SPATIAL AND TEMPORAL VARIABILITY OF SOIL FERTILITY UNDER RAINWATER HARVESTING SYSTEMS: A CASE STUDY OF MAKANYA RIVER CATCHMENT

BY

REUBEN ADOLPH LUDOVIC

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ABSTRACT

A study was conducted to assess the spatial and temporal variability of soil fertility under rainwater harvesting (RWH) systems in three villages along the toposequence on the Makanya river catchment, Same district, Tanzania. The study aimed at assessing the soil fertility status and patterns along the toposequence, mapping spatial patterns of soil fertility under RWH, identifying and determining the nature and magnitude of the factors causing soil fertility changes under RWH systems along the toposequence within the cropping seasons, and assessing spatial and temporal variability of soil fertility within selected fields under RWH systems in Makanya village. Random soil samples were collected from Makanya, Mwembe and Tae villages and were used for the characterization of physical and chemical soil properties on the catchment. Runoff water samples were collected and analysed for plant nutrients in the runoff. GPS and GIS were used for positioning both soil and water sampling points and to establish geospatial information database and generate maps of the study area. Geostatistical analysis was done to carry out soil fertility surface interpolation. Soil fertility management practice data were collected through a questionnaire survey and analysed using SPSS software. The study revealed that, more than 92% of 144 interviewees were practicing RWH systems in the study area. The soil fertility attributes showed that, total nitrogen was very low to medium level (0 – 0.5 %). Soil pH ranged from strongly acid to moderately alkaline. Exchangeable K on the upper zone was very low (0 – 0.13 cmol(+)/kg) for the majority of samples (62 %), whereas available P was adequate (39.49 – 81.16 mg P /kg soil) only on the lower zone. Fertility attribute maps on the mid and upper zone tended to be systematically distributed following the slope facet, while on the lower zone, maps showed the patterns distribution to follow availability of harvested rainwater. Generally, most of the soils under rainwater harvesting in the area had low fertility status attributable to low organic carbon, total nitrogen and potassium, thus required improvement for high and sustainable crop yields.

DECLARATION

I, Reuben Adolph Ludovic, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work and has not been submitted for a degree in any other University.

Signature: ____________________

Date: 30 . 08 . 2004

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DEDICATION

To my parents Ma-Dorothea Kokuhilwa and Ta-Ludovic Sheshelwa.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	Percent
^0C	Degree Celsius
CA	Catchment area
Ca^{2+}	Calcium ion
CB	Cropped basin
cmol (+)/kg	Centimole per kilogram
cS/m	cente-Siemen per meter
EC	Electrical Conductivity
FAO	Food and Agricultural Organisation
FYM	Farmyard manure
GIS	Geographical Information Systems
GPS	Global Positioning Systems
Id	Identifier
IRRI	International Rice Research Institute
K^+	Potassium ion
$K_2Cr_2O_4$	Potassium dichromate
kg	Kilogram
mg/kg	milligram per kilogram
mg/l	milligram per litre
Mg^{2+}	Magnesium ion
N	Nitrogen
Na+	Sodium ion
RMSE	Root mean square error

RWH	Rainwater harvesting
SAT	Semi-arid tropics
SSFM	Site specific fertility management
SUA	Sokoine University of Agriculture
SWMRG	Soil Water Management Research Group
SWMRP	Soil Water Management Research Programme
TN	Total nitrogen
WPLL	Western Pare Lowlands

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

On the basis of the amount and distribution of rainfall, more than 50% of mainland Tanzania can be categorised as semi-arid (De Pauw, 1984; LRDC, 1987). Furthermore, over 40% of the rural people in Tanzania are food insecure and most of them are found in the semi-arid areas (Ngailo *et al.*, 1994). In these semi-arid areas, the fundamental problem facing agriculture and livestock production is low soil fertility and inadequate soil-moisture (Rwehumbiza *et al.*, 1999).

A good progress has been made in some semi-arid areas of Tanzania to reduce soil water constraints through rainwater harvesting (RWH). In the broad sense, rainwater harvesting is the process of concentrating, collecting and storing rain water for different uses at a later time in the same area where the rain falls, or in another area during the same or later time (Hatibu and Mahoo, 2000).

Water harvesting is not a new idea or technology because for thousands of years, systems designed to increase the amounts of water for crop production have been used in the semi-arid and arid tropical regions. The first water harvesting techniques are believed to have originated in Iraq over 5000 years ago. In Africa however, the potential of rainwater harvesting for improved crop production received a great attention in the 1970s and 1980s. This was due to the widespread droughts in Africa that left trails of crop failures and serious threat to human and livestock life. Consequently, a number of water harvesting projects were set up in sub-Sahara

Africa to combat the effect of drought by improving plant production and in some areas rehabilitating abandoned and degraded land (Critchley and Reij, 1989), cited by Hatibu and Mahoo (1999).

Water harvesting has tended to be conceived as an isolated technique of improved water management in semi-arid and arid areas. In reality the optimal yields can not be achieved by simply supplying more water to a crop. In water scarce tropical agro-ecosystems, water and low soil fertility are the most important factors limiting improved crop yields. Combining water harvesting with other methodologies for improved water and soil management can have a tremendous effect to the farming systems. Therefore, successful water harvesting practices should involve an integrated approach to soil and water management.

According to Agromisa Foundation (1997), in most RWH systems, soil fertility must be improved or at least maintained in order for the soil to remain productive in a sustainable way. The improved water availability and higher yields derived from water harvesting lead to greater exploitation of soil nutrients. In many areas where RWH systems are being practiced, lack of soil moisture and low content of plant nutrients like N and P are recognized as significant constraints to plant growth (FAO, 1991).

In the semi-arid areas, low physical soil fertility is associated with crusting, collapse of soil structure and erosion resulting from the decline of vegetation cover and organic matter when the land is cultivated. The low chemical and biological soil fertility status are associated with non-incorporation of the harvested crop parts and crop residues into the soil, leaching, non or inadequate application of fertilizers, denitrification and immobilization of the plant nutrients in soils (Smaling and Fresco, 1993).

Soil fertility is one of the indicators of soil quality and its spatial and temporal variability can be realized within a time scale of less than a year (Arnold *et al.*, 1990; Coleman *et al.*, 1992), cited by Halvorson *et al.* (1997). Soil quality is the capability of soil to produce crops in a sustainable manner, and to enhance human and animal health without adversely impairing the natural resource base or the environment (Parr *et al.*, 1992). Thus, in semi-arid and arid areas, in order the soil to be productive in the sustainable way, need to be improved in moisture as well as fertility.

In the semi-arid areas, some of the agronomic practices used to ensure that crops use soil-water effectively with high productivity include: (i) A judicious fertilizer use commensurate with the nutrient status of soil, nutrient needs of crops, plant population and availability of soil moisture, (ii) crop rotation including fallowing with the aim of exploiting the difference in crop characteristics to restore soil structure and fertility and (iii) limited supplementary irrigation to carry the crop through a particular damaging dry spell (moisture stress).

According to Hatibu and Mahoo (2000), the ecological situation in semi-arid areas can be described as "dry with low nutrients". In such cases, the techniques for harvesting both soil nutrients and water would be the most relevant soil and water conservation approach. The introduction and adoption of rainwater harvesting systems/technologies in semi-arid areas of Tanzania, has significantly reduced the constraint of soil moisture to crop production (SWMRG, 2001). However, there have not been parallel and equivalent efforts in the introduction and adoption of strategies to improve soil fertility.

Thus, it is absolutely important to understand the fertility status of soil and its variability in spatial and temporal scale. The interpretation and thorough understanding of these phenomena within a landscape or fields is necessary for both farmers and scientists. It is against the above background that this study was initiated. It is hoped that, this study will contribute knowledge on the improvement of soil fertility under RWH systems and hence accelerate the development of a sustainable farming system in semi-arid areas.

1.2 Objectives

The main objective of this study was to assess the magnitude and extent of spatial and temporal variability of soil fertility under RWH systems in Makanya river catchment of Western Pare Lowlands. The specific objectives were the following:

(i) To assess status and patterns of the soil fertility along the toposequence under RWH systems in the study area.

(ii) To map spatial patterns of soil fertility under RWH in the study area.

(iii) To identify and determine the nature and magnitude of the factors causing soil fertility changes along the toposequence under RWH systems within the cropping season in the study area.

(iv) To assess spatial and temporal variability of soil fertility within the selected fields under RWH systems in the study area.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Rainwater harvesting systems

2.1.1 Definition of rainwater harvesting

From the crop production point of view, rainwater harvesting can be defined as the process of concentrating rainwater from a large land area into a small area so as to improve the soil moisture regime. Rainwater harvesting can also be referred to as a method of inducing, collecting, storing and conserving local surface runoff for agriculture in arid and semi-arid regions (Boers and Ben-Asher, 1982). In its broadest sense, rainwater harvesting is defined as the process of concentrating, collecting and storing rainwater for different uses at a later time in the same area where the rain falls, or in another area during the same or later time (Hatibu and Mahoo, 2000). According to FAO (1991), rainwater harvesting in its broadest sense is defined as the collection of runoff for its productive use. Productive uses include provision of domestic and stock water, concentration of runoff for crops, fodder and tree production and less frequently water supply for fish and duck ponds.

Runoff may be harvested from roofs and ground surfaces as well as from intermittent or ephemeral watercourses. A wide variety of rainwater harvesting techniques for many different applications is currently used. Water harvesting techniques that harvest runoff from roofs or ground surfaces fall under the term rainwater harvesting, while all systems which collect discharges from watercourses are grouped under the term floodwater harvesting.

2.1.2 Major categories of rainwater harvesting

In crop production systems, RWH is composed of a runoff producing area normally called the catchment area (CA) and a runoff utilization area normally called cropped basin (CB). Therefore, RWH systems for crop production are divided into several categories basically determined by the distance between CA and CB. Ideally the catchment area should have a high runoff coefficient while the cultivated area should have a deep, fertile loamy type soil (FAO, 1991). The categories are briefly described below.

i) In-situ Rainwater harvesting

In-situ RWH is the capturing of rain where it falls. It is sometimes called water conservation and is basically a prevention of net runoff from a given cropped area by holding rainwater and prolonging the time for infiltration. It is basically all the conventional approaches to soil and water conservation, designed to enhance infiltration of rainwater into the soil (Hatibu and Mahoo, 2000).

In semi-arid areas, in order for crop fields to be productive, water needs to get to the roots of the crop. This can be achieved through in-situ RWH. In-situ RWH is achieved mainly through earth banks, deep tillage, contour farming and ridging, and other agronomic practices.

ii) Micro catchment rainwater harvesting

Another category of rainwater harvesting is micro-catchment system that involves a distinct division of CA and CB but is adjacent to each other (Gowing *et al.*, 1999). This system is used mainly for growing medium water demanding crops such as maize, sorghum, groundnuts and millet. The major techniques of RWH under micro-catchment rainwater harvesting system include pitting, strip catchment tillage, contour bunds, semi-circular bunds, and meskat-type system.

iii) Macro catchment rainwater harvesting

Macro-catchment RWH is a system that involves the collection of runoff rainwater from large areas, with an appreciatable distance between CA and CB. In this system, when the catchment is large and located at a significant distance from the cropped area, the runoff is conveyed through structures of diversion and distribution networks. The most important systems include hillside sheet or rill runoff utilization, ephemeral stream diversion, and RWH with storage. This includes intermediate components such as means for collecting, transferring and storing the runoff. According to Gowing *et al.* (1999), the system is difficult to differentiate from conventional irrigation systems, but it is referred as RWH as long as the water for harvesting is not available beyond the rainy season.

2.2 Extent of rainwater harvesting in Tanzania

There is a widespread practices of RWH in Tanzania, according to a study undertaken by Gowing *et al.* (1999) on the assessment of the extent to which different RWH systems are practiced in Tanzania. However, their potential is largely neglected by research and extension services and they are under exploited. For example, RWH with storage of water for livestock has received government support in the past, though many storage reservoirs have been rendered useless by siltation.

Several in-situ RWH techniques can be identified in Tanzania. These include deep tillage, contour farming, ridging, conservation tillage, and pitting and agronomical practices. Conventional ploughing is an in-situ RWH, in the sense that loosening the soil encourages infiltration. Experience in Tanzania has indicated that, tillage systems are well adapted to tractor and or draught animal cultivation. In the Lake Victoria Zone, like in Mwanza and Shinyanga regions for example, use of oxen and tractor plough in land preparation is a common practice.

Planting pits have been documented as an indigenous practice of RWH in different areas of Tanzania. A notable example is the '*Ngoro'* technique of the Matengo Highlands in Mbinga district. It has been reported by Willcocks *et al.* (1996) cited by Gowing *et al.* (1999) that, this system was documented during the colonial era and has recently received much attention.

Micro-catchment RWH techniques identified to be practiced in Tanzania includes pitting, strip catchment tillage, semi-circular bunds, maskat type (basin system), and contour bunds (barriers basin). According to Gowing *et al.* (1999), strip catchment tillage (also known as contour strip cropping) involves alternating strips of crops with strip grass or cover crops. The system is widely practiced in many semi-arid areas in Tanzania, although farmers and extension workers may not recognize it as RWH measure. Moreover, contour bunds are generally constructed manually with soil either being thrown upslope (*fanya juu*) or down slope (*fanya chini*). The fanya chini system is more common in steep slope areas in Arusha, Morogoro, and Tanga regions in Tanzania.

According to Gowing *et al.* (1999), basin system commonly known as the 'negarim or meskat' micro-catchment technique is the best known RWH system. Further, it was noted that, no observed experience of systematically design micro-catchment basin systems in semi-arid Tanzania. However, it is apparent that some farmers recognize natural distribution of runoff that occurs in the farming landscape and adjust their management to reflect differences in land capability.

In Tanzania, identified macro-catchment RWH techniques include hillsides sheet system, stream bed, ephemeral stream diversion, and storage system (Hatibu and Mahoo, 1999; Gowing *et al.*, 1999). Rainwater harvesting technique using ephemeral stream diversion is common in semi-arid areas in Tanzania, and can be witnessed in the Lake Victoria zone, WPLL, and Dodoma region. Ephemeral stream diversion is macro-catchment RWH system, in the sense that natural runoff is collected from a relatively large area and transferred over a long distance.

The hillsides sheet and runoff utilization, which exploit naturally generated runoff, is also widely used in semi-arid areas. In Tanzania, farms in these areas are called '*mashamba ya mbugani*' and are found throughout semi-arid areas, where crops grown includes maize, rice, sugar cane, vegetables and bananas. Fields under this water management practices are attractive not only for their improved moisture regime, but also because of higher fertility levels (Gowing *et al.* 1999; Hatibu and Mahoo, 1999, 2000).

Macro-catchment RWH systems often yield high volumes of runoff and it may be advantageous to store it in a reservoir or use it to recharge ground water. In semi-arid areas in Tanzania, simple reservoir systems are widely used for livestock watering, and are sometimes known as '*charco dams or haffirs*'. On the other hand, simple reservoir formed by micro dams (*ndiva*) are commonly used in the Pare Mountains for agricultural and domestic purposes and less frequently used for watering fishponds.

2.3 Effects of rainwater harvesting on soil and agricultural production

Water harvesting techniques tend to increase the amount of water stored within the soil and surface catchments, though this does not necessarily affect all soil properties (FAO, 1991). The effect of RWH on soil properties depends on how the tillage operation is done (Pearson *et al.*, 1995). Tillage systems have important influence on soil physical properties (FAO, 2000) and associated chemical and biological properties (Pearson *et al.*, 1995). The principal soil physical properties that are mostly affected by tillage are soil density, porosity, pore size, pore size distribution, soil texture, and infiltration rate (FAO, 2000). Soil fertility and soil temperature are also affected by tillage systems (Hulugalle, 1990).

The effect of in-situ RWH on soil and agricultural production has been portrayed in '*ngoro*' pit system. Experiments have shown that, the *ngoro* technique a cultural practice used on hillsides in the southern Tanzania, produced higher maize yields in wet years than cultivation of maize on ridges or on flat (Ley, 1990). The system also is most effective for preventing erosions as overflow from one pit is trapped in the next. Other experimental results (Bwana, 2003) have indicated that, ridging before planting and tie ridging had lower moisture variations and high moisture contents throughout the season. Further more, the maize yields from ridged plots was 1000 kg ha^{-1} equivalent to 33 % more than for no primary tillage (*kuberega*).

Rainwater harvesting has enabled farmers to grow marketable crops in dry areas, providing opportunity for poverty reduction. According to Hatibu (2003) and Senkondo *et al.* (1999), research has shown that gross margins obtained by a farmer improved significantly by adopting this technology. Paddy rice is now a semi-arid tropic's (SAT) crop in Tanzania, as the results of improved management of rainwater. For this reason, farmers have changed from the cultivation of sorghum and millet, to rice.

2.4 Rainwater harvesting systems and soil fertility

Soil fertility is a major component of soil productivity. According to Stocking (1994), soil fertility refers to the capacity of the soil to support the growth of plants on a sustained basis under given conditions of climate and other relevant properties of land. Ponnamperuma (1975) defined soil fertility as the status of the soil with respect to the amount and availability of the plant nutrients necessary for optimal growth of a specified crop. The term soil fertility is projected here to encompass not only essential plant nutrients but also aspects of soil structure, including water holding capacity and biological activities that influence both efficiency of use and sustainability of the resource (Pieri and Steinar, 1997).

