THE INFLUENCE OF VEGETATION ON THE WATER RESOURCES OF THE NARO MORU CATCHMENT

A WATER BALANCE APPROACH

Njeru Jeremiah Lewis

September 1995

A thesis submitted in partial fulfilment for the award of masters of science degree in Hydrology of the University of Nairobi

DECLARATION

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

Njeru.

Njeru Jeremiah Lewis

13|9|1995

Date

This thesis has been submitted for examination with our approval as University supervisors.

Dr. G. S. Ongwenyi

13th September, 1995

Date

Dr. D. N. Mungai

28/9/93

Date

Mr. J. M. Omwenga

28/9/93

Date

DECLARATION

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

Njeru.
Njeru Jeremiah Lewis

13/9/1995
Date

This thesis has been submitted for examination with our approval as University supervisors.

Dr. G. S. Ongwenyi

13th September, 1995
Date

Dr. D. N. Mungai

28/9/93
Date

Mr. J. M. Omwenga

28/9/93
Date

CONTENT

CHAPTER ONE: INTRODUCTION

CHAPTER TWO: THE STUDY AREA

CHAPTER THREE: MATERIALS AND METHODS

CHAPTER FOUR: RESULTS AND DISCUSSIONS

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

ABSTRACT

On the slope West and North of Mt Kenya, population increase has lead to rapid land use change and increased demand for water resources. In this area, Water resources are limited and fragile. To achieve socio economic development, advisory and utilisation tools are required to guide sustainable development of water resources. As a contribution to this challenge, the influence of vegetation on the water resources of the Naro Moru river was investigated through a water balance approach.

The Naro Moru river, an important water source within the upper Ewaso Ngiro basin, extends from the peak region of Mt. Kenya (5200 meters above sea level) and moves out Westwards traversing five ecological zones to the confluence with the Ewaso Ng'iro at 1800 meters above sea level.

The study covered the Alpine, Moorland, Forest and Foot zones of the catchment. Climatic and soil water measurement were made during the study period.

Measurement of rainfall, windspeed, temperature, humidity and sunshine hours were made on daily basis and evapotranspiration calculated from the climatic data using the Penman method. The climatic water balance was hence calculated as the difference between rainfall and evapotranspiration.

Soil water content was determined gravimetically on monthly intervals in the Alpine and Moorland zones and using a neutron probe on weekly intervals in Forest and Footzone. From the soil water measurements, the available soil water for different vegetation systems and its change with time and space was evaluated

The influence of vegetation on the water resources was hence investigated by evaluating the climatic water balance, the available soil water and the vegetation water balance.

The climatic water balance of the four zones was found to be significantly different in the five zones In the 1st wet and dry periods, the climatic water demand was met only in the Alpine and Moorland zones. In the 2nd wet period, the climatic water demand was met in all the zones except in the Footzone.

The available soil water for different vegetation, ecological and slope conditions was found to be significantly different. The Potato and grass vegetation showed higher and less varied soil water compared to the natural Forest vegetation and cypress plantation vegetation. The Moorland zone showed higher available soil water content compared to the Alpine zone. The lower Forest showed higher available soil water compared to the upper Forest and Footzone.

From the vegetation water balance analysis, the vegetation water requirement was higher for the natural Forest and Cypress plantation compared to the Potato crop and Grass vegetation. In the Alpine and Moorland zone, the latter vegetation showed high water use. Weather conditions wet and dry period) were found to be important for the differences observed in the vegetation water balance. Vegetation water requirement was generally higher than water use in the dry period and lower than water use in the wet periods.

It is recommended that when planning for water resources, weather, ecological and vegetation differences should be considered. Further, future research activities should aim at developing practical water balance models which could be transfered to other similar areas. This could be achieved through field measurements of soil water, deep percolation and surface runoff.

ACKNOWLEDGEMENT

I would like to thank the many people who have in one way or another contributed to the success of this study.

I would like to thank the University of Nairobi for offering a full scholarship without which this study could not have been possible. I am greatly indebted to my supervisors for their critical comments and suggestions. These included Dr. G.S. Ongwenyi and Dr. D.N Mungai of Nairobi University, Mr. J.M. Omwenga of Ministry of water Development and Dr. H.P. Liniger of Laikipia Research Programme.

During the field work, I received immense support from the Laikipia Research Programme first as a learning institution and secondly as a family. Dr. H.P. Liniger supported in all ways possible the dynamic field work and to him I register my special appreciation. Mrs. Alice Kibe typed and corrected typographical errors in the draft thesis. Special thanks go to her. The research assistants both in the Socio-economy and Ecology sector were all the time ready to help and may God bless them.

Last but not least, I would like to extend special appreciation to my freinds Catherine and Dorine for their kindness and understanding through out the study.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

On the slopes West and North of Mt Kenya, small scale mixed farming is the dominant land use (Kohler, 1987). 70% of the plots are between 1 and 4 acres and are too small to support the households which average 6 to 7 persons (Kohler and speck, 1983; Kohler, 1987; Flury, 1987). Most farmers cite water as a priority for development and see irrigation as a means to intensify land production (Kohler and Speck, 1983).

In extreme dry periods, water availability becomes fatal to humans and their production systems (Decurtins et al, 1988). The importance of water resources is seen in terms of recurrent crop failure, low production on grazing land and continued soil loss (Liniger, 1991).

Population increase, estimated at 7.8% per annum in the 1989 Laikipia District development plan, as been rapid due to natural births and immigration from adjacent densely populated districts. The population increase has lead to an increased demand for water resources. However, water resources are only enough for domestic use and livestock watering with irrigation being possible only at a kitchen garden, approximately 10m^2, scale (Wiesmann, 1992b; Flury, 1987).

Sustainable development of the limited water resources is hence a prerequisite for social economic development of this area.

1.2 Statement of the research problem

Research on social economy and ecology has continued for the last two decades on the slopes West and North of mount Kenya. This research, carried out by the

University of Berne, Switzerland in collaboration with the University of Nairobi has revealed that the Social economic development of this area is limited by their fragile and limited water resources

Advisory and utilization tools are required to guide the sustainable development of the water resources (Liniger, 1992a) and thus the social economic development of this area.

Towards this need to provide tools to guide the development of water resources, several studies have been carried out at three (site, catchment and basin) levels of research (Liniger 1992a). Further contributions are required to provide processes to link the three research levels and understand the interaction between the social and natural resources systems. Towards the latter, the influence of land use and its change on water resources is of importance and is addressed in this study.

Rainfall is an important water source in this area. Among the various uses into which rain water is put, the vegetation water requirements is important. To plan rainwater, information on vegetation water requirements is thus necessary.

The Forest zone forms a vital water recharge area and is important in sustaining water resources in this area (Liniger 1992a, Decurtins, 1992). The Forest however comprises of different vegetation types whose influence on the water resource should be investigated

Within the small scale farming system, irrigation is recommended at a kitchen garden scale due to limited water resources. The influence of the different landuse systems practised in this area on the water resource should be investigated so as to effectively manage the water resources.

As an effort to meet these challenges, the influence of vegetation on the water resources of the Naru Moru catchments is investigated.

1.3 Conceptual Framework

Climatic water requirements, evapotranspiration, is meet from the water availed through rainfall. The balance between climatic water input (rainfall) and output (evapotranspiration) gives important first information on the water resources of any area. This information on the climatic water balance, though a valuable 1st step when investigating water resources, does not take into account soil and vegetation conditions which are of importance to the water resources system. A comprehensive water balance evaluation, referred to in this study as the vegetation water balance, should hence consider climatic, soil and vegetation conditions.

A simple vegetation water balance equation for a situation with no lateral subsurface water flow in and out of the area under study is presented by Liniger (1991) as:

$P=SWc+Ro+Dp+ETa$.............(1)

This equation is presented in a simplified model as shown in Figure 1.1.

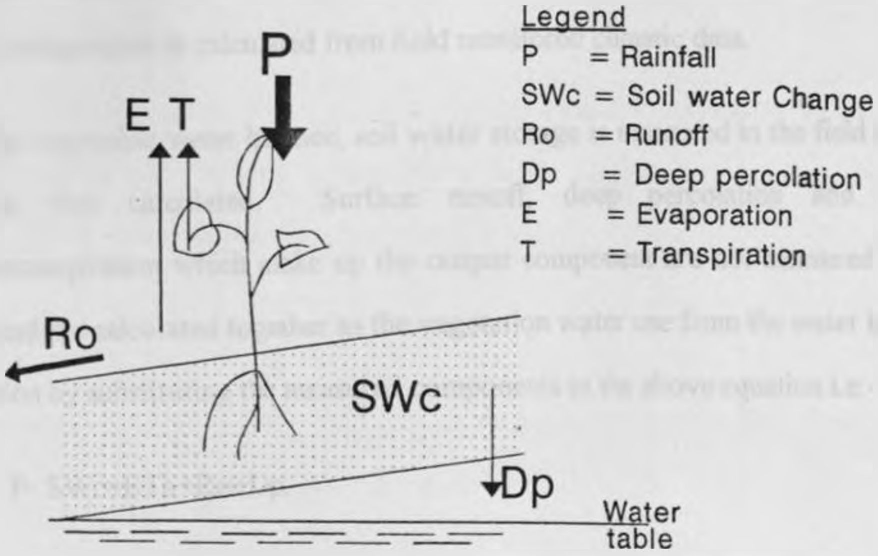


Figure 1.1 : The water balance model.

In the vegetation water balance equation, the water availed from rainfall (P) goes to meet soil water change (SWc), surface runoff (Ro), ground water recharge (Dp) and the actual evapotranspiration (ETa).

In this system, rainfall forms the input component, soil water change the storage component while runoff, deep percolation and the actual evapotranspiration forms the output component. Different vegetation types will influence the storage and output components of the vegetation water balance system differently and consequently the water resources of the area in which they are located

The influence of different vegetation types in different ecological zones on the water resources of the Naro Moru catchment is thus evaluated by investigating their influence on the storage and output component of the vegetation water balance system. As a first step, the climatic water balance within the zones is also evaluated.

The climatic water balance is calculated as the difference between rainfall and the potential evapotranspiration. Rainfall is measured in the field while Potential evapotranspiration is calculated from field monitored climatic data.

For the vegetation water balance, soil water storage is measured in the field and its change thus calculated. Surface runoff, deep percolation and actual evapotranspiration which make up the output component are not measured in the field and are calculated together as the vegetation water use from the water balance equation by substituting the measured components in the above equation i.e.-

$$P - SWc = ETa + Ro + Dp$$

Using data on the climatic water balance, soil water storage and vegetation water use, the influence of different vegetation on the water resource is investigated. The different vegetation types investigated include Grass, natural Forest, Cypress plantation and Potato crop on typical and steep slopes. The zones covered in the study includes Alpine, Moorland, upper Forest, lower Forest and Footzone.

1.4 Hypotheses

Three hypotheses were initially formulated regarding the climatic water balance, soil water content and the vegetation water balance of the different vegetation systems investigated. These are listed below.

1) H_0 Rainfall and potential evapotranspiration and consequently the climatic water balance does not show significant differences in the five zones.

H_1 Alternative.

2) H_0 The soil water content under different vegetation types is not significantly different within (for different vegetation types) and between (for similar vegetation types) the five zones.

H_1 Alternative.

3) H_0 The vegetation water balance for the different vegetation types is not significantly different within (for different vegetation types) and between (for similar vegetation types) the five zones.

H_1 Alternative.

1.5 Objectives

The broad objective for this study was to investigate the influence of vegetation on the water resources of the Naro Moru catchment.

The specific objectives of the study were as follows:-

i) To quantify rainfall and the potential evapotranspiration and hence calculate the climatic water balance in five ecological zones.

ii) To quantify soil water content under different vegetation types within and between the five ecological zones covered in the study.

iii) To calculate the vegetation water balance of the different vegetation types investigated in five ecological zones of the study area.

1.6 Literature review

1.6.1 Introduction

Water is necessary for life and has played a vital role in the development of human societies throughout the world. In Kenya, rapid population growth has lead to land pressure in the high potential areas (Decurtins, 1985). This means that the vast arid and semi arid areas, which make up 80% of Kenya's land area, have an important role in meeting production demands for the increasing population (Liniger, 1991).

On the semi-humid to arid slopes west and North of Mt Kenya, human population has been increasing rapidly due to natural births and immigration from the neighbouring densely populated high Potential districts (Kohler, 1987). As the population increase, this area, formerly a ranching region, has been subdivided and placed under cultivation. The problem that may arise from this land use change has been investigated for the last two decade by the university of Bern-Switzerland in collaboration with the university of Nairobi (Decurtins, 1985). The research has focused on land use and social economic dynamics (Kohler, 1987, Wiesmann, (992b) and soil and water resource utilization and management (Liniger, 1992a).

From land use studies (Kohler and Speck, 1983; Kohler, 1987; Flury, 1987) it has been found out that small scale mixed farming is the dominant land use. From the studies, plot size distribution analysis has shown that 70% of the plots in the small scale farming sector are 1 to 4 acres. In this dry environment, these plots are too small to support, at sustainable level, the household which averages 5 to 6 persons.

The status of water resource and its utilization has shown to play an overriding role on the development process (Liniger, 1992). The farmers perceive irrigation as a means of increasing the production potentials of their small plots (Kohler, 1987). These farmers originate from higher potential areas where water resources are not limited and lack knowledge on water conservation farming techniques (Liniger, 1991). As the population increase, estimated at 7.8% per annum (District development plan, 1989), water demand for domestic, livestock and irrigation purposes has been increasing (Wiesmann, 1992b; Flury, 1987).

The water resources of this area have a unique setting. It is limited, limits the development process and calls for priority consideration when being allocated for various needs (Decurtins et al, 1988). Water resources are fragile and should not be looked at only in terms of availability but also as regards their best use and management (Liniger, 1991). During extremely dry periods, lack of water becomes fatal to both humans and their production systems (Decurtins at al, 1988). The importance of the water resource is seen in terms of recurrent crop failure, low productivity in grazing land and continued soil loss (Liniger, 1991). River water discharges varies widely for the dry and wet periods and there is a consumption conflict between the upstream and downstream users (Decurtins et al, 1988).

There is hence a need to develop advisory and utilization tools (Roberts, 1961; Decurtins et al, 1988; Liniger, 1991) to guide the sustainable development of the water resources and hence achieve social and economic development in this area.

1.6.2 Water resources studies

The challenge to develop water resources advisory and utilization tools has lead to several studies at three (site,, catchment and basin) levels of research.

These studies includes hydrogeographic documentation (Leibundgut, 1986, Decurtins, 1992), water and soil conservation (Liniger, 1991), the potentials of episodic stream (Ondieki, in preparation), river reach water balance (Gathenya, 1992) and stream flow modelling (Thomas 1992) among others.

These efforts have lead to:-

i) The establishment of an hydro-meteorological monitoring network and data base.

ii) Approaches to model soil and water resources and their utilization.

There is however need for further contribution to provide processes to link the three research levels and means to understand the interaction between the social and natural resource systems.

Towards an understanding of the interaction between the social and natural resource systems, the influence of vegetation on the water resources of the Naru Moru catchment is investigated in this study.

Population increase on the slope West and North of Mt.Kenya has lead to rapid landuse and vegetation change (Kohler, 1985) with important implications on the natural resources especially soil and water resources(Decurtins et al, 1988).

Investigation on the slopes West and North of Mt.Kenya (Liniger and Decurtins, 1990) using short period climatic and soil water campaign data noted variation in the hydro-climatological conditions in this area. Detailed climatic and soil water information is required to evaluate soil water change and the vegetation water requirement and use for different vegetation in this sensitive mountain environment and hence investigate the relationship between different vegetation\landuse systems and the water resources.

From the above study, Liniger and Decurtins (1990), the Forest zone is documented as important for recharging the soil and the water table and thus ensuring a continuous base flow during the dry periods and soil and ground water recharge during the wet periods. Elsewhere, it has been noted that though Kenya has a very limited forest base, the conservation of this small forest base is the cheapest and most economically sound method of ensuring that enough water in controlled amounts is available for our generation and that to come (Owino, 1977). Within the Naru Moru catchment, the Forest zone however comprises of different vegetation types whose influence on the water resource should be investigated.

Within the small scale mixed farming, irrigation has been found to be possible only at a 10m^2 kitchen garden scale (Decurtins et all, 1988; Decurtins, 1992) due to limited water resources. For effective management of the water resources, it is important to investigate how the different land use practices use the limited water resources.

This study hence takes up these challenges and attempts to contribute towards these knowledge gaps. To this end, the influence on vegetation on the water resources of the Naru Moru catchment is investigated.

1.6.3 Water balance evaluation

The evaluation of the water resources of any area requires an assessment of its hydrogeographic characteristics and further the development of its water balance model (Decurtins, 1985). Such an assessment must take into account the interaction between the hydrogeographic systems with the whole ecosystem Dunne and Leopold (1978) notes that within the Amboseli national park, the death of woodlands and replacement by saline tolerant grasses is due to hydrological changes in this area and notes that to understand this ecosystem, there is need to appreciate changes in rainfall, groundwater and the water balance of the system. Water resource evaluation thus calls for a balancing approach where all the various components of the hydrogeographic system and their interactions with the ecosystem are considered. For this reason, many water resource studies have been achieved through a water balancing approach (see Liniger, 1991, Decurtins, 1992).

Mather (1978) defined water balancing as the accounting of all the water input, storage and outputs of an area over a given period of time. Franquin (1978) noted that the appropriate water balance equation can be constructed depending on the desired results and the data available. Liniger (1991) investigating rainfed farming performance under different management systems used a simple water balance model which assumed no lateral subsurface runoff and deep percolation. The water balance equation for the model is given in equation 1 section 1.3 as:-

$$P= SWc+Ro+Dp+ETa$$

P presents rainfall, SWc presents soil water change, Ro presents runoff, Dp presents deep percolation and ETa presents actual evapotranspiration. P can be measured within standard meteorological stations while SWc and Ro can measured in soil water balance plot experiments. Dp can be measured in lysimeter studies. ETa is usually estimated from climatic, soil and plant data and is usually the most problematic variable of five variables presented in this equation. Kiangi (1977) discuses various methods that have been used to estimate ETa within the East African region. Due to the type of data available, the above water balance equation is used in this study. Rainfall and soil water change are measured in the field. The other parameter of the water balance equation are not measured and are calculated from the measured parameters as discussed in section 3.4.2.

1.6.4 Climatic and soil water measurements

Vegetation water requirement is influenced by temperature, windspeed, relative humidity and radiation (Liniger, 1991). These variables should be properly measured in the field for a successful water balance evaluation. The national water master plan (991) presents indicative values for these variables for different location in Kenya. For this study, Rainfall, pan evaporation, temperature, windspeed, relative humidity and sunshine duration were measured in the field using standard Meteorological instruments as described by Mwebesa (1980).

Assessment of soil moisture content and its change with depth and time is vital for the vegetation water balance calculation (Olembo, 1979; Liniger, 1991). Field soil water content assessment is however difficult and problematic (Liniger, 1991). Generally both direct and indirect methods are available (Smiley and Steed, 1983). Direct methods, such as gravimetric sampling, involve field sampling and laboratory analysis to determine soil water content. The indirect methods, such as the neutron attenuation, tensiometers and conductivity blocks, involve indirect soil moisture assessment which require a calibration to infer on the soil water content.

Smiley and Steed (1983) notes that the direct methods have a disadvantage in that require careful attention to eliminate error both during field sampling and laboratory analysis and are usually destructive to the soil profile. Their advantage is that they usually requires less financial input.

The disadvantage of the indirect methods is that they usually have a sensitive procedure, are expensive to finance and require an accurate calibration. They are however relatively more accurate, less destructive to the soil profile and require a short sampling time thus allowing a routine soil water content monitoring programme For this study, the direct gravimetric method and the indirect neutron attenuation method were used.

1.7 Operational definitions

Various operational terms are used in this study. These terms are defined below in the context of this study.

Field Capacity : The field capacity is usually taken as the upper limit of the available soil water. It is laboratory determined as the volumetric soil water content at a suction of between 0.1 and 0.33 bars (Brady, 1974). For this study, the field capacity was field determined as the volumetric soil water content 2 to 3 days after saturation and after free drainage has ceased (Gardner, 1988; Liniger, 1991).

Wilting Point : The wilting point is the lower limit of the available soil water and is the taken as the soil water content at which plants lose turgor beyond recovery due to soil water deficit. It is laboratory determined as the volumetric soil water content at a suction of 15 bars (Brady, 1979; Weg et al, 1975). Since the study area was rather wet throughout the study period, no real wilting points were observed during the study period except in the drier Footzone (Munyaka). For this study, the wilting point was field determined as the lowest soil water content observed in a dry period (Gardner 1988).

Available Water Capacity : Available water capacity is usually taken as soil water held between the upper (field capacity) and lower (wilting point) limits of the available soil water (Gardner, 1988).

Percolation soil water : This is the soil water content above the upper (field capacity) soil water limit (Gardner, 1988). This water goes into ground water storage and or subsurface runoff depending on the drainage conditions of the profile.

Reference Crop Evapotranspiration : This is a climatic indicator of the vegetation water requirements under different climatic conditions. It is defined as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall green grass cover of uniform height actively growing, completely shading the ground and not short of water (Doorenbos and Pruitt, 1977).

Vegetation water requirement : The maximum water requirement of a vegetation system and defined as the depth of water needed to meet water loss through evapotranspiration of a disease free crop growing in large fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Doorenbos and Pruitt, 1977).

Actual Evapotranspiration : The actual amount of water used to meet the climatic water requirement for evaporation and transpiration under limited water conditions (Doorenbos and Kassam, 1986).

Vegetation Coefficient : This term is used for this study to refer to a coefficients used to calculate the maximum vegetation water requirement (ETveg) from reference crop water requirement (ETo). The vegetation coefficients changes across the plant or crop growing period (Doorenbos and Pruitt, 1977).

Ecological Zone : For this study, an ecological zone was taken as a belt of a given vegetation whose area of spatial extension is determined by the horizontal and vertical variations of rainfall and temperature (Decurtins, 1992). The five zones investigated in this study includes Alpine, Moorland, upper Forest, lower Forest and Footzone.

Vegetation and slope Systems : The vegetation and slope systems investigated in this study are defined on the basis of vegetation type and the slope of their location. The different vegetation type investigated includes Grass, natural Forest, Potato crop and Cypress plantation. The slopes investigated are categorized into typical (on the ridge top) and steep (on the valley sides).

Wet and Dry periods : This refers to the three main wet and dry periods experienced during the study period and defined on the basis of rainfall i.e, 1st wet period between November and December 1991, dry period between January to March 1992 and 2nd wet period between April and June 1992. These follow closely the dry and wet periods experienced in this area as documented by Berger (1989).

1.8 The scope and limitations of the study

1.8.1 The scope of the study

The study was carried out in five of the six ecological zones of the Naro Moru river catchment. The research was conducted at site level. One site was selected in each of the five zones. Climatic and soil water conditions were measured at these sites between November 1991 and June 1992. Climatic data was analyzed on daily basis while soil water data was analyzed on a weekly basis for the neutron probe measurements and monthly basis for the gravimetric measurements. For the vegetation water balance calculation, only rainfall and soil water storage were measured in the field. The other parameters were combined to form the vegetation water use component and were calculated as the difference between rainfall water input and soil water change.

1.8.2 Limitations of the Study

For the sites R1 and R2, accessibility was a problem due to the long walking distance to these sites and their high altitudes. At these two sites, only rainfall and gravimetric soil water measurements were carried out. Additionally, for all sites surface runoff and deep percolation were not measured in the field and hence actual evapotranspiration for the different vegetation systems could not be calculated in the water balance equation.

CHAPTER TWO

THE STUDY AREA

2.1 Introduction

The Naru Moru, the perrenial river system investigated in this study drains the slopes Northwest of Mount Kenya and form one of the several small cathchments that make up the Mount Kenya sub-catchment of the Ewaso Ngiro basin.

Figure 2.1 shows the location of the study area. Figure 2.2 Shows the Naru Moru river within the upper Ewaso Ngiro basin upstream of Archers post. Figure 2.3 shows a profile of the catchment and indicates its geology, soils, vegetation, and landuse characteristics.

Various studies have been carried out in this area regarding geology (Baker, 1967), soils (Desaules, 1986), rainfall and agroclimatology (Berger, 1987), hydrogeographic mapping (Leibundgut, 1984), social economy (Kohler, 1987) and soil and water resources conservation (Speck, 1982; Liniger, 199a) among others. This chapter discusses briefly the cahracteristics of the study area that are relevant to this study.

