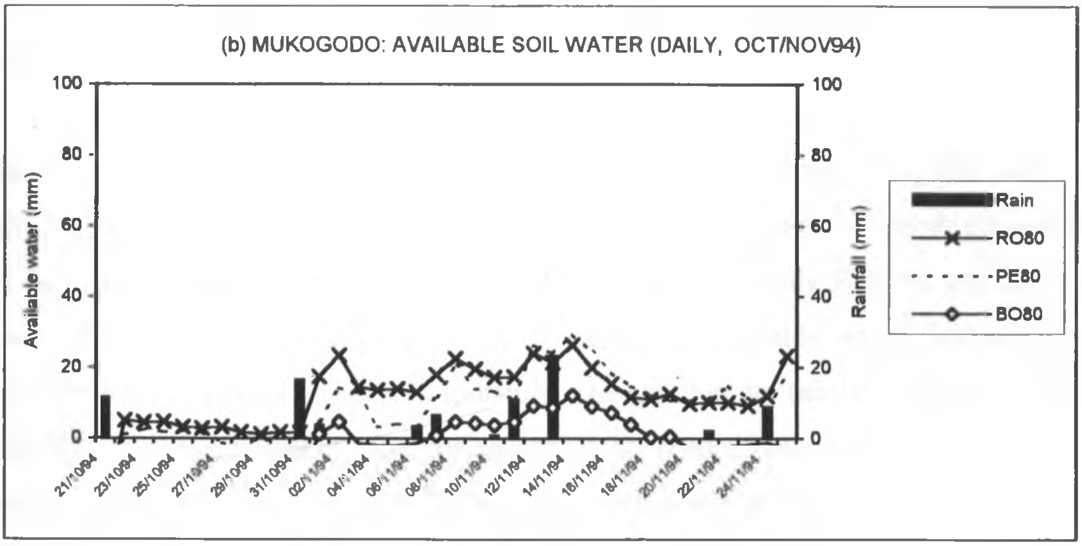
Given that the rainy seasons are usually too short, there is a tendency among farmers wanting to plant early in an attempt to avoid crop failure. However, at the end of a dry season the soil is too dry to plant as the little available water is in the lower part of the profile. This means farmers have to wait for the rains before planting. The least amount of available water in MT during the period reported here was 17 mm for the top 80 cm of soil, while within the same depth none was available in CT. Assuming even distribution of moisture, this represents an extra 6.4 mm of available water per 30 cm depth for the top part of soil profile. This has important implications as during planting time the onset of rains and amounts received are difficult to predict. Therefore under MT, relatively smaller early rainfall amounts would suffice to start the crop during the following rainy season; as thereafter the moisture carried over would sustain growth during any dry spells that may immediately follow the early rains. But Liniger (1991a) suggests that better plant establishment and development under mulch system may increase demand for moisture, which implies that any extra moisture conserved will be rapidly utilized. However, with good root development, the plants can be able to extract water stored in the lower part of the profile and thus leading to better crop establishment and subsequent higher yields.

The difference in water storage between MT and CT was mainly due to both high infiltration and conservation of the stored moisture. The high moisture build up under MT was particularly influenced by shading and insulation by mulch cover which reduced direct evaporation. Removal of weeds during the short rains season also eliminates water loss through transpiration of the unproductive plants. This results in high residual soil moisture under MT at the end of the dry season. On the other hand, the difference in water storage between CG and OG would be explained by the high water loss through runoff in the latter treatment. Compared to the scarce grass in OG plots, the abundant grass biomass in CG plots definitely utilizes more water. Therefore, despite the higher rain water infiltration and storage in CG, available water was depleted in both grazing systems soon after the end of the rains.

Available water at Mukogodo exhibited similar magnitude and trend in both the long and short rains seasons. Therefore, like Karuri, only data for the long rains are presented and discussed. Figure 4.23(a) shows that there was no available water in any of the surface cover conditions in the driest period (mid-March). However, in the wettest period, that is, in middle of May, small amounts of moisture accumulated in all cases. The amounts were 19, 13, 20, and 9 mm 80 cm^{-1} for RO, PO, PE and BO, respectively. That in BE is not presented in the graph as it was similar to BO. Attention is drawn on the scale of Mukogodo graph for it is larger compared with that used for Karuri and Kalalu graphs.

Even under good cover conditions, a maximum of only 35 mm 80 cm^{-1} of available water was recorded in a period of one year. This shows that soil moisture is very limited at Mukogodo even in the wettest part of the year. Data collected in the short rains season of 1992/1993 when above average rainfall was received indicate that a maximum of only about 60 mm 80 cm^{-1} was stored under the bush canopy (Mutunga, 1995). Even at that time, as it was in the current study, moisture penetrated to only about 50 cm under good





RO: Runon (bush canopy), PO: Perennial open, PE: Perennial enclosed and BO: Bare open
80: Soil depth up to 80cm

Figure 4.23 Available soil water at Mukogodo during the (a) long rains of March to August 1994 and (b) daily campaign in October and November 1994.

cover, and to less than 30 cm on bare ground. This points out why the area does not have any potential for crop production under rain-fed conditions.

Averaging available water over the long rains (March-August) season gave means of 3.8, 3.9, 3.6 and 0.7 mm 80 cm^{-1} for RO, PO, PE and BO, respectively. Statistical analysis of data for the two seasons indicate that there was no significant difference ($p<0.05$) among the 4 soil cover conditions.

Even though most of the rain infiltrates in sites with good cover (RO and PE), most of it was lost either by direct evaporation or transpired by plants before it was measured in the weekly monitoring schedule. Therefore weekly monitoring of soil moisture would not adequately detect and show the dynamics in such a system. It thus became necessary to monitor soil moisture daily over a given period of time in an attempt to detect any temporal variations.

Based on the above hypothesis, soil moisture was monitored daily during the short rains season for a period of 36 days from 21/10/94 to 25/11/94. It was not possible to monitor all the 5 treatments due to logistical limitations. Therefore only RO, PE and BO were monitored daily. Figure 4.23(b) presents the results of available water obtained during this monitoring period. The soil moisture change due to rainfall events is clearly noticeable unlike in weekly measurements. Also unlike for weekly data, sites with adequate soil cover (RO and PE) had significantly higher ($p<0.01$) available water than those where cover had been depleted (BO). Only 10 rainfall events which gave a total of 104 mm of rain were recorded during the daily campaign, despite the time being the short rains season. From this amount of rainfall, only 2.9 mm day^{-1} would be available for evaporation. This was far below the potential climatic demand as records indicated that average daily pan evaporation was 6.1 and 4.4 mm in the months of October and November respectively.

Calculation using the methodology outlined in section 4.1.3.3 give 109 mm as the storage capacity for the soil profile under bush canopy; while that on bare ground would store only 55 mm of available water within a depth of 80 cm. This showed that at Mukogodo the capacity to store water is limited more by depth rather than by soil texture and structure for the profile under bush canopy. On the other hand, water storage in bare ground was mainly constrained by soil structure, followed by depth limitation. Therefore, given the soil's natural condition (not eroded and crusted or compacted at the surface), the soil had adequate capacity to store water for forage production.

It is important to note that the lower limit used to calculate available water may not actually apply to most hardy plants like the *Acacia* species found in Mukogodo. Marshall and Holmes (1988) caution that drought tolerant plants can use soil water below *PWP* limit over long periods. It was also observed during soil profile description that roots of most plants that are adapted to this environment penetrated beyond the depth that moisture was monitored. Such plants would therefore extract water from the weathering rocky layers below the effective soil depth.

4.4.2 Soil water balance

From the foregoing sections, it is clear that the various land uses and management systems influence the partitioning of rainfall into runoff and that which infiltrates, and subsequently soil water storage. To get the overall picture, it is important to compute the water balance for each site within the different land uses and management systems. Equation 2.10 in section 2.3 gives the approach used in computing water use within a specified period. Rainfall (P), runoff (R), and soil water change (ΔS), are directly measured, while water use (W), which constitutes of actual evapotranspiration (ETa) and deep percolation (D) are calculated. In this section, seasonal water balance is presented for two LR and two SR seasons, while weekly computations for two successive growing seasons which cover a period of one year (March 1994 to February 1995) are given in Appendices A13 to A15.

4.4.2.1 Karuri

At Karuri runoff was considered to be negligible in the forest according to the infiltration capacity and rainfall intensities measured on site. Subsurface water flow and ground water capillary rise were also taken as negligible for the depth monitored. However, from soil moisture observations, deep percolation is experienced during the rainy period in all 3 land uses. The amount of water used in each land use was directly proportional to the amount of rainfall received in the season (Table 4.22). For example the least amount of water was used in SR93/94 when the lowest seasonal rains were received. Effective rainfall for the four seasons ranged between 88% and 98% as runoff water was low. Grazing land had the highest water use, while the forest had the least. However, statistically the difference among the land uses was not significant ($p<0.05$). This would be due to very high variability between seasons. The soil water change was negative only in LR95 under PC and GL due to high water use. This may be attributed to a relatively large proportion of water going to deep percolation than in the other seasons. This argument is supported by the fact that in this season the climatic water demand was similar to that in the other 3 seasons. In LR95 grass used more water than was supplied by rainfall within that period. This means that water from the previous season's storage must have been utilized to meet the deficit. Water use was higher in PC (4-18%) and GL (7-20%) than NF in the 4 growing seasons at Karuri. This is the case due to more deep percolation taking place in NF compared to PC and GL.

4.4.2.2 Kalalu

As Kalalu is located in a semi-humid to semi-arid area, on gentle slope physiograpy with very deep ground water, subsurface water flow and capillary rise are unlikely to occur. Soil moisture monitoring indicated that no changes took place below 160 cm in all the growing seasons and therefore deep percolation was considered non-existent during the study period. However, Liniger (1991a) reported deeper percolation (beyond 160 cm) under mulching and agroforestry systems in a wet season.

Mulch tillage system which in all seasons stored most available water had also, on average, the most water use, even though it was not significantly higher ($p<0.05$) than the other systems (Table 4.23). In cropland more water was used under MT than CT in the long rains, but the reverse was true in the short rains. This was the case because in the latter season mulch cover and removal of weeds reduce water loss through evaporation and transpiration respectively. In grazing land however, CG utilizes more water than OG in both seasons owing to high storage and subsequent higher consumption by the abundant

Table 4.22 Water balance at Karuri in four seasons (September 1993-August 1995).

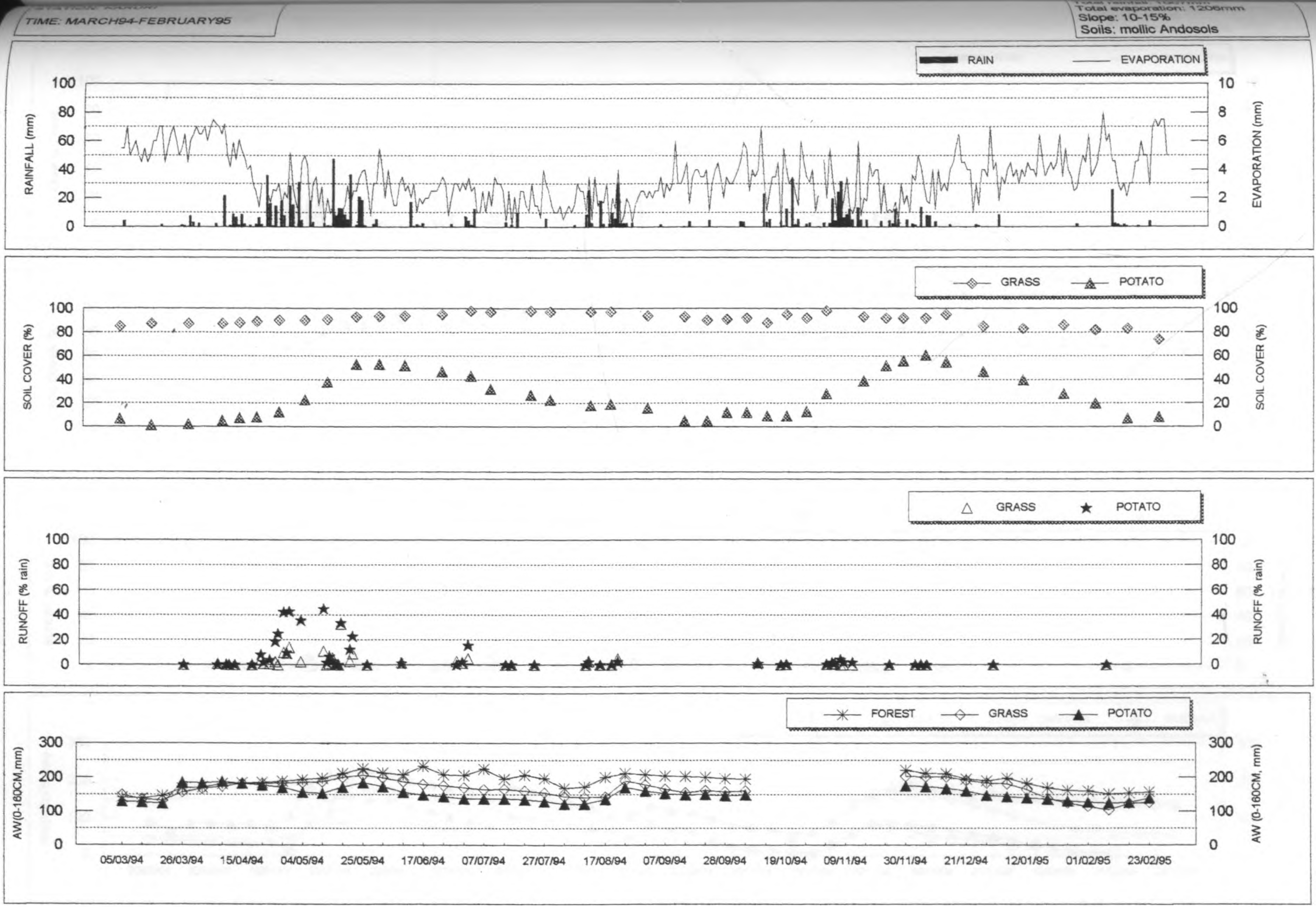
Season	Rainfall, P (mm)	Runoff, R (mm)			Soil water change, ΔS (mm 160 cm^{-1})			Water use, W=ETa+D (mm)			Climatic water demand, Ep (mm)	Deep percolation Yes (+)/No (-)
		NF	PC	GL	NF	PC	GL	NF	PC	GL		
SR 93/94	196.4	0	6.9	3.4	21.1	7.9	5.7	175.3	181.6	187.3	737.7	+
LR 94	652.7	0	76.6	14.8	69.6	40.8	41.0	583.1	535.3	596.9	595.7	+
SR 94/95	375.4	0	2.2	1.1	51.4	22.0	53.1	324.0	351.2	321.2	672.4	+
LR 95	466.0	0	26.6	7.3	72.8	-24.1	-12.1	393.2	463.5	470.8	602.1	+

Table 4.23 Water balance at Kalalu. in four seasons (September 1993-August 1995).

Season	Rainfall, P (mm)	Runoff. R (mm)				Soil water change, ΔS (mm 160 cm^{-1})				Water use. W=ETa (mm)				Climatic water demand. Ep (mm)	Deep percolation Yes (+)/No (-)
		CT	MT	OG	CG	CT	MT	OG	CG	CT	MT	OG	CG		
SR 93/94	204.7	6.3	0	32.7	0	-29.3	-1.7	-12.7	-25.2	227.7	206.4	184.7	229.9	873.6	-
LR 94	489.2	20.9	3.0	178.0	24.2	80.3	27.5	-43.8	38.6	388.0	458.7	355.0	426.4	701.0	-
SR94/95	282.7	12.9	0.7	57.8	9.0	-56.1	23.3	-40.7	-47.6	325.9	258.7	265.6	321.3	769.3	-
LR 95	537.4	59.4	4.2	185.2	27.0	88.7	-18.6	-23.9	50.1	389.3	551.8	376.1	460.3	638.9	-

Table 4.24 Water balance at Mukogodo in four seasons (September 1993-August 1995).