According to Arshad and Coen (1992), soil depth to a root restricting layer, available water holding capacity, bulk density or penetration resistance, hydraulic conductivity, aggregate stability, soil organic matter content, nutrient availability, pH, and electrical conductivity are soil quality indicators that are generally responsive to management practices. However, the quantification of soil quality requires specific soil indicators that can be spatially and temporally measured (Smith *et al.,* 1993). These indicators are mainly soil properties whose values relate directly to soil quality but may also include policy, economic, or environmental considerations.

According to FAO (1991), in dry areas, soil fertility is usually the second most limiting production factor after moisture stress. The physical, chemical and biological properties of the soil affect the yield response of plant to extra moisture that is added. The important aspects of soils that affect plant performance under RWH systems are the texture of the soil. Generally, it is the medium textured soils, the loams, which are suited for RWH for agricultural purpose. Other aspects include soil structure and the depth of soil, which is particularly important where RWH is proposed for supplementary irrigation. Well maintained fertility levels and high infiltration rates are also important soil properties.

According to Pierce *et al.* (1983), soil productivity is the capacity of the soil to produce specified plant or sequence of plants under a physically defined set of management practices. Soils high in organic matter and nutrients, of medium texture, of good tilth, and 1.5 m or deeper are recognized as of high soil productivity. In order to attain high productivity, it is advisable to increase soil organic content in the cropping area under rainwater harvesting. Therefore, it is important to note that, for maximum soil productivity under RWH, soil moisture improvement must match with availability of plant nutrients so as to continue cultivating the land in a sustainable way. Research has shown that where RWH techniques are practiced and combined with soil fertility management, the yield proved to increase positively. In Tanzania for example, crop yields of maize were twice as much when conservation farming practices to increase rainwater infiltration into the soil were combined with soil fertility management (Hatibu *et al.*, 1993).

In Zimbabwe for example, since 1995, farmers in Chivi village started using infiltration pits to harvest and temporarily store water that is intercepted by the contour ridge. Similarly, most of the farmers in Guti village in Zimbabwe have fields on sandy soils under rainwater harvesting. These farmers have recently developed a new technique using infiltration pits for composting, which makes it possible to combine water harvesting and soil fertility management.

2.5 Spatial and temporal variability of soil fertility in rainwater harvesting areas

According to Hillhorst *et al.* (2000), a less conspicuous but equally vital issue is the variability of good quality soil, which provide the nutrients, water and foothold for plants in both natural and managed ecosystems. Nutrients are transported all over the world through trade in agricultural products and fertilisers but also, mainly more locally, by forces such as erosion, deposition, volatilisation and leaching. Although still in balance at global level, nutrients flow have become unbalanced at lower spatial scale.

Hillhorst *et al.* (2000) in the study of managing soil fertility in Africa, found that, the situation is different in most parts of Africa where the main problem is inadequate return of nutrients to compensate for losses when crops are harvested and residues taken elsewhere, or due to leaching and erosion. If insufficient inputs are applied to compensate for these soil losses, soil fertility will decline. The information now available on soil degradation in Africa indicates the gravity of the overall situation, as shown by Stoorvogel and Smaling (1990) in their study of the soil nutrients depletion in sub Saharan Africa, which estimate average annual losses of nitrogen at 22 kg, phosphorus at 2.5 kg and potassium at 15 kg for each hectare of arable land.

Soil fertility variability has been well documented at national, regional and global levels (Chuma *et al.*, 2000). However, there has been little research on the importance of variability at farm and field level and how it affects productivity in small farming systems. Variations in crop growth caused by diverse soil properties within the farm are generally more pronounced in low input farming systems where production conditions are less favourable (Carter and Murwira, 1995).

Variability of soil fertility and moisture in the soil could also be a function of catena sequence, and this can influence farmers' management practice. Cater (1993) cited by Chuma *et al.* (2000), having illustrated the diversity of land use patterns along a catenary's sequence, found that, farmers' management practices were strongly influenced by variation in topography and soil type. Hatibu and Mahoo (1999), having displayed the link and potential of catena on RWH in semi-arid areas in Tanzania, observed that, an informal land use along the catena exists in many villages, for exploiting runoff.

2.6 Causes of spatial and temporal variability of soil fertility

Soil fertility management practices employed by farmers are determined by a wide variety of factors that are largely spatial dependent. According to Scoones and Toulmin (1999) cited by Hilhorst *et al.* (2000) three broad categories of factors influencing soil fertility management practices can be distinguished as biophysical, socio-economic and institutional. Biophysical parameters include climate, soil types, crops and livestock. Socio-economic and institutional factors influencing soil fertility management include population density, broader livelihood strategies, macro-economic policies, marketing support services and credit systems, land tenure, and research and extension policies.

Soil properties variability is related to spatial and temporal variability of climate. In the study of the effect of topography and climate on soils of the northwestern slopes of Mount Kenya, it was found that, the two most important components of climate that control soil properties are moisture and temperature. Moisture is important because it is involved in most of the physical, chemical and biochemical processes, including leaching. On the other hand, temperature influences the rate of chemical and biochemical processes in soils (Mbuvi *et al.*, 1997).

Population is one of the socio-economic and institutional factors that influence soil fertility management practices, due to over exploitation of land resources, as a result, causing fertility variability in spatial and temporal aspect. According to Lompo *et al.* (2000), population growth from the 1960s onwards in Burkina Faso has had a major impact on the production and land management system in Kirsi. In the past, vegetation was abundant and this helped to maintain high fertility as leaves fell and decomposed in the soil. As pressure on productive land grew, farmers abandoned the practice of leaving fields for fallow as they could only survive by cultivating continuously even if this exhausted the soil.

Another socio-economic and institutional factor that influence variability of fertility management practices is national policies. Lompo *et al.* (2000), in the study of rehabilitating soil fertility in Burkina Faso, observed that, in the past, farmers used imported fertilizers to improve soil fertility, but following national currency devaluation in 1994 and structural adjustment policies, prices have gone up so much beyond the purchasing power of most farmers, who are now using a variety of organic soil amendments to improve soil productivity. However, the number of livestock hold is low for most households, though better management may increase the levels of manure production.

In Zimbabwe, farmers use relatively large amounts of mineral fertilizers, household waste and cattle manure in crop production. These are used however in various quantities and a range of ways, depending on their socio-economic status and spatial and temporal diversity of the farming environment (Campbell *et al.*, 1995), cited by Chuma *et al.* (2000). Farmers' soil fertility management practices are also closely related to wealth status (Campbell *et al.*, 1997) cited by Chuma *et al.* (2000). Wealth farmers generally possess more farming implements, apply more cattle manure, and compost and recycle more stover. By contrast, poor households rely more on household waste and leaf litter. All these create an obvious variability normally in low input farming environments, where economic status anomalies can't be avoided. In Southern Zimbabwe, farmers had experience of adding nutrients through the application of kraal manure, leaf litter, termitaria, compost, household waste and inorganic fertilizers. They also had ideas on the timing of application in view of temporal and spatial variability (Chuma *et al.*, 2000).

According to Mallarino (1998), spatial variability of P and K and other nutrients in soils differ markedly among fields. The causes for variability on a large scale are different from the causes of variability on small scale. Soil types, landscape characteristics, previous crops, or proximity to feeding lots usually create variation over a scale of several hectares. Management practices such as tillage, fertilization, and manuring create large nutrients variability on a scale of a few meters. In a similar way, variability can be caused by rainwater management practice like RWH. In RWH practices, for example, soil fertility can be improved through adding runoff water, which normally carries organic matter and sediments containing plant nutrients into the cropped fields (Sauer *et al.*, 1999; Hatibu and Mahoo, 2000).

Runoff water from the grazing land can contribute to soil fertility if the water is harvested for crop production. Sauer *et al.* (1999) compared the quality of runoff water from soil treated with two types of animal wastes. In this study, poultry litter and cattle manure and urine were applied to grass plots where artificial rainmaker was used to supply water equivalent to a rainstorm of 0.02 mms^{-1}. Runoff water from plots receiving poultry litter had significantly higher concentration of most nutrients than runoff received from the other plots. This indicates that, the surface runoff water from grazed animal manure could have a great impact on the water quality.

In a nutrient balance study reported by Smaling and Fresco (1993) for the well-inventoried Kisii district in Kenya, the net fertility losses in each growing period was caused by removal of the above ground crop parts, leaching, denitrification and water erosion. Removal of nutrients by means of harvested product was the strongest negative contributor to the balance, followed by water erosion, and for N, leaching also strongly contributed negatively. Soil erosion has also great influence on the decline of soil fertility on both spatial and temporal scales. Barrows and Kilmer (1963) found soil erosion to carry away as much as 70% of applied phosphorus fertilizer in the crop field. In a study of analysis of water quality, Ankumah (1999) observed that, soil sediments carried 80% of P and 73% of N load in water from eroded soil. A similar situation exists in the areas where RWH is practiced.

Soil nutrient level variation overtime, may be a consequence of a major leaching event (Smaling *et al.*, 1993), change in the rate of mineralization of organic matters or simply a consequence of the effect of changes in soil moisture conditions on the amount of extractable nutrients. In a review study reported by Lamers *et al.* (2002), it was observed that, within-field fallow, kraaling, spot application of manure, use of crop residues and household waste and intentional relocation of settlements, contributed to temporal variation in soil fertility.

In the semi-arid areas, variability of soil fertility can be caused by salinity problems. According to Metternicht and Zinck (1996), salinization – alkalinization is a time and space dynamic soil degradation process in semi-arid regions. Parent material, topographic position and dry climate (which favours salt concentration in the top soils) are the main factors controlling the current spatial distribution of salt – and sodium-affected areas. In semi-arid areas where rainwater harvesting is applied as supplementary irrigation, salinity of supplementary irrigation water affects soil electrical conductivity (EC) (Patel *et al.*, 2000).

Hartsock *et al.* (2000) noted that, electrical conductivity varied in both space and time, but the spatial patterns in conductivity were temporally stable. The comparison of EC and soil fertility elements was also done and it was also found that, EC relates to factors that affect soil productivity, use, and management and therefore, EC may be useful in the preparation of agricultural management plans.

2.7 Application of GIS and geostatistical analysis in soil fertility mapping

2.7.1 Application of GIS in soil fertility mapping

Geographical Information Systems (GIS) is an organized collection of computer hardware, software, and geographical data designed for capturing, storing, updating, manipulating, analysing, and displaying all forms of geographically referenced information (Aronoff, 1989). The key capabilities of GIS are handling and analysing data that are referenced to a geographic location. The potential of the system is most apparent when the quantity of the data involved is too large to be handled manually.

The term GIS can be used interchangeably with spatial information systems. According to Laurin and Thompson (1992), spatial information systems are defined as contemporary computer based tools for working with data for phenomena on, above or below the earth's surface. Spatial is a term used here to refer located data for objects positioned in any space, not just geographical, as a term used for other world space. An information system is used here as a collection of data and tools for working with the data.

Nearly all the information on RWH systems planning has some geographical or spatial reality. The data that is available for planning is of different types (spatial and non-spatial) and from different sources. Using GIS, sharing of information is made easier and efficient, and it can help planners to think globally while planning locally. Thus the role of GIS in RWH systems and soil fertility mapping is recognized starting from data capturing, management, manipulation, data analysis and data display. In studies involving analysis of objects and phenomena where geographic location is an important characteristic or critical to the analysis, like RWH systems and soil fertility mapping, GIS has been increasingly used, and it has proved to be a powerful tool (Mallarino, 1998; Uboldi and Chuvieco, 1997).

According to Mallarino (1998), a study on the improvement of soil fertility management in Colombia was done using grid sampling, differential global positioning systems (DGPS) and yield monitors. In this study, data management with GIS computer software allowed a more detailed evaluation of treatment differences for different parts of fields and for estimating interactions between response to fertilization and other growth factors.

Uboldi and Chuvieco (1997) used digital image processing and GIS techniques in the assessment of current agricultural management in a semi-arid area located in a valley in Argentina. The study focused on the identification of those sectors affected by over or under utilization and, consequently, to improve current land management. Several soil parameters were included in the GIS in order to obtain a land suitability map on the basis of certain physical characteristics. The value of spatial analysis in land use management was greatly enhanced by the use of GIS.

Metternicht and Zinck (1996) used remote sensing and GIS to map salt and sodium affected areas in the semi-arid valleys of Cochabamba in Bolivia, by combining digital image classification with field observation of soil degradation features and laboratory testing results. Salinity – alkalinity classes were established using electrical conductivity and pH values. The overall accuracy was slightly low (64%), but accuracies of 100 percent were obtained for some classes.

Furthermore, Martinez and Zinck (1994) used GIS in the modelling spatial variations of soil compaction in the Guaviare colonization area in Colombian Amazonia. They highlighted the effects of tropical rainforest clearing and poor pasture management with particular emphasis on fertility depletion and surface layer compaction. They found out that, there was deterioration of both physical and chemical soil properties.

2.7.2 Application of geostatistical analysis in soil fertility mapping

According to Johnson *et al.* (2001), geostatistics are statistical methodologies that use spatial coordinates to help formulate models used in estimation and prediction. Geostatistical analyst refers to exploratory and interpolation methods that use information on the spatial coordinates of the data for surface fitting. For sometime, geostatistical tools have been available, but never integrated tightly with GIS modelling environments. Integration is important because, GIS analyst could be able to quantify the quality of their surface models by measuring the statistical error of predicted surfaces. Map quality is defined as the sum of a maps precision and accuracy and is quantified as the mean square error of the residuals (predicted minus measured) obtained with a validation data (Mueller *et al.*, 2000). The quality of soil fertility maps is fundamental to site-specific fertility management (SSFM). This is because most SSFM recommendations are based primarily on whole field traditional fertility recommendations. Factors that affect map qualities include the nature of soil variability, intensity of sampling and method of interpolation.

Mueller *et al.* (2000) in the study of soil fertility map quality studied the impact of spatial structure, grid sampling intensity and interpolation techniques on the accuracy of soil fertility maps in several fields in Kentucky. The fields were sampled on a 30m grid and the samples were analysed for pH, P and K. The data were interpolated with geostatistics analysis tools (Kriging and inverse distance squared). The root mean square errors (rmse) were calculated using an independent check data set. The results showed that, although the data were spatially structured, most predictions were poor at the 30m-grid scale.

According to Mueller *et al.* (2000), among many factors influencing economic crop responses include soil fertility levels. Field scale variation in soil fertility can be a major source of uneven crop growth on soils of arid and humid tropics (Dobermann *et al.*, 1995). Field scale variation directly affects farmers' performance but also remains a major problem for the design and analysis of field experiments. Soil heterogeneity is usually not considered in defining indices of soil fertility or land quality, but uneven crop growth may be quite pronounced (Herrmann *et al.*, 1994).

Dobermann *et al.* (1995) in their study on source of soil variation in an acid Ultisol in the Philippines used the special tool of geostatistical analysis and the factorial Kriging (FKA) to analyse processes causing spatial variation in soil chemical properties (pH, P, K, Na, Ca, Mg, and Al). Soil samples were measured at two depths within a single field. The factorial Kriging was applied to the data to identify, interpret and map the processes causing spatial variability of soil fertility characteristics. The results showed that, those multivariate geostatistical techniques such as FKA were suitable for distinguishing the different processes causing spatial variation at different scale. The intensive vertical and lateral soil water flow determined the spatial variation of most soil chemical properties studied. Some superimposed processes acting at different spatial scale over different time are inherent factor of soil genesis, whereas specific types of land use affect others.

According to Smith *et al.* (1993) in the study of evaluation of soil quality, multiple variable indicator kriging (MVLT), a geostatistical technique was reported as the method that could be applied on a small scale basis (e.g. an individual field or farm) or on larger scale (e.g. growing region) depending on the number and locations of soil samples.

According to Kuzyakova *et al.* (2001), application of geostatistics was used in the processing of soil and agrochemical studies. In this study, enhancement of experimental data processing was highly portrayed. Application of Kriging, particularly, the advantage of the analysis of smoothed maps, was demonstrated and the role of geostatistical techniques in the design of field experiments was shown. In this study, analysis of variograms leads to important conclusion on the reasons behind the variation in soil parameters and their correlation.

The above cited studies demonstrate the feasibility of geostatistics, GIS, GPS mapping and laboratory soil testing for studying and evaluating soil fertility status and variability under rainwater harvesting systems.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study area

3.1.1 Location

The study area is located between latitudes 4^0 8′ and 4^0 25′ South, and longitudes 37^0 45′ and 37^0 54′ East. The location of the study area is shown in the map in Figure 3.1. The study area lies along the Moshi – Dar-es-salaam highway, about 140 km from Moshi town, Tanzania. It stretches from the main road up to the South Pare Mountains, and on the other side of the road, it extends some few kilometers towards the Makanya lowlands. The area is located on the western slopes of South Pare Mountains on the leeward side, at an elevation between 600 m and 2500 m above mean sea level (amsl).