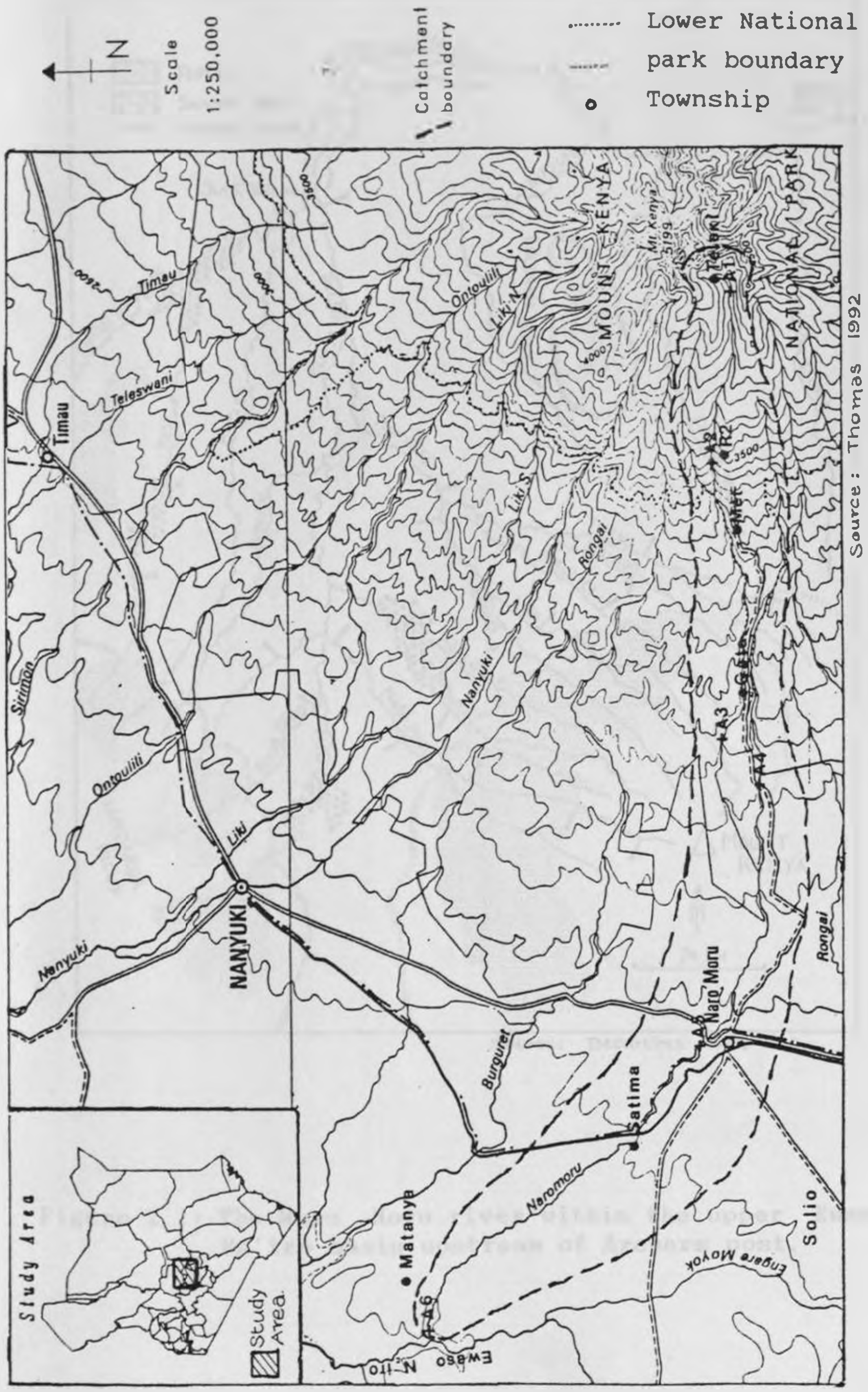
2.2 General characteristics

The Naru Moru catchment is located between latitude 0°03' and 0°11' South and longitute36°55' and 37°15' East. It covers an area of approximately 170 km^2 formed into a 50km long but narrow strech which reaches 5km at its widest point.

The altitude ranges between 1800 and 5200 metres above sea level (a.s.l). In the upper reaches, i.e above 3600 meters a.s.l, the Naru Moru river flows through a glacial formed U shaped valley and shows fast youthful flow. Below 3600 meters a.s.l, the valley becomes a deep fluvial formed V shaped valley.

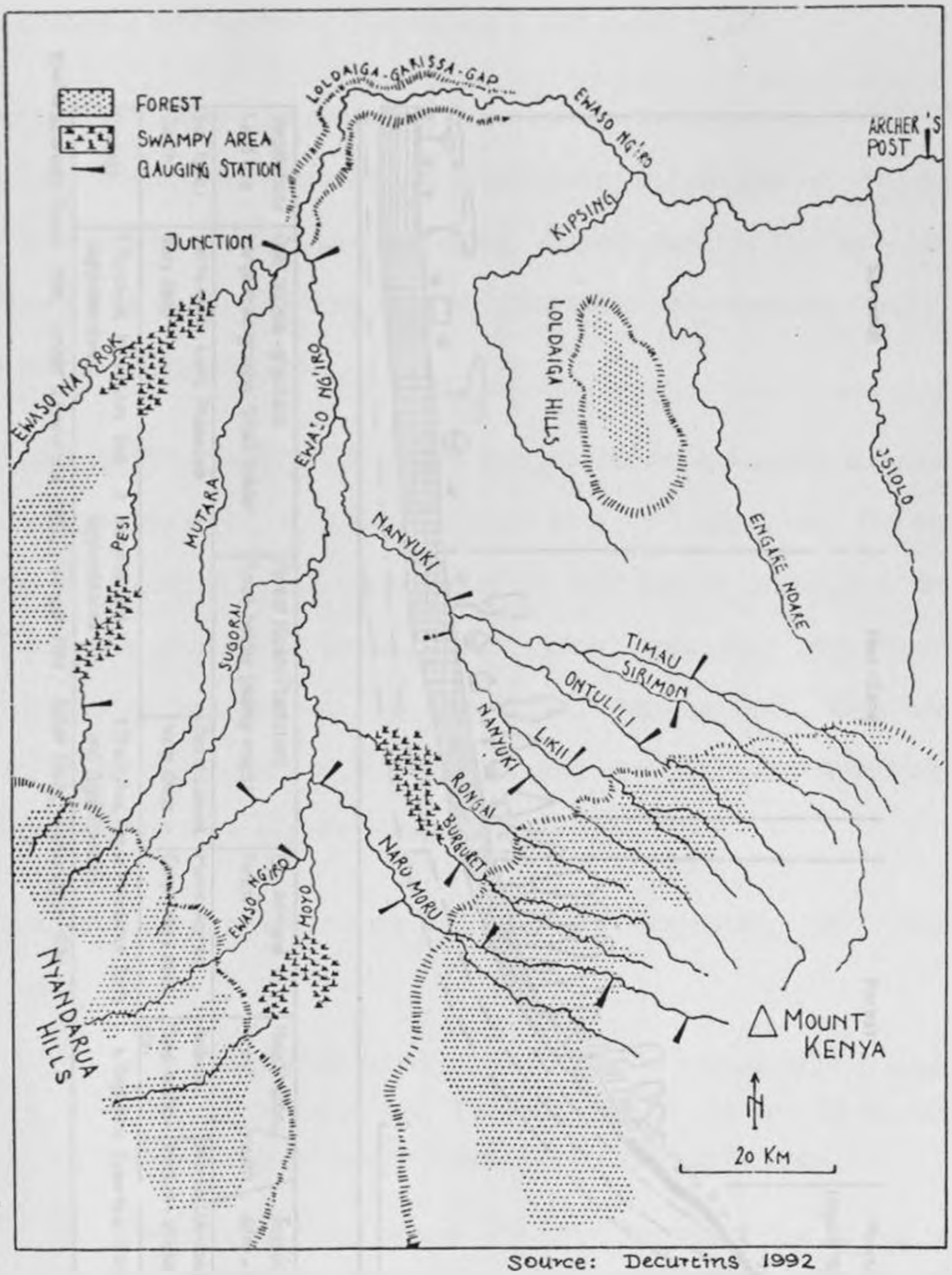
Legend:

- - - Cathment boundary
— Contour lines
═ Main road
Dry weather road
Rail line
.... Lower National
park boundary
o Township



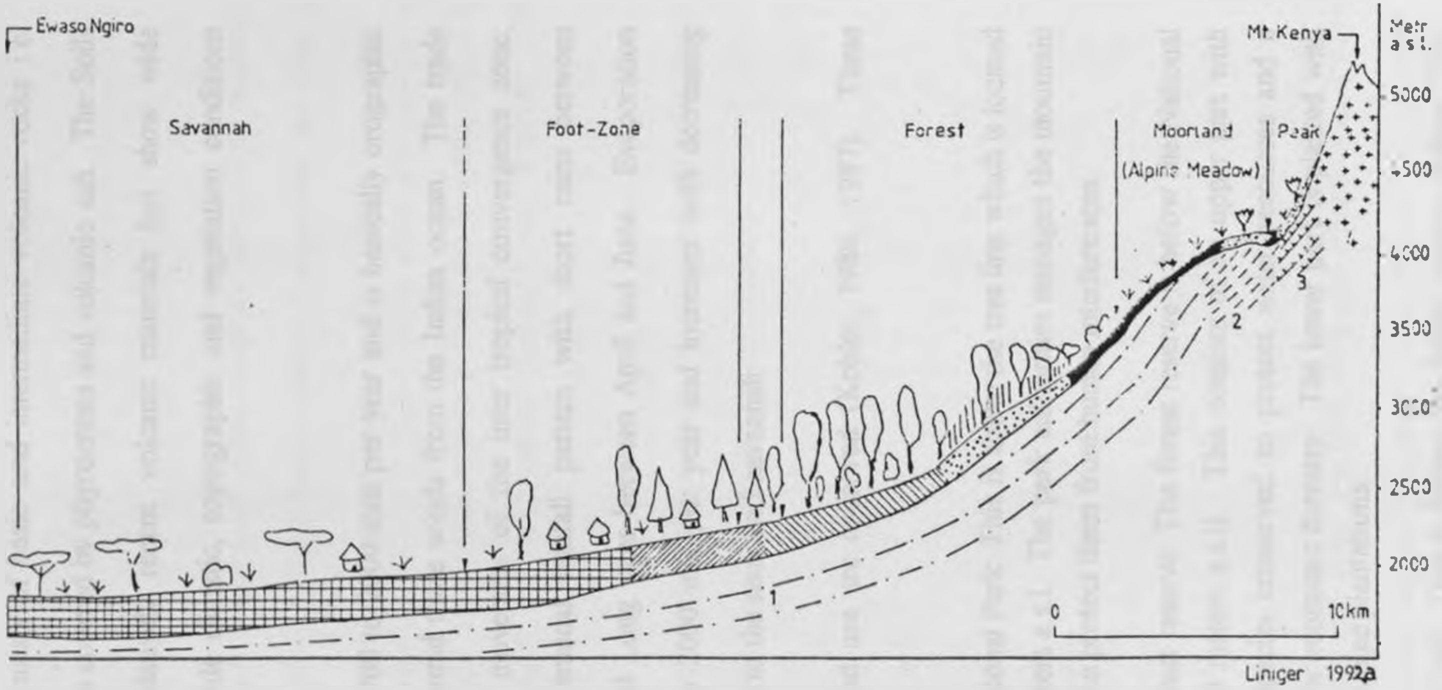
Source: Thomas 1992

Figure 2.1: Location of the study area.



Source: Decurtins 1992

Figure 2.2: The Naru Moru river within the upper Ewaso Ng'iro basin upstream of Archers post.



Vegetation / Land Use	Open accacia - grassland Large scale grazing, Small-holder	Forest (Open / Plantation) Small-holder (mainly crops)		Dry montane Forest	Mixed bamboo/ Forest	Heath	Tussock grass Afro - alpine Vegetation
Soil type / Depth	Verto-luvic, Luvic Phaeozem Very deep		Ferric Luvisol Very deep	Humic Acrisol Deep - very deep	Andosol Deep-moderate	Histosol/Andosol Medium - shallow	Litho/Regosol Shallow
Geology	1. Porphyric Phonolites and Agglomerates	2 Kenytes and Agglomerates	3 Trachytes, Fissile Phonolites, Tuffs and Agglomerates		4. Nepheline Syenites, Porphyric Phonolites		

Data sources: Speck 1981, Liniger & Decurtins 1990, Winiger 1986, Baker 1967, Leibundgut 1986

Figure 2.3: A profile of Naru Moru catchment.

In the lower reaches, the river shows a meandering flow in an open valley towards it's confluence with the Ewaso Ng'iro at about 1800 meters a.s.l.

The geology (Figure 2.3) consists of basic and intermediate volcanic rocks i.e. trachytes, kenytes, and basalts covered by phyrocrasts and volcanic ash. The Soils are mainly derived from relatively recent volcanic materials but show wide differentiation due to the wide climatic, topographic and vegetation conditions experienced in the study area.

Average rainfall varies from 700 to 2000 mm per year and is basically orographic produced by the ascent of humid trade winds from the Indian ocean. The trade winds are controlled by the movement of the inter tropical convergence zone, ITCZ, which produces a bimodal rainfall pattern with short rains between November and December and Long rains between April and June. Evaporation rates range between 1200 to 2000 mm per year and increases with decreasing altitude from the humid peaks to the semi arid savannah.

Three main categories of land use are observed (Kohler, 1986, 1987). These includes:-

i) Mount Kenya National Park: This is above the tree line which is located at about 3200 meters a.s.l. The park authorities manages the mountain natural resources to protect them from human interferences.

ii) Mount Kenya Forest reserve: The forest reserve is below the National Park (below 3200 meters a.s.l). This consists of an upper part with indigenous tree species conserved to protect water resources and a lower part used for economic forestry. The lower part is planted with exotic cypress and pine plantations.

iii) Individual owned land: This is below the forest reserve (below 2100 meters a.s.l). The land was previously owned by European farmers but is now subdivided into small plots. The plots are under small scale mixed farming.

The population growth rate in this area is estimated at 7.8% per annum (Laikipia District Development Plan, 1989). This high population growth rate is due to the combined effect of natural births and immigration from the adjacent high potential districts experiencing land pressure.

2.3 Ecological Zones

Decurtins (1992) observed five ecological zones within the Naro Moru catchment. These zones are defined on the basis of temperature and vegetation but does not follow strictly any temperature and humidity index.

Other classification are based on available moisture (Pratt and Gwynne, 1977) and the balance between rainfall and evaporation (Jaetzold and Schmidt, 1983; Sombroek et al, 1982).

Due to the hydro-geographic nature of this study, the zones are defined following the classification presented by Decurtins (1992) which includes:-

i) The Afro-alpine zone,

ii) The Moorland zone,

iii) The Forest zone,

iv) The Footzone and

v) The Savanna zone.

This study covers the first four zones. For this study, the Forest zone is further sub-divided into upper and lower Forest and thus the study addresses five zones.

2.3.1 Afro-Alpine Zone

2.3.1.1 Topography and Drainage

This zone rises from 4000 to 5200 meters a.s.l with an average altitude of 4510 meters a.s.l to cover an area of approximately 5 km^2 (Decurtins, 1985). The Lewis and Tyndal glaciers in this zone forms the source of the main Naro Moru, the Naro-moru north river (Decurtins, 1992).

2.3.1.2 Geology and soils

The central core of Mount Kenya covers the upper part of this zone, and consists of porphyritic phonolites and nephelites synite. In the lower part of the zone are trachytes, fissile phonolites, turfs and agglomerates (Winiger, 1986).

Lithosols and dystric Regosols are formed on rock outcrops while Lithosols, dystric Regosol, and Rankers are found on ridges and moraine. Rankers, Dystric Fluvisols and Humic Gleysols are found in the valley bottoms. Soils on ridges and moraine(Regosol, Luvisols and Rankers) are well drained (Speck, 1982).

2.3.1.3 Climate and Hydrology

Rainfall varies between 600 to 1000 mm per year with evaporation rates varying between 1200 and 1400 mm per year. Daily evaporation rates varies between 0.1 mm per day in the wet season and 0.4 mm per day in the dry season. This zone forms the origin of the main Naro Moru (Naro Moru North) river which originates from the glaciated peaks (Decurtins and Liniger, 1990).

2.3.1.4 Vegetation and Land use

The upper part of this zone is covered by ice, snow and rock scree on steep slopes. On the lower part are giant groundsel (senecio keniodendron) Afro-alpine vegetation (Decurtins, 1992). Land use is tourism and park reserve.

2.3.2 Moorland Zone

2.3.2.1 Topography and Drainage

This zone rises from 3500 to 4200 meters a.s.l. with an average altitude of 4000 meters a.s.l. It cover an area of 16 km^2 (Decurtins, 1985). The glacial cut U shaped river valley changes abruptly into a V-shaped fluvial cut valley below 3600 meters a.s.l. The southern Naro-Moru river as well as many small streams in form of ground water outlets originate from this zone (Decurtins, 1992).

2.3.2.2 Geology and Soils

The upper part consists of Kenytes and Kenytes agglomerates while the lower parts consist of porphyritic phonolites and agglomerates (Baker, 1967). The major soil types are shallow Histosols and Andosols which are well drained in the upper part but poorly drained on ridges and variably drained on the valley bottoms in the lower part (Desaules, 1986). The soil water holding capacity of the upper part is below 50 mm and between 50 and 100 mm in the lower half of the zone (Decurtins and Liniger, 1990).

2.3.2.3 Vegetation and Land use

The Afro alpine vegetation of giant groundsel on the valley sides and tussock grass on the valley bottoms of the lower Alpine zone extends into the upper part of this zone.

This changes into *erica* and *philipia* heath vegetation in the lower part (Decurtins, 1992). Land use is basically tourism.

2.3.2.4 Climate and Hydrology

Annual rainfall ranges between 1000 mm in the upper part and 1500 mm per year and increases towards the lower part and into the Forest zone.

2.3.3 Forest Zone

2.3.3.1 Relief and Drainage

This zone rises from 2300 to 3540 meters a.s.l with an average altitude of 3200 meters a.s.l to cover an area of 26 km^2 (Decurtins, 1985). The river valley is deeply incised with few tributaries in the upper part while in the lower part the valley becomes less incised and has more tributaries (Decurtins and Liniger, 1990).

2.3.3.2 Geology and Soils

The geology of the lower Moorland consisting of porphyritic phonolites and agglomerate extends to this zone. In the upper part, there are Histosols of shallow (20 to 50cm) to medium (50 to 80cm) depth. In the middle part are humic Andosols which are moderate (50 to 80cm) to deep (80 to 120cm) and the very deep (120 to 180cm) humic Acrisols are found in the lower parts (Desaules, 1986). The soils on the valley bottom have variable drainage while those on the valley sides are well drained. The water holding capacit,v of the soils in the lower part i.e. humic Acrisols is very high exceeding 200 mm (Decurtins and Liniger, 1990).

2.3.3.3 Vegetation and Land use

The zone shows several vegetation belts. The Hagenia-Hypericum belt forms the upper tree line followed by the Montane Bamboo belt with scattered Podocarpus and Cedar trees. This belt is followed by the ever-green mountain vegetation with Juniperaus, Podocarpus and Olea tree species. Below this belt, the cypress and pine plantations marks the lower edge of the Forest. Tracts of crop land in thin bands are seen on the lower edge in alternation to exotic Forest plantations (Kohler, 1987).

2.3.3.4 Climate and Hydrology

The highest rainfall in the whole catchment, varying between 1000 and 2000 mm per year falls in this zone (Berger, 1989). Dry season evaporation (January to March and July to September) show average rates between 1.7 and 2.8 mm per day while that of the wet season (April to June and November to December) show average rates between 0.6 and 1.7 mm per day (Liniger and Decurtins, 1990). This area is considered to be the major contributor to ground water recharge due to high rainfall, high soil water holding capacities and low evaporation rates(Decurtins and Liniger, 1990).

2.3.4 The Mountain Foot Zone

2.3.4.1 Topography and Drainage

The zone rises from about 1980 to 2300 meters a.s.l to form an area approximately 47 km square with an average altitude of 2240 meters a.s.l (Decurtins, 1985). The relief of the upper part reflects the deeply incised river valleys relief of the Forest and change into less incised valleys in the lower part.

2.3.4.2 Geology and Soils

The geology is similar to that of the Forest zone consisting of porphyritic phonolites and agglomerates (Desaules, 1986). In the upper part are very deep (120 to 180cm), well drained ferric Luvisols while the lower parts have moderate to well drained verto-luvic Phaeozems. On the plateau are Planosols.

2.3.4.3 Vegetation and Land use

The original dry cedar vegetation has been replaced by crop land and partly by exotic Forest plantation. In the upper, part land is used for extensive rain fed agriculture where potatoes, wheat, beans and vegetables among other crops are grown (Kohler, 1987). Small scale mixed farming is practised in the lower part. Some of the farmers try irrigation on small plots.

2.3.4.4 Climate and Hydrology

Rainfall ranges between 900 mm per year in the upper part to 800 mm per year in the lower part (Berger, 1989). Usually, in this zone evaporation exceeds rainfall. The ratio between rainfall and evaporation ranges between 0.4 and 0.5 in the drier lower part and between 0.6 and 0.5 in the wetter upper part. Dry season (January to March and July to September) evaporation rates average 4.5 mm per day while wet season (April to June and October to December) rates average 3.3 mm per day (Decurtins and Liniger, 1990).

CHAPTER THREE

MATERIALS AND METHODS

3.1 General

Five zones (Alpine, Moorland, upper Forest, lower Forest, and Footzone) of the Naru Moru catchment were investigated. Within each zone, one site was selected for investigation. Figure 3.1 shows the location of the five sites in the catchment. In each of these sites, climatic and soil water conditions were monitored between November 1991 and June 1992. Rainfall was previously being monitored by Laikipia Research Programme (LRP) in all the five sites. Additional instruments were installed to monitor relevant climatic and soil water conditions.

3.2 Experimental sites and design

3.2.1 Experimental sites

The five experimental sites are sketched in Figure 3.2. Table 3.1 presents a summary of the field installations showing the climatic and soil water observations carried out at each site.

Table 3.1: Summary of the field experimental set-up.

Station	Zone	Altitude	Climatic Observations	Soil water content Observation
R1	Alpine	4176	Rainfall	Gravimetric
R2	Moorland	3719	Rainfall	Gravimetric
Met	Upper Forest	3048	All	Neutron Probe
Gate	Lower Forest	2438	All	Neutron Probe
Munyaka	Footzone	2073	All	Neutron Probe

* All refers to rainfall, evaporation, temperature, wind speed, humidity and duration of sunshine.

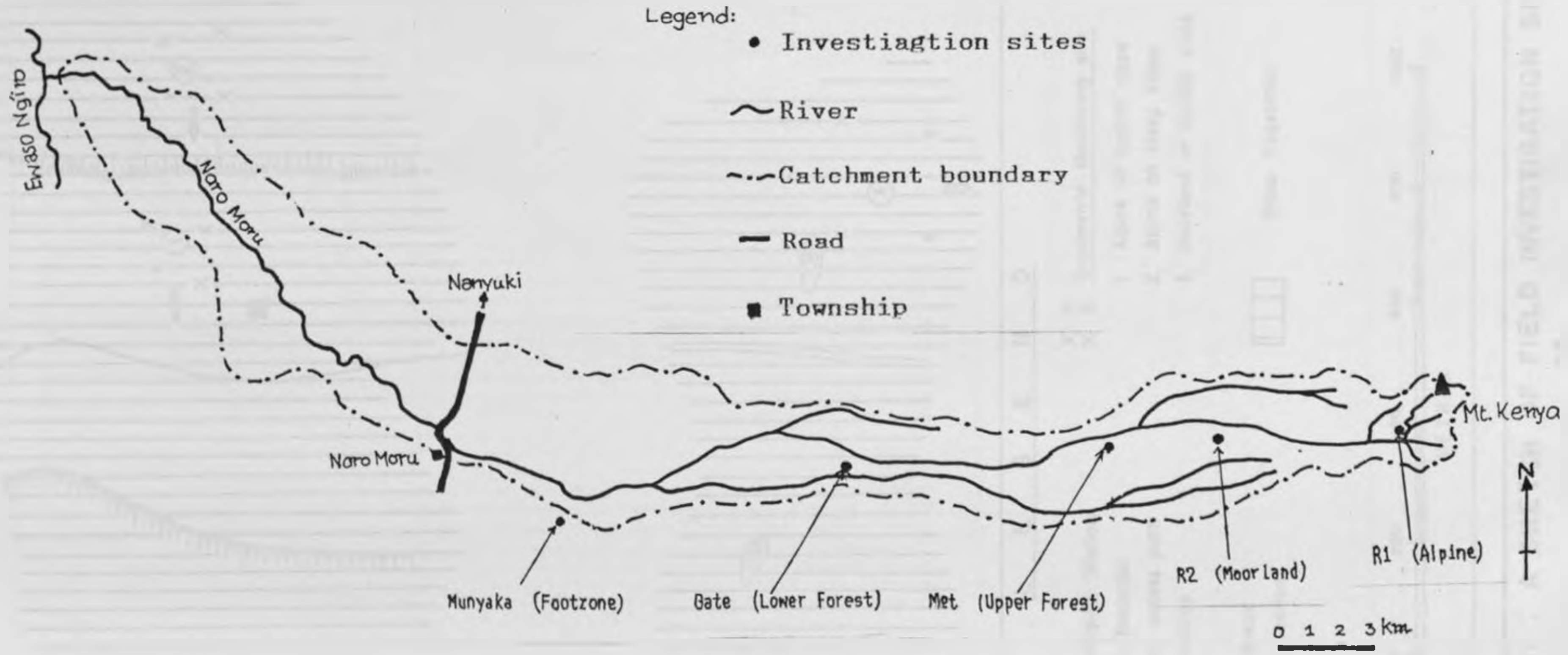


Figure 3.1: Location of Investigation sites.