Season	Rainfall, P (mm)	Runoff, R (mm)				Soil water change, ΔS (mm 80 cm^{-1})				Water use. W=ETa (mm)				Climatic water demand. Ep (mm)	Deep percolation Yes (+)/No (-)
		RO	PO	PE	BO	RO	PO	PE	BO	RO	PO	PE	BO		
SR 93/94	56.1	1.6	5.1	0	17.0	-10.7	-5.0	-13.6	-3.2	65.2	56.0	69.7	42.3	1253.2	-
LR 94	224.1	54.8	73.0	30.7	102.9	20.0	18.6	31.8	18.7	149.3	132.5	161.6	102.5	1087.1	-
SR 94/95	193.3	43.5	71.0	21.3	105.4	-20.9	-19.8	-31.7	-16.8	170.7	142.1	203.7	104.7	1148.3	-
LR 95	205.6	70.7	89.8	15.2	112.0	14.5	15.5	29.9	10.2	120.4	100.3	160.5	83.4	1050.3	-


TIME: MARCH94-FEBRUARY95
Total evaporation: 1206mm
Slope: 10-15%
Soils: mollic Andosols
RAIN
EVAPORATION
RAINFALL (mm)
EVAPORATION (mm)
0
20
40
60
80
100
0
2
4
6
8
10
GRASS
POTATO
SOIL COVER (%)
RUNOFF (% rain)
FOREST
AW(0-160CM,mm)
AW (0-160CM, mm)
0
100
200
300
05/03/94
26/03/94
15/04/94
04/05/94
25/05/94
17/06/94
07/07/94
27/07/94
17/08/94
07/09/94
28/09/94
19/10/94
09/11/94
30/11/94
21/12/94
12/01/95
01/02/95
23/02/95

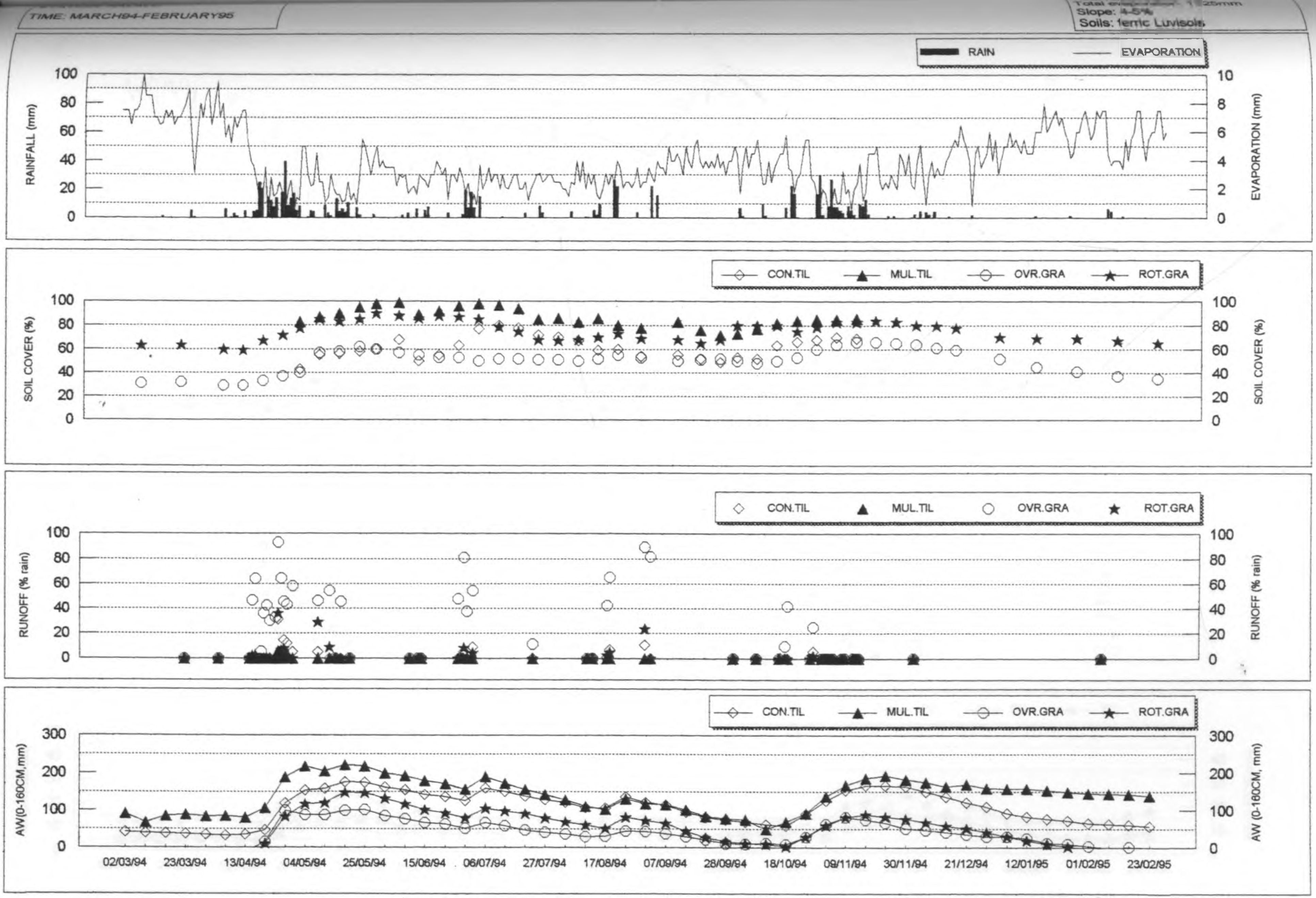


Figure 4.25 Rainfall, evaporation, soil cover, runoff and available soil water at Kalala from March 1994 to February 1995

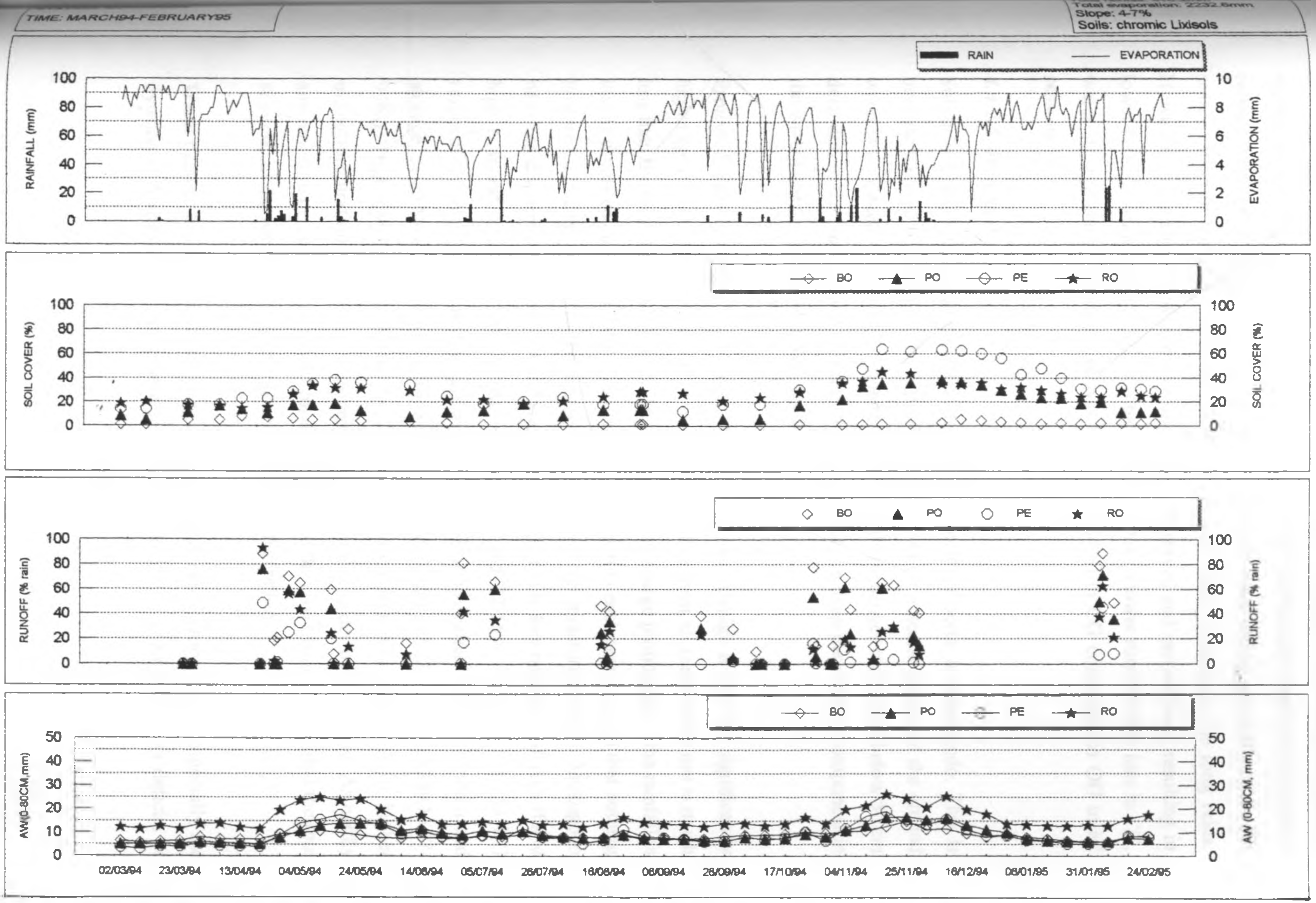


Figure 4.26 Rainfall, evaporation, soil cover, runoff and available soil water at Mukogodo from March 1994 to February 1995.

grass biomass in the former. Since there was no deep drainage, the water used mainly represents actual evapotranspiration. When compared to the climatic water demand, which reflects water requirement, it shows that there was a high water deficit especially in the SR season. In crop land, MT used more (18-42%) water than CT during the long rains. However, in the short rains, some moisture was conserved and carried over, resulting in lower (10-26%) water use in MT compared to CT. Due to lower runoff water loss in CG, water storage and subsequent use was higher (21-24%) in CG compared to OG in all seasons.

4.4.2.3 Mukogodo

Subsurface water flow and capillary rise were unlikely to occur at Mukogodo. This is because the area is semi-arid, the experimental site was on a gentle slope and the ground water is very deep. Soil moisture monitoring indicated no changes took place below 50 cm deep during the study period. Therefore this ruled out the deep percolation component in the water balance equation for Mukogodo.

Protected grass cover (PE) had the most water use, even though it was not significantly higher ($p<0.05$) than the other soil cover conditions. In almost all cases water use is much less than the rainfall in each season. This is so because a large proportion of the rainfall is lost as runoff and any available moisture is depleted within each season, such that nothing is stored and carried over to the next season. The low soil moisture status at Mukogodo has been discussed in section 4.4 and was mainly attributed to low rainfall, high runoff and high evaporative demand. Water use was 13-20% and 32-55% lower in PO and BO respectively, than RO in all four growing seasons. Due to higher water infiltration and storage, at all times PE used significantly more water than PO (23-61%) and BO (57-95%). High (8-33%) water use by PE compared to RO was attributed to higher evapotranspiration by grass in the open compared to that under bush canopy. As hardly any moisture percolated beyond 50 cm depth in any of the cover conditions within the four seasons, all the water used represents actual evapotranspiration.

Water balance for periods of six months does not give satisfactory results, especially the dynamics. Analysis over short time intervals would give a clear picture as deficits or surpluses during critical crop growing periods are shown. Therefore computations were carried out and the results are presented in Appendices A13 to A15, where weekly water balance data for each site for two growing seasons, that is, for a period one year are tabulated.

4.4.3 Implications for plant growth and soil water management

The rainfall received is seldom the same as plant requirement; either rainfall is too high or far too low. The soil therefore becomes important in water storage during times of surplus water and make it available in times of deficit. When ETa (amount of water in mm day^{-1}) is less than ETo, then we have a period of deficit and plants will get water stress. This may lead to slow or retarded growth, and if water is not replenished, the plant has to die or go dormant.

If the runoff is high, then the effective rain is greatly reduced. There is need to reduce runoff, especially on grazing land, where most of the water is lost. Once, infiltration is enhanced, water stored in the profile is conserved under mulch tillage. This water would lengthen the growing period and ultimately increase the chances of obtaining yields or improved biomass production on grazing land. In order to improve the effectiveness of rainfall, runoff should be minimized while water storage and availability to meet evapotranspiration requirements should be maximized. However, high ETa does not necessarily mean effective and efficient water use, as it could be as a result of excessive direct evaporation loss from the soil surface or transpiration by unwanted plants like weeds. Therefore to compare water demand with measured water use, respective crop coefficients and water use coefficients should be compared (Liniger, 1991a).

Deep percolation occurs at Karuri. This is important as it recharges ground water, which is the key source to the flow of the perennial rivers. The relatively high rainfall, low runoff and evaporation lead to a favourable water balance. At Kalalu deep percolation is rare, but in seasons with above average rainfall (400-600 mm), it is likely to occur in crop land. However, most water is lost as ET in both crop land and grazing land. Reduced storage and use means less biomass production in terms of crops and forage. Therefore on overgrazed land low storage leads to reduced available water for grass production. Since most rain falls within a short period, unless storage is conserved on crop land, most of the water is lost as evaporation before crops can use it. Therefore conservation techniques necessary to retain water long enough for plants to appropriate are required. Since runoff was reduced to a minimum in MT and CG on crop land and grazing land respectively at Kalalu, the two conservation measures were effective in increasing available water for use in biomass production.

Controlled grazing treatments had low runoff but high water use. The result from Kalalu points out that improvement of grasslands involves consideration of two opposing hydrological features. A critique by Pereira (1973) points out that control of grazing to prevent exposure of the soil and trampling is essential to reduce runoff and curb soil erosion. However, improving the density and productivity of grass land because of high water use decreases soil water storage. At Mukogodo, high water loss due to runoff and evaporation, results in a negative water balance even during the rainy period. The consequence of this is increased vegetation cover degradation, reduced biomass production, and therefore the carrying capacity of the rangeland.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The Upper Ewaso Ng'iro Basin has generally low rainfall which is poorly distributed and very variable while potential evaporation is high especially in the basement area. All 3 sites had negative climatic water balance as the ratio of average total annual rainfall to potential evaporation was 0.65, 0.47 and 0.16 for Karuri, Kalalu and Mukogodo respectively. Therefore this makes water the most limiting factor for rainfed crop and forage production.

At least 230 and 260 mm of plant available water can be stored at Karuri and Kalalu respectively within a depth of 160 cm. Despite limited depth, up to 90 mm of water can be stored at Mukogodo within a depth of 80 cm under good vegetation cover. Therefore given adequate rains and water conservation techniques, these soils have moderate to high potential of plant available water storage.

Soil cover reduction or total removal through tillage and overgrazing adversely affected topsoil physical properties that are important to water flow and storage in soils. Organic C decreased while bulk density increased after forest removal, in conventional tillage and in uncontrolled grazing. The changes in these properties were reflected in decreased total- and macro-porosity, decreased infiltration rates and conductivity of water; as well as reduction in available water storage. Reduction of water intake by soils under heavy grazing and conventional tillage was an indication of degradation of topsoil structure.

Runoff from both cropland and grazing land was low (<10%) at Karuri. This was attributed to preparation of furrows for potato seed placement and high soil cover in grazing land. Runoff from conventionally tilled plots at Kalalu within a growing season was low (about 10%). This was attributed to the gentle slope of the land. Virtually no water was lost as runoff under mulch tillage conditions because crop residue cover and reduced surface soil disturbance enhanced rain water infiltration. Due to low soil cover, compaction and sealing of surface soil, very high runoff was generated from overgrazed land at Kalalu and Mukogodo.

Despite protection from grazing for 6 growing seasons, hardly any change in amount of cover was observed on bare ground at Mukogodo. However, soil cover more than tripled on sites with some overgrazed perennial grass when protected for the same period. This indicated that bare sites required more than just closure to regenerate cover. Closure to grazing also reduced runoff from sites with perennial grass cover but not from those with bare ground. Therefore, because of high runoff, cover in bare ground would not recover. This means that the first step could be to improve infiltration, which may then lead to regeneration of ground cover. In the runon treatment, up to 50% of the water running from bare ground was intercepted and infiltrated. This experiment highlighted the key role bush canopy basal cover plays in reducing runoff in overgrazed rangelands. Therefore recognition should be given to different range site potentials while trying to implement any recovery measures.

Three key factors, that is, amount of soil cover, amount of rainfall and rainfall intensity significantly influenced runoff from both cropland and grazing land. Regression analysis indicated that soil cover was the most important factor, and that the relationship between rainfall and runoff was much stronger in low (<30%) cover than in high (>60%) cover conditions. Calculated minimum (threshold) amount of rainfall required to generate runoff increased with increase of soil cover. However, the range for cropland (11-14 mm day^{-1}) was narrower than for grazing land (6-12 mm day^{-1}), suggesting that apart from soil cover, other factors (e.g. surface roughness) would have contributed in generation of runoff in crop land. Analysis also indicated that there is a threshold of cover that is required to reduce runoff to a minimum especially in grazing land. Such results can be used to enforce controlled grazing to ensure that cover does not get below a certain threshold in which runoff will increase substantially.