Three case study villages were selected based on the intensiveness of RWH practiced, and their location along the toposequence in the catchment, which could assist in the assessment of the effect of runoff on nutrient movement. The study was carried out in three villages namely, Makanya, Mwembe and Tae, representing three toposequence classes, that is the upper (top hill), mid and lowlands. Tae village is located in the top hill and upper slopes of the mountain. Mwembe is found in mid slopes of the mountain, and Makanya is located in the lowlands.

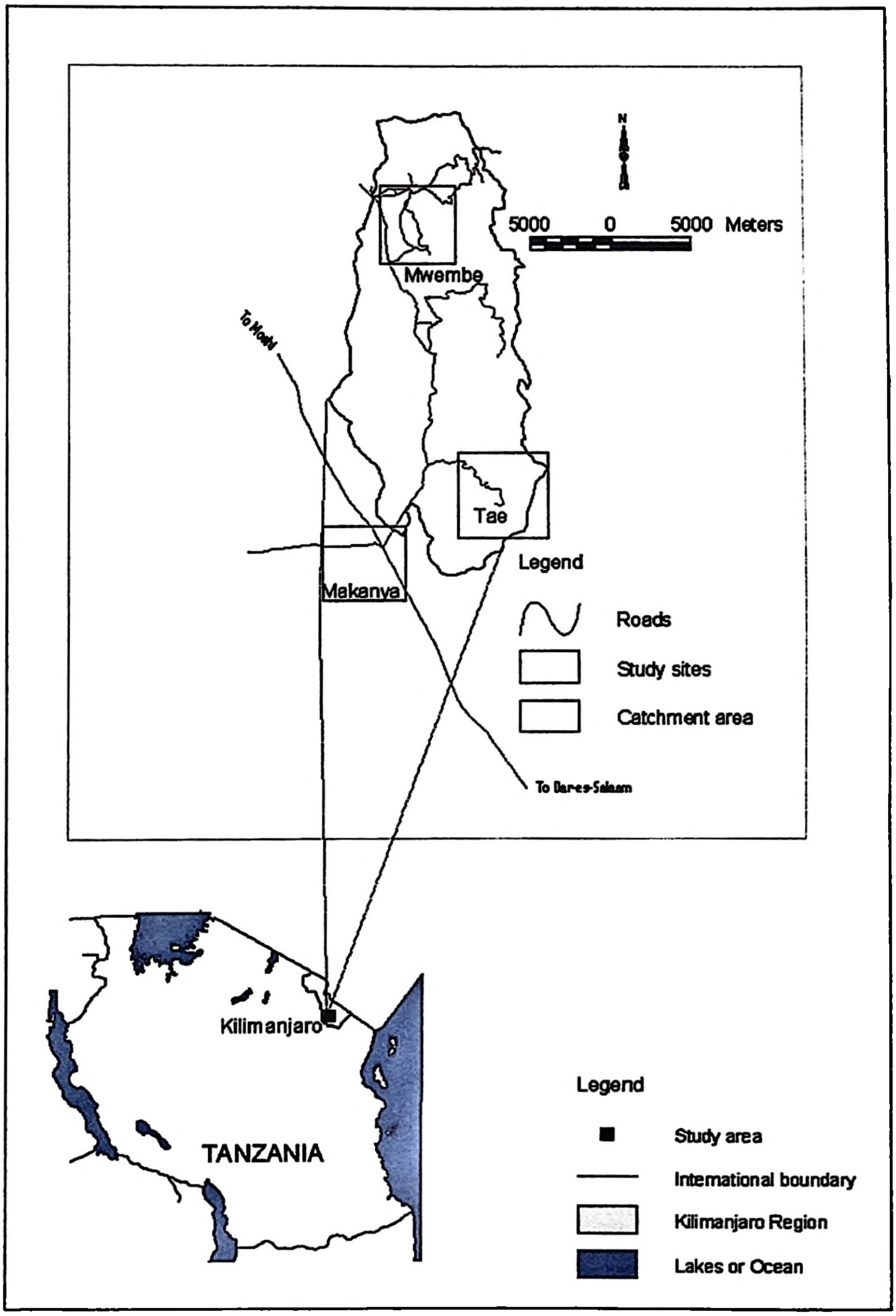


Figure 3.1. Geographical location of the study area

3.1.2 Rainfall and temperature

The rainfall pattern in the study area is bimodal, with mean annual rainfall of approximately 400 – 600 mm. The short rains (*Vuli*) start in November and extend to January. The long rains (*Masika*) start in March and extend to May. The *Vuli* rains are lower and less reliable than the *Masika* rains. The long-term rainfall distribution at Hassan Sisal Estate in Makanya (Figure 3.2), and Suji Mission in Tae (Figure 3.3) represent rainfall pattern in the lowlands and the mountain, respectively. The mountains profoundly affect the climate of the area. Agroclimatically, the study area is classified as sub-humid in the mountains with an annual mean rainfall > 600 mm to semiarid in the lowlands with an annual mean rainfall range between 400 and 600 mm.

Mean monthly temperature in the study area range from 16^0 C during the coldest months (July to August) to 32^0 C during the hottest month (January). The minimum temperature range from 13^0 C to 23^0 C during the coldest months, and the maximum temperature range from 20^0 C to 36^0 C during the hottest months.

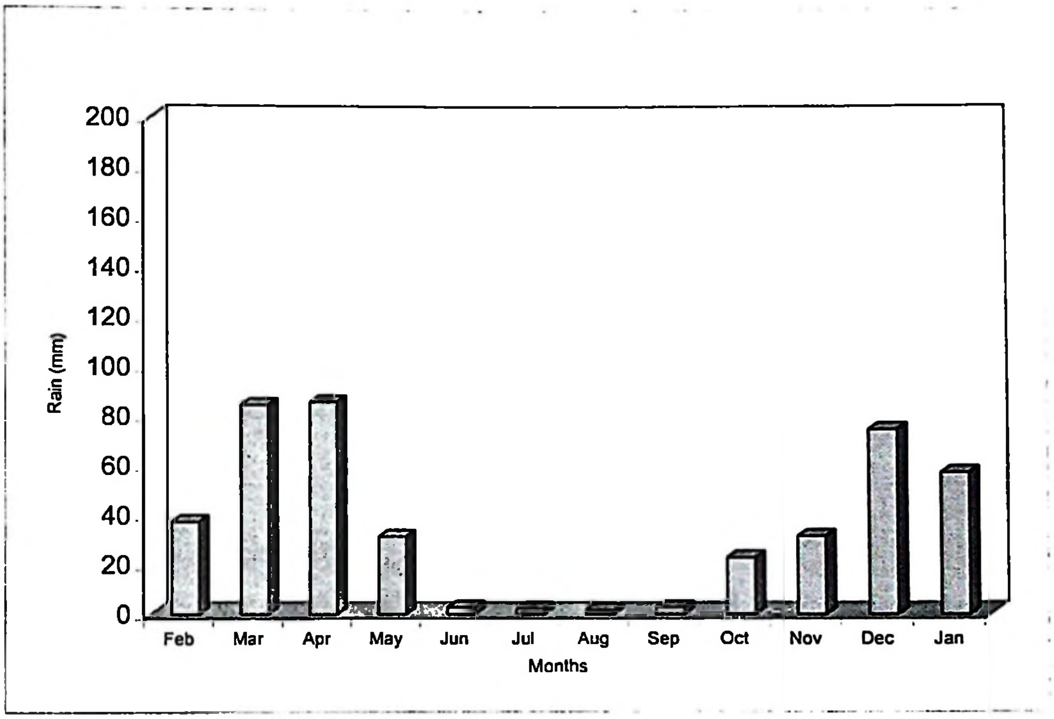


Figure 3.2. Mean monthly rainfall pattern at Hassan sisal estate from 1990 – 2002.

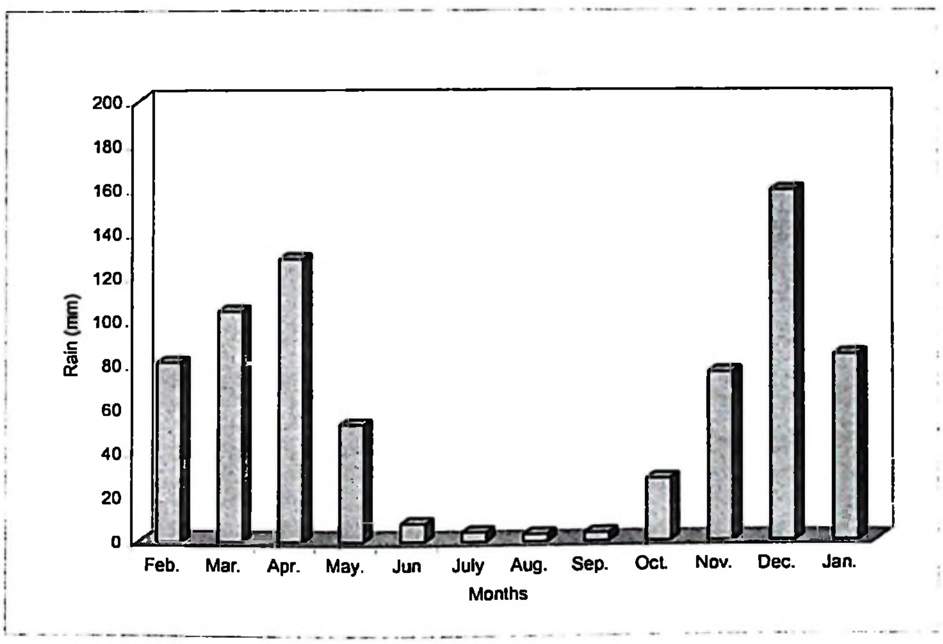


Figure 3.3. Mean monthly rainfall pattern at Suji Mission from 1990 – 2002.

3.1.3 Topography

The topography of the Makanya village is flat with gentle slope and the altitude ranges between 600 m and 700 m amsl. Mwembe village is located on the western gentle slopes of South Pare Mountains and the altitude ranges between 900 m to 1500 m amsl. The terrain of Tae village is hilly with steep slopes. The village is located on the upper slopes of the mountains. Its altitude ranges between 1200m to 2000 m amsl.

3.1.4 Vegetation and land use

Fairly uniform vegetation cover characterizes the Western Pare Lowlands. A significant portion of the area is presently scrubland, thicket, with some pockets of woodland and grassland. A few scattered shrubs and trees, mainly acacia species occur throughout in the Western Pare lowlands. The foot slopes of the Pare Mountains are dominated by shrub, and some pockets of wooded grassland but do have a relatively large area occupied by small trees and shrubs, which again are mostly acacia species. Thickets, scrub and some wooded grassland characterize the lowland. In the mountains, remnants of natural vegetation or forest can still be observed.

Land use is dominated by agricultural use and includes crop production and livestock. In Tae village, the dominant farming system is maize – legume – vegetables – livestock. Crop production system commonly used is agro-forestry, which involves coffee and banana, maize –beans, vegetables – cabbage, tomatoes, carrots, swiss chard, paprika, and taro. A few zero grazed animals are the dominant livestock rearing system. In Mwembe village, the dominant farming system is maize

– legume – vegetables. Beans, peas and lablab are mixed with maize as the main crop. In Makanya village, the dominant farming system is maize – livestock. The main crop cultivated are maize and lablab and to a small extent beans. Livestock kept include cattle, goats, sheep, donkeys and chicken. Free range grazing is the dominant livestock system.

3.1.5 Drainage pattern

In the study area, the whole western part of the catchment drains to Makanya through one point. Two drainage systems, one originating from Tae area (Mangoloma river) and another one from Mwembe, Chome and Vudee (Vudee river), join together at Kimunyu in Mgwasi village. Just below this location, sisal effluent is discharged to Makanya river. This stream crosses both the Dar-es-Salaam – Moshi road and the railway line. Soon after the Railway Bridge at Makanya, the runoff from the main stream leading to Pangani river is diverted to crop fields through numerous channels made by farmers. Similarly, diversion of runoff is done in the villages in the catchment area where drainage systems begin or pass through.

3.2 Determination of soil fertility status

3.2.1 Soil sampling

A participatory reconnaissance survey was done for the three villages Tae, Mwembe and Makanya for selecting crop fields. Based on the reconnaissance survey, survey crop fields were selected randomly from each village for soil sampling, representing crop fields from each indigenous land suitability classes. Indigenous land suitability class refers to land classes as perceived by farmers and ranked based on their suitability for crop production by using indicators such as plant, soil and water availability (Table 3.1a – 3.1c). Soil samples were collected from selected crop field for laboratory analysis in order to establish the current soil fertility status of the study area.

Composite soil samples each constituting of 10 sub samples at a depth of 0 – 30 cm within the crop fields were collected using a soil auger. Overall, eight composite soil samples were collected in Makanya village, 10 in Mwembe village and 13 in Tae village. These composite samples were collected from different RWH systems and the sampling distribution is shown in Appendix 7.

Table 3.1a. Local indicators and attributes of indigenous land suitability class I

Local indicators	Attributes
Water	• High availability of runoff (**Makanya**) • Water supply is reliable throughout the year (**Mwembe**)
Soils	• No need of fertilizer (very fertile soil) • Low frequency of watering • Soil colour is black • Sub soil is black, most, crack when is dry (**Mwembe**)
Plants	• Plant growth vigour: Mingurere (**Makanya**) • Presence of pants that survive even during the dry season (**Mwembe**) • Good crop growth • Presence of the following plants: Ziga, Ibarasa, Mirangare (Msosango), Makonje, Makongwe (Ikongwe or Likongwe)
Yields	• Normal maize yield ranges 2500 – 1000 kg ha^{-1} (**Makanya**)
Terrain status and location	• Good water movement (areas with gentle slope)

Key: **Makanya** means respective attribute is most applicable in Makanya village
Mwembe means respective attribute is most applicable in Mwembe village

Table 3.1b. Local indicators and attributes of indigenous land suitability class II

Local indicators	Attributes
Water	• Medium availability of runoff (Makanya)
Soil	• Soil become softer or powdery which is recognized during tillage • Sandy soils are less fertile • Presence of excessive sedimentation • Colour is black or dark for fertile soil • Colour is black (Mwembe) • Texture is sand clay loam (tifutifu)
Plants	• In good seasons the land productivity is very high • Fair vegetation density • Vegetation growth vigour (Mwembe) • Presence of the following plants: Sangari (coach grass), Lantana camara, Barasa (paniccum species), Zinga (Izinga), Ikongwe (Comelina), Vimbara (Bidens spp or black jack) (Mwembe)

Table 3.1c. Local indicators and attributes of indigenous land suitability class III

Local indicators	Attributes
Water	Poor availability of runoff (Makanya)
Soil	• High water holding capacity: If water get in once one will harvest • The soil is reddish • Compacted soil does not permit infiltration • Dark coloured or reddish heavy soils (cracking when dry)
Plants	• Presence of the following plants: Ndulele (tula), Ziga indicates high water holding capacity, plants are green even during dry season • Mabalanga indicates low fertility • Poor crop performance • Dominancy of cyperous rotundus
Terrain status and location	Low lying areas

In Makanya, three crop fields, each representing land suitability class as ranked by farmers were selected for more intensive soil sampling. A plot of 45 × 135 m was chosen from land suitability class one, another plot of 60 × 90 m was selected from land class two, and the third plot of 75 × 75 m selected from land class three. This selection pattern was made in order to assess spatial variability of soil fertility within crop fields (field scale) in the lowland (runoff receiving) of the study area. Soil samples were collected from the fields in regular grid cells of 15 x 45 m width. At each grid cell, 5 soil sub samples, one collected at grid center point and four sub-samples collected randomly, were obtained using a soil auger to a depth of 0 – 30 cm and these samples were combined to form a composite sample.

3.2.2 Soil analysis

The composite soil samples were air dried, ground and sieved through a 2mm sieve. The sieved soil samples were used for the characterization of the physical and chemical properties of the soil. For the purpose of determining soil fertility status, the following chemical properties were determined: soil pH, organic carbon, extractable phosphorus, total nitrogen, and exchangeable bases of Ca, Mg, Na, and K. Physical properties analysed were soil particle size distribution, and electrical conductivity.

Soil pH was measured in 1:2.5soil:water suspensions as described by Thomas (1996). The available phosphorous was determined using the Bray-I procedure (Kuo, 1996). Total organic carbon was determined by the wet digestion method of Walkey and Black (Nelson and Sommers, 1996). The total N was determined by the semi micro-Kjeldhal procedure (Bremner, 1996). The exchangeable bases were extracted by the ammonium acetate buffered at pH 7.0 method as described by Sumner and Miller (1996). The electrical conductivity was determined by the procedure as described by Rhoades (1996). Particle soil distribution of the fine earth was determined by Bouyoucos hydrometer method (Gee and Bauder, 1986) and the resulting textural class by the USDA textural triangle (USDA, 1975).