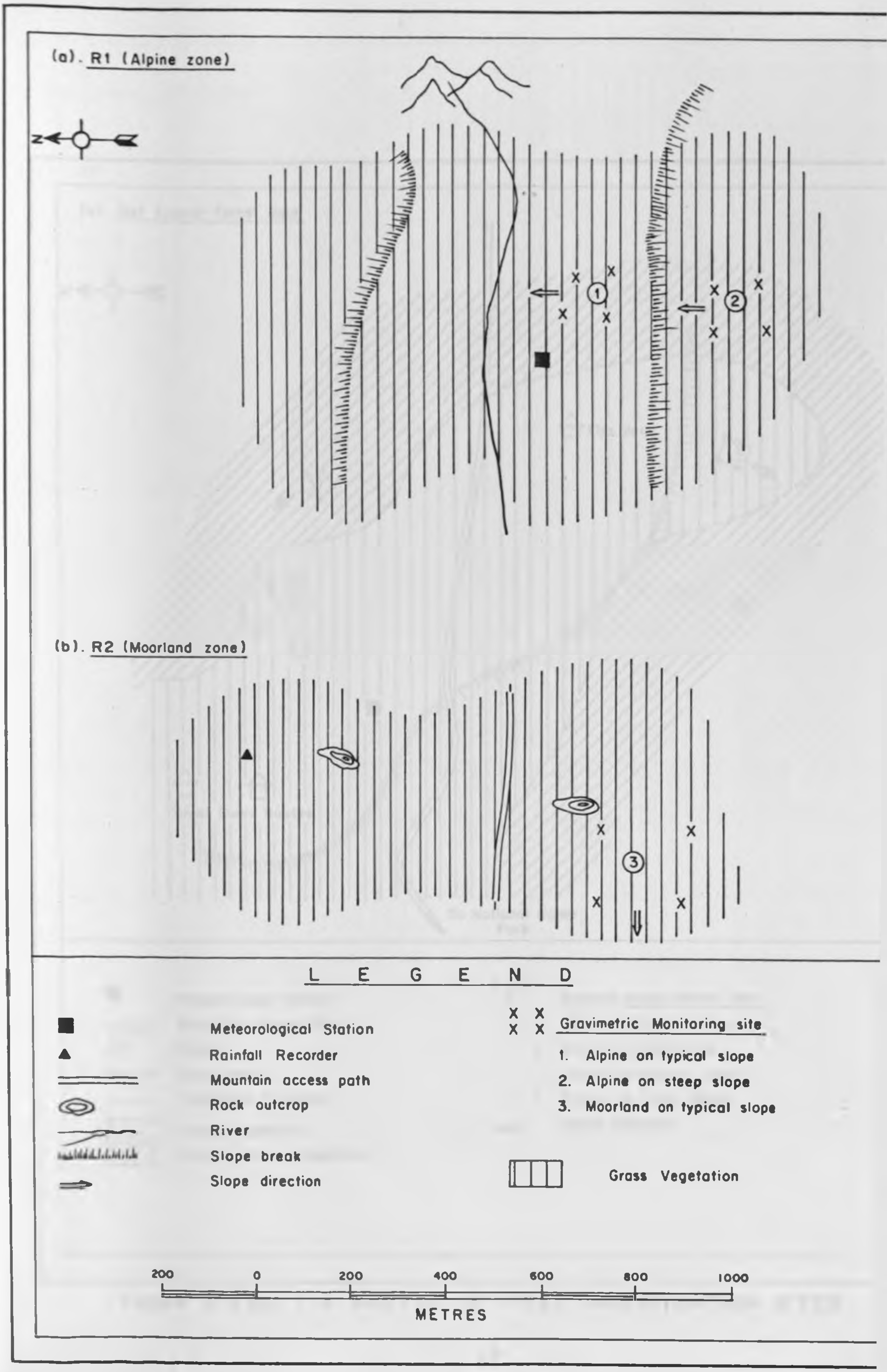


Figure 3.2 (a) : A SKETCH OF FIELD INVESTIGATION SITES

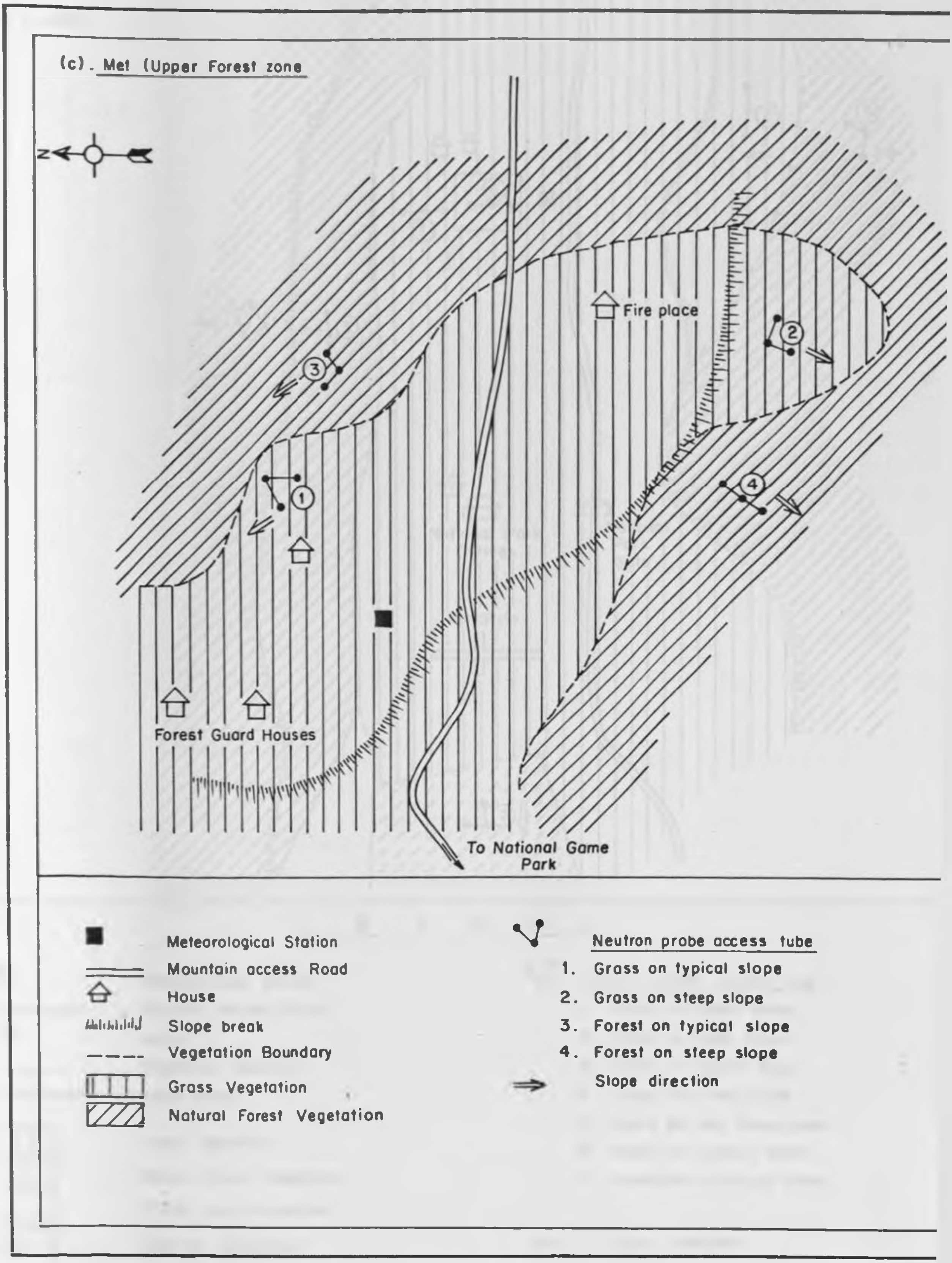


Figure 3.2 (b) : A SKETCH OF FIELD INVESTIGATION SITES

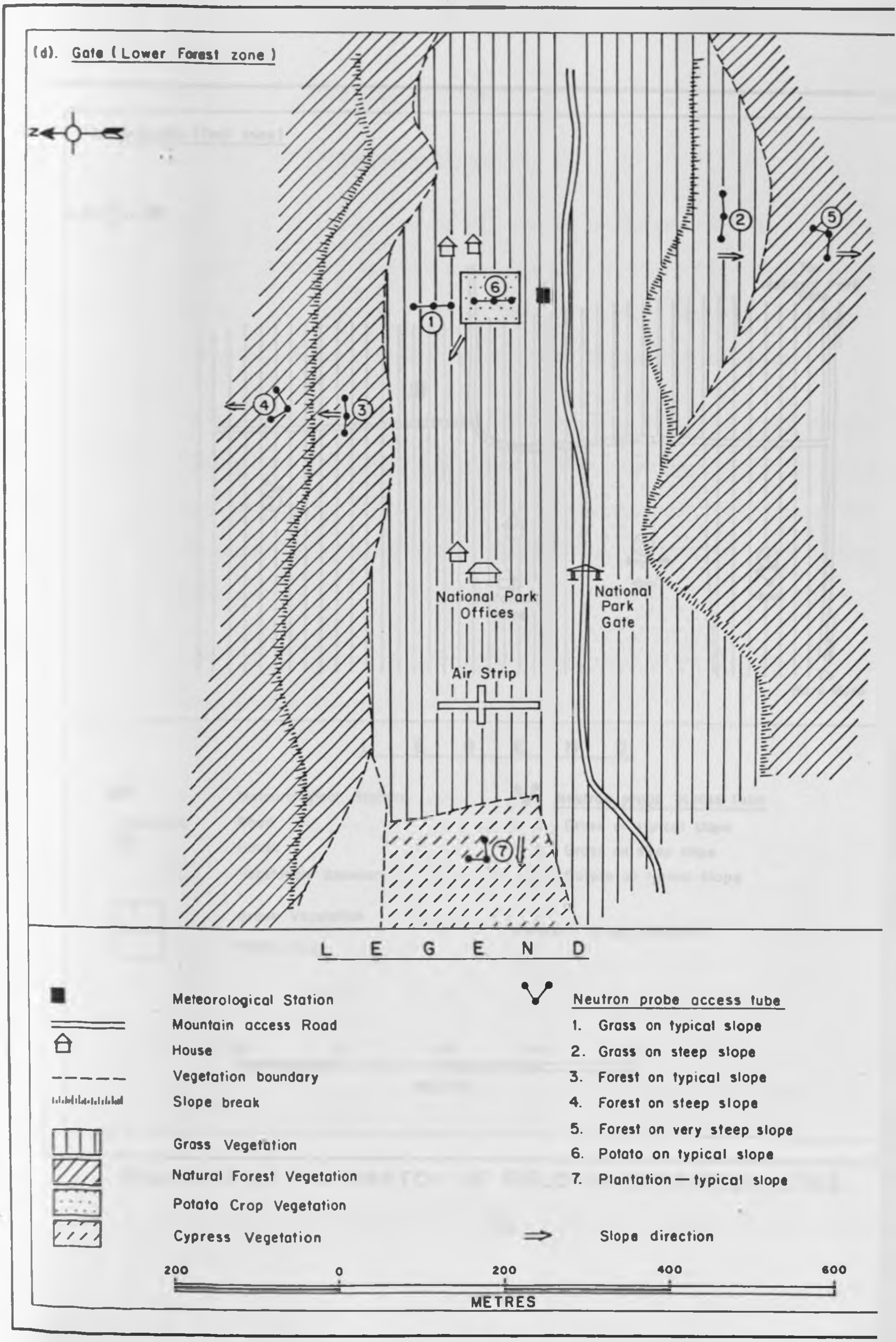


Figure 3.2 (c) : A SKETCH OF FIELD INVESTIGATION SITES

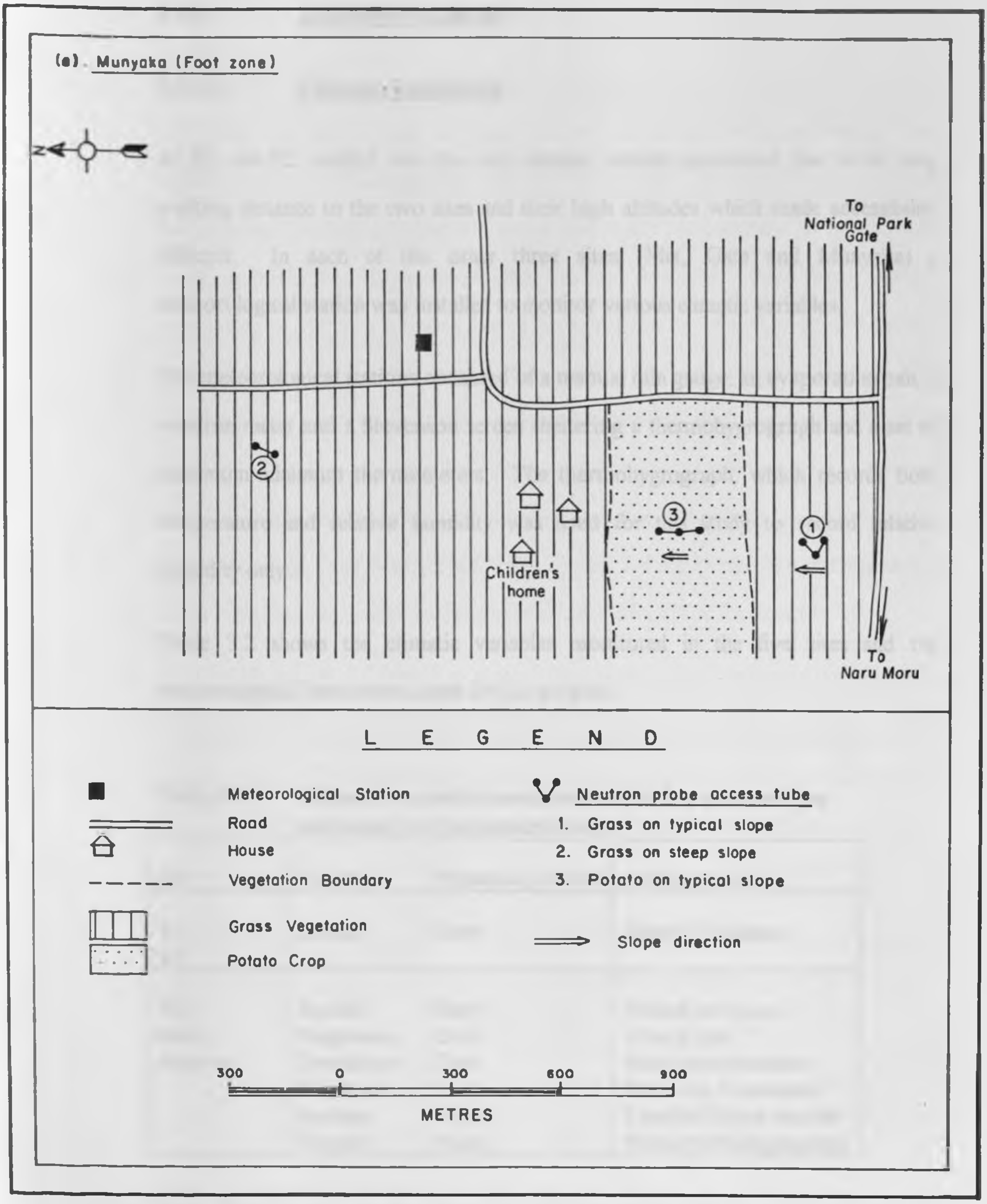


Figure 3.2 (d) : A SKETCH OF FIELD INVESTIGATION SITES

3.2.2 Experimental design

3.2.2.1 Climatic monitoring

At R1 and R2, rainfall was the only climatic variable monitored due to the long walking distance to the two sites and their high altitudes which made accessibility difficult. In each of the other three sites (Met, Gate and Munyaka) a meteorological station was installed to monitor various climatic variables.

The meteorological stations consisted of a manual rain gauge, an evaporation pan, a windrun meter and a Stevenson screen sheltering a thermohygrogragh and a set of maximum-minimum thermometers. The thermohygrograph, which records both temperature and relative humidity was used for this study to record relative humidity only.

Table 3.2 shows the climatic variables monitored in the five sites and the meteorological instruments used for this purpose.

Table 3.2: **Climatic variables monitored in the five sites and the metorological instruments used.**

Site	Variable	Monitoring interval	Instrument used
R1 R2	Rainfall	Daily	Manual rain gauge
Met Gate Munyaka	Rainfall Evaporation Temperature Windspeed Sunshine Humidity	Daily Daily Daily Daily Hourly Hourly	Manual rain gauge Class A pan Max-min thermometer Ketter cup Ananometer Campbell Stokes recorder Haenni thermohygrograph

Each of the meteorological stations was attended to by a research assistant. Records of the various climatic variables were made daily by the research assistant at 9 am and 6 pm.

3.2.2.2 Soil water monitoring

Gravimetric soil water content measurements were carried out on a monthly interval at R1 and R2 while neutron probe soil water content measurements were carried out on approximately one week interval at Met, Gate and Munyaka. It was not possible to carry out neutron probe soil water measurement at exactly one week intervals due to transport and weather problems. Soil water content monitoring at R1 and R2 was limited to a monthly interval due to accessibility difficulties as a result of the long walking distances to the two sites and their high altitudes. Soil water content measurement points at the five sites were selected on the basis of vegetation type and slope category. Both gravimetric and neutron probe measurement were done in three replications. The three replicates at each sampling points were selected randomly. Table 3.3 shows the different vegetation types and slope categories investigated for soil water in the five zones.

Table 3.3: **Vegetation types where measurements of soil water content were carried out.**

Soil water measurement	Site	Vegetation type investigated
Gravimetric	R1	Grass on typical and steep slope
Gravimetric	R2	Grass on typical slope
Neutron Probe	Met Gate Munyaka	Grass on typical slope Grass on steep slope Natural forest on typical slope Natural forest on steep slope Natural forest on very steep slope[1] Cypress plantation on typical slope[1] Potato on typical Slope[2]

Note [1] : Investigated only at Gate.

[2] : Investigated at Gate and Munyaka.

3.3 Instrumentation and measurements

3.3.1 Climatic instruments and measurements

Rainfall was measured using a standard 12.7cm diameter manual rain gauge. Rainfall records (in mm/day) were made daily at 9 am. Care was taken to specify the day of rainfall and the day of reading when making rainfall records.

Evaporation rates were measured from a standard type A pan. Records were made daily at 9 am and the number of cups added or removed from the pan used to calculate evaporation rates (in mm/day) from the pan's open water surface.

Daily maximum and minimum temperatures (in °C) were recorded from a set of Maximum-Minimum thermometers. The minimum temperatures were recorded at 9 am while the maximum temperatures were recorded at 6 pm.

Windspeed records (in Km/h) were made from a Ketterer cup anemometer (windrun meter) installed at an height of 2 meters. Windspeed records were made at 9 am and 6 pm. The difference between the 6 pm and 9 am readings was used to calculate the day's windspeed. The night windspeed was calculated from the difference between the 6 pm reading and the next day's 9 am reading.

Duration of sunshine (in h/day) was recorded from a Campbell-Stokes sunshine recorder. A card was fixed daily at 6 pm and removed the next day at 6 pm. Records were made by converting the burnt portion of the card into duration of sunshine in hours per day.

Relative humidity was measured by a recording Thermohygrograph. The Thermohygrograph operates a pen system which draws on the recording chart with a daily time scale. To make records, the weekly charts were digitized and values for 9, 13 and 18 hours for each day averaged into the day's relative humidity (in %).

For all the climatic variables, the daily values were entered into appropriate recording sheets. The records were then entered in computer worksheets from where l0 days decade and monthly averages values were calculated. For rainfall, 10 day's decade and monthly totals other than average values were calculated.

3.3.2 Soil water content measurement

3.3.2.1 Gravimetric Soil water content measurement

Gravimetric soil water content measurement at Rl and R2 involved field auger sampling at various depths, weighing and oven drying to obtain the gravimetric soil water content. Measurements were carried out at 30cm intervals except for the first two depths, 15 and 30cm, which had an interval of 15cm. Excessive soil wetness limited the number of depths that could be measured but at least two depths (15 and 30cm) were monitored at the two sites throughout the study period.

The auger sampling was done in three replicates selected randomly so that they were representative of the sampling site.

Undisturbed core ring samples were collected during the study period and used to compute the soil bulk density for the two sites. The bulk density was necessary to convert gravimetric soil water content into volumetric soil water content.

Monthly gravimetric soil water content was calculated after weighing and drying of the gravimetric samples collected in the field using the relationship:

$$O_g = M_w/M_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where:-

O_g = gravimetric water content (g/g)

M_w = weight of water in sample (g)

M_s = weight of dry sample (g)

The calculated gravimetric soil water content was converted into volumetric soil water content using the relationship:

$$O_v = O_g * BD * 1/\ H_2o \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where:-

O_v= Volumetric soil water content (cm^3/cm^3)

O_g = Gravimetric soil water content (g/g)

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

H_2o = Density of water (g/cm^3).

The dry soil bulk density used in equation 3 was calculated from volumetric ($100cm^3$) core ring samples collected during the study period using the relationship:-

$$BD = M_s/V_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where:-

BD = Bulk density (g/cm^3)

M_s = weight of dry soil sample (g)

V_s = Unit volume of the sample (100 cm^3)

3.3.2.2 Volumetric Soil water content measurement

Volumetric soil water measurement at Met, Gate and Munyaka was done using Campell Nuclear Pacific Model 503 neutron probe. The Neutron probe is fitted with a probe which contains a neutron source and detector. When measuring soil water content, the source emits fast neutrons which are thermalised on collision with water molecules in their path of motion into slow thermal neutrons. The resulting thermal neutrons form a cloud around the probe and their density is recorded by the neutron detector as a ratio of the initially emitted fast neutrons. This ratio, recorded as a neutron count, indicates the soil water content.

To introduce the probe into the soil profile, aluminium access tubes were installed at the sampling site in three replicates. Only three replicates for each vegetation system were possible so as to reduce the time and cost required to carry out the measurements. At each site, the three replicates for the different vegetation systems were selected randomly and close enough (see site sketches) to be within similar soil physio-chemical characteristics to allow comparison of the soil water data obtained.

Measurements were carried out for the depths 15, 30, 60, 90, 120, 150 and 170cm. When taking reading with the Neutron probe, a standard count (with probe inside its housing) of ten readings was taken at the beginning and end of the exercise. The first set of the ten standard count was used to test the working condition of the Neutron probe. The Neutron probe was within normal working conditions if seven of the ten standard counts were within the upper and lower standard deviation margin ofthe average count.

Neutron probe readings were made for all the monitoring depths for the three replications in each of vegetation systems investigated. Readings for the three replications were averaged and divided by a long term average standard count and the resulting neutron ratio recorded for further analysis.

To convert the neutron probe (neutron ratio) readings into volumetric soil water content, the neutron probe was field calibrated during the study period for dry and wet soil water conditions. The dry calibration was done at the end of the dry season in February 1992 while the wet one was done in the middle of the wet season in May 1992.

Calibration was done on separate access tubes located close to those used for the weekly routine Neutron probe readings. For the wet calibration, due to poor rains during the study period, the soil profile had to be ponded artificially. An iron sheet was placed around (one meter diameter) the calibration access tube and continually ponded with water for several days until a Neutron probe reading showed a high neutron count for all the reading depths. The set up was then covered with a plastic sheet for two days to allow excess water to percolate under limited evapotranspiration and hence allowing the profile to attain its field capacity.

The calibration process involved taking five neutron probe reading for each monitoring depth and a corresponding five replication of volumetric (l00 cm3) core ring samples. A standard count of twenty readings was taken at the beginning and end of the calibration exercise and the average standard count calculated. The five neutron probe readings for each monitoring depth were averaged and divided by the average standard count to calculate a neutron ratio for each depth. The five ring samples for each depth were put in air tight plastic bags and taken to the office where their wet weights were recorded. They were then placed in the oven for drying and later their average volumetric water content, in percentage, calculated. The calibration neutron ratios for each monitoring depth were regressed against their corresponding core ring samples volumetric water content. The regression relationship obtained was used to estimate volumetric soil water from the routine field neutron probe readings.

From previous experiences (Liniger, 1991), the soil water field capacity and wilting point were not laboratory determined as the soil water content at 15 and 0.3 bars respectively but were rather determined in the field. This was done by plotting the rainfall and volumetric soil water observed throughout the study period. The field capacity, the upper soil water content, was taken as the upper volumetric soil water content two to three days after a heavy rain storm. The wilting point, the lower soil water content, was set as the lowest volumetric soil water content recorded in the dry period between January and March 1992.

For both gravimetric and Neutron probe monitoring, the available soil water for each measurement depth was calculated as the difference between the observed volumetric soil water content and the set lower (wilting point) volumetric soil water content.

The available volumetric soil water content was expressed as equivalent water depth stored within a given depth of the soil profile using the relationship:

$$D = Z * O_v \text{..} (5)$$

where:-

D = Equivalent water depth (cm)

Z = Depth of the profile considered (cm)

O_v = Volumetric soil water content (cm^3/cm^3)

This relationship was used to calculate the total available volumetric soil water content stored within a profile depth of 30cm for Rl and R2 and 160cm for Met, Gate and Munyaka. The difference in the profile depths used in this calculation was due to differences in the depths to which soil water measurements were carried out at the different sites.

3.4 Water balance calculations

3.4.1 Climatic water balance

The climatic water balance was calculated on a monthly scale as the difference between water input (rainfall) and output (potential evapotranspiration). Rainfall was measured in the field. Potential evaporation was not measured but was calculated from the climatic variables measured in the field using the Penman formula. The Penman formula used is presented in Appendix 1. This formula required the input of the climatic variables of temperature, windspeed, relative humidity, sunshine duration and solar radiation.

Temperature, windspeed, sunshine duration and relative humidity were measured in the field on daily basis as discussed in section 3.3.1. Solar radiation was not measured and monthly values were estimated from values of possible evaporable water for this area (0° latitude). This was done using an equation which relates evaporable water to solar radiation (Frere and Popov, 1979b). This relationship is given as:

0.00405 mm/day (Evaporable water) = IJoule/cm^2/day (Solar radiation).

When calculating potential evapotranspiration, various modifications as suggested by Frere and Popov (1979b) were applied to the Penman formula to take into account the local conditions experienced in the study area. These modifications are discussed below.

Dry air advection: In very dry environments, where the annual average minimum temperature exceeds 5°C and the difference between monthly average maximum and minimum temperature exceeds 12°C, the above formula under estimates potential evapotranspiration. This is due to dry air advection which causes higher evapotranspiration rates than estimated by the formula. For this study, this was corrected by introducing a modification which evaluates the difference between daily maximum and minimum daily temperature before allocating the windspeed coefficient i.e.

i)If (Tmax-Tmin) > 11.5; coefficient = 0.54 + 0.07 * (Tmax-Tmin -11.5) or

ii) If (Tmax-Tmin) < 11.5; coefficient = 0.54

where :

Tmax = maximum daily temperature and Tmin = minimum daily temperature

Sunshine duration : The coefficients (a + b) used in the formula to estimate total radiation from sunshine duration data are often subject to discussion. Many tests done within Food and Agricultural Organisation (FAO) projects have revealed three sets of coefficients (Frere and Popov, 1979b p39) which depend on climatic conditions. Two of the three sets were selected for this study on the basis of the climatic conditions experienced at the different sites. Table 3.4 presents the three sets, the climatic conditions for which they are best suited and the field sites for which they were applied in this study.

Table 3.4 : **Sunshine duration coefficients used in the Penman formula.**

Coefficient (a + b)	Suitable climatic condition	Field stations were used
0.18 + 0.55	Cold and temperate zones	Not used in this study
0.25 + 0.45	Dry tropical zones	Munyaka
0.29 + 0.45	Humid zones	Gate and Met

To calculate potential evapotranspiration, the necessary climatic data were entered into a computer worksheet from where 10 days decade averages and the monthly average and total potential evapotranspiration values were calculated. Potential evapotranspiration was calculated for the sites Met, Gate and Munyaka only. At Rl and R2, the necessary climatic data was not available.