Available soil water at Karuri was significantly higher in the forest than in grass and potato plots in both dry and rainy seasons. This indicated that forest removal for farming activities resulted in reduction of soil water storage. On the other hand, mulch tillage significantly improved moisture regime at Kalalu, by increasing rain water infiltration and storage, percolation deeper into the profile, and distribution within a growing season. Therefore mulch tillage apart from increasing available water for crops and extending the growing season, also created opportunity for growing deep rooted crops (e.g. intercroping with agroforestry trees). Clearing of weeds after crop harvest resulted in favourable moisture storage. The conserved moisture was carried over and used in the following growing season, therefore providing scope of planting early even before onset of rains. These positive attributes of mulch tillage suggest that adoption of a conservation tillage system would result in several benefits compared to the conventional method that is typical practice among the farmers at Kalalu.

Controlled grazing resulted in increased available water storage at Kalalu and Mukogodo, but due to high evaporatranspiration by grass, the water was completely depleted soon after the end of the rains. Even in the wettest period of the year, rain water hardly penetrated below 50 cm under good cover conditions at Mukogodo. The limitation in moisture storage was attributed to low rainfall, high surface runoff and high evaporative demand. This explains why the area does not have any potential for crop production under rain-fed conditions, but only suitable for range forage production.

Water balance computation revealed that deep percolation occurred at Karuri and that water use under grass and potato was higher than in forest. This implied that the forest extracted less water from within the monitored soil depth, allowing the highest contribution to deep percolation. More water was stored in all conservation treatments at Kalalu and Mukogodo and it was available for plant use. Therefore water use was higher in these systems. Because of high evapotranspiration by grass in the open compared to that under bush canopy, higher water use was recorded in PE than in RO at Mukogodo.

5.2 TOWARDS BETTER MANAGEMENT OF SOIL WATER

This study identified the soils potential and limitations in terms of rain water infiltration and storage under various land uses and management systems. A detailed overview of the soil water conditions in the 3 agroclimatic zones and partitioning of rainfall into runoff, soil storage and evapotranspiration were key results realized. These results would be applied as follows:

- Assess human impact on the ecosystems in changing land use or management practices
- Input to a model for investigating rainfall-runoff relationships and stream flow prediction from climatic data
- Determine the suitability of a crop for a given area in terms of growing period and cropping calendar.
- Assess irrigation requirement both in terms of quantity and interval of water application
- Assess water use by various crop types or varieties and evaluate water-yield relationships

No conservation methods were investigated at Karuri because this study acted as a diagnosis of the current land use effects on soil properties. It formed the basis for assessing whether there is need for conservation measures given the current management practices. There is need to conserve rain water at Kalalu by improving or changing the current methods used in production. Since rainy seasons are short relative to the growing period of crops, the most satisfactory measure would be soil moisture conservation. The degraded Mukogodo rangeland requires more drastic measures than just exclusion from grazing. Design of best approaches to solve the constrains in each area should aim at increasing water entry into soil, improve its storage and use by plants. A two pronged approach is recommended in formulating management guidelines that would create favourable soil water balance:

- Reduce runoff and increase soil water storage
- Reduce direct evaporation from soil surface and transpiration by unwanted plants.

5.2.1 Reducing runoff and increasing soil water storage

5.2.1.1 Karuri

Water is not a limiting factor for agricultural production at Karuri. However, reducing runoff will not only reduce soil erosion and nutrient loss, but will also result in increased infiltration and deep percolation.

- The forest should be conserved and protected as a water catchment area for recharge of ground water which is crucial for river flow that supply water to the lowlands.
- Feasibility of dry planting should be assessed as the soil contains appreciable moisture reserves even before the onset of rains. This would ensure maximum utilization of both growing seasons and also cover establishment before arrival of heavy storms that may lead to high runoff.
- Rough tillage across the slope and preparation of small furrows for potato seed placement should be maintained. This will increase surface detention and infiltration, both of which would reduce runoff in the early part of a rainy season.
- Apart from potatoes, other suitable crops should be sought to diversify production.
- With the high soil moisture status, fodder production would minimize grazing in the forest and also conserve soil. Terracing by growing fodder grass will provide strips of continuous cover across the slope at regular intervals. Excess fodder after meeting livestock needs may be laid as trash lines to reduce down slope soil movement. This will also replenish organic matter to maintain good soil structure.
- Design and laying of diversion channels and water ways is required for safe disposal of runoff water from roads and foot paths which are a main source of runoff.

5.2.1.2 Kalalu

The range of alternative crops that can be grown at Kalalu is narrow given the marginal climate. The scope for supplementary irrigation is also limited. Conservation of water in soil would be the most suitable and affordable practice for most farmers. These include:

- Use of crop residue mulch of at least 3 t ha^{-1} to increase infiltration and improve soil moisture regime. This would facilitate production of more water demanding crops. Availability of mulch material is of concern because it is also used as livestock feed.
- Mulching combined with minimum tillage would improve topsoil structure and maintain high infiltration. But reduced tillage may not be popular among farmers as they insist on preparation of seedbed to kill weeds.
- Moisture that percolates beyond the rooting depth of annual crops can be utilized by planting crop varieties or trees with deep roots e.g. practicing agroforestry. Experience with *Gravellia* species (Liniger, 1991a) has given favourable results and has been recommended to farmers. Agroforestry trees would provide mulch material to complement that from crop residue.
- Dry planting is possible under a mulch tillage system because of the availability of residual soil moisture. The risk of crop failure is low as relatively a smaller amount of rainfall would be required to start a crop during the following rainy season.
- Overgrazing is mainly common on unsettled plots due to indiscriminate grazing. Controlled grazing can only be effected if the unsettled plots were fenced and then leased to specified users. Supplement feeds like fodder crops (mainly napier grass) should be encouraged to reduce overgrazing.

5.2.1.3 Mukogodo

Traditionally the Masaai practiced seasonal movement to allow regeneration of the limited pasture. They also kept mixed species of livestock that fed on different plant species thus reducing competition on forage. Population increase and reduction of grazing land has led to overgrazing. The following remedial measures are proposed:

- Overgrazing will continue due to ever increasing population unless alternative grazing area is set aside to ease the current grazing pressure at Mukogodo. This proposal is beyond the scope of this study but it is a major constraint for improved soil water management. Reduction of livestock numbers is also not practical.
- Exclusion of livestock did not lead to vegetation regeneration on heavily degraded land. Hence the need for additional interventions like ripping and pitting the

crusted soil surface in order to increase infiltration. Reseeding with both annual and perennial grasses would then follow. Suitable species and time required for effective cover to establish should be investigated. However, this is an expensive preposition to execute and will require the cooperation of the people to keep away the livestock.

- A cheaper alternative would be placing cut tree branches or bushes on bare ground. These would trap plant litter and sediments, slow runoff water movement and create opportunity for infiltration. With moisture accumulation and increase of fauna activity, natural reseeding is expected to take place.
- Measures to improve cover should be timed to take advantage of periods of above average rainfall, when natural regrowth is possible even in heavily overgrazed areas. The process would be hastened if livestock are excluded for only a short period. A good example is the effect of *El Nino* rains of 1997/98 that has resulted in good regrowth. Further studies are needed to follow up whether above average rainfall would be relied on to trigger off grass recovery on bare sites.
- The scope of the runon treatment can be extended by deliberately diverting runoff water from bare ground onto under bush where it is expected to infiltrate. Such 'micro-catchments' will increase moisture storage and therefore biomass production under the canopy. With controlled grazing, cover would gradually spread out beyond the canopy, especially if creeping grasses like *Cynodon* species are available.
- Control of livestock numbers is essential, but in addition, control of their distribution is important. The latter measure would, for example, be effected by water development which must take place within an integrated programme.

5.2.2 Reducing direct evaporation and transpiration from unwanted plants

The two options available for this approach are to reduce evaporation or to adapt to the existing evaporative demand.

5.2.2.1 Karuri

- Evaporation can be reduced by keeping the cropland free of weeds by insisting on early land preparation. But this will expose soil to direct raindrop impact.

5.2.2.2 Kalalu

- Encouraging deep percolation would reduce the amount of rain water retained in the surface soil layer. Water stored in the subsoil will not easily evaporate unless through transpiration by weeds. Crops grown can then utilize this water.
- Mulching reduces direct evaporation from the soil surface. The main effect of mulch was found to be cutting down direct evaporation from the soil surface rather than by increasing infiltration at Kalalu.
- Ploughing the land soon after the end of a growing season will reduce moisture loss through transpiration of weeds. Minimum tillage ensures that only the soil surface is turned, thus reducing the surface area of topsoil that is exposed.
- Growing crops with low water requirements is a way of going around (cope with) the problem of high evaporative demand. Crop types or varieties that require less water, are drought tolerant or early maturing should be researched on. These would include potato, pulses and vegetables that are quick growing.

5.2.2.3 Mukogodo

- There is limited scope in reducing evaporation losses at Mukogodo. The plants growing in this area are adapted to the arid conditions. Due to overgrazing, unpalatable plant species (like *Solanum* and *Sansevieria*), which use up water but are not consumed by livestock, have invaded the rangeland. They compete with palatable plant species for the scarce soil water. Selective bush clearing is recommended to remove the unpalatable species.

5.2.3 Future challenges

Presently at Karuri the soils are still having high organic matter and porosity, but with continuous cultivation, degradation of soil structure is expected. This would result to increased runoff, soil erosion and consequently reduction of soil productivity. Further research is required to monitor imminent soil degradation and look for practical solutions that would prevent surface water runoff, especially on steeper slopes.

More investigations should be carried out using a disc permeameter at various potentials in order to monitor soil porosity changes with continued cultivation.

Assessment of pore size distribution would be a good indicator of the status of soil structure. Such data would explain and predict water movement and storage more precisely.

There is need to collect more data, especially on water moving beyond the root zone in order to partition plant water use into evapotranspiration and deep percolation. More investigations are also required to find out why the forest used less water than grass or potato crop from the 160 cm soil depth. The forest reserve in Karuri though under protection, is open to illegal grazing, timber and fuel wood harvesting. A challenge to the Forestry Department in the area should be to start tree nurseries to encourage tree planting by farmers settled next to the forest.

Mulching was found to be a viable option in conserving water in the semi-humid to semi-arid zone. The extra labour and expense of mulch application would be compensated by reduced labour input for tillage. However, a major constraint to its applicability is the alternative use of maize stover as livestock feed. Therefore mulching may not become popular or widespread in the area. But if alternative sources of mulch material like agroforestry and live fence are introduced and popularized, then competition for maize stover can be reduced. If complemented with minimum tillage and agroforestry, the scope of mulching can be greatly increased. There is need for further research on mulching on sloping land so as to compare results obtained in this study that was on gentle land.

A crop that would be grown successfully in Kalalu and areas with similar ecological conditions as an alternative to maize is potato. Research should be carried out on suitable varieties of potato in order to increase yields.

At Mukogodo, recognition must be given to different range site potentials while trying to implement the current findings. Efforts should be made to improve knowledge and strengthen training in rangeland ecology and hydrology and, in particular, cost-effective methods for reducing runoff, promoting infiltration and improving cover and biomass production. A holistic approach is required to manage the range resources (vegetation, water, soils and livestock), but foremost, local people should be involved in making and implementing decisions and in the search for better management systems. Through the Group Ranches management committees, security of tenure and land use rights should be established, either on communal or individual basis.

Finally, this study does not only put a challenge to ecologically-inclined researchers to adapt viable and feasible soil and water conservation approaches, but also to socio-economists for follow-up research in aspects that concern the actors' adaptations in different production systems.

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APPENDICES

Appendix A1 Soil moisture and ground cover monitoring frequency.

Soil moisture

	1992						1993												1994												1995											
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Karuri																	w	w	w	w	w	w	w	w	w	w	w			w	w	w	w	w	w	d	d	w	w	w	w	w
Kalalu	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	d	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w
Mokogodo					w	w	w	w	w	w	w	w	w	f	f	w	w	w	w	w	w	w	w	w	f	f	w	d	d	w	w	w	w	d	d	w	f	f	f	w	w	w

Ground cover

	1992						1993												1994												1995											
	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Karuri																	w	w	w	f	w	w	w	w	f	f	w	w	w	w	f	f	w	w	w	w	w	f	f	w	w	w
Kalalu grass	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	w	f	f	w	w	w	w	w	w	w	w	w	f	f	f	w	w	w	w	w	f	f	w	w
Kalalu crop	w	w	w	w	w					w	w	w	w	w	w	w					w	w	w	w	w	w	w	w	f	f	f	f	f	f	w	w	w	w	w	w	f	f
Mukogodo					w	w	w	f	w	w	w	w	f	f	f	f	w	w	f	f	f	f	f	f	f	f	f	f	w	w	w	w	w	w	w	w	f	f	f	f	w	w

Legend
d —— Daily data collection
w —— Weekly data collection
f —— Fortnightly data collection

Appendix A2 Bulk density for various treatments and soil layers.

Site	Land use	Bulk density (g/cm^3)^1		
		0-10 cm	20-30 cm	40-50 cm
Karuri	NF	0.73^{a1}	0.78^{a1}	1.02^{a2}
	GL	0.88^{ab1}	0.83^{a1}	0.97^{a1}
	PC	0.89^{b1}	0.92^{a1}	0.98^{a1}
Kalalu	CT	1.14^{b1}	1.18^{a1}	1.20^{a1}
	MT	1.01^{a1}	1.15^{a1}	1.23^{a1}
	OG	1.21^{b1}	1.20^{a1}	1.22^{a1}
	CG	1.17^{b1}	1.19^{a1}	1.23^{a1}
Mukogodo	RO	1.32^{a1}	1.48^{a2}	1.56^{a2}
	PO	1.46^{b1}	1.51^{a1}	1.53^{a1}
	PE	1.43^{ab1}	1.49^{a12}	1.54^{a2}
	BO	1.49^{b1}	1.54^{a1}	1.52^{a1}
	BE	1.51^{b1}	1.55^{a1}	1.56^{a1}

[1] Soil cores of 100cm^3 volume.

Each value is arithmetic mean from 5 replicates

For each site, means with the same letter and digit superscript within each column and row respectively, are not significantly different at $p<.05$ using Duncan's Multiple Range Test.

Appendix A3 Organic carbon content for various treatments and soil layers.

Site	Land use	Organic carbon content (% weight)[1]		
		0-10cm	20-30cm	40-50cm
Karuri	NF	14.1^{a1}	7.57^{a2}	1.42^{b3}
	GL	8.42^{b1}	6.93^{ab2}	3.90^{a3}
	PC	5.61^{c1}	5.59^{b1}	1.54^{b2}
Kalalu	CT	2.19^{b1}	0.87^{b2}	0.64^{a2}
	MT	3.13^{a1}	1.07^{ab2}	0.59^{a3}
	OG	0.91^{c1}	0.86^{b1}	0.57^{a1}
	CG	2.93^{ab1}	1.20^{a2}	0.54^{a3}
Mukogodo	RO	1.64^{a1}	0.86^{a2}	0.54^{a2}
	PO	0.94^{b1}	0.70^{ab12}	0.49^{a2}
	PE	1.33^{a1}	0.66^{ab2}	0.37^{a2}
	BO	0.43^{c1}	0.44^{b1}	0.29^{a1}
	BE	0.38^{c1}	0.31^{b1}	0.24^{a1}

[1] Each value is arithmetic mean of 3 composite replicates
For each site, means with the same letter and digit superscript within each column and row respectively, are not significantly different at $p<.05$ using Duncan's Multiple Range Test.

Appendix A4 Saturated hydraulic conductivity for various treatments and soil layers.

Site	Land use	Saturated hydraulic conductivity (cm h^{-1})[1]		
		0-10cm	20-30cm	40-50cm
Karuri	NF	19.03^{a1}	6.00^{a2}	2.69^{a3}
	GL	4.57^{b1}	2.50^{b2}	2.24^{a2}
	PC	7.23^{b1}	2.05^{b2}	1.70^{a2}
Kalalu	CT	2.27^{c1}	0.95^{b2}	1.48^{a12}
	MT	4.87^{b1}	1.79^{ab2}	1.82^{a2}
	OG	1.35^{c1}	2.65^{a1}	1.11^{a1}
	CG	9.93^{a1}	2.75^{a2}	2.16^{a2}
Mukogodo	RO	11.59^{a1}	5.11^{a2}	2.50^{a3}
	PO	5.24^{b1}	2.63^{ab2}	1.84^{a2}
	PE	9.31^{a1}	3.08^{a2}	2.36^{a2}
	BO	0.60^{c2}	1.55^{b1}	1.73^{a1}

[1] Soil cores of 100cm^3 volume

Each value is geometric mean from 5 replicates and those in brackets are the range

For each site, means with the same letter and digit superscript within each column and row respectively, are not significantly different at $p<.05$ using Duncan's Multiple Range Test.