3.3 Determination of nutrients in runoff rainwater

3.3.1 Runoff water sampling

Runoff water sampling was done every time when there was an episode of runoff in river Makanya. Water samples were taken at a point about 100 m to an outlet point (around Kimunyu in Mgwasi village) of Vudee Ephemeral River running from Mwembe, Vudee and Chome villages. Similarly, other water samples were collected at a point, about 100 m to an outlet point of Mangoloma Ephemeral River, flowing from Tae village; and at Makanya road bridge near to a distribution point of runoff in Makanya cropland. Water samples were collected during short rains, dry season and long rains in the catchment area.

To determine the amounts of nutrients received by individual crop fields, water sampling points were located along the small channels draining runoff rainwater into the fields. Both water sampling and volume quantification of runoff rainwater in the field was done simultaneously. This was done because both parameters complemented to the measuring of nutrient density received in the fields. Distribution points of water sampling are shown in the Figure 3.4.

More samples were collected from Tae village in the catchment area, near the Shengena forest reserve. Water samples from Tea village were collected, in order to determine plant nutrients in water in the top hill area. First set of samples was collected during short rains ("*vuli*"), the second collected during long rains season ("*masika*"), and the third sample was done during short dry season (*Kipupwe*).

Water samples were collected using clean 1500 ml capacity plastic bottles. Bottles were labeled, capped and sealed using a masking tape. The number of water samples and their distribution are shown in Table 3.2.

Table 3.2. Water samples collected during fieldwork.

Water sample location	Number of samples	Rain season when samples was collected
Makanya main stream	9	4 (*masika*) and 5 (*vuli*)
Minor stream (tributaries)	8	2 (*masika*) and 6 (*vuli*)
Channels in the crop fields	7	*Masika*
Tae village	4	1 (*masika*), 2 (*vuli*) and 1 during dry season
Natural forest in Mwembe village	1	*Vuli*

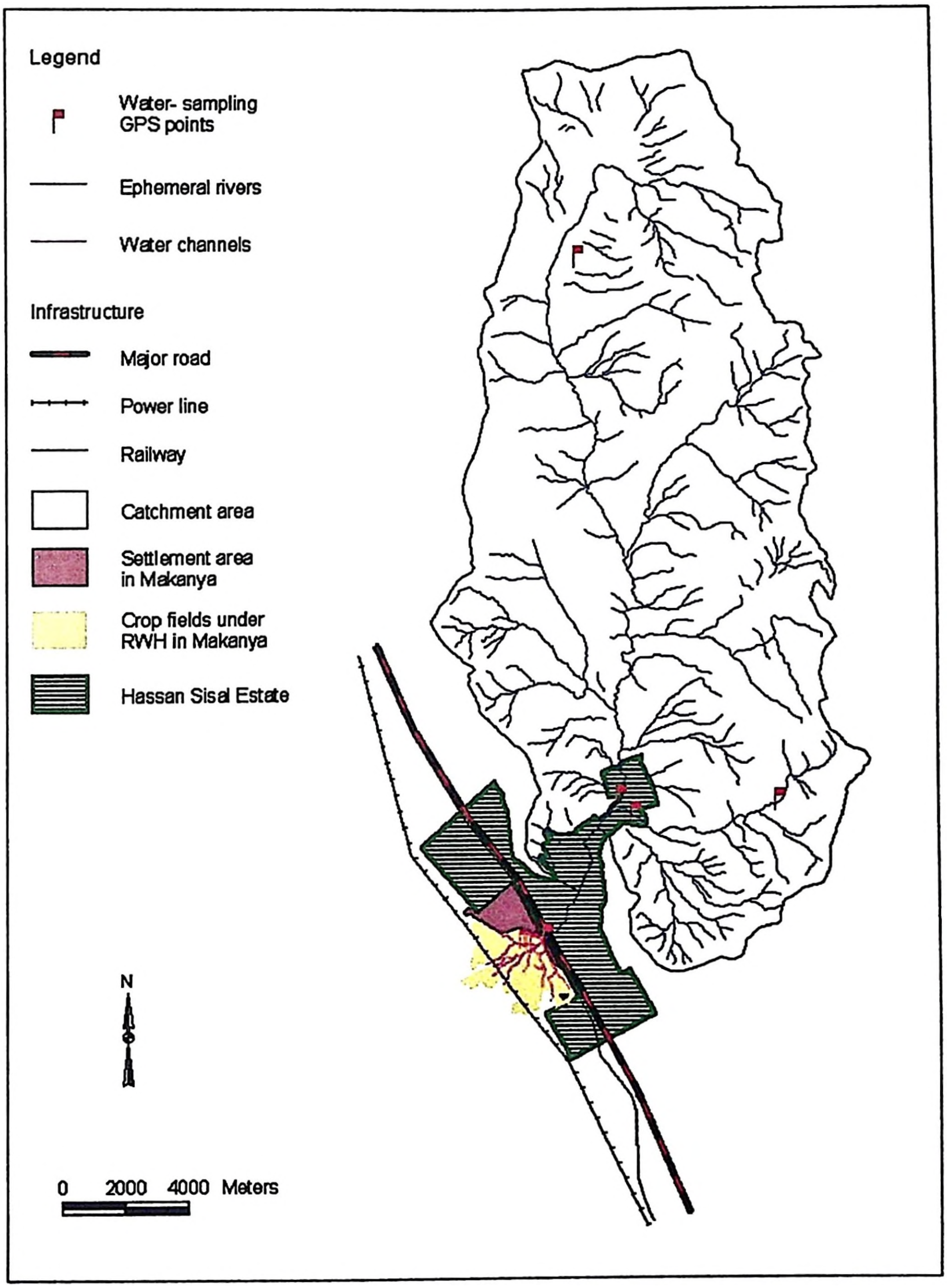


Figure 3.4. Map of Makanya river catchment showing distribution of rainwater sampling points.

3.3.2 Determination of volume of runoff water received in the selected crop fields in the lower zone (Makanya village)

The flow of harvested runoff was measured using control sections method (James, 1988). The flow was determined by using a Parshall flume installed in the channel. The head-discharge equation (1) was used for free flowing Parshall flume. That is when the tailwater does not affect the head upstream of the throat.

$$Q = c_f (KH)^{n_f}$$

For $S < S_t$ --------------- (1)

Where Q = discharge (l/s);

C_f = coefficient;

H = head (m);

n_f = flow exponent;

K = unit constant (K = 3.28 for H in m.);

S_t = transition submergence.

Free-flow conditions exist when the tailwater depth is not high enough to affect flow. A flume is considered to be submerged when the tailwater depth is sufficient to affect the flow and the submergence ratio, S, (equation 2), exceeds the transition submergence S_t.

$$s = \frac{h_d}{h_u} \text{ -- (2)}$$

Where S = submerged ratio;

h_d = head downstream of throat (m);

h_u = head upstream of throat (m).

3.3.3 Runoff water analysis

The water samples were analysed for pH, electrical conductivity (EC) and the soluble bases of Ca, Mg, K and Na. The analysis was done using standard procedures as described under section 3.2.2.

3.4 Questionnaire survey and analysis

A questionnaire survey was conducted to collect information on how farmers address the variability of soil fertility in crop fields under RWH systems, to determine the soil fertility problems and available options for managing soil fertility, to understand farmers perceptions of changes in soil fertility, the type of crops grown, and fertility management practices, and finally to determine household characteristics such as age, education, family size, landholding, and livestock keeping.
The information was obtained through interviews based on questionnaires (Appendix 1). The respondents were randomly stratified selected from the village records of head of household farmers. The strata were the men and women heads of household farmers. Ten percent (10%) of heads of household farmers were sampled and interviewed from each selected village. A total of 144 respondents from Tae (43), Mwembe (47) and Makanya (54) were interviewed.

Similarly, a second and small questionnaire (Appendix 2) was developed during the execution of the first questionnaire survey to capture the detailed information on the use and management of animal manure that appeared to be missing. This aimed at assessing the input of fairly available animal manure in the improvement of soil fertility. Extra 30 questionnaires were administered in Makanya village based on the potential of livestock farming in the village compared to other two villages. All questionnaire responses were organized into manageable groups and analysed using the statistical package for social sciences (SPSS).

3.5 Mapping of soil fertility spatial patterns in the study area

Soil fertility mapping in the study area was done based on the results of nutrient status, which included total N, exchangeable bases of K and Na, EC, and soil pH. Surface analysis for spatial soil fertility patterns was done based on integrating soil properties and GPS sampling points using Arc View GIS (ESRI, 1996), Spatial Analyst (ESRI, 1996), and Geostatistical Analyst Software (ESRI, 2001). Map surface interpolation was executed using Universal Kriging. The generated cell values were then classified in ranges and colours to indicating the value range classes for each property. Three areas along toposequence were mapped for the spatial pattern distribution for these nutrients.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Some of the properties of the soils on the Makanya river catchment

Some of the properties of the soils in the lower, mid, and upper toposequence zones on the Makanya river catchment were as given in Figures 4.1 - 4.7 and Appendix 9. The data illustrates patterns and quantities of the nutrients and other soil properties, which influence soil fertility within the toposequence zones on the catchment, in the study area.

Table 4.1. Soil particle size distributions along the toposequence on the catchment

Village name	Toposequence zone	Sand (%)			Clay (%)			Silt (%)		
		Range		Mean	Range		Mean	Range		Mean
		From	To		From	To		From	To	
Makanya	Lower	52.5	78.6	63.6	19.4	34.4	24.8	6.0	28.2	12.5
Mwembe	Mid	45.4	80.6	66.2	12.0	40.5	26.0	2.7	14.1	7.8
Tae	Upper	52.5	75.9	67.0	13.8	36.1	23.2	6.1	16.5	9.8

Soil particle size distributions along the toposequence on the catchment are presented in Table 4.1 and Appendix 9. Soil particle size distribution patterns along the toposequence (Figure 4.1) show that, sand sized particles were dominant, followed by clay and silt, respectively. The silt percentage differences in the catchment zones is not significant, however, the relatively high percentage of silt fraction in the lower zone on the catchment could be associated with deposited sediments by runoff rainwater through RWH practices as a consequence of removal of topsoil by runoff rain water in upper catchment area. The soil textural classes in the area ranged from loamy, sandy loam to sandy clay loam. The dominant soil textural class in the area was sandy clay loam. This soil textural class would favour RWH practices, because of the high water holding capacity particularly if the 2 : 1 clay minerals are dominant in the clay fractions of the soils (FAO, 1991).

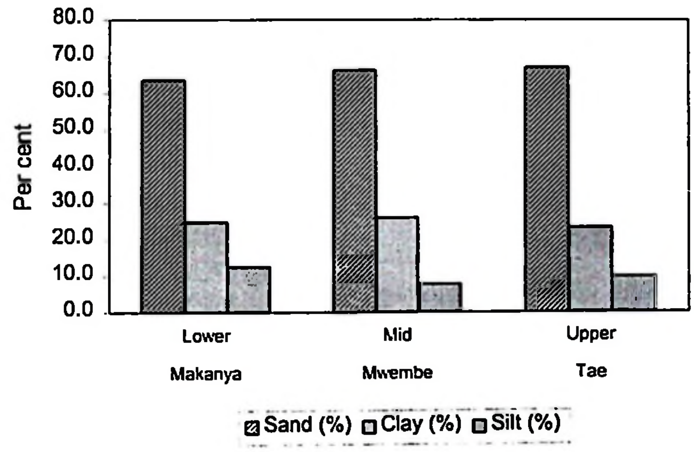


Figure 4.1. Soil particle size distributions pattern on the Makanya river catchment

The soil pH (H_2O) along the toposequence on the catchment is presented in Figure 4.2 and Appendix 9. The results show that, the pH of the soils on the catchment ranged from 7.67 to 8.35 with a mean of 8.06, 6.90 to 8.25 with a mean of 7.40, and 5.22 to 7.75, with a mean of 6.67 in the lower, mid and upper zones, respectively (Appendix 9). According to Landon (1991), these pH values are categorized as mildly alkaline to moderately alkaline, neutral to moderately alkaline, and strongly acid to mildly alkaline in the lower, mid and upper zones, respectively. The results show that, there was an incline trend of pH reaction from upper, mid to lower zone (Figure 4.2). The high soil pH values in the lower and mid zones may be due to limited rainfall to cause leaching, and magnified by the deposited soluble salts carried by the rainwater runoff. Further, this may be an indication of the presence of soluble salts in the area, probably due to basic nature of the parent materials of the soils. Soils with these pH values are considered to be suitable for irrigation as the values for satisfactory irrigated cropping are in the range of 5.1 to 8.5 (Maletic and Hutching, 1996).

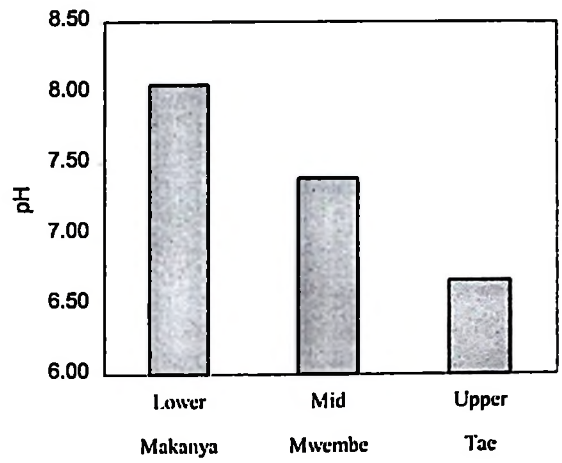


Figure 4.2. Soil pH pattern on the Makanya river catchment

The electrical conductivity values along the toposequence on the catchment is presented in Figure 4.3 and Appendix 9. The results show that, the electrical conductivity of the soils on the catchment ranged from 0.11 to 0.40 mS/cm, with a mean value of 0.23 mS/cm, 0.05 to 0.68 mS/cm, with a mean value of 0.20 mS/cm, and 0.05 to 0.33 mS/cm, with a mean value of 0.12 mS/cm in the lower, mid and upper zones, respectively (Appendix 9). The EC patterns distribution shows that, the EC values decreased as altitude increases along the toposequence (Figure 4.3). Soils with EC values ranging from 0.05 to 0.68 are considered to be non-saline (Landon, 1991), or salt free (EUROCONSULT, 1989). Nyambilila (2003) observed that the soils in Kisiwani, Gonja, Ndungu, and Kihurio in Same district were salt free. The EC patterns are well related to the soil pH pattern along the toposequence. The EC and pH values in the area decrease as altitude increase. The high value of EC in Makanya village is related to the depositional effect of nutrients particularly the basic cations from the upper slopes. Further, the scant rainfall in the area do not create effective environment to wash out the deposited nutrients, as a result, during the dry season these nutrients are brought up to the surface through the process of evaporation.

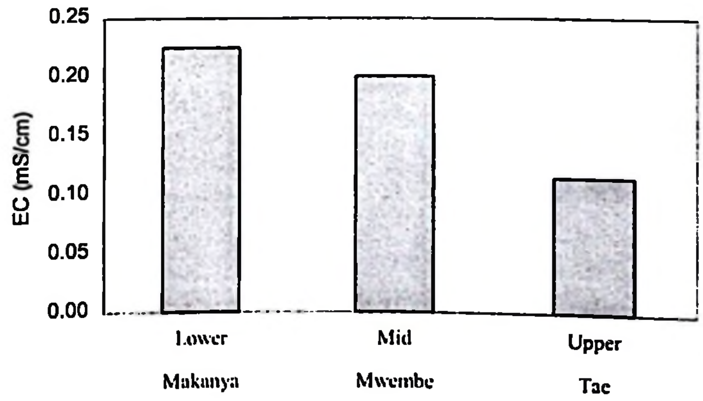


Figure 4.3. Electrical conductivity pattern on the Makanya river catchment

The percentage organic carbon content along the toposequence on the catchment is presented in Figure 4.4 and Appendix 9. Results indicate that on the catchment, the percentage organic carbon of the soils ranged from 0.62 to 2.13%, with a mean of 1.21%, 0.55 to 2.42% with a mean of 1.51%, and 0.72 to 3.72% with a mean of 1.95% in the lower, mid and upper zone, respectively (Appendix 9). According to Landon (1991) the percentage organic carbon values are categorized as low to medium, very low to medium, and low to high, respectively. The results pointed out that, pattern distribution of organic carbon tend to be high in the upper zone and relatively low in the mid and lower zones (Figure 4.4). The percentage organic carbon contents in the soils are similar to those from other studies done on the same watershed area. According to Nyambilila (2003), the percentage OC contents of soils from Kisiwani, Ndungu and Kihurio in Same district ranged from very low to very high. It was concluded that, many soils from these areas seem to be low in organic carbon. This problem is common in many soils in the semi-arid areas and this may be the consequence of limited vegetation, as a result of low and unreliable rainfall (Figures 2.2 and 2.3, and Appendix 5). The scanty vegetation affects very much the agronomical and fertility management practices due to non-return of crop residues to the soil. The problem is magnified further by the farmers' practices of burning vegetation in the fields and using some of the crop residues and remains as animal feeds, and hence loss (non recycling) of nutrients in the fields. The implication of low OC hence soil organic matter is low water retention capacity, poor soil structure, low nutrients retention capacity and low micro-organisms activities. The water retention capacity of the soil is a very important soil property in RWH systems. This is due to low and unreliable rainfall as a result, soil need to retain enough water in order to overcome the dry spell during the active growing stages of the plants.