3.4.2 Vegetation water balance

The climatic water balance discussed above (section 3.4.1) does not take into account the soil water and vegetation systems. For a conclusive water balance calculation, climatic, soil water and vegetation conditions should be evaluated together. This can be achieved through a vegetation water balance approach. The vegetation water balance equation used for this study is presented and discussed in section 1.3.

Rainfall and soil water content were measured in the field as discussed in section 3.3.1 and 3.3.2 respectively. The other variables of the water balance equation were not measured and were calculated together from the measured variables, rainfall and soil water change. The various components of the vegetation water balance are discussed in the following sections.

3.4.2.1 Vegetation water requirement

The vegetation water requirement is calculated from an equation which considers vegetation characteristics and the prevailing climatic condition. This equation is given by (Frere and Popov (1979b) as:-

$$ETveg = Kc * ETo \quad \text{..(6)}$$

where:-

$ETveg$ = Potential vegetation water requirement (mm)

Kc = Vegetation coefficient.

ETo = Reference crop evapotranspiration (mm)

The vegetation coefficient, Kc, expresses the vegetation characteristics. Kc values depend on the stage of vegetation growth, its potential to use soil water, which is a function of its root depth and density and the prevailing weather conditions. Kc values for various crops and grasses are given by Doorenbos and Kassam (1977). The Kc values used for this study were take or adapted from Doorenbos and Kassam (1977). Table 3.5 shows the Kc values used for different vegetation systems investigated in this study.

The climatic condition is expressed by the reference crop evapotranspiration (ETo). The reference crop evapotranspiration depends on daily climatic conditions and is a reference term which indicates the potential water requirement for a standard vegetation (taken as an extensive grass surface of 8 to 15 cm height) under a particular climatic condition.

Table 3.5: **Kc values for the vegetation systems**

Vegetation system	Kc value
Natural Forest	1.10
Cypress plantation	1.05
Grass	1.00
Potato crop	Various as shown below *

Note *: 0.35 from November 1991 to mid February 1992, 1.05 from mid February to 1st March 1992, 0.65 from 2nd March to 1st April 1992 and 0.35 from 2nd April to June 1992

Various methods are available for calculating the reference crop evapotranspiration using mean daily climatic data. These methods are presented by Doorenbos and Kassam (1977). In this study, the modified Penman formula as presented by Doorenbos and Kassam (1977) was used to calculate the reference crop evapotranspiration (Appendix 1).

The potential vegetation water requirement (ETveg) calculates the maximum water requirement for the vegetation system. This would only be fulfilled under non limiting conditions. However, the extent to which the potential vegetation water requirement is met depends on the vegetation type, soil water content and the prevailing climatic conditions. This actual amount of water that is available to the vegetation system is referred to as its actual water use and is usually denoted ETa. To calculate the actual amount of water available to the vegetation system, the limiting factors mentioned above should be considered. Surface runoff and deep percolation are hence required to calculate the actual amount of water use by the vegetation system. For this study, surface runoff and deep percolation were not measured in the field and hence the actual vegetation water requirement was not calculated. In its place, however the wholesome vegetation water use was calculated as a sum of the actual vegetation water use, surface runoff and deep percolation.

3.4.2.2 Vegetation water use

For each vegetation system, the water use included the water that goes to surface runoff (Ro), deep percolation (Dp) and the water that is actually available to the vegetation system to meet its potential requirement (ETa). The lumped water use component was calculated from the measured variables rainfall and soil water change by substituting in the water balance equation (see section 1.3).

The water balance for each vegetation system was calculation at a site level. The time scale for the calculation was dictated by the soil water change measurement intervals. This was approximately one week for Met, Gate and Munyaka and one month for R1 and R2.

Since the water use components; surface runoff, deep percolation and the actual vegetation water requirement influences the water resources, the water use component was thus used to investigate the influence of different vegetation systems on the water resources.

3.5 Statistical analysis and computer applications

3.5.1 Statistical Analysis

To test the hypotheses in section 1.4, the data collected in the field were subjected to statistical analysis. Both descriptive and inferential statistical techniques were used. The arithmetic mean and the coefficient of variation techniques where used for descriptive statistical analysis.

Analysis of Variance (ANOVA) technique was used to make statistical inference on the hypotheses. This technique is briefly discussed below.

Analysis of variance is a statistical technique used to investigate whether the difference observed in a set of groups of data is real or due to chance on sampling. It deals with data measure in interval scale. Johnson (1978) gives the analysis of variance model as

$$(Y_i - Y_t)^2 = (Y_i - Y_g)^2 + (Y_g - Y_t)^2 \text{.........................} (7)$$

where:-

Y_i = Individual score in a group

Y_g = Mean of a particular group

Y_t = Mean of the total data set (all groups)

= Summation from 1st score to nth score.

The three terms in equation 7 above gives different sources from which variation can arise i.e.:-

$(Y_i - Y_t)^2$ = total variation

$(Y_i - Y_g)^2$ = Within group variation

$(Y_g - Y_t)^2$ = Between group variation

To test the significance of the variation observed within or between the groups of data, a variance estimate is calculated. This is obtained by dividing the three variations in the equation with their degrees of freedom. From the calculated variance estimates, a ratio F is obtained which can then be compared to an hypothetical F distribution to test for the significance of the observed variation.

The analysis of variance technique requires that the parent population from where sampling is done be normally distributed and the range of the variance of the groups investigate be small.

3.5.2 Computer applications

Lotus 123 was used for all data entry and preliminary computations. Climatic and soil water content data entry worksheet were designed in Lotus 123. The Regression analysis and subsequent plotting of the calibration data was also done in lotus 123.

Apart from the calibration plotting in Lotus, Harvard Graphics was used for all the plotting needs of the study. Lotus Freelance Plus was used to produce grey shade images of the various categories of available soil water content for the different depths monitored in each vegetation system.

The Mstat (Micro statistics) statistical package was used for all the statistical needs of the study. For the work done in Harvard Graphic and Mstat, the data was initially entered in Lotus worksheets and imported into these packages for use. All editing work was done in WinWord 6.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

Data obtained from climatic and soil water observations at the five investigation sites were analyzed to test the hypotheses (section 1.4) formulated about the climatic water balance, soil water content and the vegetation water balance. The results of the analysis are presented and discussed in the following sections. The periods 1st wet period (November to December 1991), dry period (January to March 1992) and 2nd wet period (April to June 1992) were used in the analysis.

4.2 Climatic Water Balance

In section 1.4, the first hypothesis, Ho1, suggests that the five zones are not different in their climatic water balance. To test this hypothesis, the climatic water balance for the five zones is calculated as the difference between rainfall and potential evapotranspiration.

4.2.1 Rainfall

Appendix 3 presents the total monthly rainfall, long term mean monthly rainfall and the number of rain days per month in the study area between November 1991 and June 1992. The long term mean monthly rainfall (Thomas 1992) was calculated for periods varying between 3 years in the Alpine zone to 24 years in the Footzone. For the Alpine and Moorland zones, only the long term mean monthly rainfall is presented. This is due to lack of daily rainfall data and for these two zones, the long term mean monthly rainfall values are use in the analysis. A summary of the rainfall data is presented in Table 4. 1.

Table 4.1 Summary of Rainfall in the study area between November 1991 and June 1992

i) 1 st Wet period (1st November to 31st December 1991)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Mean Monthly					
-Observed (mm)	NA	NA	78	69	31
-Long term (mm)	87	132	145	128	93
Rain days (%)	52	85	49	48	15
Coef. of Variation(%)	26	NA	59	31	11

ii) Dry period (1st January to 31st March 1991)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Mean Monthly					
-Observed (mm)	NA	NA	60	40	33
-Long term (mm)	46	90	75	70	52
Rain days (%)	80	58	41	26	26
Coef. of Variation(%)	40	37	24	71	53

iii) 2 nd Wet period (1st April to 30th June 1992)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Mean Monthly					
-Observed (mm)	NA	NA	174	106	45
-Long term (mm)	90	121	170	113	63
Rain days (%)	68	59	67	55	32
Coef.of Variation(%)	44	44	32	60	113

From Table 4.1 the following observations can be made. Between the Footzone and the Upper Forest, rainfall increased with the altitude. Above the Upper Forest, it decreased with the altitude. The rainfall received during the study period was below the long term average. Variation in rainfall was found to increase as rainfall decreased. This was however not true in the 1st wet period (Table 4.1i) in which the Footzone, though having less rainfall, showed less variation. From rain days records, it can be observed that in the 2nd wet period, the study area received rainfall in over half of the period except for Footzone. In the 2nd wet period, the study area received more than twice the rainfall it received in dry period expect for Moorland and Footzone. The difference in the rainfall received in the wet and dry periods was less marked in the Upper Forest zone.

Analysis of variance using monthly rainfall data (Appendix 10-1) showed that the five zones were significantly different, $P = 0.034$, in the amount of rainfall they received.

4.2.2 Potential Evapotranspiration

To calculate potential evapotranspiration, data is required on the climatic variables of temperature, windspeed, relative humidity and sunshine duration. 10 days decade averages for the climatic variable monitored in the Forest and Footzone is presented in Appendix 3a. This data was not available for the Alpine and Moorland zone. For these two zones, potential evapotranspiration could not be calculated and in the analysis, previous records (Decurtins 1992) were used.

The results for the analysis of the climatic data for the Forest and Footzone is presented in Table 4.2. This data is presented in Figure 4.1.

Table 4.3 Summary of Potential Evapotranspiration in the study area between November 1991 and June 1992

i) 1 st Wet period (1st November to 31st December 1991)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Potential Evapo-transpiration					
Mean Monthly (mm)	13.70	50.30	80.80	89.95	96.00
Mean Daily (mm)	0.45	1.65	2.65	2.95	3.20
Pan Evaporation					
Mean Daily (mm)	0.20	0.85	1.50	2.10	2.80

ii) Dry period (1st January to 31st March 1992)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Potential Evapo-transpiration					
Mean Monthly (mm)	21.37	55.57	86.80	96.87	98.87
Mean Daily (mm)	0.70	1.83	2.87	3.20	3.20
Pan Evaporation					
Mean Daily (mm)	0.50	1.25	2.00	3.07	4.03

iii) 2 nd Wet period (1st April to 30th June 1992)

Zone	Alpine	Moor-land	Upper-Forest	Lower-Forest	Foot-zone
Altitude (meters)	4510	4000	3084	2467	2097
Site	R1	R2	Met	Gate	Munyaka
Potential Evapo-transpiration					
Mean Monthly (mm)	12.13	43.43	76.07	85.93	97.17
Mean Daily (mm)	0.40	1.47	2.50	2.77	2.93
Pan Evaporation					
Mean Daily (mm)	0.20	0.85	1.50	2.03	3.67

From Figure 4.1, the upper Forest, lower Forest and Footzone showed clear difference but similar trends in their temperature and sunshine duration. Windspeed and humidity however did not show clear differences among the three zones. A very steep rise in windspeed (Figure 4.1a) was observed between March and June in the Footzone. This steep increase was caused by a channelling effect between Mt. Kenya and the Aberdares ranges. The channelling effect however did not reach the adjacent lower and upper Forest stations which are at higher altitudes. The wind channelling did not shows significant effect on the other climatic variables monitored. The climatic variables showed strong relation to altitude which changes fast across the study area. Table 4.2 presents variation in the climatic variables monitored.

Table 4.2: **Mean daily values and coefficient of variation for the climatic variables monitored in the Forest and Footzone between November 1991 and June 1992.**

Climatic Variable	Mean/ Coefficient of variation	Upper - Forest(Met)	Lower - Forest (Gate)	Footzone (Munyaka)
Windspeed (Km/h)	Mean Coefficient of Variation	3.6 16.0	4.2 14.0	5.8 40.0
Temperature (°c)	Mean Coefficient of Variation	11.0 7.0	14.1 4.0	16.4 4.0
Humidity (%)	Mean Coefficient of Variation	75.7 11.0	71.4 11.0	71.5 12.0
Sunshine duration (h / d)	Mean Coefficient of Variation	3.8 28.0	4.9 23.0	6.0 13.0

It was observed that temperature and humidity were less varied compared to the other variables. Relative humidity and temperature would hence contribute less compared to wind speed and sunshine duration to any variation observed in the calculated potential evapotranspiration.

From the climatic data, potential evapotranspiration rates in the study area were calculated. Daily and monthly potential evapotranspiration rates in the study area between November 1991 and June 1992 are presented in Appendix 4. This data is summarized in Table 4.3.

From Table 4.3 the following observations are made. Potential evapotranspiration was inversely related to altitude increasing from the higher altitude Alpine zone (RJ) towards the lower altitude Footzone (Munyaka). Potential evapotranspiration (mean daily and monthly) rates observed during the dry and wet periods were different. This difference was however small in the Footzone.

Analysis of variance (Appendix 10-1) using monthly data showed that the five zones were significantly different, P = 0.0, in their potential evapotranspiration rates.

Its frequently necessary to estimate potential evapotranspiration from pan evaporation data since pan evaporation can be measured easily in the field. This can be done using appropriate conversion coefficients (Decurtins 1992). Conversion coefficients are calculated as a ratio of potential evapotranspiration to pan evaporation. Such coefficients were calculated in this study and compared to those used previously by Decurtins (1992). The comparison is presented in Table 4.4 below.

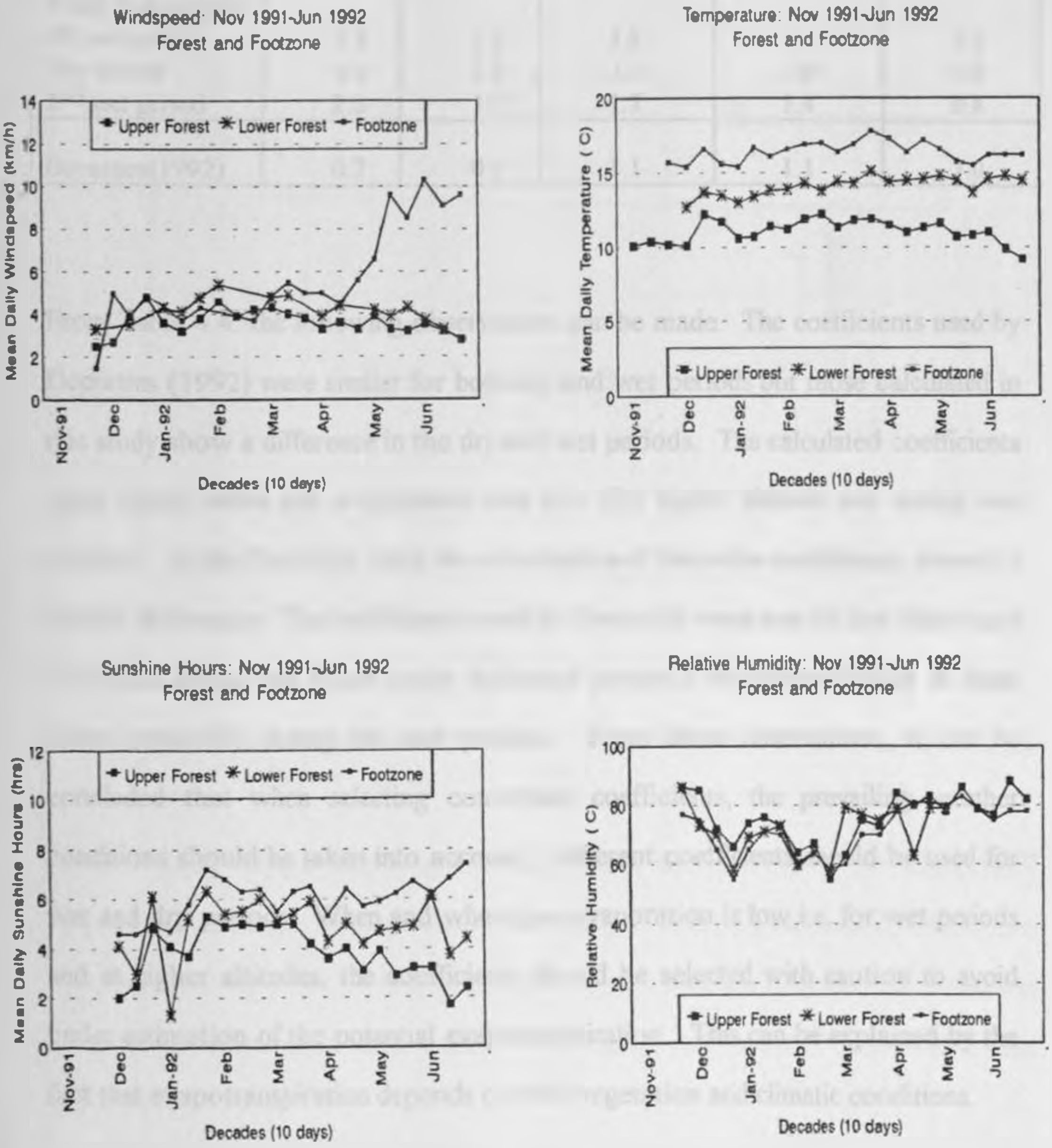


Figure 4.1 Windspeed, temperature, sunshine hours and relative humidity plots (10 days average)

Table 4.4: **Coefficients used to convert pan evaporation to potential evapotranspiration.**

	Alpine (R1)	Moorland (R2)	Upper Forest (Met)	Lower Forest (Gate)	Footzone (Munyaka)
Study (calculated)					
1st wet period	2.3	1.9	1.8	1.4	1.1
Dry period	1.4	1.5	1.4	1.0	0.8
2nd wet period	2.0	1.7	1.7	1.4	0.8
Decurtins(1992)	0.7	0.9	1.1	1.1	1.0

From Table 4.4. the following observations can be made. The coefficients used by Decurtins (1992) were similar for both dry and wet periods but those calculated in this study show a difference in the dry and wet periods. The calculated coefficients were higher when pan evaporation was low (for higher altitude and during wet periods). In the Footzone, both the calculated and Decurtins coefficients showed a smaller difference. The coefficients used by Decurtins were low for the Alpine and Moorland zones and hence under estimated potential evapotranspiration in these zones especially during the wet periods. From these observations, it can be concluded that when selecting conversion coefficients, the prevailing weather conditions should be taken into account. Different coefficients should be used for wet and dry periods. When and where pan evaporation is low i.e. for wet periods and at higher altitudes, the coefficients should be selected with caution to avoid under estimation of the potential evapotranspiration. This can be explained by the fact that evapotranspiration depends on both vegetation and climatic conditions.

4.2.3 The climatic water balance

Total monthly rainfall, potential evaporation and the resulting climatic water balance are presented in Appendix 5. The Monthly climatic water balance is presented in Figure 4.2

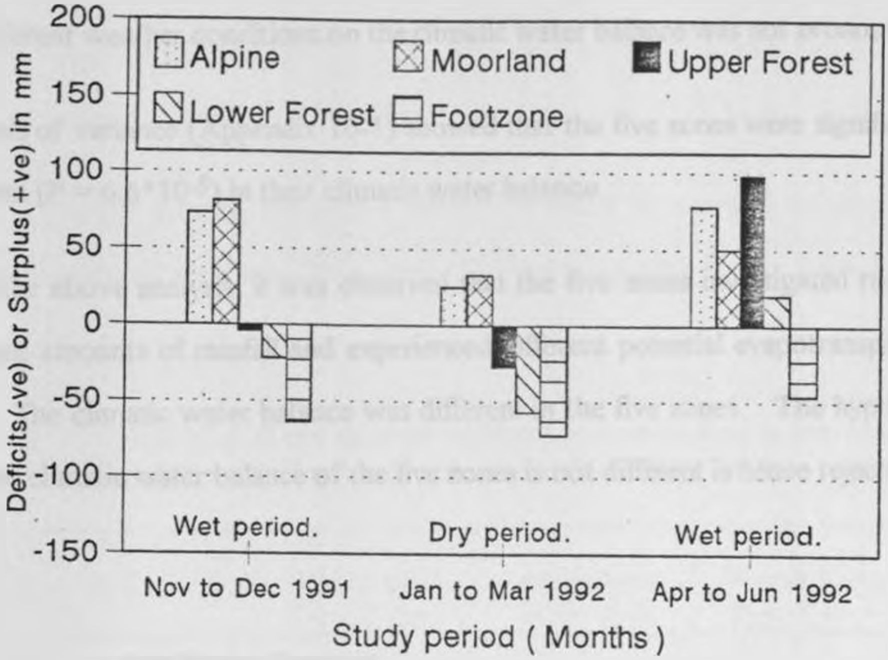


Figure 4.2 : **Climatic water balance - mean monthly surplus or deficit for two wet and one dry period.**

From Figure 4.2, the following observations can be made. In the 1st wet and dry periods, the climatic water demand was meet only in the Alpine zone and Moorland zones. During this period, the upper Forest, Lower Forest and Footzone experienced a climatic water deficit. The deficit was however very small in the upper Forest zone.

In the 2nd wet period, the climatic water demand was meet in all the zones except for Footzone. During this period, the upper Forest showed an higher climatic water surplus compared to the other zones.

From these observations, the following conclusions can be drawn. The climatic water demand was always meet in the Alpine zone while it was never meet in the Footzone. The climatic water balance in the study area varied between dry and wet periods. Compared to the other zones, the upper Forest zone showed higher climatic water surplus in the longer 2nd wet period. In the Footzone, the effect of the different weather conditions on the climatic water balance was not pronounced.

Analysis of variance (Appendix 10-1) showed that the five zones were significantly different ($P = 6.6*10^{-5}$) in their climatic water balance.

From the above analysis, it was observed that the five zones investigated received different amounts of rainfall and experienced different potential evapotranspiration rates. The climatic water balance was different in the five zones. The hypothesis that the climatic water balance of the five zones is not different is hence rejected.

4.3 Soil Water Content

4.3.1 Introduction

The second hypothesis (H_{02}) in Section 1.4 stated that the soil water content under different vegetation systems within and between the five zones is not different. Data obtained from soil water monitoring was analysed to test this hypothesis. Due to differences in soil water monitoring intervals, results for the Alpine and Moorland zones (monitored on monthly intervals) are presented separately from those of the Forest and Footzone (monitored on weekly intervals).

In the analysis, the term soil water is used to refer to the available volumetric soil water content.

4.3.2 Alpine (RI) and Moorland (R2)

In these two zones, soil water was investigated only for Grass vegetation. Soil bulk density and available soil water capacity in the study area is presented in Appendix 6. Using the bulk densities and the lower soil water limits, the gravimetric soil water content measured in the two zones was converted into available volumetric soil water content (see section 3.3.2.1). This was done on monthly basis for the period between November 1991 to May 1992.

Figure 4.3 below presents the total available soil water for a profile 30cm deep in the Alpine (RI) and Moorland (R2) zones. This data is summarized in Table 4.5.

Table 4.5: **Summary of the total (0 to 30cm) soil water data in the Alpine and Moorland zone: November 1991 to May 1992.**

	Alpine zone Typical slope	Alpine zone Steep slope	Moorland zone Typical slope
Monthly maximum (mm)	228	267	213
Monthly Minimum (mm)	40	66	169
Range (mm)	118	202	44
Coefficient of variation(%)	45	53	8

From Table 4.5 and Figure 4.4 several observations can be made. The Moorland zone showed higher and less varied soil water compared to the Alpine zone. In the Alpine zone, soil water increased in the wet period and decreased in the dry period. This was however not true for the 1st wet period (between November and December 1992). This difference in soil water in the dry and wet periods observed in the Alpine zone was not observed in the Moorland zone.

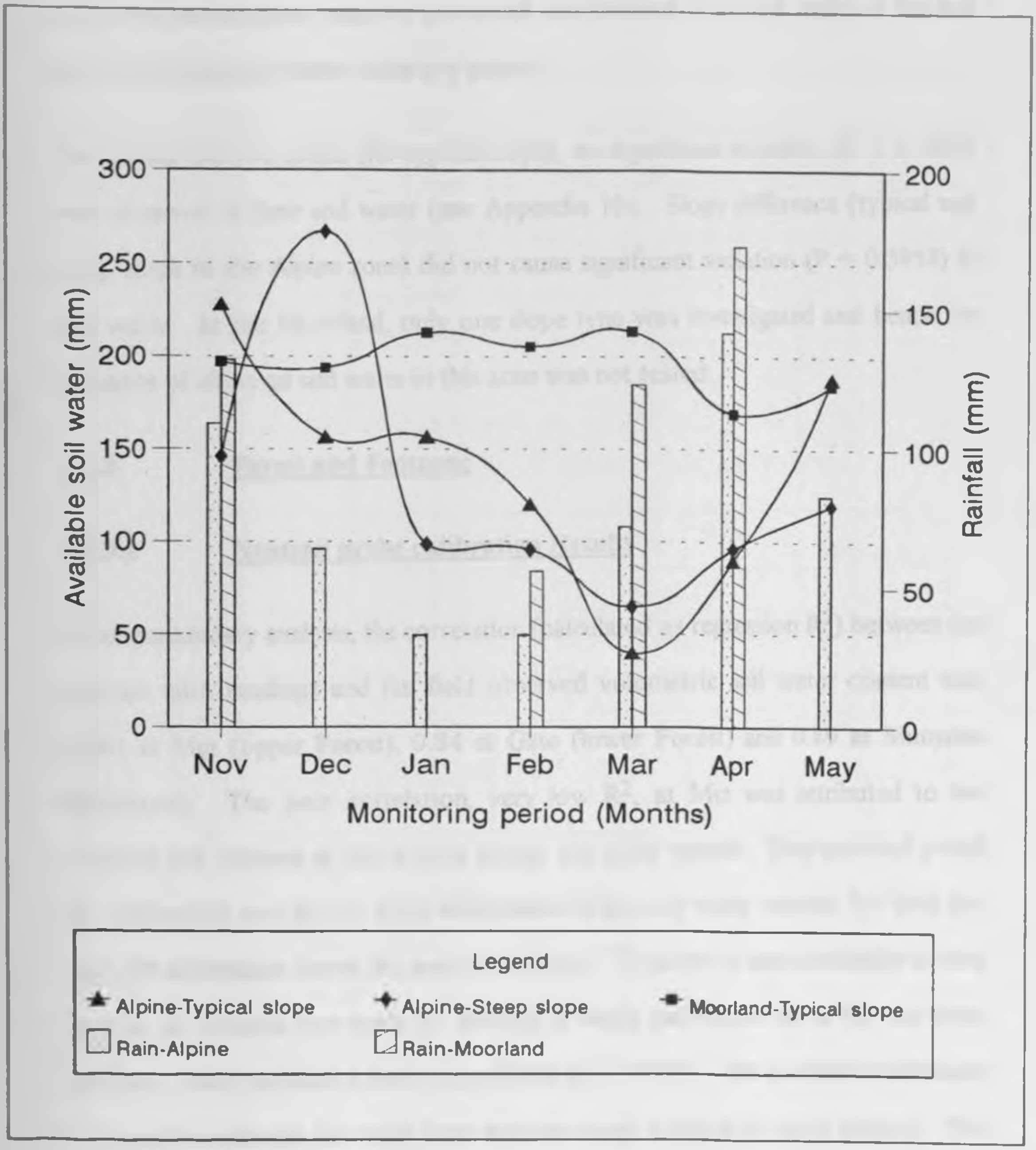


Figure 4.3 : **Total(0-30cm) Available Soil Water in the Alpine and Moorland zones between November 1991 and May 1992**

For the Alpine zone where both typical and steep slopes are investigated, the typical slope was more sensitive to rainfall and showed more soil water in the wet periods and less soil water in the dry period.