Appendix A 5 Soil water retention ($m^3 m^{-3}$) for various soil horizons and topsoil conditions.

Soil profile horizons (means of 3 replicates)

KARURI

Pressure	Horizon depths (cm)			
head (cm)	0-18	40-72	72-112	112-160
1	0.6365	0.6045	0.5071	0.5181
100	0.4204	0.4437	0.4349	0.4167
341	0.3674	0.3892	0.3924	0.3774
516	0.3251	0.3614	0.3470	0.3446
1033	0.2913	0.3253	0.3255	0.3199
3100	0.2745	0.3016	0.3102	0.3058
5168	0.2698	0.2967	0.2957	0.2918
10330	0.2434	0.2858	0.2813	0.2767
15495	0.2397	0.2716	0.2683	0.2641
AWC	0.1277	0.1176	0.1241	0.1133

KALALU

Pressure	Horizon depths (cm)			
head (cm)	0-23	23-52	52-71	120-143
1	0.5617	0.5119	0.5673	0.4853
100	0.4115	0.4419	0.4531	0.4286
341	0.3704	0.3935	0.4038	0.3995
516	0.3506	0.3712	0.3818	0.3701
1033	0.3218	0.3552	0.3669	0.3525
3100	0.2912	0.3358	0.3458	0.3378
5168	0.2745	0.3157	0.3329	0.3126
10330	0.2616	0.2957	0.3169	0.2964
15495	0.2533	0.2855	0.2979	0.2874
AWC	0.1171	0.1080	0.1059	0.1121

MUKOGODO

Pressure	Horizon depths (cm)			
head (cm)	0-11	22-39	39-58	58-85
1	0.4344	0.4844	0.4550	0.4393
100	0.2945	0.3327	0.3513	0.3537
341	0.2865	0.3178	0.3225	0.3181
516	0.2698	0.2736	0.2789	0.2827
1033	0.2369	0.2677	0.2646	0.2586
3100	0.2153	0.2463	0.2483	0.2415
5168	0.2004	0.2237	0.2206	0.2167
10330	0.1852	0.2102	0.2145	0.2042
15495	0.1789	0.2049	0.2019	0.1966
AWC	0.1076	0.1129	0.1206	0.1215

Topsoil (0-10cm, means of 5 replicates)

KARURI

Pressure	Land use		
head (cm)	NF	GL	PC
1	0.6593	0.6248	0.5889
100	0.4054	0.4344	0.4449
341	0.3633	0.3917	0.3827
516	0.3416	0.3769	0.3635
1033	0.3178	0.3532	0.3476
3100	0.2826	0.3348	0.3153
5168	0.2603	0.3129	0.2966
10330	0.2386	0.2883	0.2827
15495	0.2219	0.2768	0.2641
AWC	0.1414	0.1149	0.1186

KALALU

Pressure	Management system			
head (cm)	CT	MT	OG	CG
1	0.5371	0.5616	0.4913	0.5776
100	0.4147	0.4045	0.4368	0.4283
341	0.3863	0.3824	0.3991	0.3932
516	0.3686	0.3682	0.3735	0.3692
1033	0.3531	0.3365	0.3667	0.3467
3100	0.3356	0.3064	0.3396	0.3245
5168	0.3152	0.2905	0.3299	0.3124
10330	0.2989	0.2759	0.3146	0.2954
15495	0.2813	0.2627	0.3082	0.2846
AWC	0.1050	0.1197	0.0909	0.1086

MUKOGODO

Pressure	Management system			
head (cm)	RO	PO	PE	BO
1	0.4629	0.4177	0.4443	0.3594
100	0.3043	0.3428	0.3356	0.3322
341	0.2845	0.3278	0.3335	0.3182
516	0.2482	0.2822	0.2716	0.2835
1033	0.2206	0.2648	0.2498	0.2687
3100	0.2079	0.2466	0.2321	0.2503
5168	0.1875	0.2386	0.2242	0.2490
10330	0.1676	0.2299	0.2165	0.2416
15495	0.1581	0.2233	0.2048	0.2396
AWC	0.1264	0.1045	0.1287	0.0786

Appendix A6 Infiltration rates (cm h^{-1}) measured by a double ring infiltrometer

KARURI				KALALU					MUKOGODO			
Time (min)	NF	GL	PC	Time (min)	CT	MT	OG	CG	Time (min)	RO	PO	BO
1	252.0	96.0	127.0	1	139.0	176.0	57.0	130.0	1	178.0	111.3	38.3
2	198.0	56.0	72.0	2	81.0	148.0	46.0	76.0	2	86.0	62.7	17.3
3	150.0	48.0	65.0	3	65.0	115.0	38.0	54.0	3	74.0	43.5	15.3
4	124.0	36.0	59.0	4	54.0	102.0	31.0	43.0	4	62.0	42.8	14.7
5	120.0	31.2	54.0	5	46.0	89.0	26.0	36.0	5	56.0	37.0	14.3
6	116.3	28.6	49.0	6	43.6	86.0	21.0	33.0	6	54.0	32.2	13.3
7	111.6	27.3	46.0	7	43.0	83.0	18.0	31.6	7	50.0	30.0	13.2
8	102.4	24.9	43.0	8	42.5	80.9	16.9	28.3	8	49.0	28.3	12.9
9	96.4	25.0	39.0	9	41.6	79.2	15.3	27.0	9	46.0	22.3	12.6
10	99.7	23.6	36.0	10	40.3	76.3	14.7	25.5	10	46.0	22.0	12.3
12	91.5	22.0	33.3	12	39.0	75.1	15.3	24.0	12	39.0	20.8	11.3
14	87.9	21.4	31.5	14	38.3	73.4	14.0	23.4	14	37.0	17.2	10.7
16	88.3	21.0	29.7	16	37.4	71.7	14.6	24.0	16	36.8	16.6	10.9
18	83.4	20.3	25.9	18	36.9	70.3	14.3	23.9	18	35.9	16.0	10.6
20	85.1	19.6	21.7	20	35.9	66.9	14.0	23.9	20	35.2	15.8	10.5
25	80.3	18.3	17.6	25	35.6	67.0	13.7	23.0	25	34.7	15.3	9.1
30	78.9	18.9	15.3	30	35.0	65.4	14.0	21.6	30	34.3	14.0	8.6
35	76.2	18.0	13.5	35	34.9	63.1	13.7	23.0	35	33.6	14.1	7.5
40	77.4	17.5	13.6	40	34.3	63.3	13.7	22.9	40	33.6	13.8	6.2
45	72.6	16.3	11.9	45	33.6	63.3	11.3	23.0	45	33.5	12.5	6.8
50	74.1	16.6	12.1	50	33.1	63.6	10.8	22.1	50	33.6	12.2	6.0
55	73.3	15.3	10.5	55	33.3	61.2	11.0	21.3	55	33.2	12.3	6.6
60	70.8	15.3	9.7	60	33.1	59.4	10.8	21.5	60	32.4	12.0	6.5
75	71.5	14.2	10.1	75	32.4	59.0	9.3	20.9	75	31.4	11.9	6.6
90	69.3	13.4	9.6	90	31.6	57.1	9.6	21.3	90	30.8	11.6	6.3
105	66.3	13.1	9.5	105	31.6	57.3	9.3	21.3	105	30.8	11.6	6.5
120	65.7	13.4	9.7	120	31.9	57.3	9.3	21.3	120	30.3	11.4	6.7

Appendix A7 Monthly and annual total rainfall (mm) for the period 1992-1995

KARURI

Month	1992	1993	1994	1995	Mean
Jan		127.1	1.8	10.0	46.3
Feb		64.5	27.3	35.7	42.5
Mar		2.7	19.9	70.8	31.1
Apr		54.3	199.2	139.4	131.0
May		181.9	239.2	74.4	165.2
Jun		74.0	49.5	39.7	54.4
Jul		33.8	32.9	102.0	56.2
Aug	52.4	37.6	112.0	39.7	60.4
Sep	28.8	49.7	9.8	74.6	40.7
Oct	45.3	0.0	109.2	100.0	63.6
Nov	44.0	87.1	172.1	61.0	91.1
Dec	62.2	30.5	38.6	46.4	44.4
Total		743.2	1011.5	793.7	827.0

KALALU

Month	1992	1993	1994	1995	Mean 1992-95	Mean 1986-95
Jan	7.1	174.2	0.0	1.2	45.6	30.5
Feb	0.0	32.2	28.3	11.0	17.9	18.4
Mar	4.0	0.0	6.8	67.9	19.7	52.3
Apr	77.3	65.7	212.9	178.0	133.5	143.3
May	43.3	141.6	84.7	146.1	103.9	96.2
Jun	21.4	42.7	55.8	50.1	42.5	53.1
Jul	49.5	1.7	55.7	24.6	32.9	52.5
Aug	84.5	38.9	73.3	70.7	66.9	64.2
Sep	32.2	51.1	21.9	88.8	48.5	50.4
Oct	45.8	26.1	112.7	46.0	57.6	56.4
Nov	23.2	83.7	114.3	69.6	72.7	76.5
Dec	81.0	15.5	20.4	93.9	52.7	43.6
Total	469.3	673.4	786.8	847.9	694.3	737.5

MUKOGODO

Month	1992	1993	1994	1995	Mean 1992-95	Mean 1989-95
Jan	2.2	114.4	0.0	0.0	29.1	19.6
Feb	0.1	5.5	11.2	57.0	18.4	16.1
Mar	5.9	3.2	22.3	56.9	22.1	26.2
Apr	43.5	9.7	45.7	31.5	32.6	63.5
May	7.9	49.5	67.4	72.0	49.2	36.9
Jun	11.4	37.4	15.4	2.5	16.7	12.3
Jul	30.1	14.6	40.1	28.2	28.2	32.0
Aug	15.0	22.4	33.2	14.5	21.3	15.5
Sep	3.5	0.0	4.6	49.9	14.5	9.9
Oct	25.8	16.9	43.9	53.1	34.9	40.4
Nov	30.3	27.0	63.7	19.9	35.2	50.3
Dec	71.6	1.0	24.1	35.6	33.1	41.2
Total	247.3	301.6	371.6	421.1	335.4	359.0

Appendix A8 Monthly and annual total pan evaporation (mm) for the period 1992-1995

KARURI

Month	1992	1993	1994	1995	Mean
Jan		92.6	168.8	126.5	129.3
Feb		110.5	153.4	141.2	135.0
Mar		183.7	196.0	164.2	181.3
Apr		131.8	131.7	94.1	119.2
May		82.1	76.7	93.9	84.2
Jun		70.6	74.5	98.8	81.3
Jul		70.8	62.4	72.4	68.5
Aug	69.6	75.6	54.4	78.7	69.6
Sep	89.8	82.7	103.8	95.2	92.9
Oct	82.3	111.3	119.7	122.1	108.8
Nov	104.5	100.1	70.6	69.0	86.0
Dec	105.8	121.4	110.6	115.6	113.3
Total		1233.2	1322.6	1271.7	1269.6

KALALU

Month	1992	1993	1994	1995	1992-95 Mean	1986-95 Mean
Jan	161.1	110.7	205.5	175.2	162.1	175.7
Feb	209.0	101.3	188.3	165.5	177.6	188.7
Mar	227.7	121.2	228.8	152.4	207.2	198.5
Apr	159.3	128.3	128.4	96.0	125.9	122.9
May	106.3	110.7	85.7	93.6	92.8	100.5
Jun	119.9	101.3	83.2	109.1	100.1	100.8
Jul	97.5	121.2	81.2	81.6	90.2	98.5
Aug	103.6	128.3	93.7	106.2	102.4	103.4
Sep	110.7	110.1	115.9	113.7	112.6	117.7
Oct	101.3	120.6	113.2	116.5	112.9	119.8
Nov	121.2	101.8	74.7	94.1	97.9	109.4
Dec	128.3	147.3	124.8	133.9	133.6	140.0
Total	1645.9	1454.8	1523.4	1437.8	1515.5	1576.0

MUKOGODO

Month	1992	1993	1994	1995	1992-95 Mean	1989-95 Mean
Jan	196.6	109.8	244.5	231.0	195.5	199.2
Feb	253.1	152.5	220.7	191.0	204.3	206.9
Mar	259.9	228.4	259.1	186.4	233.4	228.7
Apr	198.7	193.2	204.9	173.0	192.5	187.3
May	206.9	142.1	170.7	158.2	169.5	173.2
Jun	191.9	147.4	157.6	190.5	171.8	172.3
Jul	167.6	165.1	151.6	143.2	156.9	153.0
Aug	163.5	177.4	143.2	199.0	170.8	170.4
Sep	198.9	211.0	235.1	192.9	209.5	206.2
Oct	215.8	221.5	189.9	198.4	206.4	198.8
Nov	194.3	161.0	130.7	152.4	159.6	156.2
Dec	141.6	194.5	170.6	182.1	172.2	163.7
Total	2388.8	2103.9	2278.6	2198.1	2242.4	2215.9

Appendix A9 Longterm (5-10 years) Penman evapotranspiration (ET) and pan evaporation (Ep) for Embori (near Karuri), Kalalu and Matanya (0^{0}04' S/36^{0}57.5' E, semi-arid zone)

		EMBORI			KALALU			MATANYA		
Month	Decade	ET	Ep	ET/Ep	ET	Ep	ET/Ep	ET	Ep	ET/Ep
Jan	1	4.2	4.7	0.90	4.9	5.1	0.96	5.1	4.5	1.14
Jan	2	4.4	5.0	0.87	5.4	6.0	0.91	5.6	5.0	1.12
Jan	3	4.4	5.2	0.85	5.7	6.4	0.88	6.5	5.3	1.21
Feb	4	4.7	5.7	0.83	5.8	6.9	0.83	6.1	6.1	1.00
Feb	5	4.1	5.5	0.75	5.7	7.0	0.81	6.0	5.7	1.04
Feb	6	5.2	6.9	0.75	6.3	7.6	0.82	6.0	6.0	1.01
Mar	7	4.8	6.0	0.81	5.6	6.7	0.84	5.9	5.7	1.03
Mar	8	5.0	6.0	0.83	5.7	6.8	0.84	5.7	5.4	1.06
Mar	9	4.7	5.4	0.87	5.2	5.8	0.89	5.2	4.6	1.13
Apr	10	4.6	5.1	0.90	4.6	4.9	0.94	4.7	4.7	1.00
Apr	11	3.9	4.5	0.86	4.0	4.2	0.95	4.7	4.3	1.09
Apr	12	3.6	3.6	1.01	3.4	3.2	1.06	4.5	4.3	1.05
May	13	3.4	3.9	0.88	3.9	3.7	1.07	4.4	4.8	0.93
May	14	2.9	3.0	0.96	3.6	2.8	1.28	4.7	5.0	0.94
May	15	3.4	3.6	0.96	4.0	3.3	1.22	5.2	5.5	0.94
Jun	16	2.8	3.1	0.90	3.9	3.1	1.28	5.0	5.0	1.00
Jun	17	2.8	3.2	0.87	3.8	3.1	1.21	4.9	5.0	0.98
Jun	18	3.1	2.8	1.11	4.1	3.3	1.24	4.9	5.4	0.92
Jul	19	2.9	2.3	1.25	3.7	3.0	1.26	4.8	5.1	0.93
Jul	20	2.5	2.2	1.12	3.6	3.0	1.20	4.6	5.0	0.92
Jul	21	2.8	2.3	1.20	3.5	3.2	1.11	4.7	5.6	0.84
Aug	22	3.2	2.7	1.21	3.9	3.1	1.25	4.9	5.7	0.85
Aug	23	3.4	2.9	1.19	4.0	3.2	1.24	5.0	6.0	0.83
Aug	24	3.3	3.0	1.12	4.1	3.3	1.23	5.3	6.2	0.85
Sep	25	3.9	3.3	1.18	4.2	3.7	1.13	5.5	6.5	0.84
Sep	26	4.4	4.0	1.08	4.5	3.9	1.14	6.3	6.8	0.92
Sep	27	4.4	4.1	1.07	4.5	4.2	1.09	5.8	6.6	0.88
Oct	28	4.3	3.9	1.11	4.6	3.9	1.19	5.8	6.1	0.95
Oct	29	4.2	3.8	1.09	4.3	3.7	1.18	4.7	5.0	0.94
Oct	30	3.6	3.2	1.13	4.1	3.1	1.34	4.7	4.2	1.12
Nov	31	3.2	3.2	1.01	3.5	3.3	1.06	4.3	4.0	1.08
Nov	32	3.7	4.4	0.85	3.7	3.7	0.98	4.1	3.7	1.11
Nov	33	3.5	3.4	1.04	4.2	3.7	1.12	4.1	3.6	1.14
Dec	34	3.7	4.0	0.93	4.2	3.9	1.07	4.1	3.5	1.17
Dec	35	3.8	4.3	0.87	4.5	4.6	0.97	4.2	4.0	1.05
Dec	36	4.0	4.7	0.85	5.0	5.2	0.96	4.8	4.5	1.07
Mean		3.8	4.0	0.98	4.4	4.3	1.07	5.1	5.1	1.00

Appendix A10 Rainfall characteristics and runoff at Karuri.