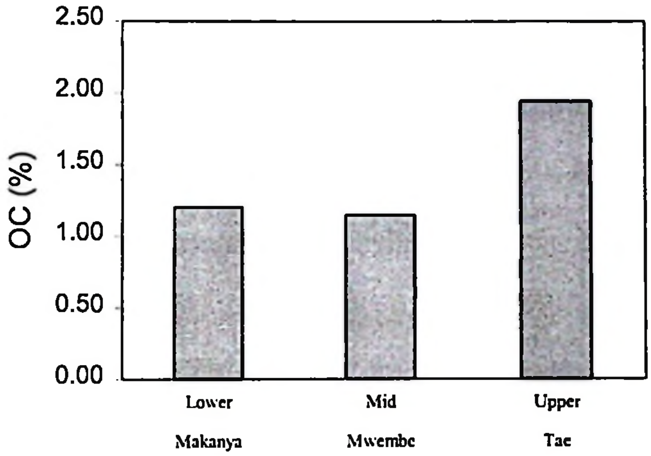


Figure 4.4. Organic carbon pattern on the Makanya river catchment

The total nitrogen contents along the toposequence on the catchment are presented in Figure 4.5 and Appendix 9. The results indicate that, the percentage total nitrogen contents in soils on the catchment ranged from 0.13 to 0.47 % with a mean of 0.25 %, 0.08 to 0.35 %, with a mean of 0.22 %, and 0.08 to 0.55 %, with a mean of 0.33 % % in the lower, mid and upper zone, respectively (Appendix 9). According to Landon (1991), the soils from these zones had low to medium, very low to medium, and very low to high percentage total N in the lower, mid and upper zone, respectively. Fertility patterns along the toposequence showed that, the percentage total N (Figure 4.5) was relatively high on the upper zone, followed by the lower zone and the least content was on the mid zone. Nyambilila (2003) reported similar levels of total nitrogen content in Same district. The total N contents correlate very well with OC contents in the study area. This indicates that the main source of N in the soils in this area would be organic matter. Nitrogen is the most limiting plant nutrient in most cultivated soil, where the mean total nitrogen is almost 0.15 %, and ranges between 0.02 to 0.5 % (Landon, 1991).

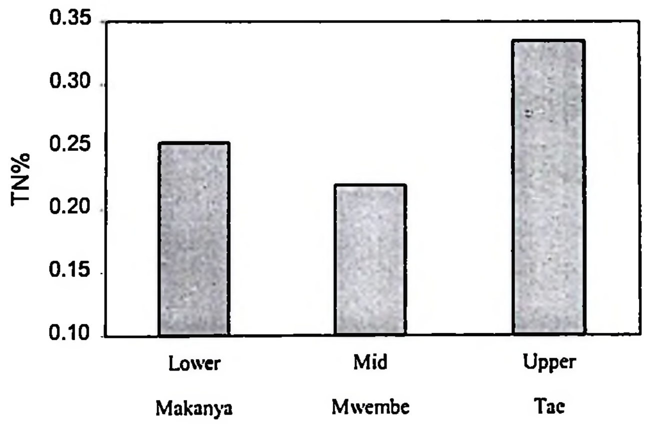


Figure 4.5. Total nitrogen pattern on the Makanya river catchment

The extractable (available) phosphorus content (Figure 4.6 and Appendix 9) in the lower, mid and upper zones of the catchment ranged from 39.49 to 81.16 mg/kg, with a mean of 56.48 mg/kg, 6.75 to 79.25 mg/kg, with a mean of 39.51 mg/kg soil, and 0 to 67.36 mg/kg, with a mean of 14.17 mg/kg soil, respectively (Appendix 9). The pattern along the toposequence (Figure 4.6) shows that, extractable P content distribution was high in the lower zone and decreased towards the upper zone in the mountains. Comparing these levels to the standard rating of P (Bray I) for agricultural crops (Landon, 1991), the soils in the lower zone had high P contents, while in the mid and top hill zones had low to high P contents. Nyambilila (2003) observed medium P in soils in parts of Same district. This may suggest that, the parent materials in the area are rich in phosphorus. High P values observed in the lower zone (Makanya village) could probably be the effect of natural erosion, as Tae and Mwembe villages are located on the mountain slopes which are the removal areas, while Makanya village is the depositional area. The high amounts of P content cannot be accounted for by the application of P fertilisers because from the questionnaire survey, farmers in the study area don't use P fertilisers. On the other hand, the percentage organic carbon contents in the soils range from medium to high levels, hence available P are not associated with the soil organic matter based on the very low percentage P contents in organic matter (less than 0.5 %). The implications of the high P contents in the soil could create nutrients imbalance with respect to nitrogen, particularly in Makanya and Mwembe villages, and the consequence of this may result to early maturity and stunted growth of plants.

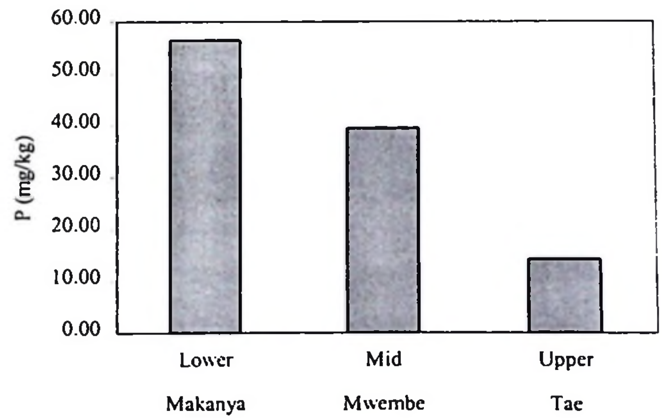


Figure 4.6. Extractable phosphorus pattern on the Makanya river catchment

The exchangeable bases Ca, Mg, K and Na contents along the toposequence on the catchment are presented in Figure 4.7 and Appendix 9. The results show that, the exchangeable K on the catchment ranged from 1.40 to 2.65 cmol(+)/kg, with a mean value of 1.76 cmol(+)/kg soil, 0.31 to 2.80 cmol(+)/kg, with a mean of 1.39 cmol(+)/kg soil, and 0 to 2.65 cmol(+)/kg, with a mean of 0.45 cmol(+)/kg soil in the lower, mid and upper zones, respectively (Appendix 9). According to Landon (1991), the exchangeable potassium of the soils was categorized as being very high medium to very high and very low to very high in the lower, mid and upper zones respectively. Nyambilila (2003) reported medium to high exchangeable K in Kisiwani, Kihurio, and Kimunyu in Same district.

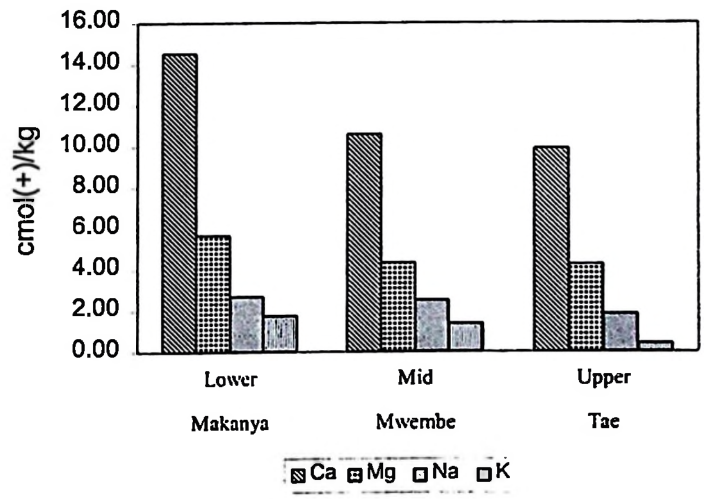


Figure 4.7. Exchangeable bases pattern on the Makanya river catchment

The exchangeable Ca in the soils on the catchment ranged from 7.35 to 22.57 cmol(+)/kg, with a mean of 14.53 cmol(+)/kg soil, 4.41 to 20.95 cmol(+)/kg with a mean of 10.60 cmol(+)/kg soil, and 2.37 to 19.23 cmol(+)/kg with a mean of 9.91 cmol(+)/kg soil, in the lower, mid and upper zones, respectively (Appendix 9). Also, exchangeable Mg content in soils on the catchment, ranged from 4.08 to 7.93 cmol(+)/kg with a mean of 5.67 cmol(+)/kg soil, 3.06 to 9.83 cmol(+)/kg with a mean of 4.34 cmol(+)/kg soil and 1.34 to 5.66 cmol(+)/kg with a mean of 4.27 cmol(+)/kg soil in the lower, mid and upper zones, respectively. Exchangeable Na content in soils on the catchment ranged from 2.04 to 3.40 cmol(+)/kg with a mean of 2.70 cmol(+)/kg soil, 1.76 to 3.94 cmol(+)/kg, with a mean of 2.53 cmol(+)/kg soil, and 0.95 to 3.67 cmol(+)/kg, with a mean of 1.85 cmol(+)/kg soil in the lower, mid and upper zones, respectively. The pattern distribution of these exchangeable bases (Figure 4.7) indicate that, Ca, Mg, K and Na were tending to decrease toposequence wise on the catchment in the direction of elevation increase. Relatively high contents were registered on the lower zone. Overall, exchangeable Ca content was very high in the study area and could be attributed to the high contents of Ca in the parent materials (rocks and minerals) of the soils on the catchment.

Calcium, magnesium and sodium exchangeable bases content in the lower zone were rated as very high (Landon, 1991) and on the mid zone, as high to very high. On the upper zone, Ca and Mg were rated as medium to very high, and Na ranked as high to very high. In similar areas in Same district, Nyambilila (2003) observed that, Ca content were medium to high, while Mg was adequate and Na levels ranged from low to high. However, all the soils with high exchangeable Na were found to be non-sodic. The exchangeable bases in the soils on the catchment would not limit crop production. The high Ca, Mg, and Na contents in the soil would be accounted for the possibility of their high contents in the parent materials of the soil. Another reason that can explain the high basic exchangeable contents values in the soils is minimum leaching which is associated with low rainfall in the area. This is complemented with sediments deposited by the runoff rainwater through RWH by diverting runoff, particularly in the lower zone into crop fields. Based on the mean values, the basic exchangeable cations contents are well correlated with pH and EC of the soils in the area because all these properties have shown similar trends.

4.2 Spatial variations of soil fertility patterns on the Makanya river catchment

The spatial distributions of the selected soil fertility attributes namely soil pH, electrical conductivity, total nitrogen and exchangeable bases (K and Na) were mapped as shown in Figure 4.8. These spatial surface maps were developed based on soil properties and soil sampling points coordinated by GPS receiver, and spatial patterns were analysed using Arc View GIS and Geostatistical analyst.

The spatial pattern distribution of EC values on the mid and upper zones along the toposequence seems to be quite homogeneous almost throughout the respective study sites. The EC values are essentially below 0.2 mS/cm in these areas. The low EC values is a reflection of the removal of basic cations and soluble salts either through water erosion or leaching as a consequence of relatively high rainfall in the upper and mid zones. The remaining area comprising the valley bottom, EC values range from 0.2 – 0.6 mS/cm, except the small patches found on the bottom corner of the mid zone which indicate to have relatively high values (0.6 – 0.8 mS/cm).

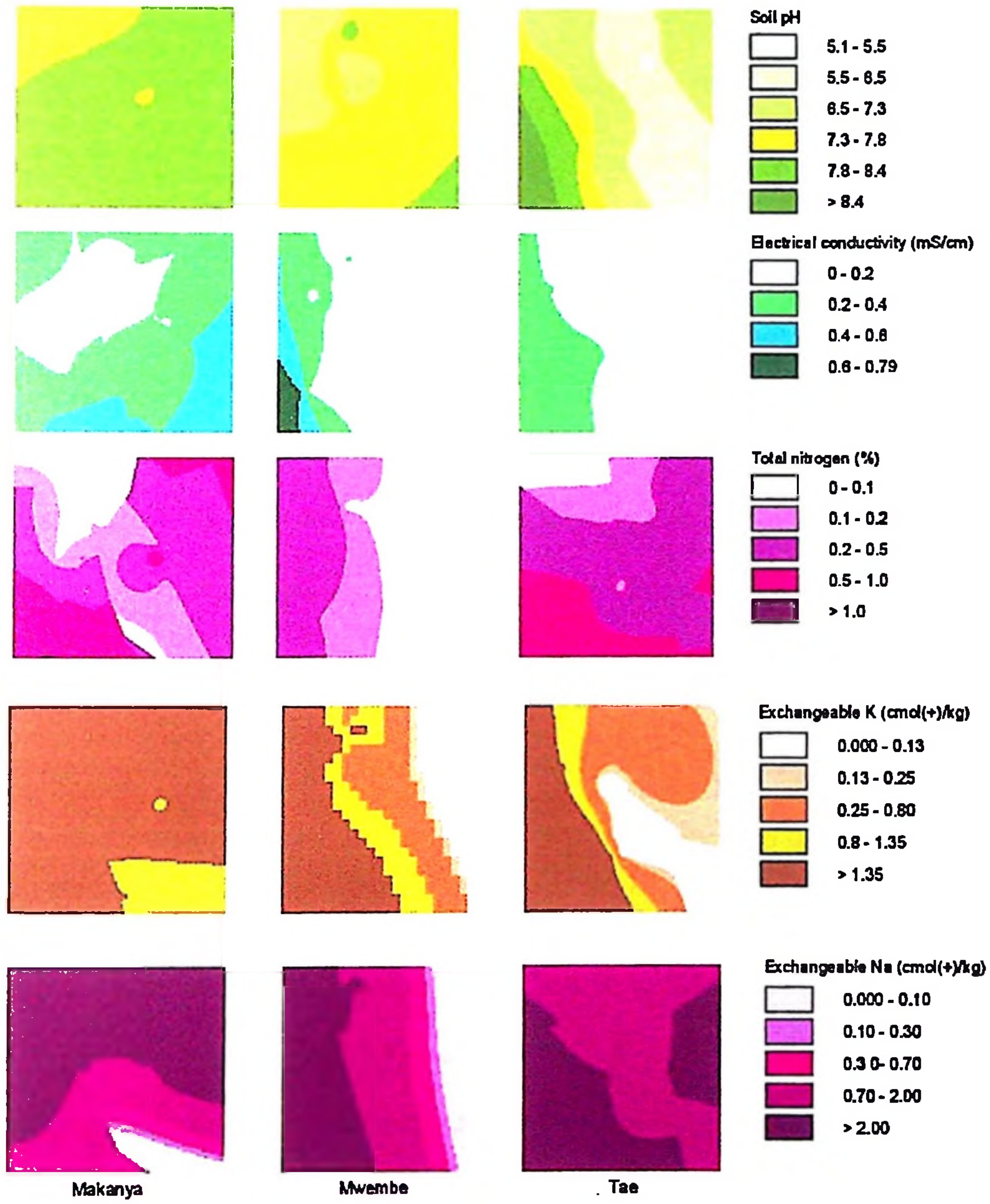


Figure 4.8. Maps of the soil fertility attributes in the selected sites along the toposequence in the study area

The electrical conductivity in the lower zone (Makanya) of the catchment portrays different pattern distribution as compared to the mid and upper zones. EC values in this area seem to fall into three classes. The dominant class includes the area surrounding the receiving area of rainwater runoff where the EC values range from 0.2 – 0.4 mS/cm. A patch which EC values range from 0 – 0.2 mS/cm is surrounded by the dominant class. The bottom part in this zone shows to have relatively high EC values (0.4 – 0.6 mS/cm). The EC values found in the lower zone are the same as values obtained in bottom part of the mid and upper zones on the catchment. This suggest that accumulation of exchangeable basic and soluble salts through harvesting rainwater runoff, either by diverting runoff as is in the lower zone (Makanya village) or side hill sheet/rill runoff utilization as noted in the mid and upper zones, could explain source of this spatial variation patterns in the study area.

Spatial patterns distribution of soil pH and exchangeable K in the study area indicates some common patterns. In the mid and upper zones on the catchment, K showed to be low in elevated terrain areas, and relatively high in the valley bottoms. Similarly, soil pH level in the upper zone showed to increase from the upper slopes to the bottom. Soil pH in the mid zone is almost uniform (7.3 – 7.8) throughout the area, except two small patches that range from 7.8 to 8.4. In the lower zones, soil pH and exchangeable K concentration values are relatively high and uniform in the area under RWH practice. In the whole study area, the cause of the spatial pattern variation is possibly associated with slope facet and RWH practices. Runoff tends to erode surface soil, which accumulate on the lowlands thus the enrichment of the runoff receiving area. The concept of accumulation of nutrients in the lowlands is highly displayed in the distribution of these fertility attributes in the study area. Hatibu and Mahoo (1999) reported similar argument in the tropic semi-arid areas, of Tanzania, where high value crops like vegetables are grown.