Comparing the two zones (for typical slope), no significant variation ($P = 0.1409$) was observed in their soil water (see Appendix 10). Slope difference (typical and steep slope in the Alpine zone) did not cause significant variation ($P = 0.5858$) in soil water. In the Moorland, only one slope type was investigated and hence the influence of slope on soil water in this zone was not tested.

4.3.3 Forest and Footzone

4.3.3.1 Neutron probe calibration Results

From preliminary analysis, the correlation (calculated as regression R^2) between the neutron ratio readings and the field observed volumetric soil water content was 0.001 at Met (upper Forest), 0.84 at Gate (lower Forest) and 0.89 at Munyaka (Footzone). The poor correlation, very low R^2, at Met was attributed to the extreme soil wetness at this station during the study period. This deprived a real dry calibration and lead to small differences in the soil water content for both dry and wet calibration, hence the poor correlation. To improve the correlation at Met station, an attempt was made to develop a single calibration curve for the three stations. This produced a better correlation ($R^2 = 0.94$). The combined calibration was used to estimate soil water from neutron count ratios in the three stations. The calibration equation developed for the three station is given as:-

$$y = 30.40035*X - 14.3249$$

where:-

y = Estimated volumetric soil water content and

X = Neutron probe ratio reading.

The calibration data is presented in Table 4.6. The table shows the calibration neutron ratios (X), their associated calibration core rings volumetric soil water content (Y) and the soil volumetric water content (y) estimated from the calibration equation. A plot of the calibration curve in relation to core rings volumetric soil water content is shown in Figure 4.4. The calibration equation estimated volumetric soil water content in the three station adequately but tended to slightly under estimated it in the Upper Forest Met station.

Table 4.6: **Calibration data for Met, Gate and Munyaka station.**

	MET			GATE			MUNYAKA		
Dry/ wet Cal.	Neu-tron Ratio (X)	Field Vol water (Y)	Cal. Vol water (y)	Neu-tron Ratio (X)	Field Vol water (Y)	Cal. Vol water (y)	Neu-tron Ratio (X)	Field Vol water (Y)	Cal. Vol water (y)
Dry									
Cal	2.54	63.07	62.73	1.98	44.09	45.97	0.87	13.29	12.09
15cm	2.54	66.54	62.73	1.82	41.54	41.10	0.98	15.96	15.44
30cm	2.52	64.75	62.73	1.97	43.74	45.51	0.88	15.96	12.47
60cm	2.54	60.50	62.92	2.13	47.18	50.52	1.16	18.30	20.83
90cm	2.65	48.74	66.11	2.20	52.51	52.56	1.10	18.90	19.05
120cm	2.50	69.04	61.51	2.13	49.24	50.55	1.52	26.41	31.79
150cm	2.45	62.97	60.14	2.34	54.30	56.70	1.46	26.23	30.14
170cm									
Wet									
Cal	2.43	63.67	59.66	1.87	46.51	42.57	1.39	34.48	27.93
15cm	2.48	66.07	60.97	1.97	44.57	45.60	1.63	34.54	35.23
30cm	2.33	61.92	56.62	1.97	47.37	45.52	1.64	34.13	35.60
60cm	2.41	59.65	58.92	2.23	52.70	53.47	1.63	32.61	35.23
90cm	2.55	67.10	63.08	2.23	55.16	53.47	1.58	30.71	33.71
120cm	2.68	68.29	67.15	2.09	49.40	49.21	1.75	40.33	38.88
150cm	2.77	65.88	69.79	2.30	54.00	55.54	1.76	38.18	39.18
170cm									

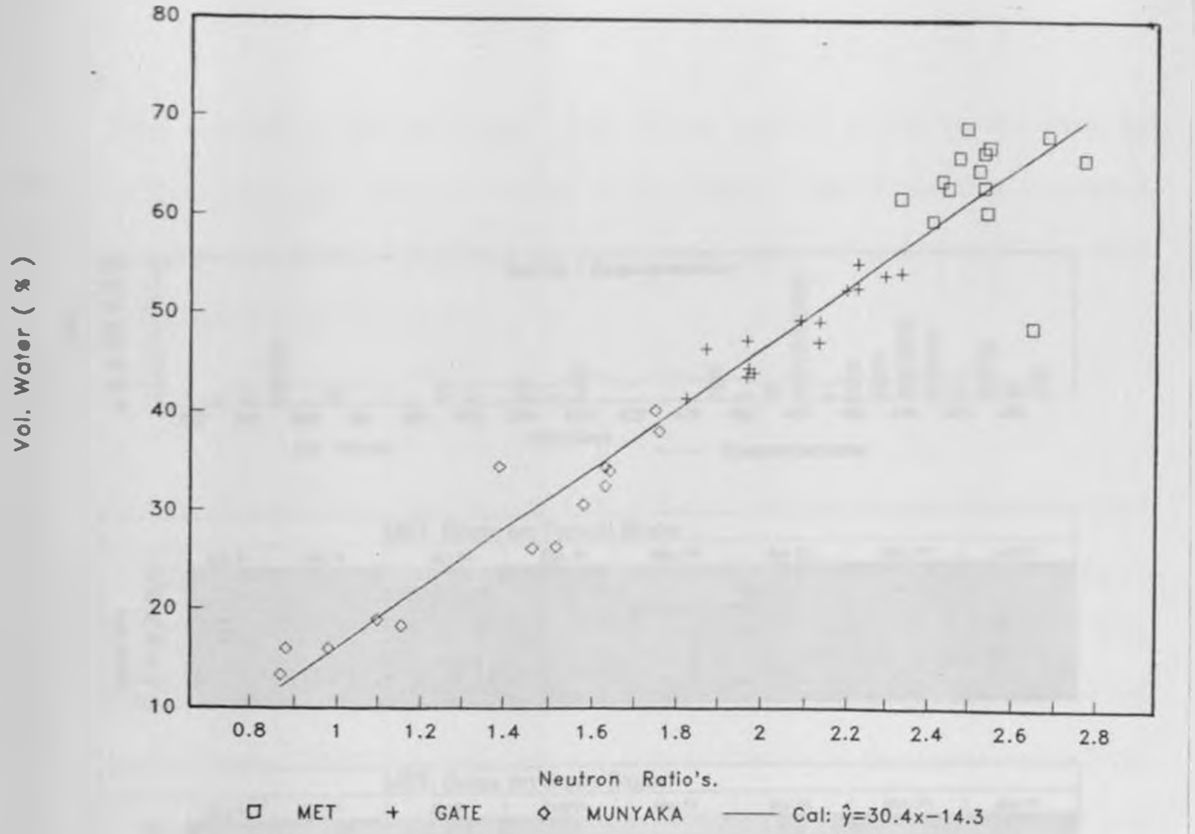


Figure 4.4: **Calibration curve showing the relationship between Neutron ratio and volumetric soil water content. The symbols show core ring volumetric water content for the three station.**

4.3.3.2 Soil water for different monitoring depths

Soil water observed at the seven monitoring depths was classified into seven classes (section 3.3.2) of the available soil water capacity at each of the three zones. The results of this classification are presented in Figure 4.5 and discussed below.

The Upper Forest zone: From Figure 4.5a, the four vegetation systems investigated in this zone showed profiles with available soil water between 100% and 50% of the available soil water capacity in this zone. The profiles were hence above half of their soil water holding capacity. The four vegetation systems showed soil profiles at percolation through out the study period. This means the profiles contributed to deep percolation and subsurface runoff. Above the 60cm depth, the profiles showed variation in the available soil water content especially for Grass on steep slope and Natural Forest on typical slope.

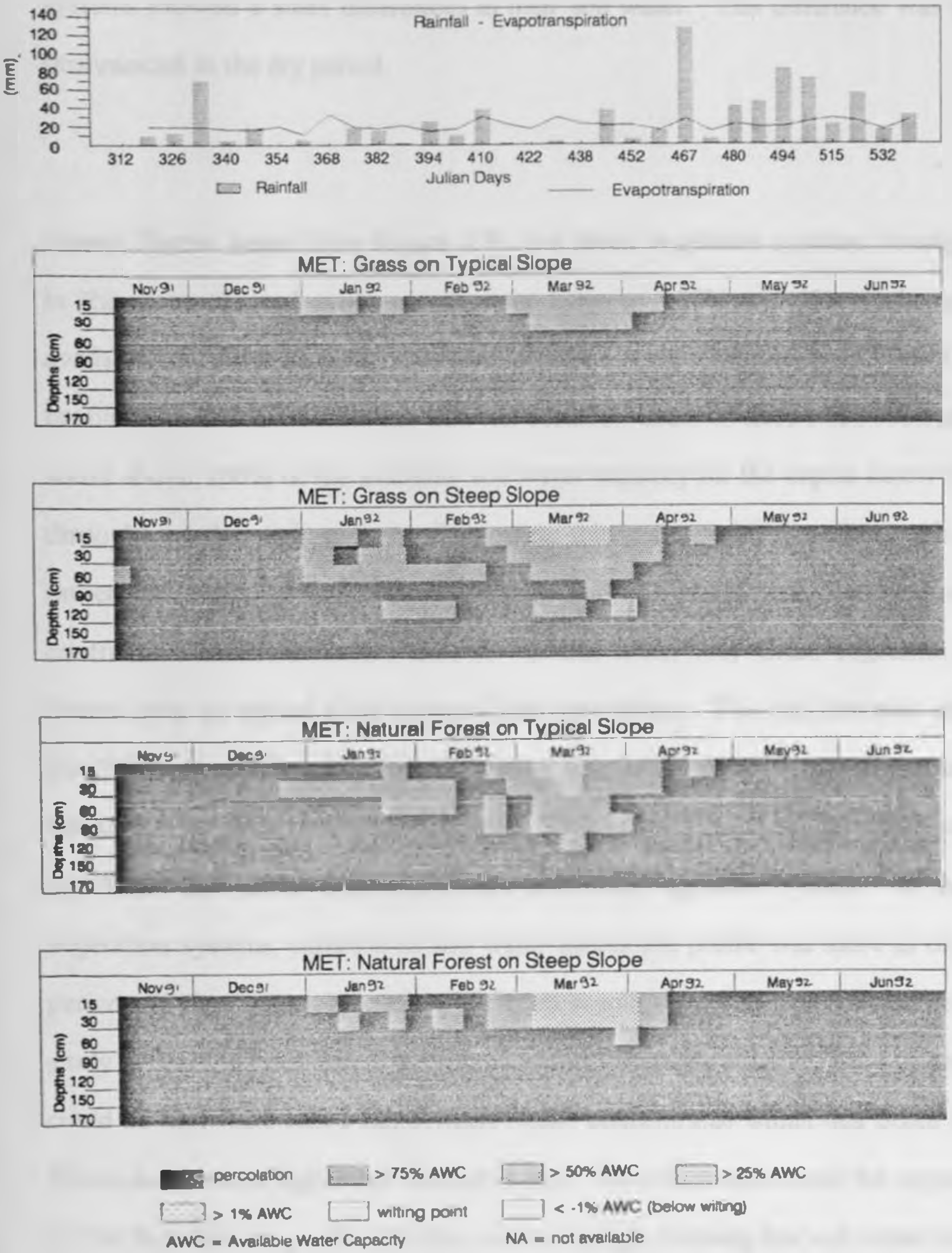


Figure 4.5a: Available soil water for the different monitoring depths in seven classes of the available soil water capacity in the Upper Forest zone.

This variation in the soil water, which would possibly be due to the effect of evapotranspiration, was more during the dry period Generally, the four vegetation systems showed a small differences in their soil water. This difference was more pronounced in the dry period.

Lower Forest zone: From Figure 4.5b, the seven vegetation systems investigated in this zone showed profiles soil water between 100% and 1% of the zone's available soil water capacity. All the vegetation systems showed variation in their profile soil water both in the dry and wet periods Grass on steep slope showed soil water above 100% of the available soil water capacity for the depths below 90cm through out the study period. Comparing this system with the others, this was rather too high. A possible explanation for this phenomena could be water contribution from subsurface inflow. In this zone, only Grass vegetation and Potato crop on typical slope showed deep percolation. This was however only in the 2nd wet period. The Natural Forest vegetation show two (0 to 60cm and below 90cm) water extraction depths. This could be due to different rooting depths for this mixed (Grass, bamboo and tree) vegetation system. In all the vegetation systems, variation in soil water across the profile was more in the dry period In the Cypress Plantation, variation in soil water was high through out the study period for the depths 0 to 90cm A possible explanation for this phenomena could be that there was a rapid water intake concentrated within this depth (0 to 90cm) and hence a high water extraction rate. This observation could be supported by the fact that the profile for this system, though showing low soil water below 120cm, experienced limited soil water variation at this depth indicating limited water uptake at this depth

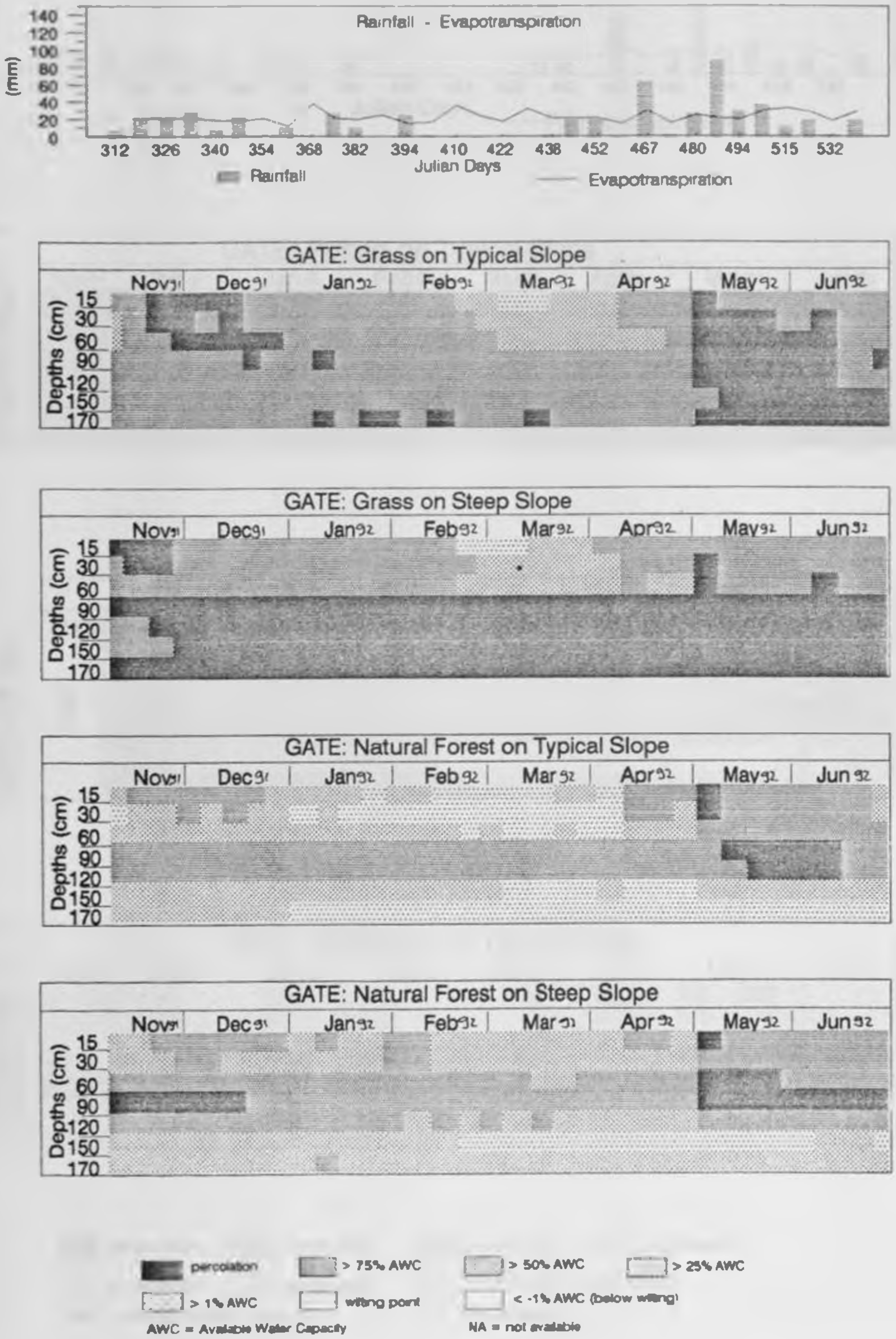


Figure 4.5b: Available soil water for the different monitoring depths in seven classes of the available soil water capacity in the Lower Forest zone.

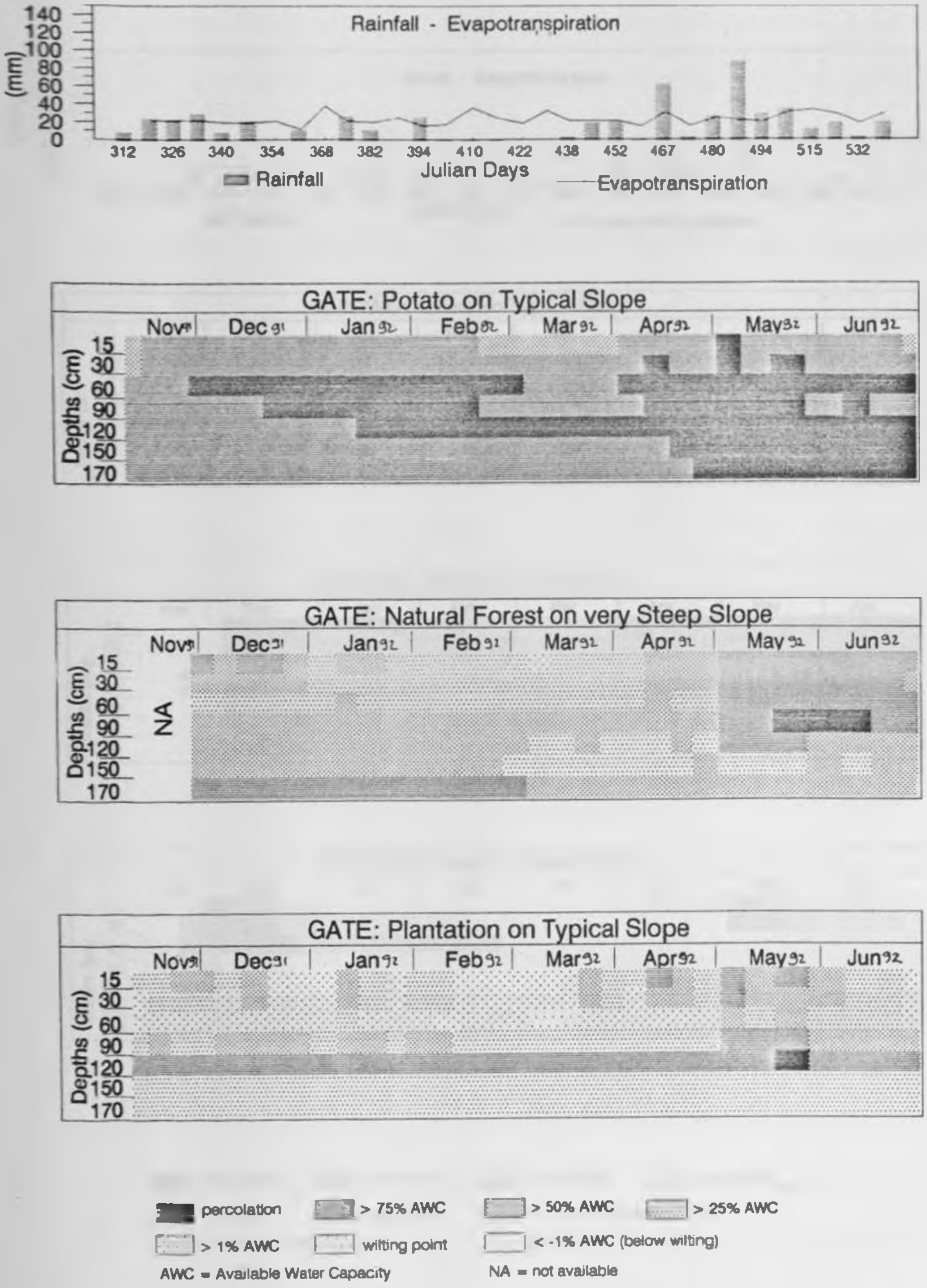


Figure 4.5b contd.

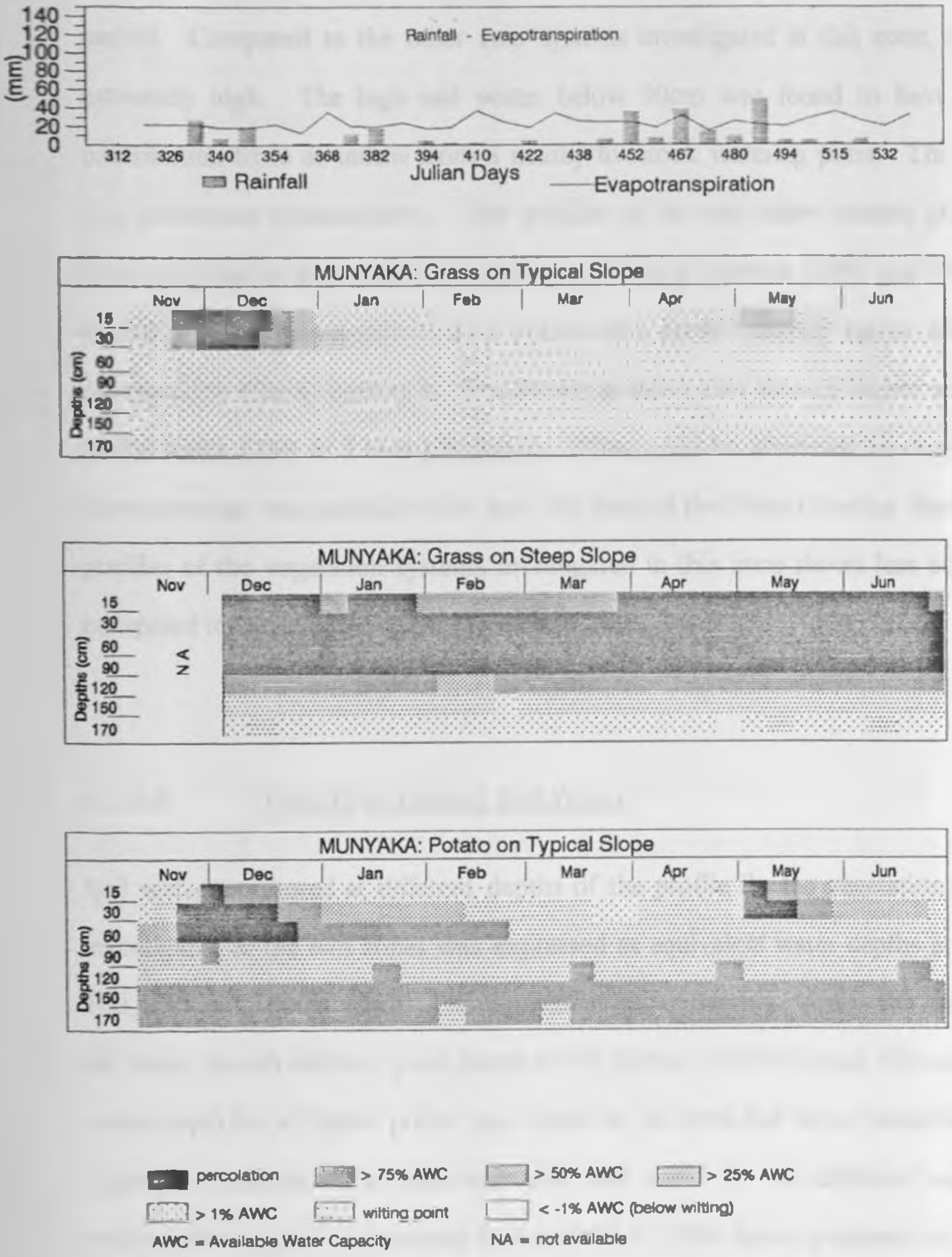


Figure 4.5c: Available soil water for the different monitoring depths in seven classes of the available soil water capacity in the Footzone.

Footzone: From Figure 4.5c (above), Grass on steep slope showed available soil water above 100% of the soil water capacity above 90cm through out the study period Compared to the other two systems investigated in this zone, this was extremely high. The high soil water below 90cm was found to have been a contribution from an inflow from a nearby livestock watering point. This system was hence not representative. The profiles of the two other systems (Grass on Potato on typical slope) showed available soil water between 100% and 0% of the available soil water capacity. The Potato crop profile showed higher soil water compared to Grass vegetation. The Potato systems also showed higher soil water in the lower (150 to 170cm) horizons. This could be attributed to contribution from previous wet periods which now lay beyond the Potato rooting depth. The profiles of the vegetation systems investigated in this zone shows less soil water compared to those of the upper Forest and lower Forest.

4.3.3.3 Total (0 to 160cm) Soil Water

Soil water monitored at different depths of the profile for the vegetation systems investigated in the two zones was expressed as equivalent water depths at 45, 75, 100, 130 and 160cm depth. The equivalent water depth expresses the amount of soil water stored within a given depth of the profile. For this study, the equivalent water depth for a 160cm profile was taken as the total soil water available to the vegetation systems. The observed total soil water for the different vegetation systems investigated is presented in Appendix 8. This data is presented in Figures 4.6 to 4.8. Table 4.7 shows variation (coefficients of variation) in the total available soil water for the different vegetation systems investigated.