Date	Rainfall characteristics				Runoff			
	Amount	Intensity		Erosivity	% of rainfall		Amount (mm)	
	(mm)	I15	I30	EI30	GL	PC	GL	PC
11/09/93	29.6	39.6	37.6	46.1	6.3	17.4	1.86	5.15
02/11/93	10.4	12.0	9.6	2.8	0.0	0.0	0.00	0.00
05/11/93	9.9	11.2	11.0	3.1	1.1	1.9	0.11	0.19
11/11/93	28.5	38.4	22.0	21.7	4.5	4.4	1.29	1.26
20/11/93	10.1	4.8	4.4	0.8	1.1	2.2	0.12	0.22
25/11/93	10.9	11.6	6.0	1.2	0.0	0.0	0.00	0.00
13/12/93	5.3	4.4	3.0	0.3	0.0	0.0	0.00	0.00
14/12/93	11.6	10.0	8.0	2.0	0.0	0.8	0.00	0.10
12/02/94	13.3	10.8	8.8	2.7	0.0	0.0	0.00	0.00
15/02/94	11.0	7.2	6.0	1.5	0.0	0.0	0.00	0.00
25/03/94	7.7	9.2	6.8	1.3	0.0	0.0	0.00	0.00
06/04/94	20.7	14.0	11.8	6.6	0.6	0.0	0.13	0.00
09/04/94	8.2	2.0	6.4	1.2	0.0	0.0	0.00	0.00
10/04/94	6.8	7.6	5.4	0.8	0.0	0.0	0.00	0.00
13/04/94	8.0	4.4	3.8	0.6	0.0	0.0	0.00	0.00
19/04/94	6.1	11.2	8.4	1.5	0.0	0.0	0.00	0.00
21/04/94	34.5	20.8	17.6	16.9	1.1	5.8	0.39	2.00
22/04/94	14.8	10.8	6.2	2.2	0.8	2.3	0.11	0.34
24/04/94	14.0	16.8	11.8	4.4	0.9	4.1	0.13	0.57
26/04/94	17.1	23.2	17.6	9.1	1.0	18.5	0.17	3.17
27/04/94	7.9	16.0	12.6	2.9	0.0	24.9	0.00	1.97
29/04/94	26.4	60.4	39.8	42.7	9.8	42.5	2.59	11.23
30/04/94	14.8	7.2	5.2	1.8	0.0	0.0	0.00	0.00
01/05/94	28.4	38.8	21.2	20.9	1.6	44.3	0.46	12.57
05/05/94	17.2	34.4	25.8	17.2	2.5	34.9	0.43	6.01
13/05/94	45.1	31.6	26.6	44.2	5.8	44.8	2.59	20.20
14/05/94	6.8	9.2	7.4	1.2	0.0	1.9	0.00	0.13
15/05/94	12.8	16.4	13.0	4.7	0.0	0.7	0.00	0.09
16/05/94	12.4	16.0	13.2	5.5	0.6	1.9	0.08	0.24
17/05/94	8.5	18.4	12.0	3.3	0.0	0.0	0.00	0.00
18/05/94	5.0	8.5	6.2	0.6	0.0	0.0	0.00	0.00
19/05/94	31.3	64.4	51.2	68.7	7.7	26.7	2.41	8.36
22/05/94	18.9	35.6	18.6	12.0	1.8	11.7	0.33	2.21
23/05/94	17.4	33.6	27.8	17.8	8.7	22.7	1.51	3.95
09/06/94	17.2	22.6	19.8	11.8	1.7	1.1	0.29	0.20
28/06/94	7.3	26.0	14.6	4.1	2.9	0.0	0.21	0.00
30/06/94	13.7	20.8	12.6	5.4	1.6	2.3	0.22	0.32
02/07/94	11.2	21.2	17.4	6.5	5.0	15.4	0.56	1.72
15/07/94	9.1	11.2	8.6	1.8	0.0	0.0	0.00	0.00
25/07/94	5.6	10.0	7.4	1.1	0.0	0.0	0.00	0.00
10/08/94	8.2	8.8	8.2	1.7	0.0	0.0	0.00	0.00
11/08/94	24.2	26.8	25.6	19.4	3.0	2.1	0.73	0.51
15/08/94	16.6	15.2	10.8	4.8	0.0	0.0	0.00	0.00
19/08/94	9.5	18.0	14.8	4.6	0.0	0.0	0.00	0.00
20/08/94	5.9	6.4	5.4	0.6	0.0	0.0	0.00	0.00
21/08/94	29.9	33.2	26.0	26.3	4.8	2.6	1.45	0.79
11/10/94	22.7	28.0	20.0	14.1	1.7	0.8	0.39	0.19
13/10/94	5.0	4.4	4.0	0.4	0.0	0.0	0.00	0.00
19/10/94	11.8	9.6	8.4	2.7	0.0	0.0	0.00	0.00
21/10/94	33.5	10.8	8.4	7.1	0.5	0.4	0.17	0.15
23/10/94	5.1	3.6	3.2	0.3	0.0	0.0	0.00	0.00
31/10/94	9.2	6.0	4.4	0.8	0.0	0.0	0.00	0.00

Appendix A10 continued.

Date	Rainfall characteristics				Runoff			
	Amount	Intensity		Erosivity	% of rainfall		Amount (mm)	
	(mm)	I15	I30	EI30	GL	PC	GL	PC
04/11/94	18.1	5.2	5.2	1.9	0.3	0.6	0.06	0.10
06/11/94	22.5	13.6	9.0	5.3	0.8	1.9	0.17	0.42
07/11/94	29.6	14.4	11.6	9.1	1.0	1.5	0.30	0.46
08/11/94	6.1	5.6	4.0	0.5	0.0	0.0	0.00	0.00
09/11/94	9.0	16.4	9.6	2.2	0.0	4.4	0.00	0.40
10/11/94	11.2	10.6	7.4	1.3	0.0	2.2	0.00	0.25
13/11/94	13.5	12.2	8.3	2.0	0.0	1.7	0.00	0.23
26/11/94	11.2	12.0	9.0	2.7	0.0	0.0	0.00	0.00
05/12/94	13.0	8.4	7.6	2.4	0.0	0.0	0.00	0.00
08/12/94	5.8	11.6	5.8	1.0	0.0	0.0	0.00	0.00
01/01/95	8.3	4.3	2.3	0.5	0.0	0.0	0.00	0.00
09/02/95	24.5	17.2	12.2	8.7	0.0	0.0	0.00	0.00
02/03/95	16.9	10.0	7.0	2.7	0.0	0.0	0.00	0.00
04/03/95	14.8	26.8	13.4	6.7	0.0	0.0	0.00	0.00
06/03/95	7.0	2.4	0.0	0.0	0.0	0.0	0.00	0.00
23/03/95	10.9	10.8	6.4	1.5	0.0	0.0	0.00	0.00
24/03/95	6.7	3.4	2.7	0.4	0.0	0.0	0.00	0.00
25/03/95	11.0	10.2	8.3	3.3	0.0	0.0	0.00	0.00
04/04/95	16.6	21.0	16.2	12.9	0.0	0.0	0.00	0.00
05/04/95	14.3	17.6	14.2	5.9	1.1	0.4	0.15	0.06
10/04/95	5.1	3.6	2.2	0.6	0.0	0.0	0.00	0.00
12/04/95	5.2	7.2	5.4	1.0	0.00	0.00	0.03	0.02
19/04/95	10.6	38.8	20.6	9.1	0.00	0.00	0.00	0.00
28/04/95	14.6	54.8	27.6	17.9	7.7	21.7	1.13	3.17
29/04/95	5.0	3.2	3.0	0.2	0.4	1.0	0.02	0.05
30/04/95	14.7	21.5	17.3	6.9	0.0	0.0	0.00	0.00
01/05/95	5.7	6.2	4.5	0.3	0.0	0.0	0.00	0.00
06/05/95	5.8	8.6	6.6	1.1	0.0	0.0	0.00	0.00
11/05/95	16.1	17.3	11.5	4.4	0.0	0.0	0.00	0.00
12/05/95	12.5	20.7	16.4	11.2	2.3	12.2	0.29	1.52
15/05/95	8.4	12.7	10.3	4.2	0.0	0.0	0.00	0.00
19/05/95	10.6	38.8	20.6	9.1	0.0	0.0	0.00	0.00
28/05/95	14.6	54.8	27.6	17.9	5.0	2.1	0.73	0.31
07/06/95	7.0	11.5	9.6	1.4	0.0	0.0	0.00	0.00
28/06/95	13.2	8.8	5.6	1.8	0.0	0.0	0.00	0.00
29/06/95	10.2	11.2	10.2	2.8	0.0	0.0	0.00	0.00
06/07/95	11.3	16.3	11.5	4.2	3.1	0.7	0.35	0.08
08/07/95	5.4	13.2	10.0	1.6	0.0	0.0	0.00	0.00
10/07/95	18.4	26.0	24.4	16.2	3.7	14.9	0.68	2.74
13/07/95	13.5	18.0	15.2	6.7	1.7	9.7	0.23	1.31
14/07/95	23.9	36.0	27.8	26.7	15.2	62.6	3.63	14.96
28/07/95	9.6	6.8	5.8	1.3	0.0	0.0	0.00	0.00
30/07/95	7.1	7.6	7.4	1.3	0.0	0.0	0.00	0.00
03/08/95	5.0	4.8	4.8	0.5	0.0	0.0	0.00	0.00
05/08/95	15.3	19.6	13.0	6.4	0.3	12.6	0.04	1.93
08/08/95	7.7	17.2	9.6	2.2	0.0	6.5	0.00	0.50
29/08/95	5.8	8.7	5.8	1.9	0.0	0.0	0.00	0.00

Appendix A11 Rainfall characteristics and runoff at Kalalu.

Date	Rainfall characteristics				Runoff							
	Amount	Intensity		Erosivity	% of rainfall				Amount (mm)			
	(mm)	I15	I30	EI30	CT	MT	OG	CG	CT	MT	OG	CG
28/08/93	10.9	15.3	12.7	3.7	0.0	0.0	18.5	0.0	0.00	0.00	2.02	0.00
14/09/93	6.4	11.5	10.2	2.6	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
24/09/93	11.5	19.4	17.2	3.1	0.0	0.0	38.6	0.0	0.00	0.00	4.43	0.00
29/09/93	11.0	13.7	12.0	5.2	0.0	0.0	30.9	0.0	0.00	0.00	3.39	0.00
30/09/93	8.3	16.2	14.6	3.2	0.0	0.0	44.1	0.0	0.00	0.00	3.66	0.00
15/10/93	7.2	10.0	9.8	2.1	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
30/10/93	10.3	12.4	8.6	2.6	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
31/10/93	5.5	5.6	4.4	0.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
02/11/93	33.3	33.2	27.0	26.3	12.1	0.0	54.5	0.0	4.01	0.00	18.14	0.00
05/11/93	7.1	28.4	14.2	4.1	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
06/11/93	9.6	14.4	11.6	2.8	23.5	0.0	0.0	0.0	2.25	0.00	0.00	0.00
25/11/93	13.4	7.8	5.5	2.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
27/11/93	11.7	28.4	16.2	5.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
28/11/93	11.4	11.2	9.8	3.1	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
08/12/93	13.2	14.2	12.2	4.4	0.0	0.0	7.9	0.0	0.00	0.00	1.04	0.00
12/02/94	11.3	17.2	13.0	3.8	0.0	0.0	10.6	0.0	0.00	0.00	1.20	0.00
14/02/94	7.9	16.4	9.1	2.1	0.0	0.0	10.6	0.0	0.00	0.00	0.84	0.00
15/02/94	6.0	9.6	6.4	0.8	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
06/04/94	5.0	6.4	5.0	0.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
17/04/94	5.0	12.4	7.4	1.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
18/04/94	23.9	42.0	31.4	30.3	0.0	0.0	56.6	2.1	0.00	0.00	13.53	0.51
19/04/94	20.4	34.4	17.1	6.3	0.0	0.0	64.1	2.6	0.00	0.00	13.09	0.53
21/04/94	14.2				0.0	0.0	5.6	0.0	0.00	0.00	0.79	0.00
22/04/94	11.8				0.0	0.0	36.1	0.0	0.00	0.00	4.25	0.00
23/04/94	7.5				0.0	0.0	42.5	0.0	0.00	0.00	3.19	0.00
24/04/94	13.7				0.0	0.0	37.6	0.0	0.00	0.00	5.15	0.00
26/04/94	17.7				0.0	0.0	33.2	0.0	0.00	0.00	5.88	0.00
27/04/94	39.6	32.0	27.8	31.0	31.2	5.9	93.1	36.1	12.35	2.34	36.89	14.29
28/04/94	8.4	21.6	8.0	2.3	0.0	0.0	64.5	6.3	0.00	0.00	5.42	0.53
29/04/94	13.6	15.6	10.2	1.7	14.6	0.0	45.5	7.8	1.98	0.00	6.18	1.06
30/04/94	16.9	28.6	24.8	3.4	12.1	3.9	43.0	0.0	2.05	0.66	7.27	0.00
02/05/94	8.2	17.9	15.4	2.9	5.0	0.0	58.2	0.0	0.41	0.00	4.78	0.00
11/05/94	9.1	19.2	16.2	4.8	5.1	0.0	46.5	29.0	0.46	0.00	4.23	2.64
15/05/94	12.7	28.4	17.8	7.5	0.0	0.0	54.2	9.1	0.00	0.00	6.89	1.15
17/05/94	5.6	4.0	3.8	0.4	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
19/05/94	10.5	13.6	11.0	2.5	0.0	0.0	45.6	0.0	0.00	0.00	4.79	0.00
22/05/94	6.4	9.2	6.4	1.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
12/06/94	15.7	39.6	29.2	18.2	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
16/06/94	7.6	16.8	14.2	3.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
29/06/94	18.9	20.8	17.0	9.5	0.0	0.0	47.6	0.0	0.00	0.00	8.99	0.00
01/07/94	17.9	32.8	29.4	17.9	5.2	0.0	81.0	8.1	0.93	0.00	14.50	1.45
02/07/94	7.1	10.4	9.2	1.9	0.0	0.0	37.5	0.0	0.00	0.00	2.66	0.00
04/07/94	13.5	22.8	22.2	11.1	8.9	0.0	54.3	4.5	1.20	0.00	7.32	0.61
25/07/94	8.1	24.4	13.2	3.5	0.0	0.0	11.4	0.0	0.00	0.00	0.92	0.00
16/08/94	5.5	13.2	8.6	1.3	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
18/08/94	6.8	23.2	13.4	3.3	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
20/08/94	18.0	44.0	25.4	16.8	0.7	0.0	42.7	2.5	0.13	0.00	7.68	0.45
21/08/94	20.9	32.8	22.2	15.9	6.8	0.0	65.0	4.9	1.42	0.00	13.59	1.02
02/09/94	21.4	43.2	39.2	35.6	10.6	0.0	89.2	23.5	2.26	0.00	19.09	5.03
19/09/94	6.1	6.0	5.6	0.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
03/10/94	5.9	8.8	8.8	0.9	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00

Appendix A11 continued.