Spatial patterns distribution of the total nitrogen along the toposequence in the study area indicated that, in the upper zone of the catchment, almost more than half of the area has higher than 0.2 percent of total nitrogen. On the mid zone, almost the entire area has total nitrogen percent below 0.2 and this comprise steep slope areas, while the valley bottom parts (along the ephemeral river of Mwembe) shown to have relatively higher value of total N (0.2 – 0.5 %). In the lower zone of the catchment, total N is delineated into several distinct areas. The receiving area of rainwater runoff and the tail area that receive runoff occasionally had relatively high (0.5 – 1.0) total N percentage, while the remaining area, contain below 0.5 total N percentages. The reasons that can be given for the receiving area to contain high total N percentage is possibly due to surface soil organic matter contained in the harvested rainwater runoff. The decrease of total N on the mid part of the lower zone is probably caused by the small amounts of runoff received at the same time, the vegetation is very sparse. Unless the rainfall is high as was in 1997/98 *elnino* rains, otherwise runoff harvested decreases as you move away from the receiving area. The tail part has high value of total N (0.5 – 1.0 %), possibly due to limited plant growth, as a consequence to limited water availability hence reduced removal of N from the soils by plants. The upper zone of the catchment has relatively high percent N content (0.2 – 1.0 %), possibly due to high vegetation available in the area. Based on the rainfall data, (Figures 2.2 and 2.3, and Appendix 5), the upper zone of the catchment has relatively high rainfall, thus high vegetation is expected, hence high organic matter. Neue and Snitwongse (1988) reported organic matter to be the main source of available nitrogen in most soils.

Spatial patterns distribution of exchangeable sodium in the upper zone of the catchment in the study area shows that, the highest values of Na (above 2.0 cmol(+)/kg) are found on small patch on the hill slopes area and in the area located on the foot slopes. The foot slopes area is where the agricultural activities are supported by RWH practices. The high concentration of extractable Na, most probably could be due to enrichment as a result of runoff that is normally stored overnight in the micro-dam (*ndiva*).

Plate 1: Micro-dam (*ndiva*) made of stones

In the mid zone on the catchment, higher sodium contents are prominent on the valley bottoms, and decreasing towards steep slopes. In other words, sodium concentration decreases with topographic position, and it follows the slope facet sequence. Thus, the spatial patterns of exchangeable Na is probably more controlled by terrain and associated with natural RWH.

In the lower zone in Makanya village, higher concentrations of extractible Na (above 2.0 cmol(+)/kg) are shown in the receiving area, and it tends to decrease downwards. This could be explained by the area being the runoff receiving area, and associated with RWH practice particularly macro-catchment techniques. However, this influence is not evenly distributed, as it tends to decrease downwards following the existing gentle slope.

The overview of soil fertility attributes maps indicated that, some nutrients in the catchment zones in the study area increase with terrain elevation and others decreased as elevation on the terrain increases. On the other hand, some soil fertility attributes exhibited different distribution patterns and this was found to be common in the lower zone. It was observed that, where macro-catchment RWH system by diverted rainwater runoff is practiced, the distribution patterns of soil fertility is related to water.

4.3 Factors contributing to soil fertility variability under RWH systems on the Makanya river catchment

The understanding of the factors contributing to the spatial fertility variability is important as this would contribute to future agricultural and environmental management plans for the Makanya river catchment. Spatial fertility variability determines how the agricultural land will be managed in the most productive and sustainable way, and to conserve environmental and natural resources.

Therefore, factors contributing to soil fertility variability in the area were one of the focal points. Three key factors namely, runoff water quality, runoff rainwater quantity, fertility management practices and crop management, were selected to assess the magnitude and spatial variability of soil fertility under RWH systems on Makanya river catchment. Runoff rainwater quality was assessed through the determination of some fertility attributes in water. The runoff rainwater quality was assessed through monitoring events of received runoff in the lower zone (Makanya village), which was assumed to have had an impact in the crop fields. Another measurement was to quantify the volume of runoff received. The fertility management practices on the other hand were assessed through questionnaire survey. The following sections portray the results and findings obtained on this context.

4.3.1 Extent of rainwater harvesting in the study area

In the whole study area, the results (Table 4.2) shows that, out of 144 respondents 92% indicated practicing RWH while 8% indicated not practicing RWH. However, through field survey, it was observed that, those 8% disclaimed practicing RWH also they were practicing RWH without their knowledge. The problem of misinterpretation was raised based on how people define RWH in the study area, particularly in the lower zone (Makanya village). For example a farmer in Makanya village considered RWH practice only when rainwater runoff is diverted into the crop fields (Plates 2 and 3).

Table 4.2. Extent of RWH on the Makanya river catchment

Extent of RWH practices	Frequency	Percent
Practicing RWH	132	91.7
Not practicing RWH	12	8.3
Total	144	100.0

Furthermore, the study revealed that, most female household farmers (Plate 4) were involved in RWH practices. Table 4.3 illustrates that all the interviewed female farmers were practicing RWH. On the other hand, the three main categories of RWH systems namely, in-situ, micro-catchment and macro-catchment RWH (Table 4.4) are being practiced in the study area. This indicates that in the tropic semi-arid area, rainfed farming system is always done together with RWH systems to improve yields and sustainability.

Table 4.3. Extent of RWH practices on the basis of gender and village on the Makanya river catchment

Village	Gender	RWH practice extent			
		Practicing RWH		Not practicing RWH	
		Frequency	Percent	Frequency	Percent
Makanya	Male	41	78.8	11	21.2
	Female	2	100.0		
	Village-level	43	79.6	11	20.4
Mwembe	Male	39	100.0		
	Female	8	100.0		
	Village-level	47	100.0		
Tae	Male	36	97.3	1	2.7
	Female	6	100.0		
	Village-level	42	97.7	1	2.3

Plate 2: Runoff rainwater diverted into main field channels at Makanya Road Bridge

Plate 3: Runoff rainwater directed into the fields

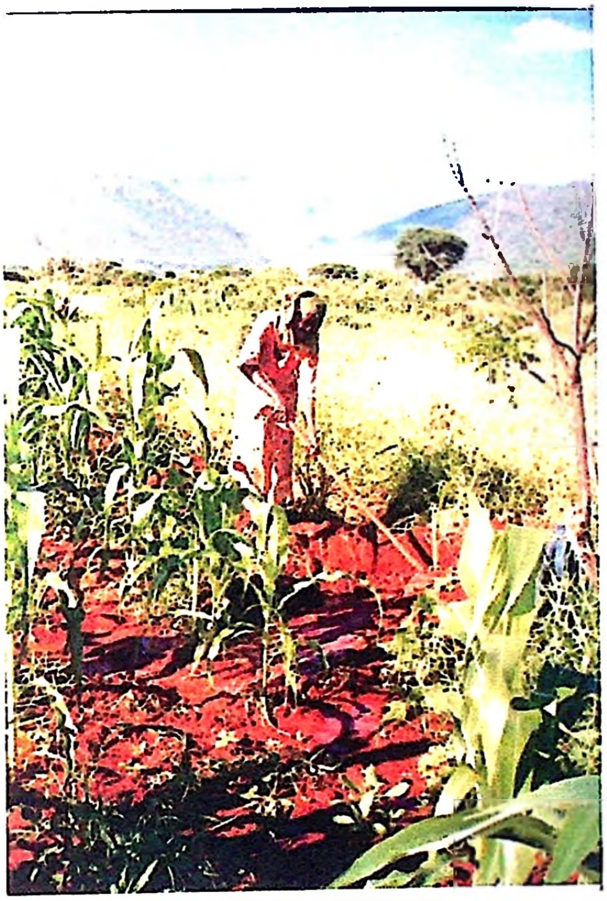


Plate 4: Female farmer diverting rainwater runoff into a maize field

Table 4.4. Extent of the use of RWH categories on the Makanya river catchment

			RWH techniques					
			In-situ RWH		Micro-catchment RWH		Macro-catchment RWH	
			Using	Not using	Using	Not using	Using	Not using
Village	Makanya	Frequency	5	49	8	46	32	22
		Percent within village	9.3%	90.7%	14.8%	85.2%	59.3%	40.7%
		Percent within the study area	3.5%	34.0%	5.6%	31.9%	22.2%	15.3%
	Mwembe	Frequency	47	0	44	3	44	3
		Percent within village	100.0%	0%	93.6%	6.4%	93.6%	6.4%
		Percent within the study area	32.6%	0%	30.6%	2.1%	30.6%	2.1%
	Tae	Frequency	36	7	28	15	21	22
		Percent within village	83.7%	16.3%	65.1%	34.9%	48.8%	51.2%
		Percent within the study area	25.0%	4.9%	19.4%	10.4%	14.6%	15.3%
Catchment	The whole study area	Frequency	88	56	80	64	97	47
		Percent in the study area	61.1%	38.9%	55.6%	44.4%	67.4%	32.6%

4.3.2 Farmers experiences on soil fertility levels on the Makanya river catchment

Farmers' experiences on soil fertility in the study area are presented in Table 4.5. The study revealed that, 13.5% respondents were experiencing soil fertility changes in Makanya village, whereas 24.1% do not experience changes. The situation was different in other villages located in the mid and upper zones on the catchment. In Mwembe and Tae villages almost all interviewees had the feeling that, positive or negative changes in soil fertility exist. Farmers' perceptions on soil fertility changes were on both, fertility depletion and enrichment. The majority from all villages in the study area claimed to have more fertility enrichment than depletion. Local indicators of soil fertility used by farmers to assess soil degradation or enrichment were decline in crop yields and stunted crop growth and increase in crop yields, respectively (Table 4.7).

Table 4.5. Farmer's experiences on soil fertility changes on the Makanya river catchment (n = 141)

Farmer's perception	Villages in the catchment					
	Makanya		Mwembe		Tae	
	Frequency	Percent	Frequency	Percent	Frequency	Percent
Experiencing soil fertility changes	19	13.5	46	32.6	38	27.0
Not experiencing soil fertility changes	34	24.1	1	.7	3	2.1

The difference perceptions appeared in the toposequence zones can be related with respective zones location on the catchment. In Makanya village for example, farmers believed that, harvested rainwater runoff collect nutrients in the upper catchment. This has some truth, since as the runoff move downwards to the lowland, it erodes surface soil, which has high organic matter, which then accumulate in the lowlands. This contributes to soil fertility in the lower zone where micro-catchment RWH is practiced. Obviously, other interviewees in Makanya village perceived the soil fertility as depleting, possibly because of the accessibility to runoff. Because of low rainfall, the limitation of runoff results in sparse and stunted crop growth in the area.

In Mwembe and Tae villages, the perception judgement of the respondents depends where his/her farm is located. All the farms in the bottom and foot slopes are perceived as being fertile. This is probably due to eroded surface soil with high organic matter, which accumulated in the lowlands. Due to the areas being dry and located in the mountainous slopes, the majority of farmers have fields in the bottom and foot slopes areas.

4.3.3 Soil fertility management on the Makanya river catchment

4.3.3.1 Use of farmyard manure in crop production

The distribution of livestock in the study area is presented in Table 4.6. The livestock groups considered in this study area were those found in the area, and that are considered to contribute to soil fertility. With an exception of Tae village, most farmers let their animals graze on communal lands. Some nutrients may return to the farm through harvesting runoff, which erode soil surface organic matter, although much of the manure will remain on the communal grazing lands. Majority of farmers in Tae village, stall – feed their cattle in zero grazing units, because of the scarcity of agricultural land. This facilitates the collection and storage of manure and ensure that manure remain on the farm.

Table 4.6. Livestock keeping on the Makanya river catchment

Village		Livestock groups					
		Cattle		Goats, sheep, pigs and donkeys		Chicken and ducks	
		Own	Don't own	Own	Don't own	Own	Don't own
Makanya	Frequency	18	36	28	26	19	35
	Percent within village	33.3%	66.7%	51.9%	48.1%	35.2%	64.8%
	Percent within livestock group	26.9%	46.8%	32.2%	46.4%	21.3%	64.8%
	Percent within study area	12.5%	25.0%	19.6%	18.2%	13.3%	24.5%
Mwembe	Frequency	23	24	30	16	30	16
	Percent within village	48.9%	51.1%	65.2%	34.8%	65.2%	34.8%
	Percent within livestock group	34.3%	31.2%	34.5%	28.6%	33.7%	29.6%
	Percent within study area	16.0%	16.7%	21.0%	11.2%	21.0%	11.2%
Tae	Frequency	26	17	29	14	40	3
	Percent within village	60.5%	39.5%	67.4%	32.6%	93.0%	7.0%
	Percent within livestock group	38.8%	22.1%	33.3%	25.0%	44.9%	5.6%
	Percent within study area	18.1%	11.8%	20.3%	9.8%	28.0%	2.1%
The whole study area	Frequency	67	77	87	56	89	54
	Percent in the study area	46.5%	53.5%	60.8%	39.2%	62.2%	37.8%

A more detailed study about livestock possession, use of farmyard manure and some reasons for limited use of farmyard manure was done in Makanya village. The study revealed that, the majority of livestock keepers possessed between 1-5 and 6-20 animals (Table 4.7). The number of sheep, goats and chicken owned in the village is very small, hence insignificant contribution to soil fertility. However, even the little available farmyard manure is not fully utilized for soil fertility improvement. Table 4.8 show that only 52.6% responded as livestock keepers applied farmyard manure in the crop fields, and 36.8% do not use it at all.

Table 4.7. Livestock keepers in Makanya village

Livestock group classes	Cattle		Sheep		Goats		Chicken	
	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
1-5	6	54.5	7	50.0	4	36.4	4	28.6
6-20	3	27.3	6	42.9	6	54.5	10	71.4
21-50	2	18.2	1	7.1	1	9.1	0	0
Total	11	100.0	14	100.0	11	100.0	14	100.0

Table 4.8. Extent of the use of farmyard manure by livestock keepers in Makanya village (n = 19)

Use of FYM	Frequency	Percent
Applied in the crop fields	10	52.6
Not used at all	7	36.8
Burnt or sold	1	5.3
Sold or given as an offer	1	5.3

The reasons given for limited use of farmyard manure in Makanya village (Table 4.9) are that, crop fields are inherently fertile and fields are located far away from homestead or kraal (*boma*). Other reasons given as to the limitation of use of FYM were non-assurance of getting higher yields due to limited soil moisture, limited knowledge about the use and benefits, and a number of farmers believe that by harvesting rainwater runoff automatically one harvest nutrients as well, thus no need for the use of FYM.

Agropastoral livestock keepers, being unaware of the use and potential of FYM in crop production either throw away the manure or burn it (Table 4.10). It was observed that the farmers with sizable number of animals (Table 4.11) are the ones who either burn or throw away the FYM. . Many nutrients are lost through the burning of manure, particularly C, S, H and O. Disposing farmyard manure in this fashion could be due to accumulations at homestead and transportation cost for carrying manure into the fields when the kraal (*boma*) is located very far away from the crop fields.

Table 4.9. Reasons for limited use of farmyard manure (n = 9)

Causes	Frequency	Percent
Crop fields are fertile	4	44.4
Fields located far away from the source	2	22.2
Other	3	33.3

Table 4.10. Final destination of the unused FYM in Makanya village (n = 10)

Final destination	Frequency	Percent
Thrown away	6	60.0
Burnt	4	40.0

Table 4.11. Use of farmyard manure per livestock group in Makanya village

Use of farmyard manure		Cattle classes (n = 10)			Goats classes			Sheep classes (n = 14)			Chicken classes (n = 14)	
		1-5:	6-20:	21-50:	1-5:	6-20:	21-50	1-5:	6-20:	21-50:	1-5: small	5-20: medium
Applied in the crop fields	Frequency	3		1	2	4		3	3	1	2	7
	Percent	30.0%		10.0%	18.2%	36.4%		21.4%	21.4%	7.1%	14.3%	50.0%
Not used at all	Frequency	1	3		1	2	1	2	3		2	2
	Percent	10.0%	30.0%		9.1%	18.2%	9.1%	14.3%	21.4%		14.3%	14.3%
Burnt or sold	Frequency			1	1	0	0	1				1
	Percent			10.0%	9.1%	0	0	7.1%				7.1%
Sold or given as an offer	Frequency	1			4	6	1	1			4	10
	Percent	10.0%						7.1%			28.6%	71.4%
	Frequency total	5	3	2	4	6	1	7	6	1		

4.3.3.2 Soil fertility management practice in the study area

The common types of soil management practices in the study area are given in Table 4.12. These common soil fertility management practices include the use of crop residue (86.10%), intercropping (76.4%), application of farmyard manure (75.7%) and application of mulch (71.5%). Agro-forestry practices (66.0%) were found to be most applicable in Mwembe and Tae villages, most probably due to high rainfall compared to Makanya village. Bush fallowing (39.6%) appeared to be the most favoured practice in Makanya village compared to Mwembe and Tae villages. The most used fallowing period was one year or less. This practice is more in the lower zone of the catchment, possibly due to rapid depletion of plant nutrients and also availability of agricultural land in Makanya village compared to the mountainous areas (Tae and Mwembe). The application of inorganic fertilisers was found to be extremely low. In Makanya village only one respondent (0.7%) has been using inorganic fertilisers, no interviewee indicated to have used fertiliser in Mwembe village whereas in Tae village three respondent (2.1%) used inorganic fertilizers. Among the reasons contributing to very limited use of inorganic fertilisers as portrayed by the farmers is associated with non-assurance of getting higher yields, due to unreliable rainfall and high soil fertility status of the soils.