Table 4.7: **Variation (C.V) in the total available soil water in the Forest and Footzone between November 1991 and June 1992.**

Zone Station	Upper Forest (Met)	Lower Forest (Gate)	Footzone (Munyaka)
Grass - Typical slope	5.0	11.9	182.2
Grass - Steep slope	9.8	7.0	4.7
Natural Forest - Typical slope	8.1	16.2	
Natural Forest - Steep slope	12.4	9.3	
Natural Forest - Very seep slope		24.7	
Potato crop - Typical slope		6.5	18.1
Cypress Plantation - Typical slope		26.3	

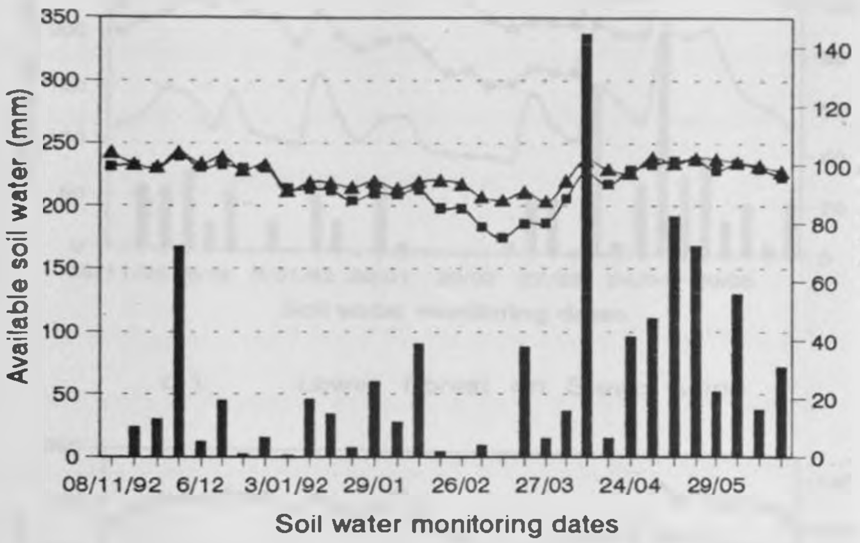
Note : All values are in %

In reference to Table 4.7 and Figures 4.6 to 4.8, the total available soil water under different vegetation, slope and ecological zones is discussed below.

a) Total soil water under different vegetation: Figure 4.6 presents the total available soil water for the vegetation systems investigated in the upper forest, lower Forest and Footzone.

Upper Forest: Figure 4.6a and b, presents the total soil water for the vegetation systems investigated in the upper Forest zone. The higher soil water on typical slope for the Grass system could be attributed to its lower water requirement while the higher soil water on steep slope for the natural system could be attributed to less runoff for the Natural vegetation as compared to the Grass system. The difference in soil water between the two vegetation system was more in the dry period for typical slope and more in the wet period for steep slope. On typical slope, assuming limited runoff under the two system, soil water was more different in the dry period when the vegetation water requirements were more different.

a) Upper Forest on Typical slope



b) Upper Forest on Steep slope

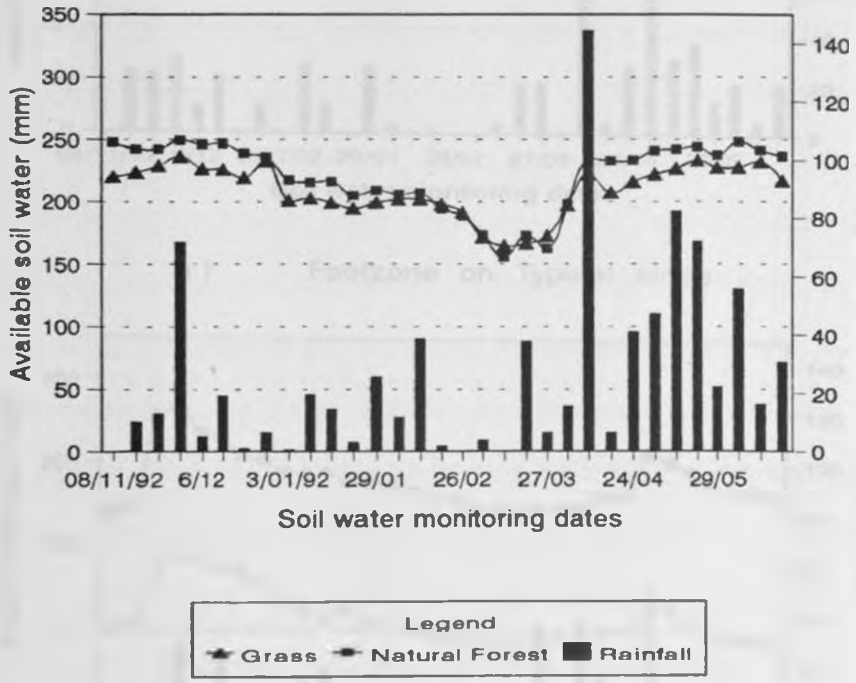
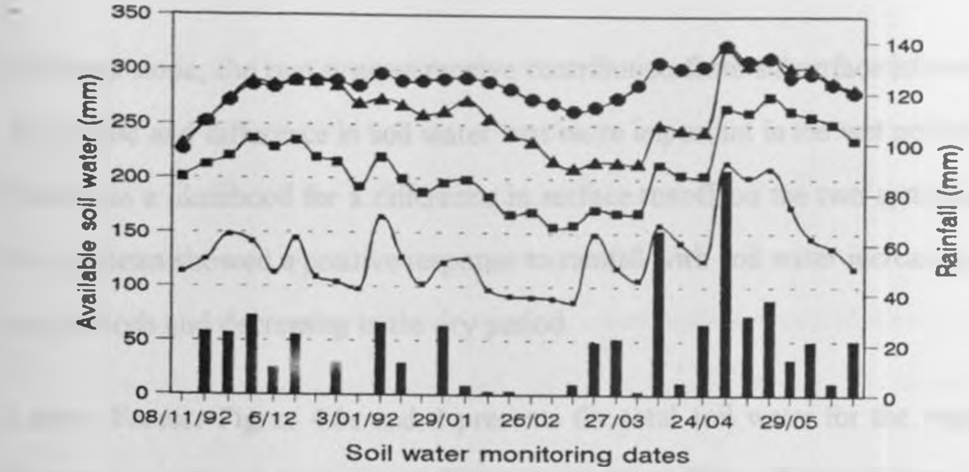
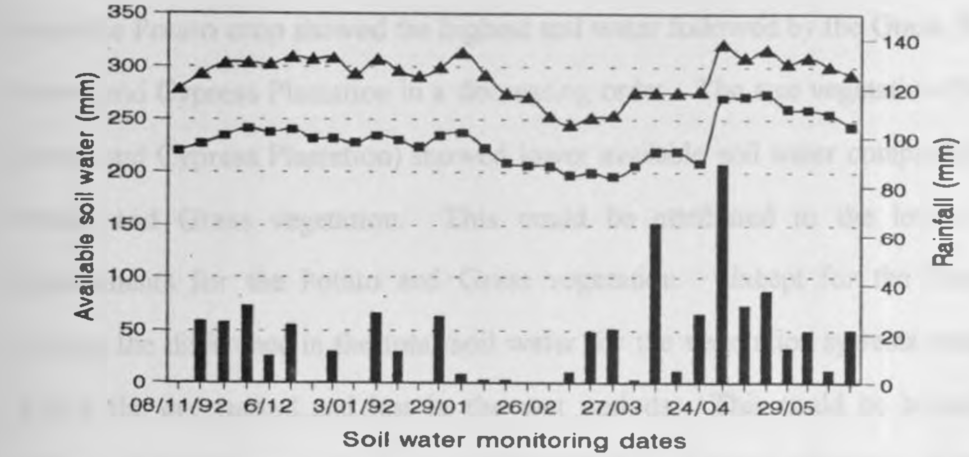


Figure 4.6: Total(0-160cm) Available Soil water in the Forest and Footzone under different vegetation system.

c) Lower Forest on Typical slope



d) Lower Forest on Steep slope



e) Footzone on Typical slope

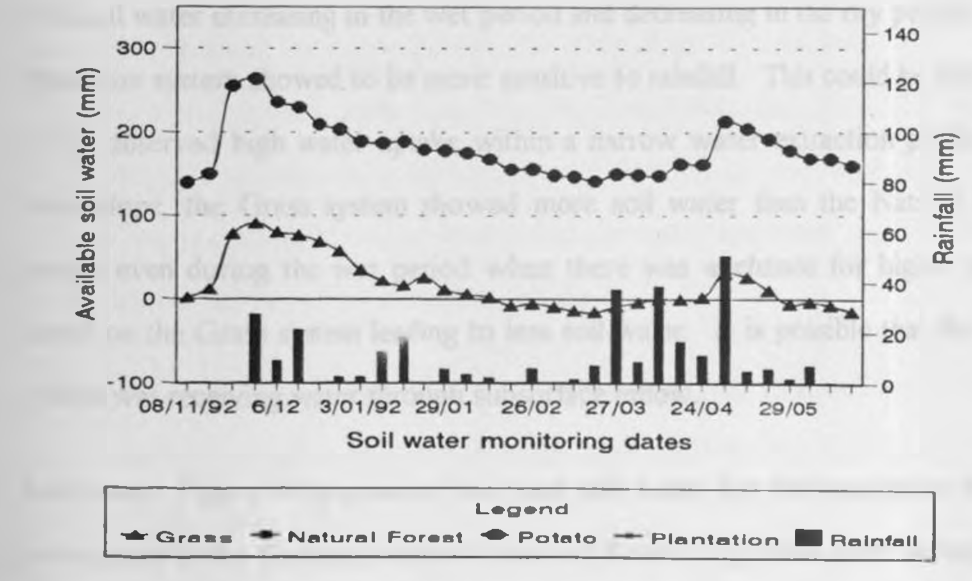


Figure 4.6 contd.

On steep slope, the two systems receive contribution from subsurface inflow in the dry period and difference in soil water was more important in the wet period when there was a likelihood for a difference in surface runoff on the two systems. The two systems showed a positive response to rainfall with soil water increasing in the wet periods and decreasing in the dry period.

Lower Forest: Figure 4.6c and d presents the total soil water for the vegetation systems investigated in the Lower Forest zone where Grass, Natural Forest, Potato crop and Cypress Plantation vegetation systems were investigated. On typical slope the Potato crop showed the highest soil water followed by the Grass, Natural Forest and Cypress Plantation in a decreasing order. The tree vegetation (Natural Forest and Cypress Plantation) showed lower available soil water compared to the Potato and Grass vegetation. This could be attributed to the lower water requirements for the Potato and Grass vegetation. Except for the Plantation system, the difference in the total soil water for the vegetation systems was more during the dry period and less in the wet periods. This could be because the difference in the vegetation water requirement was more important in the dry period when soil water was limited. All the systems responded positively to rainfall with soil water increasing in the wet period and decreasing in the dry periods. The Plantation system showed to be more sensitive to rainfall. This could be attributed to the observed high water uptake within a narrow water extraction profile. On steep slope, the Grass system showed more soil water than the Natural Forest system even during the wet period when there was a chance for higher surface runoff on the Grass system leading to less soil water. It is possible that the Grass system was receiving water through subsurface inflow.

Foot zone: Figure 4.6e presents the total soil water for the vegetation systems investigated in the Footzone where Grass and Potato vegetation were investigated. The Potato crop showed more and less varied soil water compared to the Grass vegetation Both systems responded positively to rainfall with soil water increasing in the wet periods and decreasing in the dry period. The lower soil water for the Grass system could be attributed to higher surface runoff and higher water requirement compared to the Potato crop which had a lower requirement at the beginning of the growing period. Analysis of variance (Appendix 10-3) indicated that the total soil water observed under different vegetation systems was significantly different.

b) Total soil water for different slope: Figure 4.7 presents the total available soil water observed on typical and steep slopes in the upper and lower Forest zones.

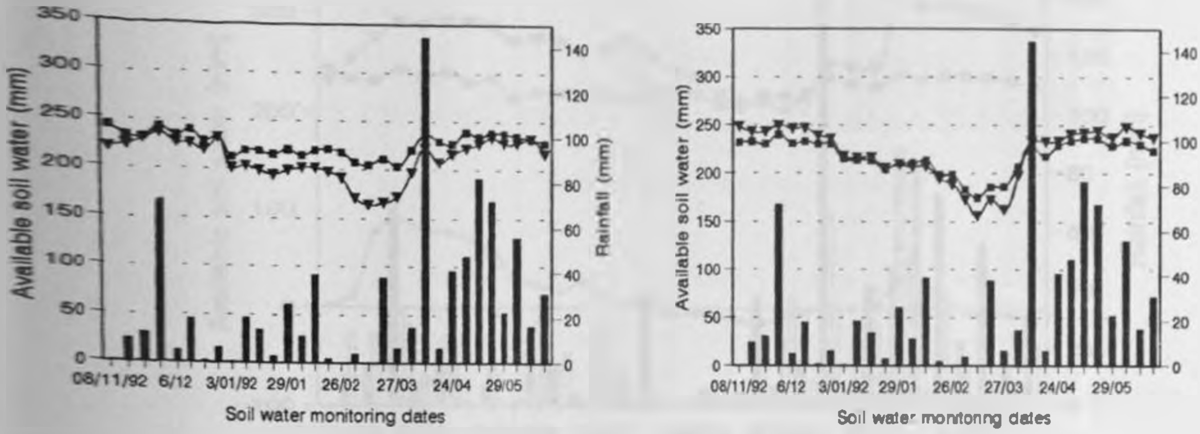
Upper Forest: In the upper Forest, the typical slope showed more soil water for the Grass vegetation while the steep slope showed more soil water for the natural vegetation. For the Grass vegetation, on which more surface runoff expected, the typical slope would experience less runoff and hence higher soil water. For the natural Forest, less runoff would be expected. The steep slope has higher possibility for subsurface inflow and hence higher soil water.

Lower Forest: In the lower Forest, the steep slope showed more soil water for both Grass and natural vegetation. For the Grass vegetation, the higher soil water was likely due to subsurface inflow (see section 4.3.3.2). However, in the natural Forest, surface runoff would be limited and the higher soil water on the steep slope could also be attributed to subsurface inflow.

Analysis of variance (Appendix 10-3) indicated that the total soil water observed under different slope categories was significantly different except for Natural Forest in the Upper Forest zone.

a) Upper Forest : Grass vegetation

b) Upper Forest : Natural Forest vegetation



c) Lower Forest : Grass vegetation

d) Lower Forest : Natural Forest vegetation

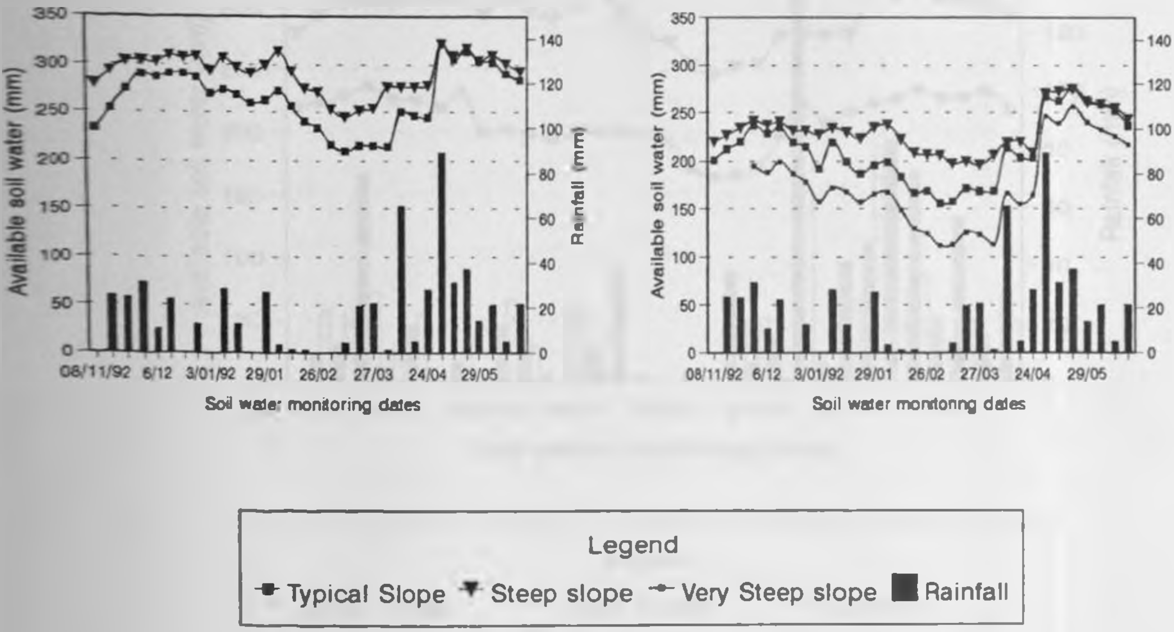
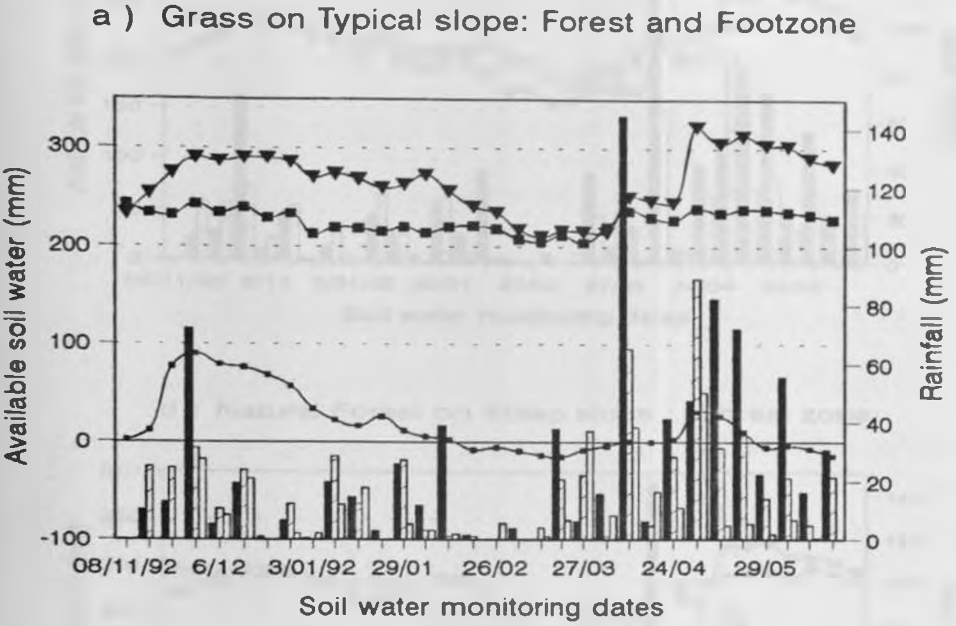
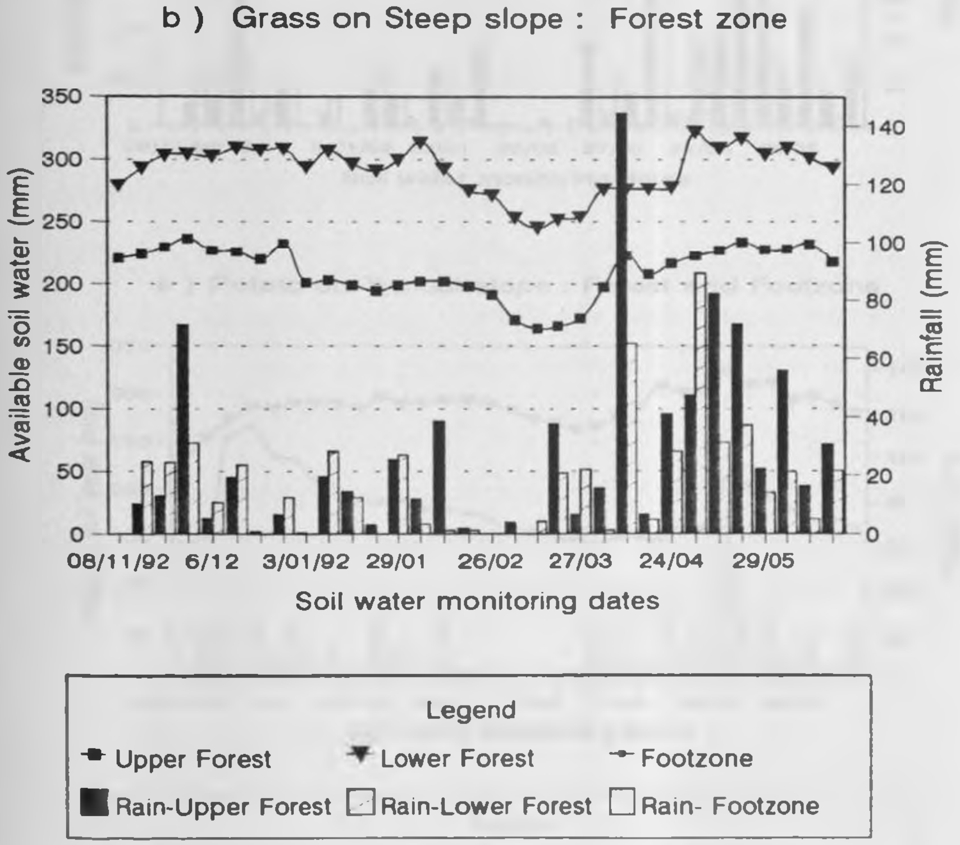


Figure 4.7: Total(0-160cm) Available Soil water in the Forest and Footzone for different slope categories.



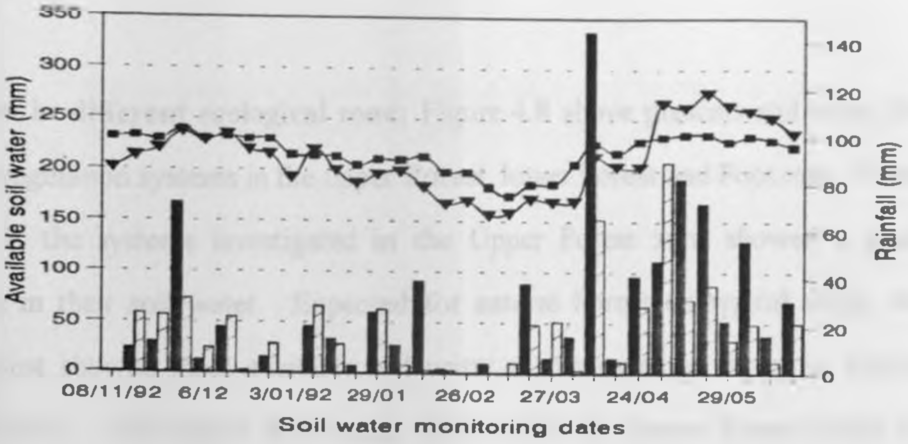
a) Grass on Typical slope: Forest and Footzone



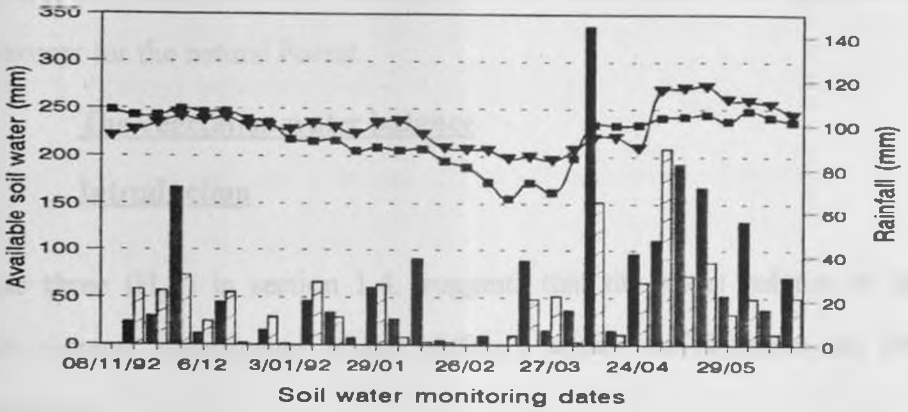
b) Grass on Steep slope : Forest zone

Figure 4.8: Total(0-160cm) Available Soil water in the Forest and Footzone.

c) Natural Forest on Typical slope : Forest zone



d) Natural Forest on Steep slope : Forest zone



e) Potato on Typical slope : Forest and Footzone

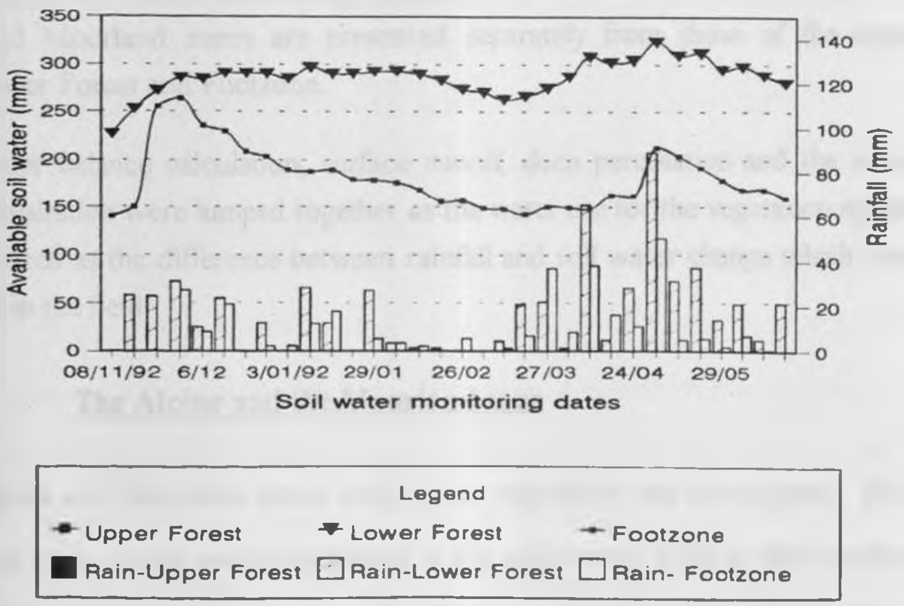


Figure 4.8 contd.