Date	Rainfall characteristics				Runoff							
	Amount	Intensity		Erosivity	% of rainfall				Amount (mm)			
	(mm)	I15	I30	EI30	CT	MT	OG	CG	CT	MT	OG	CG
11/10/94	9.0	13.2	7.6	1.9	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
19/10/94	6.1	6.0	5.6	0.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
21/10/94	13.8	28.4	16.2	7.1	0.0	0.0	9.5	0.0	0.00	0.00	1.31	0.00
22/10/94	16.8	31.4	24.7	10.6	0.0	0.0	41.7	0.0	0.00	0.00	7.00	0.00
30/10/94	16.6	23.6	15.8	8.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
31/10/94	14.8	15.2	13.8	6.2	8.5	0.0	38.8	3.1	1.26	0.00	5.74	0.46
02/11/94	8.0	8.0	6.0	1.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
03/11/94	25.0	91.6	46.4	55.7	32.5	3.0	45.7	13.9	8.12	0.74	11.42	3.46
04/11/94	6.7	2.0	2.0	0.2	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
05/11/94	7.7	12.0	8.2	1.7	0.0	0.0	13.6	0.0	0.00	0.00	1.05	0.00
06/11/94	5.0	7.8	4.4	1.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
09/11/94	9.4	18.0	11.2	2.9	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
10/11/94	9.4	14.8	10.2	2.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
13/11/94	14.9	18.8	12.2	4.3	0.0	0.0	31.1	0.0	0.00	0.00	4.64	0.00
14/11/94	9.2	7.6	5.2	1.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
15/11/94	12.2	15.6	14.8	5.2	10.0	0.0	61.6	0.0	1.21	0.00	7.51	0.00
08/02/95	5.7	6.0	4.0	0.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
02/03/95	46.0	32.8	30.4	50.1	0.0	0.0	22.1	0.0	0.00	0.00	10.17	0.00
05/03/95	13.0	17.2	14.4	5.9	0.0	0.0	14.7	0.0	0.00	0.00	1.91	0.00
05/04/95	11.7	20.4	10.6	4.3	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
06/04/95	19.4	27.2	16.0	10.1	0.0	0.0	34.3	0.0	0.00	0.00	6.64	0.00
12/04/95	5.0	3.2	3.0	0.2	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
13/04/95	28.1	42.6	37.8	35.4	15.4	0.0	51.4	1.9	4.33	0.00	14.44	0.54
14/04/95	31.2	34.6	31.9	13.7	44.6	1.7	78.4	5.9	13.90	0.54	24.47	1.85
19/04/95	12.8	17.6	14.4	5.2	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
20/04/95	5.0	22.4	19.2	1.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
24/04/95	15.8	31.6	27.6	21.3	6.4	0.0	48.0	0.0	1.01	0.00	7.58	0.00
27/04/95	7.3	3.6	2.3	0.2	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
29/04/95	17.5	14.8	10.6	5.1	0.0	0.0	29.5	0.0	0.00	0.00	5.16	0.00
30/04/95	12.7	79.2	40.0	51.2	0.0	0.0	37.7	0.0	0.00	0.00	4.79	0.00
01/05/95	14.7	15.2	11.2	4.7	29.9	0.0	62.4	0.0	4.39	0.00	9.17	0.00
02/05/95	6.9	2.0	1.8	0.2	11.8	0.0	28.9	0.0	0.81	0.00	2.00	0.00
11/05/95	5.2	12.4	6.6	0.9	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
14/05/95	35.3	131.6	67.4	123.5	21.6	0.0	60.0	4.4	7.62	0.00	21.17	1.56
19/05/95	5.2	16.0	10.0	1.7	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
27/05/95	11.2	29.6	22.2	9.7	0.0	0.0	23.9	0.0	0.00	0.00	2.68	0.00
28/05/95	7.8	10.0	9.8	2.2	0.0	0.0	2.5	0.0	0.00	0.00	0.19	0.00
30/05/95	38.3	64.8	54.2	91.9	32.1	0.0	65.3	23.6	12.30	0.00	25.02	9.03
07/06/95	23.8	43.6	38.2	37.4	5.2	0.0	50.0	2.0	1.24	0.00	11.90	0.49
28/06/95	8.8	26.7	23.9	13.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
29/06/95	8.5	32.4	17.0	5.9	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
01/07/95	5.6	12.4	9.0	1.4	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
30/07/95	9.4	21.6	16.8	5.5	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00
13/08/95	57.3	70.4	51.8	89.7	24.1	6.3	66.2	23.6	13.84	3.63	37.92	13.50
01/09/95	32.5	32.0	31.2	38.4	3.5	0.0	33.8	0.0	1.15	0.00	10.99	0.00

Appendix A12 Rainfall characteristics and runoff at Mukogodo.

Date	Rainfall characteristics				Runoff									
	Amount	Intensity		Erosivity	% of rainfall					Amount (mm)				
	(mm)	I15	I30	EI30	BO	BE	PO	PE	RO	BO	BE	PO	PE	RO
30/11/92	8.6	13.6	6.8	1.2	33.2	39.3	13.5	0.0	1.4	2.86	3.38	1.16	0.00	0.12
06/12/92	7.9	20.2	11.6	1.8	29.7	33.6	11.6	0.0	2.6	2.35	2.65	0.92	0.00	0.21
10/12/92	20.7	38.4	24.0	10.6	52.2	56.3	24.1	12.0	20.9	10.81	11.65	4.99	2.48	4.33
12/12/92	10.1	6.0	5.0	0.4	34.8	40.6	11.1	0.8	5.6	3.51	4.10	1.12	0.08	0.57
17/12/92	22.5	38.0	24.6	11.8	78.7	79.5	55.5	39.8	39.0	17.71	17.89	12.49	8.96	8.78
27/12/92	5.0	6.8	4.4	0.6	24.9	31.8	1.3	0.0	0.0	1.25	1.59	0.07	0.00	0.00
07/01/93	25.6	16.0	12.0	5.6	75.9	84.0	43.6	8.3	29.5	19.43	21.50	11.16	2.12	7.55
13/01/93	6.6	3.2	3.0	0.4	17.6	23.0	0.0	0.0	0.0	1.16	1.52	0.00	0.00	0.00
16/01/93	5.5	5.2	2.6	0.3	15.4	17.2	1.0	0.0	4.1	0.84	0.95	0.06	0.00	0.23
17/01/93	4.8	9.6	4.8	0.7	23.8	26.6	1.9	0.0	1.3	1.14	1.28	0.09	0.00	0.06
18/01/93	8.0	6.4	5.8	1.3	48.2	51.9	5.1	0.0	5.0	3.86	4.15	0.41	0.00	0.40
19/01/93	8.2	9.2	7.0	1.9	49.0	52.6	10.8	0.7	11.7	4.02	4.31	0.89	0.06	0.96
20/01/93	14.4	22.8	22.6	10.8	66.2	68.4	41.0	14.2	35.2	9.53	9.85	5.90	2.04	5.07
29/01/93	32.5	26.0	17.0	7.9	45.7	47.9	10.6	1.3	15.9	14.85	15.57	3.45	0.42	5.17
10/02/93	5.1	20.8	10.5	2.3	19.8	20.9	0.0	0.0	2.0	1.01	1.07	0.00	0.00	0.10
27/03/93	3.2	3.2	3.2	0.2	2.0	4.3	0.0	0.0	0.0	0.06	0.14	0.00	0.00	0.00
18/04/93	7.9	6.8	6.4	1.1	4.8	13.0	0.0	0.0	0.0	0.38	1.03	0.00	0.00	0.00
06/05/93	11.9	60.0	31.0	22.2	91.2	91.8	62.7	26.4	59.9	10.85	10.92	7.46	3.14	7.13
11/05/93	5.4	26.8	15.0	4.3	92.0	96.9	27.4	0.0	25.4	4.97	5.23	1.48	0.00	1.37
12/05/93	6.3	7.6	7.2	1.3	49.8	53.3	15.0	0.0	16.0	3.14	3.36	0.95	0.00	1.01
20/05/93	17.3	65.6	39.0	36.7	92.8	88.7	64.7	28.1	54.0	16.05	15.35	11.19	4.86	9.34
08/06/93	8.0	16.4	13.4	3.7	29.9	41.4	0.0	0.0	1.4	2.39	3.31	0.00	0.00	0.11
09/06/93	12.6	6.4	5.8	1.8	19.8	30.0	2.2	0.0	1.5	2.49	3.78	0.28	0.00	0.19
10/06/93	7.1	4.8	4.4	0.6	10.7	10.0	0.0	0.0	0.0	0.76	0.71	0.00	0.00	0.00
11/06/93	6.5	6.4	4.6	0.3	7.3	11.2	0.0	0.0	0.0	0.47	0.73	0.00	0.00	0.00
18/07/93	14.6	43.2	25.4	13.7	56.8	60.5	28.8	0.5	22.3	8.29	8.83	4.20	0.07	3.26
05/08/93	9.8	32.0	23.0	12.1	60.2	54.8	19.6	0.9	12.7	5.90	5.37	1.92	0.09	1.24
26/08/93	12.6	28.0	27.2	15.1	71.8	48.8	30.0	0.0	0.0	9.05	6.15	3.77	0.00	0.00
30/10/93	8.8	10.0	7.0	1.3	26.0	15.6	0.0	0.0	0.0	2.29	1.37	0.00	0.00	0.00
31/10/93	5.3	16.4	10.4	2.8	69.4	52.2	26.1	0.0	12.6	3.68	2.76	1.38	0.00	0.67
01/11/93	8.2	16.8	11.8	3.1	64.0	46.8	34.1	0.0	0.0	5.25	3.84	2.79	0.00	0.00
28/11/93	7.8	12.0	11.2	3.5	62.2	46.4	11.8	0.0	9.0	4.85	3.62	0.92	0.00	0.70
12/02/94	6.5	9.2	5.0	0.6	8.6	11.2	0.0	0.0	3.1	0.56	0.73	0.00	0.00	0.20
14/02/94	2.6	10.4	5.3	0.5	13.4	13.9	0.0	0.0	0.0	0.35	0.36	0.00	0.00	0.00
15/02/94	2.1	5.2	3.8	0.2	6.2	4.8	0.0	0.0	0.0	0.13	0.10	0.00	0.00	0.00
25/03/94	8.5	10.4	7.6	1.9	38.6	30.1	1.0	0.0	2.2	3.28	2.56	0.09	0.00	0.19
28/03/94	7.6	15.6	14.2	3.9	60.3	46.9	28.8	2.3	21.6	4.58	3.57	2.19	0.17	1.64
21/04/94	5.5	5.6	4.6	0.5	9.3	9.9	0.0	0.0	0.0	0.51	0.54	0.00	0.00	0.00
22/04/94	21.3	48.0	41.4	40.9	88.4	90.7	76.1	48.7	75.5	18.83	19.32	16.20	10.37	16.08
26/04/94	7.4	5.2	3.0	0.5	18.3	15.1	0.9	0.0	2.4	1.35	1.12	0.07	0.00	0.18
27/04/94	4.9	9.6	6.8	0.9	28.2	21.0	1.9	0.0	1.4	1.38	1.03	0.09	0.00	0.07
01/05/94	19.0	33.2	26.2	18.4	70.2	71.1	61.0	25.2	39.2	13.34	13.51	11.58	4.79	7.44
05/05/94	16.6	45.6	30.2	19.8	65.0	67.2	57.2	40.2	45.7	10.79	11.16	9.50	6.68	7.59
16/05/94	15.5	24.4	17.8	9.8	61.8	51.4	44.9	3.2	27.3	9.59	7.97	6.95	0.49	4.23
17/05/94	3.2	7.2	4.4	0.3	7.6	1.7	0.0	0.0	0.0	0.24	0.05	0.00	0.00	0.00
22/05/94	6.5	9.2	9.0	1.9	20.0	19.1	0.7	0.0	0.7	1.30	1.24	0.04	0.00	0.04
11/06/94	6.3	16.4	10.4	2.1	30.8	23.3	2.5	0.0	6.9	1.94	1.47	0.16	0.00	0.44
29/06/94	2.9	6.8	4.8	0.3	40.0	15.4	0.0	0.0	0.0	1.16	0.45	0.00	0.00	0.00
01/07/94	12.2	23.6	18.0	8.0	80.9	68.8	55.7	17.0	41.8	9.86	8.39	6.80	2.08	5.09
12/07/94	21.8	41.2	30.0	27.0	65.8	66.2	60.0	23.3	35.2	14.34	14.44	13.08	5.09	7.67
18/08/94	11.4	20.0	15.2	5.0	46.2	34.0	24.6	0.6	15.3	5.27	3.88	2.81	0.07	1.74
20/08/94	6.8	6.0	5.4	0.9	18.6	19.9	5.4	0.0	0.6	1.26	1.36	0.37	0.00	0.04

Appendix A12 continued.

Date	Rainfall characteristics				Runoff									
	Amount	Intensity		Erosivity	% of rainfall					Amount (mm)				
	(mm)	I15	I30	EI30	BO	BE	PO	PE	RO	BO	BE	PO	PE	RO
21/08/94	9.2	20.8	14.4	4.3	42.0	34.4	33.9	10.8	26.1	3.87	3.16	3.12	0.99	2.40
22/09/94	4.6	11.2	9.4	1.4	38.3	39.3	28.5	0.0	23.4	1.76	1.81	1.31	0.00	1.08
03/10/94	6.9	7.6	6.4	1.5	28.0	21.5	5.0	2.3	3.5	1.93	1.48	0.34	0.16	0.24
11/10/94	5.1	6.4	5.2	0.7	9.6	7.1	0.0	0.0	0.0	0.49	0.36	0.00	0.00	0.00
13/10/94	3.6	17.2	8.6	1.4	51.9	44.4	38.4	0.0	16.1	1.87	1.60	1.38	0.00	0.58
21/10/94	11.7	6.8	6.6	2.1	47.3	52.7	26.4	13.1	15.9	5.53	6.17	3.09	1.53	1.86
31/10/94	16.6	17.6	10.4	7.9	77.5	62.4	53.8	16.3	11.8	12.87	10.36	8.93	2.71	1.96
01/11/94	3.8	5.2	3.6	0.3	14.1	14.3	6.1	0.6	1.5	0.54	0.54	0.23	0.02	0.06
07/11/94	6.5	5.2	3.6	0.5	14.4	12.2	0.0	0.6	0.0	0.94	0.79	0.00	0.04	0.00
11/11/94	11.1	12.4	10.4	3.1	69.1	70.3	61.7	11.6	19.6	7.67	7.80	6.85	1.29	2.18
13/11/94	23.4	8.0	7.2	3.7	43.6	31.2	24.1	1.2	13.6	10.21	7.30	5.64	0.28	3.18
21/11/94	2.1	4.4	3.0	0.2	13.8	11.9	3.9	0.0	3.2	0.29	0.25	0.08	0.00	0.07
24/11/94	9.0	12.8	6.8	0.8	65.4	58.8	61.0	15.5	25.6	5.88	5.29	5.49	1.39	2.30
28/11/94	3.5	7.2	4.6	0.3	63.2	45.4	29.5	3.5	29.8	2.21	1.59	1.03	0.12	1.04
05/12/94	13.9	20.4	12.4	4.5	42.5	30.5	22.4	0.8	17.1	5.91	4.23	3.11	0.12	2.37
07/12/94	6.2	16.0	9.0	2.1	40.9	28.9	14.7	0.0	7.6	2.54	1.79	0.91	0.00	0.47
08/02/95	23.4	29.0	26.3	32.5	79.0	78.0	49.9	7.1	37.7	18.49	18.25	11.68	1.65	8.82
09/02/95	24.8	39.6	39.0	40.7	88.6	86.8	71.6	45.5	62.4	21.97	21.53	17.76	11.28	15.48
13/02/95	8.8	28.4	14.8	4.6	48.9	36.5	35.9	7.9	21.1	4.30	3.21	3.16	0.70	1.86
02/03/95	35.2	23.6	19.4	22.0	65.4	66.1	58.4	8.8	42.3	23.01	23.27	20.57	3.11	14.89
03/03/95	21.8	15.6	14.6	9.8	69.0	69.8	64.8	5.6	51.5	15.05	15.22	14.13	1.22	11.23
06/03/95	5.1	11.6	9.0	1.4	46.4	46.1	5.5	0.0	3.2	2.36	2.35	0.28	0.00	0.16
10/03/95	10.3	17.5	11.8	4.9	58.7	62.9	40.5	1.5	47.6	6.04	6.48	4.17	0.16	4.90
10/04/95	17.0	27.2	19.6	10.2	64.1	59.4	43.1	13.2	33.5	10.89	10.10	7.33	2.25	5.70
27/04/95	11.6	4.8	4.6	1.1	38.4	41.2	12.3	1.7	9.9	4.46	4.78	1.43	0.19	1.15
29/04/95	5.4	5.6	4.2	0.4	21.9	17.6	2.9	0.0	4.4	1.18	0.95	0.16	0.00	0.24
01/05/95	4.0	5.2	4.2	0.4	13.5	15.6	4.4	0.0	3.7	0.54	0.62	0.18	0.00	0.15
02/05/95	4.9	10.6	5.7	0.5	35.0	34.4	14.6	0.0	6.2	1.72	1.68	0.71	0.00	0.31
05/05/95	10.0	26.8	18.2	6.5	64.1	64.2	37.5	7.1	37.5	6.41	6.42	3.75	0.71	3.75
10/05/95	9.8	21.6	19.0	6.9	52.5	56.9	24.9	0.0	18.1	5.14	5.58	2.44	0.00	1.77
11/05/95	29.1	59.6	30.8	37.0	69.3	71.2	60.8	16.8	49.9	20.18	20.71	17.69	4.90	14.51
16/05/95	21.0	41.6	22.8	18.6	68.7	62.9	63.5	10.5	47.6	14.42	13.22	13.33	2.21	9.99
06/07/95	5.0	12.8	8.0	1.2	0.0	0.0	0.0	0.0	0.0	0.00	0.00	0.00	0.00	0.00
10/07/95	6.7	8.4	4.6	0.6	18.2	15.3	5.0	0.0	0.0	1.22	1.03	0.33	0.00	0.00
11/07/95	6.9	18.0	10.0	2.0	21.3	22.5	10.2	0.0	6.5	1.47	1.55	0.71	0.00	0.45
14/07/95	7.0	12.8	10.0	1.9	40.4	35.0	4.0	0.0	0.0	2.83	2.45	0.28	0.00	0.00
20/08/95	11.4	21.2	17.2	6.9	44.1	39.3	20.0	3.9	13.6	5.03	4.48	2.28	0.45	1.55
04/09/95	13.7	26.0	19.6	9.5	52.1	63.8	12.9	0.0	20.2	7.14	8.74	1.76	0.00	2.76