The causes of soil fertility changes on the catchment as identified through questionnaire survey are categorized as the factors contributing to soil fertility improvement (fertility enrichment) and factors that encourage or cause soil fertility depletion. Wind and drought were pointed out as the major causes of soil fertility decline. Drought was pointed out probably because it destroys crops hence decline in vegetation which limit the effective amounts of crop residues to be incorporated into the fields, thus negatively influencing the nutrients re-cycling process. Generally drought affect mulching and also bush fallow lose its meaning as vegetation decline.

Fertiliser application is strongly pointed out as one of the factors that can increase soil fertility. However, this management practice option appeared not to be favoured in the study area, as it has been presented in Table 4.12. It is suggested that this reluctant behaviour could be influenced by farmers' economic status and enhanced by some of agricultural policies. Agricultural Structural Adjustment Program in the 1990s is an example of agricultural policies that involved abolishing farm input subsidies. This has had serious implications for the rural economy, as producers are no longer able to obtain agricultural inputs at affordable prices. Similar argument was advised by Lompo *et al.* (2000) in Burkina Faso.

Table 4.12. Soil fertility management practices on the Makanya river catchment

Fertility management practice	Makanya (n = 54)		Mwembe (n =47)		Tae (n = 43)		Makanya Catchment (N = 144)	
	Frequency	Percent	Frequency	Percent	Frequency	Percent	Frequency	Percent
Application of inorganic fertilisers	1	1.85	0	0	3	6.98	4	2.80
Application of farmyard manure	26	48.15	41	87.34	42	97.67	109	75.70
Agro-forestry practices	6	11.11	47	100.00	42	97.67	95	66.00
Application of mulch	14	25.93	46	97.87	43	100.00	103	71.50
Intercropping	23	42.59	46	97.87	41	95.35	110	76.40
Use of crop residue	35	64.81	47	100.00	42	97.67	124	86.10
Bush fallowing	34	62.96	5	10.64	18	41.86	57	39.60
Others	6	11.11	46	97.87	12	27.91	64	50.00

Table 4.13. Reasons for not using inorganic fertilisers and farmyard manure in Makanya village (n = 30)

Reasons or causes	Frequency	Percent
Soil is fertile	5	16.7
Knowledge about the use and benefits of fertilisers and manure is limited	1	3.3
Inorganic fertilisers enhance wilting of plants	2	6.6
Non assurance of getting higher yields	1	3.3
Other reasons	2	6.7
No reason	19	63.3

In Makanya village (Table 4.13) for example, most of the respondents (63. 3%) failed to give reasons for not using inorganic fertilisers or manure in crop production. However, reasons for limited use of inorganic fertiliser as well as manure were high fertility status of the soils (17%) and inadequate comprehension of the advantages of using fertilisers and manures (3%). Also farmers pointed out that, inorganic fertilizers enhance wilting of plants (7%) and the use of these materials is not favoured due to non-assurance of getting higher yields.

4.4 Nutrients content in rainwater runoff along the toposequence on the Makanya river catchment

The analytical data for pH, electrical conductivity and contents of Ca, Mg, Na, and K parameters for the *vuli, kipupwe and masika* rainwater runoffs were as presented in Figures 4.9 – 4.14 and Appendix 4.

The analytical data of the chemical properties of rainwater runoffs on the Makanya river catchment (Appendix 4) showed that, pH level of the water ranged from 7.9 to 8.3. This alkaline water reaction could be due to soluble salts contained in water, which could be related to the eroded soluble salts gathered by runoff water on the catchment. The possible source could be associated with the accumulated salts in the topsoil during the dry seasons and exchangeable cations content in the soils. In the semi-arid and arid areas, concentration of salts in the topsoil normally is associated with dry climate, as a result salts accumulate on the surface during the dry period (Metternicht and Zinck, 1996). Of course, during rain season, the effect is not much reduced since rains are normally not enough to washout or leach the accumulated salts on the surface. Another possible source of soluble salts in water could be associated with soil parent materials in the area. This could be probably an indication that the parent materials of the soils were basic.

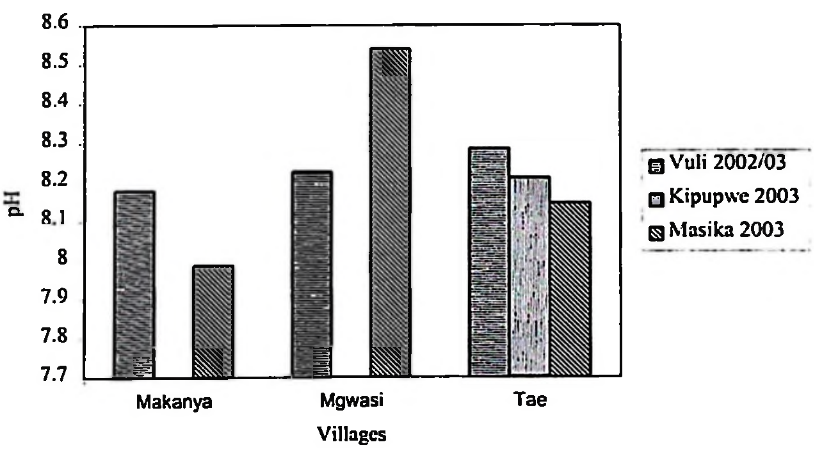


Figure 4.9. Variability of pH in rainwater runoff along the toposequence on the catchment

The mean runoff rainwater pH value (Figure 4.9) shows some variations along the toposequence. Generally the water pH values decreased from the upper to lower zone with exception of the pH of the runoff at Mgwasi station for the *masika* rains. However, pH level was of alkaline reaction (above 7.8) for the all sample stations in the three seasons on the catchment. Water pH variations were portrayed at each sampling station in terms of temporal variation. For the Tae (upper zone) and Makanya (lower zone) stations, pH showed to decrease from *vuli* to *masika* season. The temporal variation of pH could be related to the temporal distribution of the rainy seasons. The *vuli* normally start after very long dry period (four to five months). This makes the area to lose vegetation as a consequence, when the vuli rains starts, erodes the soils accompanied with soluble salts easily. As a result, runoff rainwater contains high sediment containing soluble salts and exchangeable bases and hence high pH level. In the *kipupwe*, pH level decreases because rains stop and water become clearer as a result of low sediment load in runoff. In the masika, the water pH level continues to decrease because runoff rainwater contains low sediments loads because rains start shortly after vuli season. This makes the soil to remain covered with vegetation, hence reduce erosion effect on the soil. On the other hand, the decrease of pH shown along the toposequence in the study area could be associated with water clearance as one descends along the toposequence.

The EC values of runoff rainwater was measured based on the fact that it is the measure of the water salinity. The results (Appendix 4) showed that, EC values of water ranged from 0.14 to 1.06 mS/cm. This range falls in the category that ranged from none restriction on use and slight to moderate (FAO, 1985). The EC values of the sampled runoff water were in the tolerant limits. However, this should be kept monitored because, its accumulation in the soil could cause salinity problem. A salinity problem can occur if the total quantity of salts in the irrigation water is high enough for the salts to accumulate in the crop root zone to the extent that yield are affected. Excessive soluble salts in the root zone inhibit water uptake by plants. All in all, the soils in the study area (Appendix 9) appeared to be non-saline.

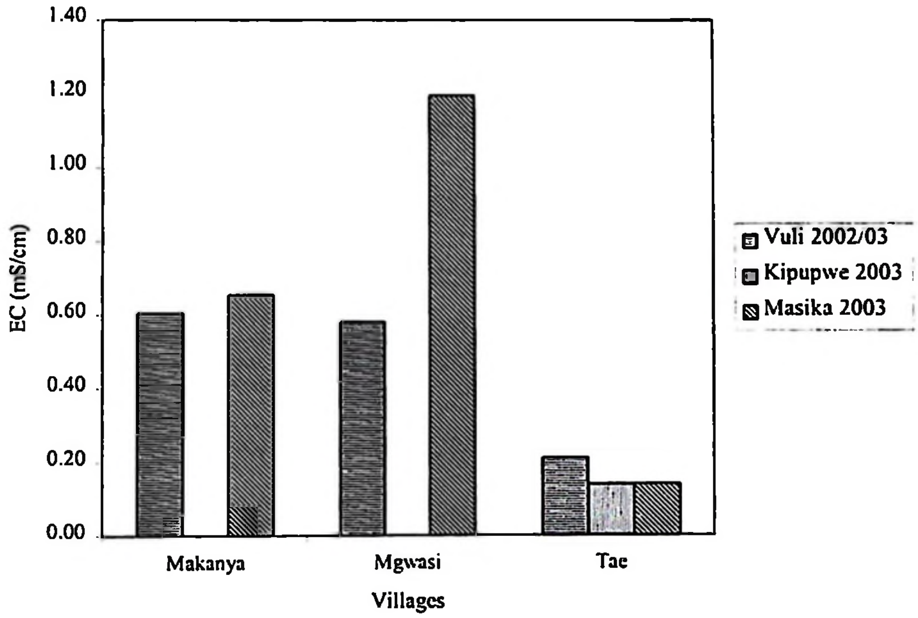


Figure 4.10. Variability of EC in rainwater runoff along the toposequence on the catchment

The electrical conductivity trend of runoff water along the toposequence is presented in Figure 4.10. The results show that, the EC values tended to increase from *vuli* to *masika* at Makanya and Mgwasi station while Tae station (upper zone) showed almost no change. The difference in EC values at Mgwasi for the *vuli* and *masika* seasons could be due to the amount of sediments in the water samples and possibly related to the presence of soluble salts.

The variation in the content of Ca, Mg, K and Na runoffs collected along the toposequence are presented in Figures 4.11 to 4.14, respectively and in Appendix 4. The data shows that, the concentration of the bases in water are relatively small at Tae station in the upper zone compared to mid and lower zones. The contents of the bases in the water runoff on the catchment have same bearing to the exchangeable bases in the soil and the pH of the soils (Figure 4.2 and 4.7). The basic cation contents in the water runoffs would also depend on the volume of discharges for the various rainy seasons.

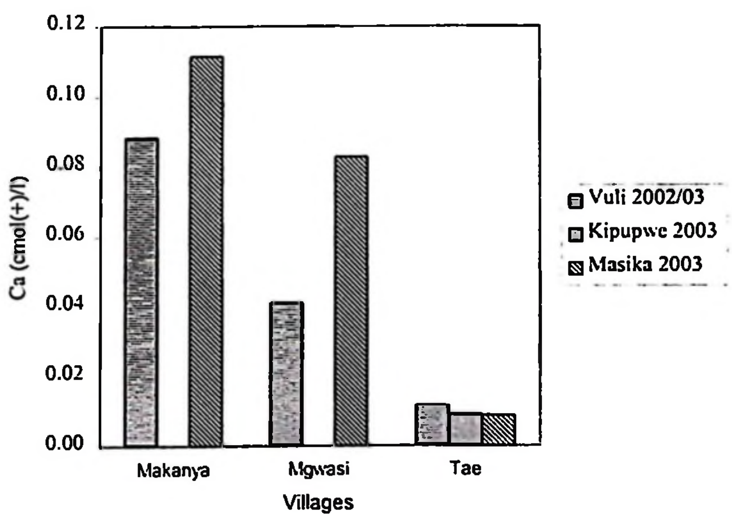


Figure 4.11. Variability of the amount of Ca in rainwater runoff along the toposequence on the catchment

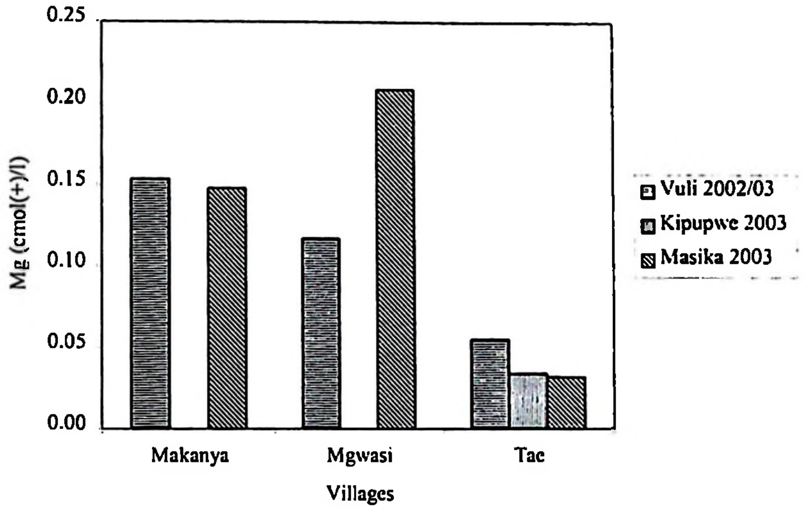


Figure 4.12. Variability of the amount of Mg in rainwater runoff along the toposequence on the catchment

The amount of discharges of flow is related to the amount of rainfall and intensities, hence, the higher the rainfall and intensities, the higher the extent of soil erosion. The contents of the basic cations in the water runoffs in the lower zone were found to be higher than those for the upper zones and this could be due to accumulation of eroded soluble salts as runoff move downwards to the lowlands. The variations in the basic cations concentrations in the runoffs between vuli and masika could probably due to temporal variation. The temporal variability could also explain the changes in the vegetation, EC etc. during the rainy season (*vuli, kipupwe* and *masika*).

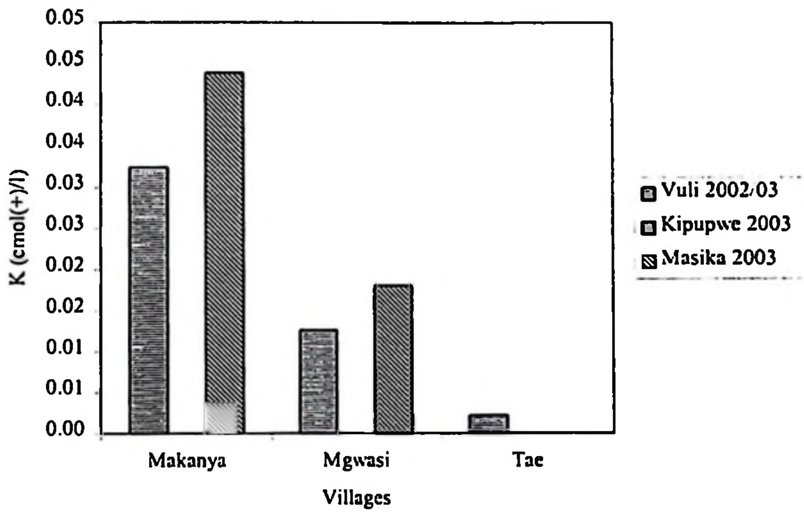


Figure 4.13. Variability of the amount of K in rainwater runoff along the toposequence on the catchment

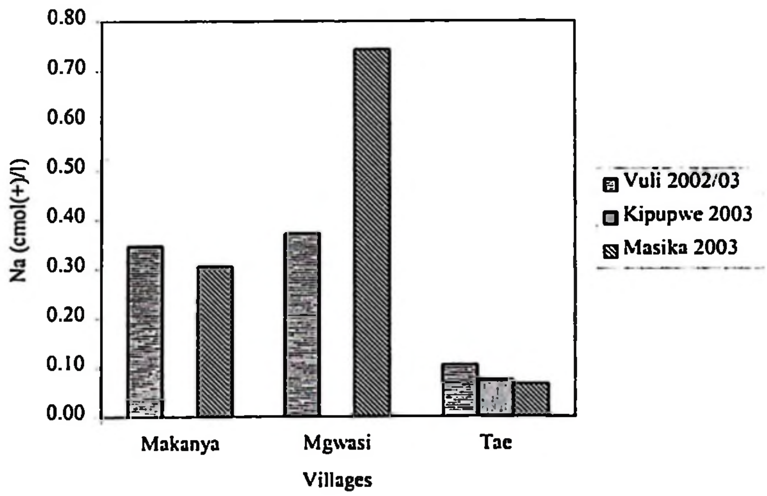


Figure 4.14. Variability of the amount of Na in rainwater runoff along the toposequence on the catchment

This trend of water quality variability along the toposequence could initiate the necessity of assessing the quality of runoff rainwater intended for the supplementary irrigation through RWH practices.

4.5 Nutrients accumulated by diverted rainwater runoff in the selected crop fields in Makanya village

In Makanya village in the lower zone, a number of crop fields were selected (Figure 22) to investigate the effects of diverted runoff into these fields on nutrients accumulation, hence changes in soil fertility status of the fields. Table 4.14a presents the selected crop fields as represented by farmers' names and harvested volume of water by diverting rainwater runoff from the Makanya river. The results show that, the volume of runoff rainwater diverted into the fields by single episode ranged from 68 to 523 m^3 ha^{-1}. This indicates that, those who own small field harvest more water by diverting runoff into their fields.