Soil water in different ecological zone: Figure 4.8 above presents soil water for different vegetation systems in the upper Forest, lower Forest and Footzone. From Figure 4.8, the systems investigated in the Upper Forest zone showed a small difference in their soil water. Expected for natural Forest on typical slope, the lower Forest showed more available soil water as compared to the upper Forest and Footzone. The higher soil water observed in the lower Forest could be attributed to its higher soil water capacity. Analysis of variance (Appendix 10-3) indicated that the total soil water observed in the three zones was significantly different except for the natural Forest.

4.4 The vegetation water balance

4.4.1 Introduction

Hypothesis three (H_{03}) in section 1.4, suggests that the water balance of the vegetation systems investigated is not different within and between the five ecological zones.

Using the climatic and soil water data, this hypothesis was tested. Due to differences in soil water monitoring intervals, the water balance results for the Alpine and Moorland zones are presented separately from those of the upper Forest, lower Forest and Footzone.

In the water balance calculation, surface runoff, deep percolation and the actual evapotranspiration were lumped together as the water use for the vegetation system and calculated as the difference between rainfall and soil water change which were measured in the field.

4.4.2 The Alpine and the Moorland zone

In the Alpine and Moorland zones, only Grass vegetation was investigated. Both typical and steep slopes were investigated in the Alpine zone while in the Moorland zone only typical slope was investigated. The water balance results for the Alpine and Moorland zones are presented in Table 4.8.

Table 4.8: Water balance results for the Alpine and Moorland zone between November 1991 and May 1992.

	Rainfall (mm/d)		vegetation water requirement (mm/d)		Vegetation water use (mm/d)		
	Alpine	Moorland	Alpine	Moorland	Alpine Typical	Alpine Steep	Moorland Typical
1st Wet	2.8	4.4	0.5	1.7	4.4	-1.8	NA*
Dry	1.5	2.9	0.7	1.8	1.9	3.7	1.9
2nd Wet	3.0	4.0	0.4	1.4	1.3	2.8	7.2

Note *: Data not available

From Table 4.8, several observations are made about the vegetation water requirement and use in the two zones.

The Moorland zone showed a higher vegetation water requirement. For both zones, the vegetation water requirement was higher in the dry period. In the Alpine zone where both typical and steep slopes were investigated, the steep slope showed higher water use except in the 1st wet period. Assuming similar water requirement for Grass vegetation on both slopes, the higher water use on the steep slope could be attributed to the higher possibility for surface and subsurface runoff. In the 1st wet period, the steep slope showed a negative water use. This could be attributed to subsurface inflow from the valley sides.

In the 2nd wet period, the Moorland zone showed higher water use compared to the Alpine zone. This could be attributed to higher vegetation water requirement in the Moorland zone. Since this zone has a lower soil water capacity compared to the Alpine zone (see Appendix 6), its profile would fill up fast hence a higher possibility for surface runoff. The Moorland zone received more rainfall and hence had more water available for use to the vegetation

4.4.3 The Forest and Footzone

To evaluate the water balance of the vegetation systems investigated in these two zones, the vegetation water use for different vegetation systems, slope categories and ecological zone was investigated.

4.4.3.1 Vegetation water use under different vegetation systems

The vegetation water use and requirement for different vegetation systems investigated on typical slope in the Forest and Footzone is presented in Figure 4.9. From Figure 4.9, a number of observation can be made about the vegetation water use and requirement in the upper Forest, lower Forest and Footzone.

a) **Upper Forest zone:** In this zone, Grass and Natural Forest were investigated. The vegetation water use was similar for the two systems in the three periods covered. The amount of water available for use to the vegetation was calculated as the difference between rainfall and soil water change. Since the two systems showed deep percolation through out the three periods and very limited soil water change, the calculated water use for both systems was hence similar. The vegetation water requirement was slightly higher for the Natural Forest in the three periods since the coefficient used to calculate water requirements was higher for the Natural Forest vegetation. In the 1st wet period, the difference between water use and water requirement was small for the two systems. In the 1st wet and dry periods, despite the fact that both systems show good soil water, the calculated water use was below or equal to the water requirement. Possibly, rainfall was under estimated (dew is not taken account of) or the coefficients use to calculate the water requirements from the penman Potential evapotranspiration were over estimated. In the 2nd wet period, the water use was two times more than the requirement for the Grass and one and half times more than the requirement for the natural Forest

In this period, the amount of water available for use above the requirement went to deep percolation and possibly surface runoff. This was possibly the reason why the Grass vegetation (with higher potentials for surface runoff) shows high water use compared to the Natural Forest vegetation.

b) Lower Forest zone: In the 1st wet period, the vegetation water requirement was higher than the water use for Grass and Natural Forest and equal to the use for the Cypress Plantation. The water requirement was slightly below water use for the Potato crop. Compared to Grass and Natural Forest, the higher water use for the Cypress Plantation could be attributed to high evapotranspiration rates which was being meet from soil water storage. For the Potato crop, the water use above the requirement was due to its lower water requirement. In the dry period, the water requirement was higher than the water use for all the systems. The difference between water requirement and use during this period was small for the Potato crop. This was due to the lower water requirement for the Potato crop compared to the other systems. In the 2nd wet period, the difference between water requirement and use was small for all the systems except for the Potato crop. In the Grass and Natural Forest, the use was slightly below the requirement while in the Cypress Plantation, the use is slightly above the requirement. In the Potato crop, water use is three times more than the requirement. Since the Potato has a lower water requirement, the higher water use could be attributed to deep percolation (Figure 4.6b) observed under this system.

c) Footzone: Vegetation water requirement and use was lower for the Potato crop compared to Grass vegetation in the three periods. The water requirement was higher than use throughout the three periods for the Grass vegetation. For the Potato crop, the requirement was higher than use in the dry period only.

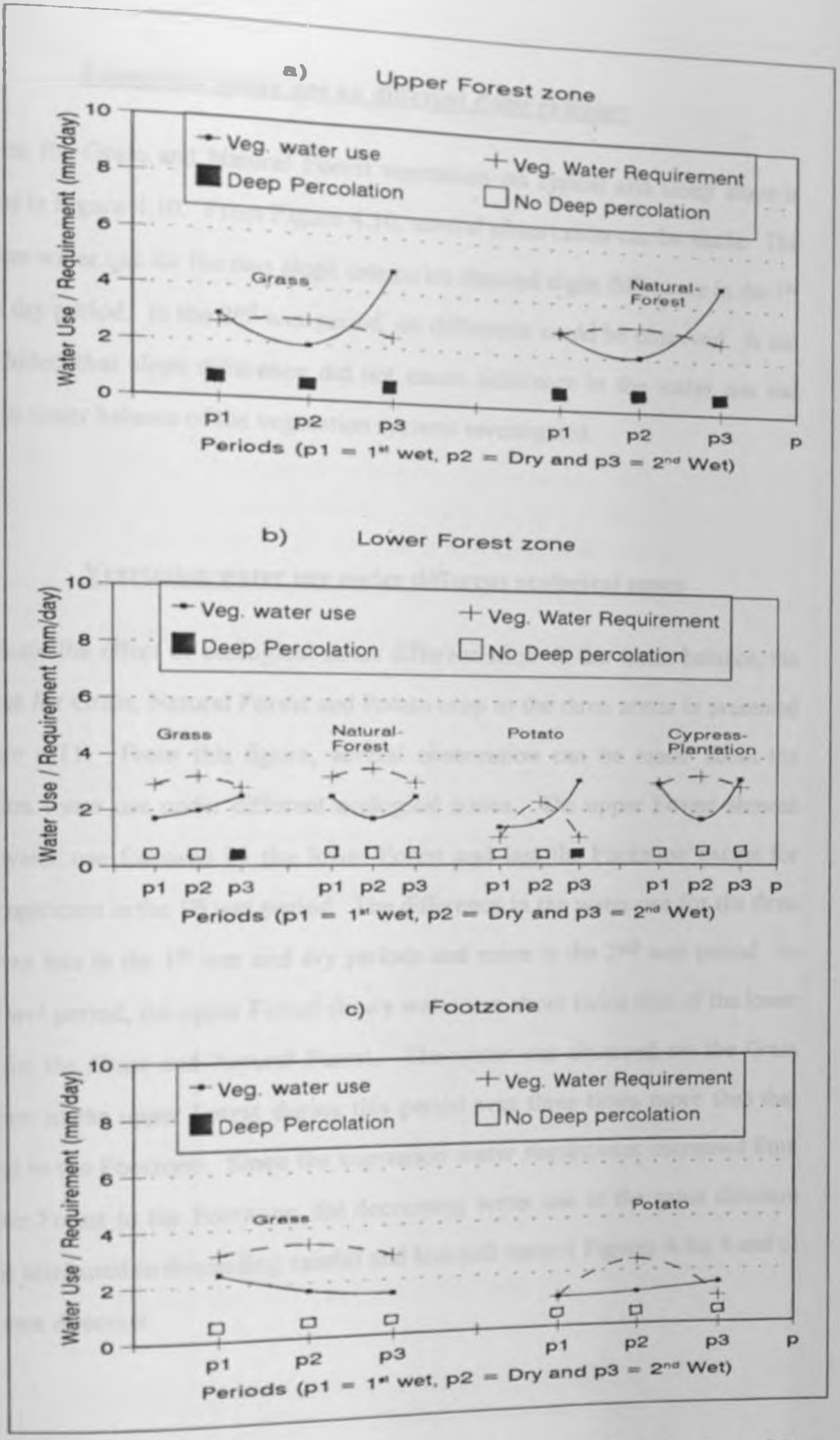


Figure 4.10: Vegetation water use and requirement under different vegetation systems.

4.4.3.2 Vegetation water use on different dope category

Water use for Grass and Natural Forest vegetation on typical and steep slope is presented in Figure 4.10. From Figure 4.10, several observation can be made. The vegetation water use for the two slope categories showed slight difference in the 1st wet and dry period. In the 2nd wet period, no difference could be observed. It can be concluded that slope difference did not cause difference in the water use and hence the water balance of the vegetation systems investigated.

4.4.3.3 Vegetation water use under different ecological zones

To evaluate the effect of ecological zones differentiation on the water balance, the water use for Grass, Natural Forest and Potato crop in the three zones is presented in Figure 4.11. From this figure, several observation can be made about the vegetation water use under different ecological zones. The upper Forest showed higher water use followed by the lower Forest and last the Footzone except for Grass vegetation in the 1st wet period. The difference in the water use for the three zones was less in the 1st wet and dry periods and more in the 2nd wet period. In the 2nd wet period, the upper Forest shows water use about twice that of the lower Forest for the Grass and Natural Forest. The water use observed on the Grass vegetation in the upper Forest during this period was three times more than that observed in the Footzone. Since the vegetation water requirement increased from the upper Forest to the Footzone, the decreasing water use in the same direction could be attributed to decreasing rainfall and less soil water (Figures 4.6a, b and c) in the same direction.

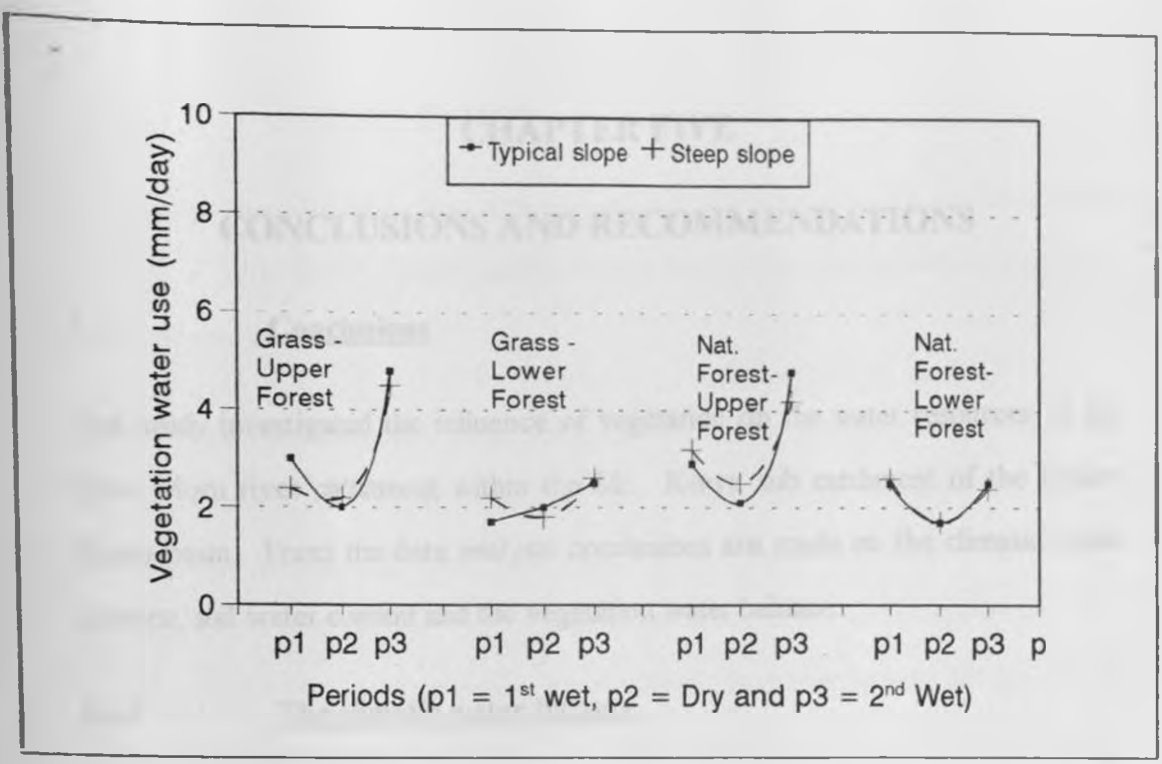


Figure : **Vegetation water use (mm/day) on different slope categories**

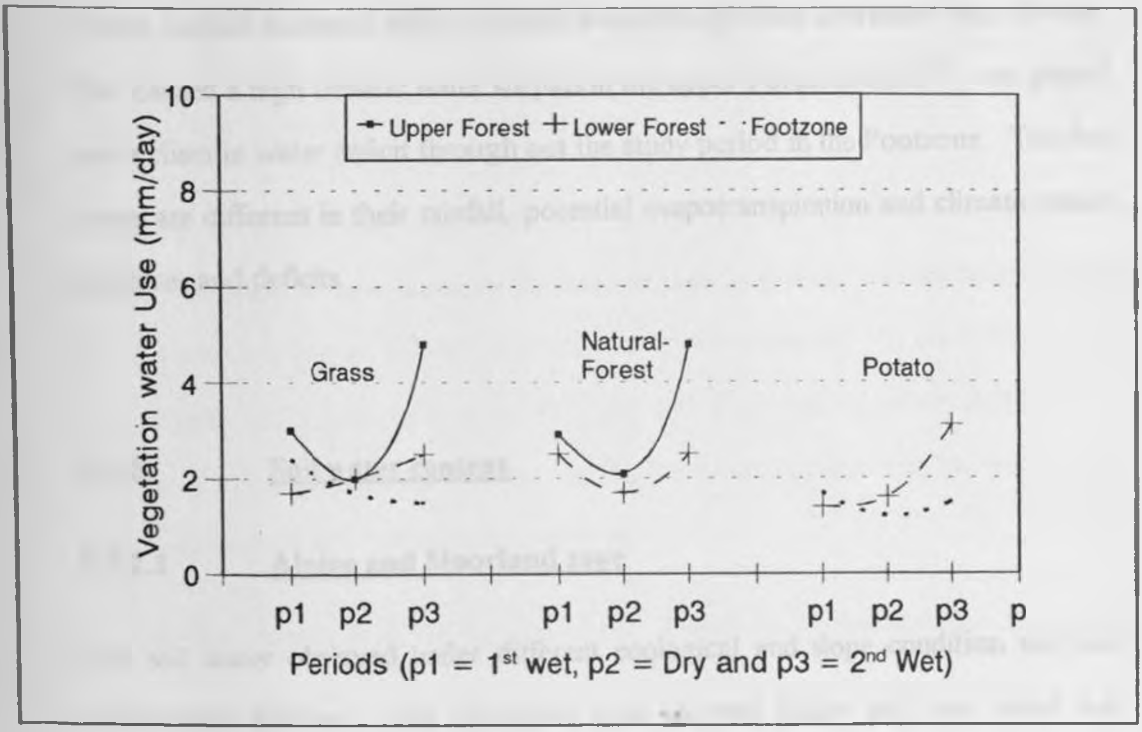


Figure : **Vegetation Water Use (mm/day) for different Ecological zones.**

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The study investigated the influence of vegetation on the water resources of the Naru Moru river catchment within the Mt. Kenya sub catchment of the Ewaso Ngiro basin. From the data analysis conclusions are made on the climatic water balance, soil water content and the vegetation water balance.

5.1.1 The climatic water balance

In the study area, rainfall and potential evapotranspiration showed strong relationship to altitude. Above the upper Forest, both rainfall and potential evapotranspiration decreased with altitude. Between the Footzone and the upper Forest, rainfall increased while potential evapotranspiration decreased with altitude. This caused a high climatic water surplus in the upper Forest in the 2nd wet period and a climatic water deficit through out the study period in the Footzone. The five zones are different in their rainfall, potential evapotranspiration and climatic water surpluses and deficits.

5.1.2 Soil water content

5.1.2.1 Alpine and Moorland zone

The soil water observed under different ecological and slope condition was not significantly different. The Moorland zone showed higher and less varied soil water. Variation in soil water between wet and dry periods was less in the moorland zone and more in the Alpine zone.

5.1.2.1 Forest and Footzone

a) Neutron probe calibration: A single calibration equation was found to estimate soil water from neutron probe counts better than individual calibration equations for each stations.

b) Soil water for different monitoring depths: The four systems investigated in the upper Forest zone experienced deep percolation through out the study period. In the lower Forest, only Grass and Potato systems experienced deep percolation and only in the wet periods. None of the systems in the Footzone experienced deep percolation. While variation in soil water was observed throughout the soil profile in the lower Forest and Footzone, the same was observed only within the upper part (60 cm) of the profile in the upper Forest zone.

The vegetation system showed profile soil water between 100% and 50% of the available soil water capacity in the upper Forest, between 100% and 1% of the available soil water capacity in the lower Forest and between 100% and 0% of the available soil water capacity in the Footzone.

c) Total (0 to 160cm) available soil water: In the upper Forest, the four vegetation systems show a small difference in their soil water. In the lower Forest and Footzone, a bigger difference in soil water was observed. In the lower Forest zone, Grass and Potato crop showed higher soil while natural Forest and Cypress Plantation showed lower soil water. In the Footzone, Potato crop showed higher soil water compared to the Grass vegetation.

The higher rainfall received in the upper Forest was important for the small difference observed in the soil water for the different vegetation systems in this zone. In the lower Forest and Footzone, vegetation water requirement was important for the soil water differences observed under different vegetation systems. The possibility to generate surface runoff was also important for the differences observed in soil water for these two zones. All the systems investigated in the three zones responded positively to rainfall and show higher soil water in the wet periods and lower soil water in the dry period. The total available soil water observed under different vegetation systems was significantly different.

In the upper Forest, the typical slope showed higher soil water for Grass vegetation while the steep slope showed higher soil water for the Natural Forest vegetation. In the lower Forest, the steep slope showed more soil water for both Grass and Natural Forest vegetation. For both slopes, surface and sub-surface runoff was important for the soil water observed on the two slopes. The soil water observed on the two slope categories was significantly different.

The lower Forest showed higher available soil water compared to the upper Forest and the Footzone. The systems in the upper Forest showed a smaller difference in their available soil water. The higher soil water in the lower Forest was attributed to its higher soil water holding capacity. Soil water observed in the three zones was different.

5.1.3 Vegetation water balance

5.1.3.1 Alpine and Moorland zone

Comparing the two zones, vegetation water use and requirement was higher in the Moorland zone. Higher potential evapotranspiration caused higher vegetation water requirement in the Moorland zone. Higher rainfall and vegetation water requirement and a smaller soil water holding capacity (which facilitates surface runoff) could lead to higher water use in the Moorland zone. In the Alpine zone, where both typical and steep slopes were investigated, a higher water use was observed on the steep slope. In this zone, surface runoff was important for the water use observed on the steep slope.

5.1.3.1 Forest and Footzone

In the upper Forest, the Natural Forest and Cypress Plantation vegetation showed a higher vegetation water requirement. The vegetation systems in this zone showed similar water use. In the 1st wet and dry period, despite presence of deep percolation, the vegetation water use was below the requirement in all the systems. This could be due to under estimation of rainfall, since dew is not measured, and or over estimation of vegetation water requirement if high vegetation coefficients were used. For all system, water use exceeded requirement in the 2nd wet period when rainfall is high.

In the lower Forest, the vegetation water requirement exceeded water use for the seven systems in the dry period. In this period, this water deficit was smaller for the Potato crop. In the 2nd wet period, vegetation water requirement was slightly below water use for Grass and Natural Forest vegetation and slightly above the water use for the Cypress Plantation. For the Potato crop, the water requirement was well below water use. In this zone, the vegetation requirement was important for the differences observed in the calculated water use.

In the Footzone, vegetation water requirement exceeded water use through out the study period for the Grass vegetation and only in the dry period for the Potato crop. The Grass vegetation showed higher water use and requirement compared to the Potato crop through out the study period. In this zone vegetation water requirement and surface runoff were important for the observed water use and requirement differences.

Slope difference did not cause important difference in the water balance of the vegetation systems investigated in the three zones.

The upper Forest showed higher water use followed by the Lower Forest and Footzone in a decreasing order. The difference observed between the zones was small in the 1st wet and dry periods.

5.2 Recommendations

5.2.1 Recommendations for water resource planning

The following recommendations are made for water resource planning in the study area.

i) The delicate climatic balance of increasing water demand with decreasing water supply as one moves from the upper Forest to the Footzone should be taken into account when planing for water resources. This zonal differentiation should be central when planning water resources in the catchment.

ii) The Upper Forest is important for deep percolation which is vital for river recharge and hence this zone should be protected to sustain water resources in the catchment.

iii) In the Lower Forest, Potato crop produces considerable deep percolation in the wet periods which is important for river recharge but the impact of Potato farming in this environment should be investigated.

iv) The high water use for the Cypress Plantation should be evaluated against its economic production so as to effectively assess its effect on the water resources of this area

Water conservation practices should be introduced in the lower Forest and Footzone because the vegetation water requirement in these two zone exceeds the amount of water available to the vegetation systems for use in the two zone.

5.2.2 Recommendation for future research

To make comprehensive conclusion on the influence of vegetation on the water resource in the catchment, future research should address several limitations faced by this study. These include;

i) For the water balance calculation, deep percolation and surface runoff should be evaluated separately. This would require deeper neutron probing to assess deep percolation and runoff plots to assess surface runoff.

ii) The study should be extend to cover a longer field monitoring period and hence assess the different vegetation systems on extreme weather conditions.

iii) Water balance modelling approaches would be important especially as a means to extrapolate from site measurement to spatial phenomena.

iv) The Penman formula should be evaluated to assess necessary modification so as to estimate potential evapotranspiration accurately in this sensitive high altitude environment.

v) For economic evaluations, the water balance of the different vegetation systems should be evaluated in the light of their productivity. This hence requires an assessment on primary productivity of the different vegetation systems.

REFERENCES

Baker, B.H., 1967: Geology of Mt Kenya area. Report No.79. Geological Survey of Kenya, Nairobi.

Berger, P., 1989: Rainfall and Agroclimatology of the Laikipia Plateau Kenya. Geographica Bernesia Vol A7, Bern.

Blackie, J.R. and Edwards K.A., 1979: East African Agricultural and Forestry Journal. Vol 43 (Special issue).

Chang, J., 1968: Climate and Agriculture. Adline, Chicago.

Castelino, J.B. and Khamala C.D.M., 1977: The role of water resources in development. Proceedings of the 13th annual symposium of the East Africa Academy.

Chow, V.T., 1964: Handbook of Applied Hydrology. McGraw Hill, New York.

Decurtins, S., 1985: Hydrogeogrphic investigation on Mt. Kenya and its West and North West slopes. Laikipia Report No.5. Institute of Geography. University of Bern, Switzerland.

Decurtins, S., Leibundgut C.; Wetzel J., 1988: Resources of river water in Eastern Laikipia. Institute of Geography. University of Bern, Switzerland.

Decurtins, S., 1992: Hydrogeographical Investment in the Mount Kenya subcatchment of river Ewaso Ngiro. PhD Thesis. Institute of Geography. University of Bern, Switzerland.

Desaules, A., 1986: The Soils of Mt Kenya semi arid North West Footzones. PhD Thesis. Institute of Geography. University of Bern, Switzerland.

Dunne, T. and Leopold B.L., 1978: Water in environmental planning. W.H. Freeman and company, New Yolk

Edwards, K.A. and Blackie J.R., 1979: East African Agricultural and Forestry Journal. Vol 43 (Special issue).

FAO, 1977: Guidelines for predicting crop water requirements. FAO irrigation and drainage paper No.24, Rome.

FAO, 1979b: Agrometeorological crop monitoring and forecasting. FAO Plant Production and Protection paper no. 17, Rome.

Fitzpatric, E.A.,1986: An Introduction to soil science. Longman, Hong Kong.

Flury, M., 1987: Rainfed agriculture in central division - Laikipia district. Kenya. Suitability, constrains and potential for providing food. Geographica bernesia, African studies series. Vol A6, Berne.

Franquin, P., 1978: The water balance and the vegetation. Proceedings ofthe agro-climatological needs of the semi arid Tropics, ICRISAT.

Gardner E.A., 1988: Soil water: in Understanding soils and soil data. Australian society of soil science. Brisbane, Australia.

er reach water balance. A case study of Naru-Moru river. Msc
of Agricultural Engineering, University of Nairobi.

s Saunders

H., 1983. Farm management handbook of Kenya. Ministry of

ch in social anthropology. Anrold press.