Appendix A13 Soil water balance at Karuri (March 1994-February 1995)

Date	Period (Days)	Rainfall, P (mm)	Runof, R (mm)			Soil water change, S (mm/160 cm)			Water use, ETa+D (mm)		
			NF	GL	PC	NF	GL	PC	NF	GL	PC
05/03/94	8	4.2	0.0	0.0	0.0	-3.9	14.2	8.1	8.1	-10.0	-3.9
12/03/94	7	0.0	0.0	0.0	0.0	-2.8	-12.2	-2.2	2.8	12.2	2.2
19/03/94	7	1.1	0.0	0.0	0.0	6.8	-4.5	-4.2	-5.7	5.6	5.3
26/03/94	7	9.0	0.0	0.0	0.0	22.0	25.3	32.7	-13.0	-16.3	-23.7
02/04/94	7	5.4	0.0	0.0	0.0	2.7	9.6	-2.2	2.7	-4.2	7.6
09/04/94	7	24.6	0.0	0.1	0.0	9.9	6.2	3.5	14.7	18.3	21.1
15/04/94	6	26.9	0.0	0.0	0.0	2.5	8.5	-4.6	24.4	18.4	31.5
20/04/94	5	15.1	0.0	0.0	0.0	2.1	1.1	-5.2	13.0	14.0	20.3
27/04/94	7	85.3	0.0	0.8	6.1	3.3	0.6	-6.2	82.0	83.9	85.4
04/05/94	7	87.6	0.0	3.1	25.8	5.0	1.8	-14.7	82.6	82.8	76.5
11/05/94	7	23.1	0.0	0.4	6.0	4.4	1.9	-2.8	18.7	20.8	19.9
17/05/94	6	83.2	0.0	2.7	20.7	13.2	13.2	17.9	70.0	67.4	44.6
25/05/94	8	91.3	0.0	4.3	14.5	14.0	5.9	13.3	77.3	81.2	63.5
31/05/94	6	6.8	0.0	0.3	0.2	-12.6	-7.4	-11.6	19.4	14.0	18.2
09/06/94	9	0.0	0.0	0.0	0.0	-5.1	-10.8	-16.3	5.1	10.8	16.3
17/06/94	7	21.5	0.0	0.0	0.0	24.7	-8.3	-7.8	-3.2	29.8	29.3
23/06/94	7	0.0	0.0	0.0	0.0	-24.0	-4.0	-5.8	24.0	4.0	5.8
29/06/94	6	8.9	0.0	0.2	0.0	-3.2	-5.7	-6.2	12.1	14.4	15.1
07/07/94	8	31.8	0.0	0.8	2.0	19.7	-5.2	-0.1	12.1	36.2	29.8
13/07/94	6	2.9	0.0	0.0	0.0	-29.4	1.3	0.1	32.3	1.6	2.8
21/07/94	8	10.9	0.0	0.0	0.0	10.7	-5.4	-2.3	0.2	16.3	13.2
27/07/94	6	5.6	0.0	0.0	0.0	-9.3	-5.2	-5.8	14.9	10.8	11.4
03/08/94	7	0.0	0.0	0.0	0.0	-28.2	-11.6	-6.6	28.2	11.6	6.6
10/08/94	7	1.1	0.0	0.0	0.0	3.5	-1.6	-0.6	-2.4	2.7	1.7
17/08/94	7	54.1	0.0	0.7	0.5	28.6	2.0	13.7	25.5	51.4	39.9
24/08/94	7	51.9	0.0	1.5	0.8	11.2	45.6	34.9	40.7	4.8	16.3
02/09/94	9	2.3	0.0	0.0	0.0	-3.6	-10.5	-9.5	5.9	12.8	11.8
07/09/94	5	1.5	0.0	0.0	0.0	-3.5	-13.4	-8.7	5.0	14.9	10.2
14/09/94	7	0.1	0.0	0.0	0.0	-2.4	-9.9	-3.6	2.5	10.1	3.7
21/09/94	7	3.6	0.0	0.0	0.0	-2.7	5.4	1.4	6.3	-1.8	2.2
28/09/94	7	4.6	0.0	0.0	0.0	-2.7	-3.2	-4.3	7.3	7.8	8.9
05/10/94	7	7.1	0.0	0.0	0.0	-1.3	2.7	3.7	8.4	4.4	3.4
12/10/94	7	22.9	0.0	0.4	0.2						
19/10/94	7	9.8	0.0	0.0	0.0						
26/10/94	7	52.5	0.0	0.2	0.2						
02/11/94	7	7.2	0.0	0.0	0.0						
09/11/94	7	88.3	0.0	0.5	1.0						
16/11/94	7	44.2	0.0	0.0	0.9						
23/11/94	7	8.7	0.0	0.0	0.0						
30/11/94	7	23.4	0.0	0.0	0.0						
07/12/94	7	21.4	0.0	0.0	0.0	-9.8	-0.9	-2.5	31.2	22.3	23.9
14/12/94	7	18.6	0.0	0.0	0.0	-1.5	-0.2	-4.5	20.1	18.8	23.1
21/12/94	7	1.5	0.0	0.0	0.0	-15.0	-11.1	-8.1	16.5	12.6	9.6
28/12/94	7	2.0	0.0	0.0	0.0	-5.4	-7.2	-12.3	7.4	9.2	14.3
04/01/95	7	8.3	0.0	0.0	0.0	8.4	-3.1	-4.9	-0.1	11.4	13.2
12/01/95	8	0.0	0.0	0.0	0.0	-15.0	-16.0	-3.3	15.0	16.0	3.3
18/01/95	6	0.0	0.0	0.0	0.0	-13.1	-25.9	-4.2	13.1	25.9	4.2
25/01/95	7	0.0	0.0	0.0	0.0	-7.7	-13.7	-5.1	7.7	13.7	5.1
01/02/95	8	1.7	0.0	0.0	0.0	-1.4	-10.7	-3.3	3.1	12.4	5.0
09/02/95	7	0.0	0.0	0.0	0.0	-8.6	-10.0	-2.9	8.6	10.0	2.9
15/02/95	6	31.8	0.0	0.0	0.0	1.9	19.8	1.7	29.9	12.0	30.1
23/02/95	8	4.5	0.0	0.0	0.0	2.6	2.1	12.9	1.9	2.4	-8.4

Appendix A14 Soil water balance at Kalalu (March 1994-February 1995)

Date	Period (Days)	Rainfall, P (mm)	Runoff, R (mm)				Soil water change, S (mm/160 cm)				Water use, ETa+D (mm)			
			CT	MT	OG	CG	CT	MT	OG	CG	CT	MT	OG	CG
02/03/94	7	0.0	0.0	0.0	0.0	0.0	-3.4	-2.9	-2.1	2.0	3.4	2.9	2.1	-2.0
09/03/94	7	0.0	0.0	0.0	0.0	0.0	-1.4	-22.8	-3.2	-4.7	1.4	22.8	3.2	4.7
16/03/94	7	1.1	0.0	0.0	0.0	0.0	-1.7	18.0	-3.3	-2.6	2.8	-6.9	4.4	3.7
23/03/94	7	0.0	0.0	0.0	0.0	0.0	-0.8	2.9	-1.3	-2.7	0.8	-2.9	1.3	2.7
30/03/94	7	6.1	0.0	0.0	0.0	0.0	-1.9	-5.1	-1.0	0.8	8.0	11.2	7.1	5.3
05/04/94	6	0.0	0.0	0.0	0.0	0.0	-2.8	1.7	-0.1	-5.9	2.8	-1.7	0.1	5.9
13/04/94	8	10.6	0.0	0.0	0.0	0.0	2.5	-5.1	-3.1	-1.2	8.2	15.7	13.7	11.8
20/04/94	7	58.9	0.0	0.0	26.6	1.0	11.0	26.5	28.7	59.6	47.9	32.4	3.6	-1.8
28/04/94	8	104.5	12.4	2.3	56.2	14.3	73.1	82.2	83.3	72.4	19.1	19.9	-14.9	17.8
04/05/94	6	52.0	4.4	0.7	23.7	1.6	34.9	29.2	-12.1	34.2	12.6	22.2	40.5	16.2
11/05/94	7	9.5	0.0	0.0	0.0	0.0	4.4	-12.4	1.1	2.8	5.1	21.9	8.4	6.7
20/05/94	9	51.0	0.5	0.0	15.9	3.8	17.1	16.6	11.0	27.9	33.4	34.5	24.1	19.4
25/05/94	5	9.0	0.0	0.0	0.0	0.0	-0.7	-3.8	2.6	-0.4	9.7	12.8	6.4	9.4
02/06/94	8	2.1	0.0	0.0	0.0	0.0	-13.5	-19.1	-16.9	-15.5	15.6	21.2	19.0	17.6
08/06/94	6	2.0	0.0	0.0	0.0	0.0	-6.3	-7.1	-8.3	-15.2	8.3	9.1	10.3	17.2
15/06/94	7	9.7	0.0	0.0	0.0	0.0	-13.3	-12.1	-10.1	-14.7	23.0	21.8	19.8	24.4
22/06/94	7	12.7	0.0	0.0	0.0	0.0	-5.9	-9.0	-3.3	-9.2	18.6	21.7	16.0	21.9
29/06/94	7	5.6	0.0	0.0	0.0	0.0	-9.7	-14.9	-11.7	-13.8	15.3	20.5	17.3	19.4
06/07/94	7	66.3	2.1	0.0	33.5	2.1	32.8	33.6	14.9	26.3	31.4	32.8	18.0	37.9
13/07/94	7	0.6	0.0	0.0	0.0	0.0	-9.1	-17.5	-7.8	-6.7	9.7	18.1	8.4	7.3
22/07/94	9	0	0.0	0.0	0.0	0.0	-12.0	-16.5	-12.0	-8.0	12.0	16.5	12.0	8.0
27/07/94	5	15.0	0.0	0.0	0.9	0.0	-10.2	-13.3	-5.3	-11.0	25.2	28.3	19.4	26.0
03/08/94	7	0.0	0.0	0.0	0.0	0.0	-7.1	-14.3	-5.3	-11.3	7.1	14.3	5.3	11.3
10/08/94	7	4.3	0.0	0.0	0.0	0.0	-13.6	-17.4	-7.1	-7.5	17.9	21.7	11.4	11.8
17/08/94	7	17.1	0.0	0.0	0.0	0.0	-1.5	-8.2	1.3	-8.8	18.6	25.3	15.8	25.9
24/08/94	7	48.3	1.6	0.0	21.3	1.5	30.5	27.6	14.2	29.9	16.3	20.7	12.8	16.9
31/08/94	7	3.6	0.0	0.0	0.0	0.0	-14.5	-12.1	-1.5	-9.8	18.1	15.7	5.1	13.4
07/09/94	7	21.9	2.3	0.0	19.1	5.0	-7.9	-2.1	-5.8	-6.6	27.5	24.0	8.6	23.4
14/09/94	7	0.0	0.0	0.0	0.0	0.0	-18.0	-14.9	-8.3	-21.6	18.0	14.9	8.3	21.6
21/09/94	7	0.0	0.0	0.0	0.0	0.0	-14.8	-17.1	-7.4	-17.3	14.8	17.1	7.4	17.3
28/09/94	7	0.0	0.0	0.0	0.0	0.0	-6.1	-5.5	-10.5	-9.8	6.1	5.5	10.5	9.8
05/10/94	7	7.9	0.0	0.0	0.0	0.0	-6.3	-3.8	-1.6	-5.9	14.2	11.7	9.5	13.8
12/10/94	7	9.8	0.0	0.0	0.0	0.0	-6.3	-25.0	2.3	-1.4	16.1	34.8	7.5	11.2
18/10/94	6	1.9	0.0	0.0	0.0	0.0	-3.9	19.3	-3.6	-7.4	5.8	1.4	5.5	9.3
25/10/94	7	46.2	0.0	0.0	8.3	0.0	31.4	23.1	19.5	25.9	14.8	23.1	18.4	20.3
03/11/94	9	48.9	1.3	0.0	5.7	0.5	36.3	45.6	35.9	32.0	11.3	3.4	7.3	16.5
09/11/94	6	58.7	8.1	0.7	12.5	3.5	27.2	30.9	17.9	22.1	23.3	27.0	28.4	33.2
16/11/94	7	33.8	1.2	0.0	12.2	0.0	13.1	18.3	-7.0	6.6	19.5	15.5	28.6	27.2
23/11/94	7	15.0	0.0	0.0	0.0	0.0	-0.1	7.2	-8.2	-5.8	15.1	7.8	23.2	20.8
30/11/94	7	2.2	0.0	0.0	0.0	0.0	-2.2	-10.3	-15.2	-6.3	4.4	12.5	17.4	8.5
07/12/94	7	7.4	0.0	0.0	0.0	0.0	-14.0	-7.8	-4.3	-8.5	21.4	15.2	11.7	15.9
14/12/94	7	10.3	0.0	0.0	0.0	0.0	-13.9	-11.5	-5.3	-9.5	24.2	21.8	15.6	19.8
21/12/94	7	0.9	0.0	0.0	0.0	0.0	-15.0	6.3	-5.7	-6.7	15.9	5.4	6.6	7.6
28/12/94	7	1.8	0.0	0.0	0.0	0.0	-12.0	-11.3	-6.2	-10.9	13.8	13.1	8.0	12.7
05/01/95	8	0.0	0.0	0.0	0.0	0.0	-16.7	-0.4	-0.4	-12.1	16.7	0.4	0.4	12.1
12/01/95	7	0.0	0.0	0.0	0.0	0.0	-9.5	-0.7	-5.0	-10.3	9.5	0.7	5.0	10.3
18/01/95	6	0.0	0.0	0.0	0.0	0.0	-6.0	-4.0	-12.4	-8.7	6.0	4.0	12.4	8.7
25/01/95	7	0.0	0.0	0.0	0.0	0.0	-5.1	-4.6	-2.4	-7.8	5.1	4.6	2.4	7.8
01/02/95	7	1.2	0.0	0.0	0.0	0.0	-6.2	-4.2	-5.2	-6.8	7.4	5.4	6.4	8.0
08/02/95	7	0.0	0.0	0.0	0.0	0.0	-3.0	-1.3	-4.9	-8.3	3.0	1.3	4.9	8.3
15/02/95	7	11.0	0.0	0.0	0.0	0.0	-2.2	-0.1	2.6	0.9	13.2	11.1	8.4	10.1
23/02/95	8	0.0	0.0	0.0	0.0	0.0	-3.0	-4.8	-5.2	-5.0	3.0	4.8	5.2	5.0

Appendix A15 Soil water balance at Mukogodo (March 1994-February 1995)