1983. The critical component for small scale farming in the semi
orthwest of Mount Kenya. Department of Geography, University
d

Kenya: The Forest belt and its Utilization. Mount Kenya area;
ology and Socio-economy, Winiger, M.(eds). University of Bern,

se in Transition aspects and problems of small scale farming in a
The example of Laikipia district, Kenya. Geographica Bernensia.
ies Vol A5, Berne.

lydrogeographical map of Mt Kenya area; 1:50,000 Map and
Geographica Bernesia. African Studies Series Vol A3. Berne.

search on soil conservation in the semi and highlands of Laikipia.
third National workshop on soil and water conservation.

rtins, S., 1990. Water balance of the Naru Moru basin Laikipia
me Nanyuki, Kenya.

ater conservation for rain fed farming in the semi arid Footzone
unt Kenya. Discussion paper D3 . Laikipia - Mount Kenya papers.

Water resource conservation and utilization West to North of
epts and some results of applied research for sustainable resource
per presented to the workshop on African Mountains and Highlands,
nber 1990. Rabat, Morocco.

oil cover and management . Attractive water and soil conservation for
Kenya. Paper presented to the 7th international soil conservation
ference, Sydney, Australia, 1992.

he climatic water budget in Environmental Analysis. Lexington Books,

Dry land farming in Kenya: Problems and Prospects. Paper presented
the development of Kenya Semi-arid areas. Institute of Development
sity of Nairobi

he problem of soil erosion in semi arid Kenya. in The Kenyan
ol 5 No. 1

Evaluation of soil moisture balance. Discussion paper. Department of
iversity of Nairobi

National Water master plan, 1991: Sectorial report B - Hydrology. ministry of water development, Republic of Kenya.

Olembo, T.W.,(ed) 1979: Hydrological Research in East Africa. East Afr. Agri. For. J. Vol 43 (Special issue).

Ondieki, C.N., 1991: The resource potential of dry river valleys in the upper Ewaso Ngiro basin within Laikipia district. Laikipia reports (in preparation) LRP. Nanyuki, Kenya.

Owino, F., 1977: Forest water yield and use : A Kenyan perspective. in Castelino, J.B. and Khamala C.D.M., 1977: The role of water resources in development. Proceedings of the 13th annual symposium of the East Africa Academy.

Pereira, H.C., 1962: Grazing intensities on the Atumatak catchment. East African Agricultural and Forestry Journal. Vol 27, Pages 61 to 63.

Pratt, D.J. and Gwyne, M.D., 1977: Rangeland ecology and management in East African. Hodder and Stoughton.

Roberts, I.T., 1963: An investigation into the water resources of the Ewaso Ng'iro basin Kenya.

Thomas, D.B, Baber, R.G. and Moore, T.R., 1980: Terracing of crop land in low rainfall areas of Machakos district, Kenya. Journal of Agricultural Engineering Research. Vol 25.

Thomas, M.K., 1992: Development of a stream flow model using a GIS for a rural catchment in Kenya. Msc Thesis. Graduate school. University of Cornell, USA.

Speck, H., 1983: Mount Kenya Area: Ecological and Agricultural significance of the soils with two soil maps. Geographica Bernesia. African Studies series, Berne.

Schoherer, V.; Muller I., 1985: The use of Isotopes hydro-Chemistry and Geophysics for ground water research in Laikipia District, Kenya. Laikipia Reports No.4. Institute Of Geography. University of Bern, Switzerland.

Sombroeck, W.G., Braun H.M. and Pouw, B.J., 1980: Exploratory soil map and Agro-climatic zones of kenya. Ministry of Agriculture, Kenya soil survey.

Wiesmann, U., 1990a: Population growth and migration patterns in Laikipia district,Kenya. Laikipia research programme.

Wiesmann, U., 1992b: Socioeconomic view point on highland-Lowland systems: A case study of Northwestern side of mount Kenya. Reprint from mountain research and development

Yaron, B, Danfor E and Vaadia Y., 1973: Arid zone hydrology. Chapman and Hall, London.

Appendix 1: The penman formula (FAO, 1979b)

$$\frac{\frac{\Delta}{\gamma}\left[0.75 R_A (a + b \frac{n}{N}) - \sigma T_K^4 (0.56 - 0.079\sqrt{e_d})(0.10 + 0.90 \frac{n}{N}\right] + 0.26(e_a - e_d)(1.00 + 0.54 U)}{\frac{P_o}{P} \cdot \frac{\Delta}{\gamma} + 1.00}$$

$$\frac{\cdot \frac{\Delta}{\gamma}\left[0.95 R_A (a + b \frac{n}{N}) - \sigma T_K^4 (0.56 - 0.079\sqrt{e_d})(0.10 + 0.90 \frac{n}{N})\right] + 0.26(e_a - e_d)(0.50 + 0.54 U)}{\frac{P_o}{P} \cdot \frac{\Delta}{\gamma} + 1.00}$$

E_T = estimation of the potential evapotranspiration for a given period, expressed in mm;

E_0 = estimation of the evaporation from a free water surface for a given period, expressed in mm;

P_o = mean atmospheric pressure expressed in millibars at sea level;

P = mean atmospheric pressure expressed in millibars as a function of altitude, for the station where the estimate is calculated;

Δ = rate of change with temperature of the saturation vapour pressure expressed in millibars per degree °C;

γ = the psychometric coefficient for the psychometer with forced ventilation = 0.66;

0.75 and 0.95: factors expressing the reduction in the incoming short wave radiation on the evaporating surfaces and corresponding respectively to an albedo of 0.25 and 0.05;

R_A = short wave radiation received at the limit of the atmosphere expressed in mm of evaporable water (1 mm = 59 calories) and taking for the solar constant the value of 2.00 $cal.cm^{-2}.min^{-1}$;

a and b = coefficients for the estimation of total radiation from the sunshine duration (see paragraph 2.1);

n = sunshine duration for the period considered in hours and tenths;

N = sunshine duration astronomically possible for the given period;

σT_K^4 = Blackbody radiation expressed in mm of evaporable water for the prevailing air temperature;

e_a = saturation vapour pressure expressed in millibars;

e_d = vapour pressure for the period under consideration expressed in millibars;

$T°_C$ = air temperature measured in the meteorological shelter and expressed in degrees Celsius;

$T°_K$ = air temperature expressed in degrees Kelvin where $T°_K = T°_C + 273$;

$U_{m/s}$ = mean wind speed at an elevation of 2 m for the given period and expressed in m/sec.

Appendix 2: Climatic data for the Forest and Footzone: Daily average values for 10 days decades.

i) Upper Forest Zone

Month	Decade	Rainfall (mm)	Pan Evapo-ration (mm)	Potential evapo-trans piration (mm)	Tempe-rature (C)	Relative Humidity (%)	Wind-speed (Km/hr)	Sunshine hours (Hrs)
NOV1991	1	38.6	1.3	NA	10.1	NA	NA	NA
	2	9.6	1.3	NA	10.4	NA	NA	NA
	3	75.0	1.2	NA	10.2	86	2.5	NA
DEC	4	17.1	1.0	2.4	10.1	85	2.7	2.0
	5	8.1	1.6	2.7	12.2	72	3.9	2.5
	6	6.5	2.9	3.0	11.7	66	4.8	4.8
JAN1992	7	27.8	1.4	2.7	10.6	74	3.6	4.1
	8	7.2	1.8	2.7	10.7	76	3.2	3.7
	9	40.1	2.2	2.9	11.4	73	3.8	5.3
FEB	10	37.5	2.1	3.1	11.2	64	4.6	4.9
	11	3.0	2.2	3.1	11.9	67	3.9	5.0
	12	0.0	2.2	3.2	12.2	55	4.2	4.9
MAR	13	3.9	1.9	3.1	11.3	63	4.3	5.0
	14	37.7	2.1	3.0	11.8	75	4.0	5.0
	15	22.0	2.0	3.0	11.9	73	3.8	4.2
APR	16	128.8	1.7	2.7	11.5	84	3.3	3.6
	17	45.1	1.7	2.7	11.0	80	3.6	4.0
	18	49.7	1.3	2.7	11.3	83	3.3	3.1
MAY	19	90.2	1.7	2.6	11.6	78	3.9	3.9
	20	69.8	1.3	2.4	10.7	86	3.3	2.9
	21	41.4	1.6	2.5	10.8	79	3.2	3.2
JUN	22	43.3	1.2	2.4	11.0	77	3.5	3.2
	23	32.6	0.9	2.2	9.9	88	3.2	1.7
	24	21.2	1.2	2.2	9.2	82	2.8	2.4

Note: Values given for rainfall are decade totals

Appendix 2 contd.

i) Lower Forest Zone

Month	Decade	Rainfall (mm)	Pan Evaporation (mm)	Potential evapotranspiration (mm)	Temperature (C)	Relative Humidity (%)	Wind-speed (Km/hr)	Sunshine hours (Hrs)
NOV1991	1	30.8	1.8	NA	NA	NA	NA	NA
	2	22.7	1.8	NA	NA	NA	NA	NA
	3	36.4	1.3	NA	NA	86	3.3	NA
DEC	4	28.1	1.9	2.7	12.7	73	NA	4.1
	5	6.1	2.3	2.8	13.7	70	3.5	3.6
	6	12.4	3.6	3.4	13.5	58	NA	6.1
JAN1992	7	28.5	2.5	2.8	13.0	69	4.3	1.3
	8	12.2	2.4	3.0	13.4	71	4.1	5.2
	9	30.5	3.2	3.2	13.8	73	4.8	6.3
FEB	10	1.2	3.6	3.5	13.9	60	5.4	5.4
	11	1.2	2.5	3.3	14.3	64	NA	5.5
	12	0.0	3.5	3.4	13.8	58	NA	6.0
MAR	13	4.2	3.3	2.7	14.4	79	4.8	5.1
	14	20.7	3.3	2.7	14.3	77	4.9	5.4
	15	23.2	3.2	2.7	15.1	75	NA	5.9
APR	16	65.2	2.0	3.1	14.4	79	3.9	4.3
	17	21.0	2.3	3.0	14.5	63	4.4	5.0
	18	101.2	1.8	2.9	14.6	79	NA	4.2
MAY	19	56.8	2.2	2.8	14.8	79	4.2	4.7
	20	16.4	1.5	2.7	14.5	NA	3.9	4.8
	21	25.4	1.9	2.9	13.7	NA	4.3	4.9
JUN	22	9.7	2.3	2.6	14.6	NA	3.7	6.1
	23	17.3	1.7	2.6	14.8	NA	3.3	3.7
	24	4.7	2.4	2.6	14.5	NA	NA	4.4

Note: Values given for rainfall are decade totals

Appendix 2 contd.

iii) Footzone

Month	Decade	Rainfall (mm)	Pan Evaporation (mm)	Potential evapotrans piration (mm)	Temperature (C)	Relative Humidity (%)	Wind-speed (Km/hr)	Sunshine hours (Hrs)
NOV1991	1	NA	NA	NA	NA	NA	NA	NA
	2	NA	NA	NA	NA	NA	NA	NA
	3	27.3	2.5	NA	15.7	77	1.5	NA
DEC	4	25.8	2.5	2.8	15.4	75	5.0	4.6
	5	4.4	3.0	2.9	16.6	65	3.9	4.6
	6	3.3	3.8	3.3	15.6	55	4.9	5.0
JAN1992	7	12.4	3.5	3.0	15.4	65	4.4	4.7
	8	17.8	3.4	3.1	16.7	71	3.7	5.8
	9	6.3	3.8	3.3	16.1	70	4.3	7.2
FEB	10	4.2	4.2	3.6	16.6	59	NA	6.8
	11	0.3	3.8	3.6	16.9	64	NA	6.3
	12	5.6	4.6	3.6	17.0	58	3.7	6.4
MAR	13	1.2	4.5	3.6	16.4	60	4.9	5.5
	14	6.7	4.1	3.6	16.9	70	5.5	6.3
	15	45.4	4.3	3.6	17.8	70	5.0	6.5
APR	16	38.3	3.4	3.1	17.3	78	5.0	5.3
	17	19.3	3.4	3.1	16.4	81	4.5	6.4
	18	58.3	3.0	3.1	17.2	81	5.6	5.7
MAY	19	8.9	3.0	2.9	16.6	80	6.6	5.9
	20	1.5	3.4	2.9	15.8	83	9.6	6.2
	21	8.7	3.7	3.0	15.5	79	8.5	6.7
JUN	22	0.4	4.4	3.1	16.2	75	10.3	6.2
	23	0.0	4.1	2.9	16.2	78	9.1	6.8
	24	0.0	4.6	3.0	16.2	78	9.6	7.4

Note: Values given for rainfall are decade totals

Appendix 3: Study period monthly rainfall and long term mean monthly rainfall totals(mm) and number of rain days in the study area between November 1991 and June 1992.

Zone		Alpine	Moorland	Upper-Forest	Lower-Forest	Footzone
Stations		R1	R2	Met	Gate	Munyaka
NOV:	1	NA	NA	123	90	27
	2	109	132	186	174	117
	3	NA	NA	19	19	1
DEC:	1	NA	NA	32	47	34
	2	64	NA	103	82	69
	3	NA	NA	11	10	8
JAN:	1	NA	NA	75	71	37
	2	33	NA	50	55	47
	3	NA	NA	8	13	9
FEB:	1	NA	NA	41	2	10
	2	33	56	73	58	37
	3	NA	NA	6	2	4
MAR:	1	NA	NA	64	48	53
	2	72	125	103	97	72
	3	NA	NA	13	9	11
APR:	1	NA	NA	224	187	116
	2	141	173	247	186	118
	3	NA	NA	22	24	15
MAY:	1	NA	NA	201	99	19
	2	83	NA	171	111	57
	3	NA	NA	24	17	13
JUN:	1	NA	NA	97	32	0
	2	45	68	91	41	14
	3	NA	NA	15	9	1

Note:1 = Study period total monthly rainfall

2 = Long term mean monthly rainfall

3 = Number of rain days

NA = Data not available

x 4: **Daily and monthly potential evapotranspiration rates(mm) in the study area between November 1991 and June 1992.**

	Alpine	Moorland	Upper-Forest	Lower-Forest	Footzone
	R1*	R2*	Met	Gate	Munyaka
	0.5	1.7	2.7	3.0	NA
	15.0	51.0	81.0	90.0	NA
	0.4	1.6	2.6	2.9	3.2
	12.4	49.6	80.6	89.9	96.0
	0.7	1.7	2.8	3.1	3.0
2	21.7	52.7	86.8	96.1	93.0
1	0.7	1.9	3.1	3.5	3.2
2	20.7	55.1	89.9	101.5	99.2
1	0.7	1.9	2.7	3.0	3.6
2	21.7	58.9	83.7	93.0	104.4
1	0.4	1.5	2.7	2.8	3.1
2	12.0	46.5	81.0	90.0	111.6
1	0.4	1.5	2.5	2.8	2.9
2	12.4	42.0	77.5	86.8	89.9
1	0.4	1.4	2.3	2.7	3.0
2	12.0	41.8	69.0	81.0	90.0

*For R1 and R2, calculations are based on previous records(Decurtins 1992: pg 80).

: 1 = Daily Potential evapotranspiration rates

2 = Monthly Potentail evapotranspiration rate

ndix 5: Monthly rainfall, monthly potential evapotranspiration and the climatic water balance in the study area between November 1991 and June 1992.

		Alpine	Moorland	Upper-Forest	Lower-Forest	Footzone
ns		R1	R2	Met	Gate	Munyaka
:	1	109	132	123	90	27
	2	15	51	81	90	NA
	3	94	81	42	0	NA
:	1	64	NA	32	47	34
	2	12	50	81	90	96
	3	52	NA	-49	-43	-62
I:	1	33	NA	75	71	37
	2	22	53	87	96	93
	3	11	NA	-12	-25	-56
B:	1	33	56	41	2	10
	2	20	55	90	102	99
	3	13	1	-49	-100	-89
R =	1	72	125	64	48	53
	2	22	59	84	93	104
	3	50	69	-20	-45	-51
PR =	1	141	173	224	187	116
	2	12	47	81	90	112
	3	129	126	143	97	4
AY =	1	83	NA	201	99	19
	2	12	42	78	87	90
	3	71	NA	123	12	-71
JUN =	1	45	68	97	32	0
	2	12	42	69	81	90
	3	33	26	28	-49	-90

(All values are in mm).

Note:1 = Monthly rainfall
2 = Monthly potential evapotranspiration
3 = Monthly climatic water balance (1-2)

Appendix 6: Soil density and the available soil water capacity in the study area.

i) Soil bulk density (g/cm3) : calculated from core ring samples collected during the Neutron probe calibration

Zone	Alpine	Moorland	Upper-Forest	Lower-Forest	Footzone
Station	R1	R2	Met	Gate	Munyaka
Depth(cm)					
15	1.3	0.2	0.5	1.0	1.1
30	1.4	0.3	0.6	1.0	1.1
60	1.0	1.0	0.6	1.0	1.2
90	NA	NA	0.7	1.1	1.2
120	NA	NA	0.8	1.0	1.3
150	NA	NA	0.7	1.2	1.4
170	NA	NA	0.7	1.1	1.2

ii) Available water capacity (mm of water/100cm^3).

Zone	Alpine	Moorland	Upper-Forest	Lower-Forest		Footzone	
Station	R1	R2	Met	Gate		Munyaka	
Slope	Typical	Typical	Typical	Typical	Steep	Typical	Steep
Depth(cm)							
>20	12	10	21	21	19	20	23
20 - 70	10	10	12	17	14	16	17
>70		8	10	12	10	12	13

Appendix 7 : Available soil water(mm) in the Alpine and Moorland zone

i) 15 and 30cm profile depths.

Zone	Alpine				Moorland	
Slope	Typical		Steep		Typical	
Depth	15cm	30cm	15cm	30cm	15cm	30cm
November	112	116	78	98	77	120
December	103	54	163	104	72	121
January	74	83	50	48	71	141
February	53	67	43	53	76	129
March	24	16	41	23	106	107
April	44	46	43	53	65	104
May	57	131	61	59	75	109

ii) Total(0 to 30cm) available soil water(mm).

Zone	Alpine		Moorland
Station	R1		R2
Slope	Typical	Steep	Typical
November	228	146	197
December	157	267	194
January	157	99	213
February	120	95	205
March	40	65	213
April	90	96	169
May	188	119	184

Appendix 8 :Total(0-160cm) available soil water(mm) - Forest and Footzone

Zone	Upper Forest				Lower Forest							Footzone		
Stations	Met				Gate							Munyaka		
Monitoring Dates	GT	GS	NT	NS	GT	GS	NT	NS	NsS	PoT	PIT	GT	GS	PoT
08-Nov-91	242	220	231	248	233	279	201	220	NA	226	113	2	NA	140
15-Nov-91	234	224	233	243	253	293	212	227	NA	253	125	11	NA	150
22-Nov-91	231	229	230	243	274	303	220	234	NA	272	148	77	NA	255
29-Nov-91	243	236	240	250	290	304	237	241	195	286	141	90	332	264
06-Dec-91	234	227	231	246	287	303	229	238	188	284	112	79	327	235
13-Dec-91	239	226	233	247	290	309	235	240	199	290	144	76	329	229
20-Dec-91	229	220	230	239	290	307	219	232	187	290	109	69	317	209
24-Dec-91	233	233	230	236	286	308	215	232	178	290	104	57	310	203
03-Jan-92	212	201	215	218	270	294	192	228	158	285	98	34	304	189
10-Jan-92	219	203	214	216	274	307	220	234	172	297	164	22	307	187
17-Jan-92	219	199	213	216	268	297	200	230	168	290	127	16	302	189
24-Jan-92	215	194	205	205	260	291	187	224	157	290	102	26	300	179
29-Jan-92	220	199	211	209	263	299	196	235	166	292	122	11	297	178
04-Feb-92	214	202	210	206	272	313	199	237	168	293	125	6	291	176
14-Feb-92	220	202	213	207	256	293	183	223	149	290	97	2	288	168
21-Feb-92	221	198	198	195	241	275	167	209	130	283	91	-8	291	156
26-Feb-92	218	192	198	189	234	271	169	207	124	274	90	-6	288	157
06-Mar-92	208	171	183	173	217	253	156	206	112	270	89	-10	NA	149
13-Mar-92	205	165	175	156	210	245	158	198	113	263	86	-14	294	147
20-Mar-92	211	166	186	172	216	252	172	200	126	267	149	-15	291	142
27-Mar-92	204	173	187	162	215	254	169	196	123	275	117	-9	298	150
01-Apr-92	220	197	206	198	215	276	169	207	113	287	106	-4	302	149
11-Apr-92	236	222	226	233	251	276	213	220	167	308	158	0	305	148
16-Apr-92	230	208	218	233	246	276	204	220	155	302	141	-0	305	162
24-Apr-92	227	216	229	234	244	278	203	209	165	305	125	2	301	162
01-May-92	239	222	233	241	323	322	266	271	246	324	216	31	337	213
08-May-92	234	227	236	242	306	309	262	272	239	310	202	26	326	204
18-May-92	238	233	236	244	313	316	277	275	256	312	210	10	305	192
29-May-92	237	227	229	237	304	304	264	260	240	295	174	-6	304	179
08-Jun-92	235	228	234	248	302	309	258	259	232	298	145	-4	290	169
15-Jun-92	232	232	230	241	290	301	252	255	226	289	137	-7	299	169
26-Jun-92	228	217	224	237	283	293	236	244	217	281	117	-15	288	160

Key:

GT=Grass - Typical slope

GS=Grass - Steep slope

NT=Natural Forest-Typical slope

NS=Natural Forest - Steep slope

PoT=Potato - Typical slope

PlT=Cypress Plantaion - Typical slope

NA=Data not available

Appendix 9 : Vegetation water use(mm/day) for different Vegetation, Slope and Ecological zones.

i) **VEGETATION** : Vegetation water use(mm/day) for different vegetation system.

		Upper-Forest		Lower-Forest				Footzone	
		Grass	Natural Forest	Grass	Natural Forest	Potato	Plantation	Grass	Potato
Typical-slope	1 Wet period	3	2.9	1.7	2.5	1.4	3	2.4	1.1
	1 Dry period	2	2.1	2	1.7	1.6	1.1	1.7	1.2
	2 Wet period	4.8	4.8	2.5	2.5	3.1	3.2	1.5	1.5
Steep-slope	1 Wet period	2.4	3.7	2.2	2.6	NA	NA	3.1	NA
	1 Dry period	2.2	2.5	1.8	1.7	NA	NA	1.5	NA
	2 Wet period	4.7	4.2	2.6	2.4	NA	NA	1.3	NA

ii) **SLOPE** : Vegetation water use(mm/day) on typical and steep slopes.

		Upper Forest		Lower Forest	
		Typical-slope	Steep-slope	Typical-slope	Steep-slope
Grass Vegetation	1 Wet period	3	2.4	1.7	2.2
	1 Dry period	2	2.2	2	1.8
	2 Wet period	4.8	4.6	2.5	2.6
Natural-Forest Vegetation	1 Wet period	2.9	3.2	2.5	2.6
	1 Dry period	2.1	2.5	1.7	1.7
	2 Wet period	4.8	4.2	2.5	2.4

iii) **ECOLOGICAL ZONE** : Vegetation water use(mm/day) for the two (Forest and Footzone) zones.

		Upper Forest	Lower Forest	Footzone
Grass vegetation on Typical slope	1 Wet period	3	1.7	2.4
	1 Dry period	2	2	1.7
	2 Wet period	4.8	2.5	1.5
Grass vegetation on Steep slope	1 Wet period	2.4	2.2	1.1
	1 Dry period	2.2	1.8	1.2
	2 Wet period	4.7	2.6	1.5
Natural vegetation on Typical slope	1 Wet period	2.9	2.5	NA
	1 Dry period	2.1	1.7	NA
	2 Wet period	4.8	2.5	NA
Natural vegetation on Steep slope	1 Wet period	3.2	2.6	NA
	1 Dry period	2.5	1.7	NA
	2 Wet period	4.2	2.5	NA
Potato crop on Typical slope	1 Wet period	NA	1.4	3.1
	1 Dry period	NA	1.6	1.5
	2 Wet period	NA	3.1	1.3

Note: NA = Data not Available

Appendix 10: Analysis of variance results

1) Rainfall, Potential evapotranspiration and Climatic water balance

Descripition of variation tested	Source of Variation mean square		F - ratio	P value
	Between	Within		
Rainfall in five study zones	6935.972	2356.074	2.944	0.034
Potential evapotranspiration in five study zones	9135.380	36.482	250.410	0.000
Climatic water balance in five study zones	20788.015	2442.290	8.512	6.603

2) Total(0-30cm) soil water in the Alpine and Moorland zones : Zone and Slope Variation

Descripition of variation tested	Source of Variation mean square		F - ratio	P value
	Between	Within		
Slope :Typical and Steep in the Alpine zone	1672.071	5317.429	0.314	0.141
Zone : Alpine and Moorland on typial slope	8016.071	3225.619	2.450	0.141

Appendix 10:contd.

3) Total(0–160cm) soil water in the Forest and Footzones:
Vegetation, Slope and Ecological zone variation

i) Variation in soil water under different vegetation systems

Descripition of variation tested	P values
Grass and Natural Forest – Upper Forest on Typical slope	0.032
Grass and Natural Forest – Upper Forest on Steep slope	0.072
Grass, Natural Forest, Cypress plantation and Potato – Lower Forest on Typical slope	$7.0x10^{-14}$
Grass and Natural Forest – Lower Forest on Steep slope	$3.0x10^{-14}$
Grass and Potato – Footzone on Typical slope	$2.0x10^{-13}$

ii) Variation in soil water on Typical and Steep slopes.

Descripition of variation tested	P values
Grass vegetation – Upper Forest zone	$2.3x10^{-4}$
Grass vegetation – Lower Forest zone	$2.1x10^{-4}$
Natural Forest vegetation – Upper Forest zone	0.6013
Natural Forest vegetation – Lower Forest zone	$6.5x10^{-3}$

iii) Variation in soil water in the two Ecological zones.

Descripition of variation tested	P values
Grass on typical slope – Upper Forest, Lower Forest and Footzone	0.000
Grass on Steep slope – Upper and Lower Forest zone	0.000
Natural Forest on typical slope – Upper and Lower Forest zone	0.301
Natural Forest on steep slope – Upper and Lower Forest zone	0.111
Potato on typical slope – Lower Forest and Footzone	$1.2x10^{-13}$