Date	Period (Days)	Rainfall, P (mm)	Runoff, R (mm)				Soil water change, S (mm/160 cm)				Water use, ETa+D (mm)			
			RO	PO	PE	BO	RO	PO	PE	BO	RO	PO	PE	BO
02/03/94	7	0.0	0.0	0.0	0.0	0.0	0.2	-4.2	2.7	-2.2	-0.2	4.2	-2.7	2.2
09/03/94	7	0.0	0.0	0.0	0.0	0.0	-0.4	-7.3	4.4	-1.3	0.4	7.3	-4.4	1.3
16/03/94	7	3.0	0.0	0.0	0.0	0.0	0.4	3.1	-2.4	1.6	2.6	-0.1	5.4	1.4
23/03/94	7	0.0	0.0	0.0	0.0	0.0	1.3	-1.5	0.1	-3.3	-1.3	1.5	-0.1	3.3
30/03/94	7	16.1	1.8	2.3	0.2	7.9	21.6	21.5	31.7	17.5	-7.3	-2.7	-5.8	-0.2
06/04/94	7	0.0	0.0	0.0	0.0	0.0	-9.1	-0.2	-4.0	-5.1	9.1	0.2	4.0	5.1
13/04/94	7	0.0	0.0	0.0	0.0	0.0	0.3	-0.9	-2.1	-0.5	-0.3	0.9	2.1	0.5
20/04/94	7	0.9	0.0	0.0	0.0	0.0	-0.7	0.4	0.7	-1.6	1.6	0.6	0.2	2.5
27/04/94	7	40.0	16.3	16.3	10.4	20.2	19.9	7.1	18.1	15.7	3.8	16.7	11.5	4.1
04/05/94	7	17.0	7.5	11.7	4.8	14.7	3.6	3.6	-1.9	1.3	5.9	1.7	14.1	0.9
10/05/94	6	16.6	7.6	9.5	6.7	10.8	-3.1	0.4	-5.6	1.9	12.2	6.7	15.5	3.9
17/05/94	7	18.5	4.2	7.0	0.5	9.6	-3.4	-1.3	1.9	1.2	17.7	12.8	16.1	7.7
24/05/94	7	11.1	0.0	0.0	0.0	1.5	-2.3	-3.1	-3.5	-2.1	13.3	14.1	14.6	11.6
31/05/94	7	0.0	0.0	0.0	0.0	0.0	-2.5	-1.9	-2.7	-2.0	2.5	1.9	2.7	2.0
07/06/94	7	0.0	0.0	0.0	0.0	0.0	-3.7	0.1	-3.8	-0.3	3.7	1.1	3.8	0.3
14/06/94	7	12.5	0.4	0.2	0.0	1.9	5.4	3.6	4.3	-0.7	6.7	8.7	8.2	11.2
21/06/94	7	0.0	0.0	0.0	0.0	0.0	-6.0	-1.7	-3.3	0.6	6.0	1.7	3.3	-0.6
28/06/94	7	0.0	0.0	0.0	0.0	0.0	0.0	0.1	-2.8	-0.9	0.0	-0.1	2.8	0.9
05/07/94	7	17.3	5.1	6.8	2.1	11.0	4.0	2.7	8.3	2.3	8.2	7.8	6.9	4.0
12/07/94	7	0.0	0.0	0.0	0.0	0.0	-5.0	-5.2	-3.8	-2.6	5.0	5.2	3.8	2.6
19/07/94	7	24.4	7.7	13.1	5.1	14.3	6.7	6.0	4.6	2.7	10.1	5.4	14.7	7.3
26/07/94	7	0.0	0.0	0.0	0.0	0.0	-5.1	-6.7	-5.5	-0.3	5.1	6.7	5.5	0.3
02/08/94	7	3.5	0.0	0.0	0.0	0.0	-0.6	-3.5	-1.4	-4.0	4.1	7.0	4.9	7.5
09/08/94	7	0.0	0.0	0.0	0.0	0.0	-4.9	-0.7	-7.2	-2.8	4.9	0.7	7.2	2.8
16/08/94	7	5.8	0.0	0.0	0.0	0.0	2.2	2.0	5.2	-1.8	3.6	3.8	0.6	7.6
23/08/94	7	27.4	4.2	6.3	1.1	10.4	5.5	1.4	3.5	5.6	17.8	19.7	22.8	11.4
30/08/94	7	0.0	0.0	0.0	0.0	0.0	-4.0	0.4	-1.1	-2.4	4.0	-0.4	1.1	2.4
06/09/94	7	0.0	0.0	0.0	0.0	0.0	-5.8	-3.2	-3.6	-7.9	5.8	3.2	3.6	7.9
13/09/94	7	0.0	0.0	0.0	0.0	0.0	-0.7	-0.4	-7.8	2.3	0.7	0.4	7.8	-2.3
20/09/94	7	0.0	0.0	0.0	0.0	0.0	-6.1	-6.4	-9.4	-4.0	6.1	6.4	9.4	4.0
28/09/94	8	4.6	1.1	1.3	0.0	1.8	-3.2	0.2	0.3	-3.0	6.8	3.1	4.3	5.8
04/10/94	6	9.4	0.2	0.3	0.2	1.9	21.5	8.4	28.3	9.4	-12.3	0.7	-19.1	-2.0
11/10/94	7	0.0	0.0	0.0	0.0	0.0	-10.8	-6.2	-8.2	-3.9	10.8	6.2	8.2	3.9
17/10/94	6	8.7	0.6	1.4	0.0	2.4	3.4	0.6	-10.4	-4.4	4.8	6.7	19.1	10.7
22/10/94	5	11.7	1.9	3.1	1.5	5.5	10.9	8.8	13.6	7.2	-1.1	-0.2	-0.4	-1.0
28/10/94	6	0.0	0.0	0.0	0.0	0.0	-9.6	-5.1	-2.6	-1.5	9.6	5.1	2.6	1.5
04/11/94	7	20.4	2.0	9.2	2.7	13.4	7.9	0.8	6.8	1.8	10.5	10.5	10.9	5.2
11/11/94	7	11.1	0.0	0.0	0.0	0.9	-2.2	7.0	-5.2	-1.7	13.3	4.1	16.3	11.9
17/11/94	6	27.0	5.4	12.5	1.6	17.9	-2.8	-7.0	-4.1	-4.0	24.4	21.5	29.5	13.1
25/11/94	8	6.0	2.4	5.6	1.4	6.2	-2.3	2.1	-1.0	-3.0	6.0	-1.7	5.6	2.8
02/12/94	7	3.5	1.0	1.0	0.1	2.2	-0.8	-1.6	-0.5	1.9	3.3	4.0	3.9	-0.6
09/12/94	7	22.4	2.8	4.0	0.1	8.5	4.5	-0.3	1.9	4.1	15.1	18.7	20.4	9.8
16/12/94	7	1.0	0.0	0.0	0.0	0.0	-1.1	-3.4	-4.7	-11.9	2.1	4.4	5.7	12.9
23/12/94	7	0.0	0.0	0.0	0.0	0.0	-6.9	1.1	1.4	-3.3	6.9	-1.1	-1.4	3.3
30/12/94	7	0.7	0.0	0.0	0.0	0.0	-1.8	-1.5	-3.9	7.3	2.5	2.2	4.6	-6.6
06/01/95	7	0.0	0.0	0.0	0.0	0.0	-1.4	0.3	-4.4	-6.2	1.4	-0.3	4.4	6.2
13/01/95	7	0.0	0.0	0.0	0.0	0.0	1.6	0.1	4.9	3.6	-1.6	-0.1	4.9	-3.6
20/01/95	7	0.0	0.0	0.0	0.0	0.0	-4.9	-0.2	-6.1	1.7	4.9	0.2	6.1	-1.7
31/01/95	11	0.0	0.0	0.0	0.0	0.0	1.6	-2.4	-3.2	0.9	-1.6	2.4	3.2	-0.9
03/02/95	3	0.0	0.0	0.0	0.0	0.0	0.5	1.7	5.1	-4.0	-0.5	-1.7	-5.1	4.0
13/02/95	10	48.2	24.3	29.4	12.9	39.8	10.4	6.9	14.8	17.2	13.5	11.9	20.4	-8.8
24/02/95	11	8.8	1.9	3.2	0.7	4.3	-3.8	-3.6	-5.9	0.9	10.8	9.3	14.0	3.6

Appendix A16 Analysis of variance for various soil properties and parameters

BULK DENSITY (g cm^{-3})

Karuri

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	15	15	15
Sum	12.48	13.1	14.83
Average	0.8320	0.8733	0.9887
Variance	0.0088	0.0043	0.0029

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	0.0242	2	0.0121	3.8649	0.0302	3.2594	5.2479
Depth	0.1978	2	0.0989	31.6381	0.0000	3.2594	5.2479
Interaction	0.0877	4	0.0219	7.0121	0.0003	2.6335	3.8903
Within	0.1125	36	0.0031				
Total	0.4221	44					

Kalalu

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	15	15	15
Sum	16.58	18.15	18.72
Average	1.1053	1.2100	1.2481
Variance	0.0056	0.0037	0.0031

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	0.0574	2	0.0288	3.3665	0.0322	3.2594	5.2479
Depth	0.3233	2	0.1616	38.1264	0.0000	3.2594	5.2479
Interaction	0.1207	4	0.0302	9.4232	0.0019	2.6335	3.8903
Within	0.3628	36	0.0101				
Total	0.8642	44					

Mukogodo

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	15	15	15
Sum	18.9668	21.5334	23.2054
Average	1.2625	1.4356	1.5473
Variance	0.0046	0.0029	0.0033

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	0.1154	2	0.0578	4.1276	0.0114	3.2594	5.2479
Depth	0.4895	2	0.2448	27.1264	0.0012	3.2594	5.2479
Interaction	0.2705	4	0.0676	6.0231	0.0034	2.6335	3.8903
Within	0.8322	36	0.0231				
Total	1.7076	44					

Appendix A16 continued.

SATURATED HYDRAULIC CONDUCTIVITY (cm h^{-1})

Karuri

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	15	15	15
Sum	192.32	68.07	54.78
Average	12.8213	4.5380	3.6520
Variance	160.9603	13.5757	11.4962

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	439.3240	2	219.6620	4.7767	0.0145	3.2594	5.2479
Depth	767.3764	2	383.6882	8.3436	0.0011	3.2594	5.2479
Interaction	509.6291	4	127.4073	2.7706	0.0418	2.6335	3.8903
Within	1655.4968	36	45.9860				
Total	3371.8263	44					

Kalalu

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	20	20	20
Sum	109.96	69.01	53.37
Average	5.498	3.4505	2.6685
Variance	30.2171	10.4226	7.8114

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	148.4434	3	49.4811	3.8909	0.0144	2.7981	4.2180
Depth	85.3990	2	42.6995	3.3577	0.0432	3.1907	5.0767
Interaction	161.7125	6	26.9521	2.1194	0.0681	2.2946	3.2036
Within	610.4153	48	12.7170				
Total	1005.9703	59					

Mukogodo

Anova: Two-Factor With Replication

SUMMARY

Total	0-10 cm	20-30 cm	40-50 cm
Count	20	20	20
Sum	162.4	79.45	63.09
Average	8.12	3.9725	3.1545
Variance	72.9018	9.3319	8.4630

ANOVA						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Landuse	349.7999	3	116.6000	4.9168	0.0047	2.7981	4.2180
Depth	283.5138	2	141.7569	5.9776	0.0048	3.1907	5.0767
Interaction	235.1341	6	39.1890	1.6525	0.1534	2.2946	3.2036
Within	1138.3035	48	23.7147				
Total	2006.7513	59					

Appendix A16 continued.

TOPSOIL (0-10 cm) AVAILABLE WATER CAPACITY

Karuri

Anova: Single Factor

SUMMARY

Land use	Count	Sum	Average	Variance
NF	3	46.68	15.56	1.9999
PC	3	34.68	11.56	2.4796
GL	3	36.07	12.0233	1.1705

ANOVA

						P=0.05	P=0.01
Source of Variation	SS	df	MS	F	P-value	F critical	F critical
Between landuses	28.7227	2	14.3613	7.6254	0.0225	5.1432	10.9249
Within landuses	11.3001	6	1.88334				
Total	40.0228	8					

Kalalu

Anova: Single Factor

SUMMARY

Land use	Count	Sum	Average	Variance
CT	3	36.78	12.26	1.0372
MT	3	41.31	13.77	0.8068
OG	3	25.37	8.4567	4.7449
CG	3	33.44	11.1467	4.7440

ANOVA

						P=0.05	P=0.01
Source of Variation	SS	df	MS	F	P-value	F critical	F critical
Between landuses	45.2508	3	15.0836	5.32379969	0.02611881	4.06618028	7.5909
Within landuses	22.6659	8	2.8332				
Total	67.9168	11					

Mukogodo

Anova: Single Factor

SUMMARY

Land use	Count	Sum	Average	Variance
RO	3	37.91	12.6367	3.3466
PO	3	31.36	10.4533	2.7390
PE	3	38.61	12.87	5.4925
BO	3	23.58	7.86	2.6193

ANOVA

						P=0.05	P=0.01
Source of Variation	SS	df	MS	F	P-value	F critical	F critical
Between landuses	48.9778	3	16.3259	4.5997	0.0375	4.0662	7.5909
Within landuses	28.3949	8	3.5494				
Total	77.3727	11					

Appendix A16 continued.

AVAILABLE SOIL WATER (March 1994-February 1995)

Karuri

Anova: Single Factor

SUMMARY

Land use	*Count*	*Sum*	*Average*	*Variance*
NF	31	5954.47	192.079677	493.94129
PC	31	5228.99	168.677097	367.208561
GL	31	4739.74	152.894839	443.668806

ANOVA

						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Between landuses	24099.5244	2	12049.7622	27.7044	4.2103E-10	3.0977	4.8491
Within landuses	39144.5597	90	434.9396				
Total	63244.08	92					

Kalalu

Anova: Single Factor

SUMMARY

Land use	*Count*	*Sum*	*Average*	*Variance*
CT	52	5473.13	105.2525	2000.88216
MT	52	7264.82	139.708077	2087.71462
OG	52	1873.01	36.0194231	1065.44616
CG	52	2369.95	45.5759615	2924.57117

ANOVA

						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Between landuses	380187.788	3	126729.263	62.74802	8.7241E-29	2.6489	3.8791
Within landuses	412009.319	204	2019.65353				
Total	792197.1	207					

Mukogodo

Anova: Single Factor

SUMMARY

Land use	*Count*	*Sum*	*Average*	*Variance*
RO	36	142.612458	3.96145717	166.475199
PO	36	105.846525	2.94018125	100.837014
PE	36	128.839305	3.57886958	215.950286
BO	36	-23.7912644	-0.66086846	74.5899165

ANOVA

						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Between landuses	485.155191	3	161.718397	1.1596	0.3275	2.6693	3.9246
Within landuses	19524.8345	140	139.463104				
Total	20009.99	143					

Mukogodo (Daily:21/10-25/11/1994)

Anova: Single Factor

SUMMARY

Land use	*Count*	*Sum*	*Average*	*Variance*
RO	36	443.869191	12.3296998	57.6727155
PE	36	298.728589	8.29801635	131.592744
BO	36	-82.1791532	-2.28275426	63.6694656

ANOVA

						P=0.05	P=0.01
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*	*F critical*
Between landuses	4100.77188	2	2050.38594	24.3191	2.0952E-09	3.0828	4.8132
Within landuses	8852.72236	105	84.3116416				
Total	12953.49	107					

Appendix A16 continued.

WATER USE (Evapotranspiration and Deep percolation)

Karuri

Anova: Single Factor

SUMMARY

Land use	*Count*	*Sum*	*Average*	*Variance*
NF	4	1475	368.75	28677.5833
PC	4	1532	383	23696.6667
GL	4	1576	394	31772

ANOVA P=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between landuses	1282.16667	2	641.083333	0.02285604	0.97745972	4.25649205
Within landuses	252438.75	9	28048.75			
Total	253720.917	11				

Kalalu

Anova: Single Factor

SUMMARY

Landuse	*Count*	*Sum*	*Average*	*Variance*
CT	4	1331	332.75	5744.91667
MT	4	1476	369	26752.6667
OG	4	1182	295.5	7700.33333
CG	4	1437	359.25	10924.9167

ANOVA P=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between landuses	12965.25	3	4321.75	0.33814636	0.79815846	3.4902996
Within landuses	153368.5	12	12780.7083			
Total	166333.75	15				

Mukogodo

Anova: Single Factor

SUMMARY

Landuse	*Count*	*Sum*	*Average*	*Variance*
RO	4	505	126.25	2103.58333
PO	4	431	107.75	1516.25
PE	4	597	149.25	3192.91667
BO	4	333	83.25	854.916667

ANOVA P=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F critical*
Between landuses	9398.75	3	3132.91667	1.63435204	0.23357316	3.4902996
Within landuses	23003	12	1916.91667			
Total	32401.75	15				