Table 4.14a. Quantities of rainwater runoff diverted to selected crop fields in Makanya village (*masika* 2003- rainy season)

Farmer name	Area (ha)	Qv (m^3)	m^3/ ha
Majid Sengasu	0.274	34.24	125.0
Fatuma Hussen	0.474	125.45	264.7
Shaban Bakari	0.088	45.16	513.2
Tusu Juma II	0.201	13.85	68.9
Tusu Juma I	0.211	43.53	206.3

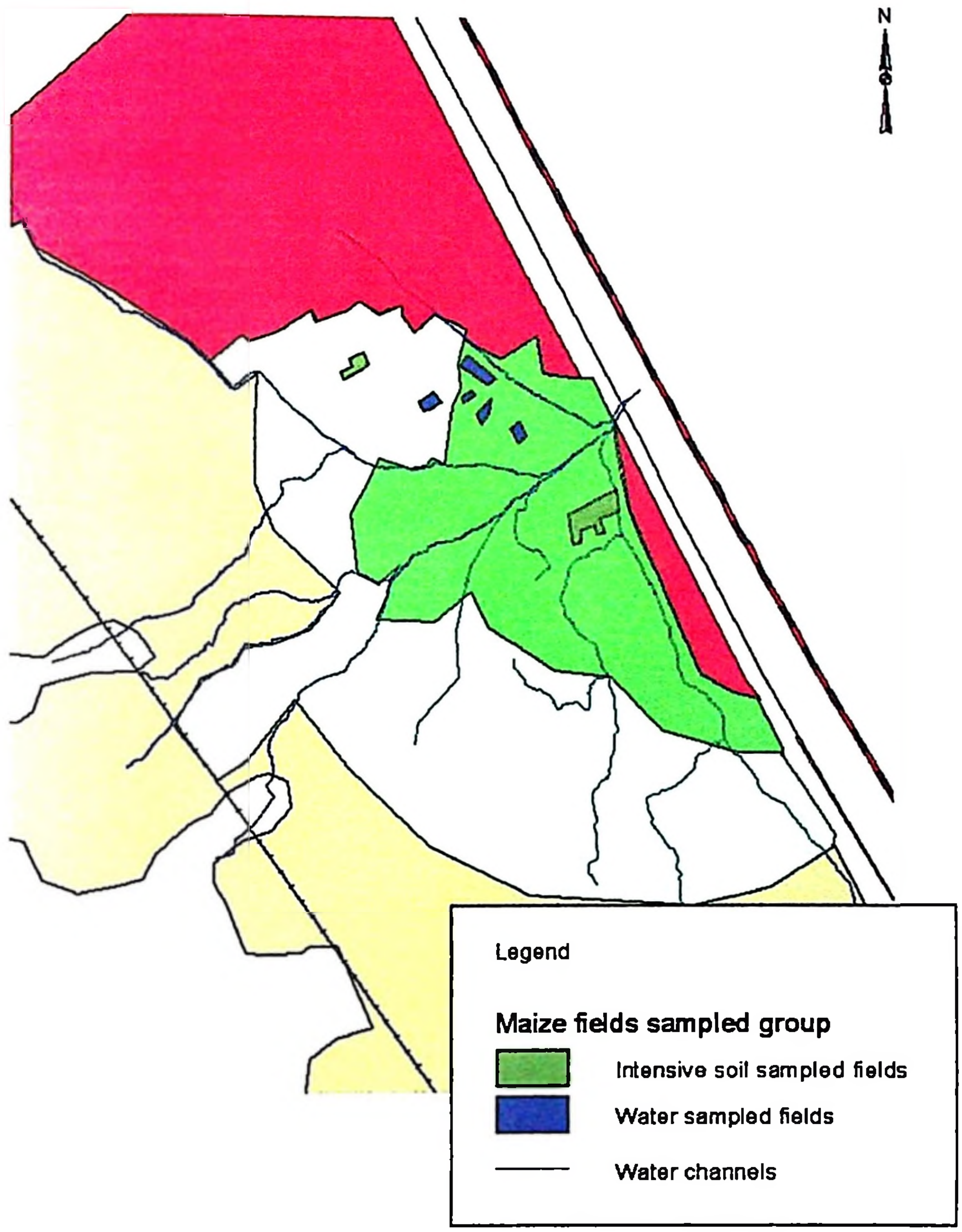


Figure 4.15. Map of Makanya village showing selected crop fields

Table 4.14b. Nutrients accumulated by diverted rainwater runoff in the selected crop fields in Makanya village

	Base content in (mol(+))/ha			
Farmer name	Ca	Mg	K	N
Majid Sengasu	50.0	87.5	25.0	225.
Fatuma Hussen	195.6	312.5	58.9	943.
Shaban Bakari	174.0	320.3	89.9	714.
Tusu Juma II	75.7	104.0	19.3	357.
Tusu Juma I	722.4	659.1	286.1	542.
Mean value	243.5	296.7	95.8	556.

Table 4.14b presents the data for fertility nutrients harvested in the selected fields that harvested rainwater runoff. The results show that, by diverting runoff rainwater once into the crop fields, the average of 45.88, 66.31, 15.75 and 164.59 mol(+) ha^{-1} of Ca, Mg, K and Na, respectively, were accumulated. This may lead to think that, for several runoffs within the cropping season, this could be a contribution as the plant nutrient pool in the soil. For the long term, Na accumulation could probably cause the problem of excessive sodium in the soil, hence sodicity (FAO, 1985).

4.6 Spatial and temporal variability of soil fertility in the runoff receiving area (Makanya village)

4.6.1 Temporal variability of soil fertility in the runoff receiving area (Makanya village)

Soil fertility variability within the selected crop fields in the land suitability classes from farmers' perception in the runoff receiving area (Makanya village) are presented in Tables 4.14a – 4.14c. The soil fertility variability was determined during *vuli* and *masika* rain seasons. The results showed that, within the selected crop fields, unsystematic spatial and temporal variation of soil fertility status were observed for both *vuli* and *masika* rain seasons.

The unsystematic spatial and temporal variation of soil fertility observed, could most probably be related to micro-slopes existing within the fields. Since the samples were taken within the farm area, for both short and long rains, various micro-slopes normally existing in the manually managed fields could facilitate both the movement and accumulation of nutrients. For example in the three land suitability classes, the increase of OC from the head to the tail of observation strip was noted. This could be influenced by existing micro-slope from the head to the tail. Another source of variation could be due to heterogeneity of agronomic practices applied in the fields. For example, the time differences in weeding can cause small differences in the nutrient level within few meters in the field.

Results from the soil samples collected in the crop field under indigenous land suitability class one (Table 4.15a) indicated an increase and decrease in values of some of the soil fertility attributes like EC and OC, respectively, from *vuli* rains to *masika* rains. Based on attribute mean values, higher values were registered in the *masika* rains compared to the *vuli* rains. The increment was noted for electrical conductivity, extractable P and total nitrogen, while OC, pH and exchangeable Na values showed to decrease. For soil samples collected from the selected crop fields in the indigenous land suitability class two (Table 4.15b), results revealed that all assessed soil fertility attributes tended to decrease in values from *vuli* rains to *masika* rains except only one attribute. The decrease was noted on EC, OC, total N, extractable P and exchangeable Na, while soil pH level tended to increase.

Results for soils sampled in indigenous land suitability class three (Table 4.15c) revealed that, some attributes increased, others decreased, and one attribute remained constant. The increments were noted for extractable P and exchangeable Na, while the decrease were registered for pH, electrical conductivity and organic carbon. Total nitrogen did not show any variation from *vuli* to *masika*.

The reasons for having several cases of incremental changes of soil fertility in the indigenous land suitability class one compared to other classes, was probably associated with macro-catchment RWH practices. This land class is located on the receiving area of rainwater runoff. Therefore, accessibility probability of harvesting runoff is very high compared to others land suitability classes. Due to the eroded soil surface organic matter by runoff, it is obvious that when harvested and applied in the crop fields, the improved change of soil fertility is expected. Of course the whole area is under RWH, but the head part, has higher chance of receiving runoff rainwater than others.

For all three suitability classes, the results showed that the OC content decreased from *vuli* to *masika*. This could be probably associated with the short period available, nearly a month (Figures 3.2) between these rain seasons. As a consequence, the generated vegetation during *vuli* doesn't get enough time decompose and generate organic matter during *masika* growing season.

Table 4.15a. Temporal variability of soil fertility in indigenous land suitability class one

Short rains (vuli) 2002-3

	Sampling strip 1				Sampling strip 2				Sampling strip 3				
Distance (m)	0-4	45-90	90-135	135-160	0-45	45-90	90-135	135-160	0-45	45-90	90-135	135-160	
Sample Id	Mnyu u 9-1	Mnyuku 6-8	Mnyuku 3-5	Mnyuku 1-2	Mnyuku 12-14	Mnyuku 15-17	Mnyuku 18-20	Mnyuku 21-22	Mnyuku 32-34	Mnyuku 29-31	Mnyuku 26-28	Mnyuku 23-25	Mean value
Lab. Id	3	24	26	23	30	25	49	29	27	48	28	16	
OC (%)	1.8	2.34	2.38	2.28	2.26	2.18	2.20	2.42	1.83	2.18	1.97	1.79	2.14
pH	8.	8.0	7.9	7.9	8.0	8.0	8.1	8.0	8.1	8.1	8.1	8.1	8.01
EC (mS/cm)	0.3	0.38	0.50	0.52	0.33	0.42	0.35	0.37	0.34	0.34	0.32	0.32	0.38
Extractable P (mg/kg)	41.5	42.47	39.95	45.66	56.04	42.80	46.70	43.57	61.14	48.50	43.57	48.52	46.70
Na (cmol(+)/Kg))	2.5	2.04	2.58	3.40	2.85	2.58	3.13	3.40	2.85	3.13	2.58	3.13	2.85
%TN	0.1	0.50	0.56	0.46	0.43	0.46	0.42	0.48	0.45	0.46	0.42	0.42	0.44
Long rains (masika) 2003													
Lab. Id	12	6	5	3	9	2	11	1	7	8	10	4	
OC (%)	2.03	2.44	2.30	2.24	1.72	2.18	1.99	2.69	2.44	2.52	0.64	2.36	2.13
pH	7.9	8.0	8.0	7.9	8.0	7.9	8.1	7.8	7.8	7.9	8.0	7.9	7.92
EC (mS/cm)	0.38	0.31	0.40	0.52	0.32	0.46	0.27	0.53	0.45	0.38	0.30	0.43	0.40
Extractable P (mg/kg)	42.29	47.07	45.71	44.88	66.82	49.78	45.91	47.07	56.80	43.57	50.32	47.87	49.01
Na (cmol(+)/Kg))	2.04	3.40	3.67	3.13	2.58	1.22	1.76	3.94	2.58	2.85	2.85	2.85	2.74
%TN	0.48	0.50	0.48	0.46	0.39	0.43	0.46	0.55	0.49	0.48	0.48	0.46	0.47

Table 4.15b. Temporal variability of soil fertility in indigenous land suitability class two

Short rains (vuli) 2002-3

	Sampling strip 1		Sampling strip 2		Sampling strip 3				Sampling strip 4				
Distance (m)	0-30	30-60	0-30	30-60	0-30	30-60	60-90	90-105	0-30	30-60	60-90	90-105	
Sample Id	Simba 19-20	Simba 21-22	Simba 17-18	Simba 15-16	Simba 8-9	Simba 10-11	Simba 12-13	Simba 14	Simba 6-7	Simba 4-5	Simba 2-3	Simba 1	Mean value
Lab. Id	62	57	61	63	55	60	64	58	104	54	59	56	
OC (%)	0.66	0.59	0.74	0.64	0.72	0.72	0.53	0.74	1.01	0.66	0.62	0.59	0.69
pH	7.8	7.7	7.9	7.5	7.7	7.9	7.8	7.7	7.6	7.8	7.7	7.8	7.74
EC (mS/cm)	0.14	0.12	0.15	0.14	0.26	0.11	0.16	0.20	0.33	0.19	0.22	0.20	0.19
Extractable P(mg/kg)	57.35	66.00	56.00	64.91	55.19	53.83	56.53	65.19	66.55	57.07	59.51	67.64	60.48
Na (cmol(+)/Kg))	2.04	2.31	1.76	2.04	2.04	1.76	2.04	2.85	3.67	2.85	2.31	2.85	2.38
%TN	0.17	0.15	0.21	0.21	0.21	0.15	0.17	0.18	0.24	0.22	0.15	0.18	0.19
Long rains (masika) 2003													
Lab. Id	65	70	72	66	74	71	73	69	75	84	68	67	
OC (%)	0.74	0.57	0.72	0.70	0.57	0.51	0.47	0.62	0.92	0.62	0.64	0.39	0.62
pH	7.7	7.7	7.9	7.7	8.1	8.2	7.8	7.6	7.9	7.9	7.8	7.9	7.84
EC (mS/cm)	0.09	0.13	0.15	0.10	0.09	0.08	0.08	0.10	0.19	0.10	0.11	0.06	0.11
Extractable P(mg/kg)	58.16	63.03	50.58	51.12	51.12	46.26	47.07	60.05	56.28	49.78	50.32	47.87	52.64
Na (cmol(+)/Kg))	2.04	2.58	1.49	1.76	2.31	2.04	2.04	2.85	2.58	2.58	2.31	1.76	2.20
%TN	0.15	0.14	0.20	0.17	0.18	0.14	0.17	0.17	0.15	0.13	0.14	0.14	0.16

Table 4.15c. Temporal variability of soil fertility in indigenous land suitability class three

Short rains (vuli) 2002-3

	Sampling strip 1			Sampling strip 2			Sampling strip 3			Sampling strip 4			Sampling strip 5		
Distance (m)	0-15	15-45	45-75	0-15	15-45	45-75	0-15	15-45	45-75	0-15	15-45	45-75	0-15	15-45	
Sample Id	James 2	James 4	James 5-6	James 11	James 9-10	James 7-8	James 12	James 13-14	James 15-16	James 21	James 19-20	James 17-18	James 22	James 23-24	Mean value
Lab. Id	20	43	14	17	41	47	21	44	18	15	19	22	50	13	
OC (%)	0.57	1.38	0.94	0.47	0.59	1.03	0.47	0.57	0.64	0.82	0.64	0.72	0.60	1.15	0.76
pH	7.6	7.2	7.5	7.4	7.0	6.8	7.1	7.2	7.0	7.6	6.8	7.2	7.3	7.4	7.22
EC (mS/cm)	0.13	0.51	0.30	0.12	0.13	0.39	0.17	0.16	0.29	0.18	0.22	0.26	0.08	0.62	0.25
Extractable P(mg/kg)	83.32	72.89	56.29	72.77	55.52	56.80	69.54	67.70	87.11	49.55	65.89	80.41	66.41	58.63	67.34
Na (cmol(+)/Kg))	2.04	2.04	2.04	1.76	2.04	2.58	1.49	2.31	2.31	2.31	2.04	2.85	2.31	2.31	2.17
%TN	0.10	0.31	0.22	0.18	0.17	0.22	0.11	0.15	0.22	0.20	0.15	0.13	0.15	0.32	0.19
Long rains (masika) 2003															
Lab. Id	31&38	45	46	53	33	32	40	34	42	37	51	39	36	5	
OC (%)	0.57	0.88	0.64	0.64	0.80	1.33	0.51	0.55	0.57	0.64	0.68	0.51	1.07	0.9	0.74
pH	7.27	6.98	7.21	7.24	7.25	6.89	7.3	7.16	6.37	6.73	7.29	6.92	8.22	7.	7.15
EC (mS/cm)	0.30	0.35	0.16	0.15	0.16	0.55	0.11	0.17	0.39	0.23	0.17	0.06	0.18	0.2	0.23
Extractable P(mg/kg)	70.17	57.84	81.71	65.38	62.77	80.14	70.82	66.66	50.84	53.95	61.21	121.39	53.70	66.9	68.82
Na (cmol(+)/Kg))	2.31	2.58	2.31	3.13	2.58	2.58	1.76	2.85	2.04	1.76	2.31	2.58	3.94	2.5	2.52
%TN	0.16	0.18	0.18	0.17	0.17	0.29	0.15	0.15	0.17	0.20	0.18	0.15	0.22	0.2	0.19

4.6.2 Spatial variability of soil fertility in the runoff receiving area

Figures 4.16 – 4.22 present spatial variability of soil fertility in the three land suitability classes as perceived by farmers in lower zone (Makanya village). The soils particle size distributions (Figure 4.16) showed that, sand percentage was increasing from suitability class one to three while clay and silt percentages showed to be relatively high in land class one compared to others. The difference in levels of sand fraction in the three classes was not significant as all portrayed high percentages contents of sand. All in all, the observed variation existing could be associated with RWH practiced in the area. High soil moisture content in class one compared to other classes is expected due to harvested rainwater, which mostly decreases as one moves from class one to class three. The quantities of rainwater harvested create better environment to generate vegetation, hence high organic matter in land suitability class one. This organic matter is very important in the improvement of the soil biological and physical properties as well as chemical properties. On the other hand, relatively high clay and silt percentage could be related with RWH practice. The runoff rainwater collects silt and some clay particles in the upper catchment, harvested as sediments in the runoff. These are potential materials in RWH areas as in the head part where land class one is located there is a higher influence of RWH practice to the soil than others due to easy rainwater accessibility and sediment depositions. Land class three located in the tail part has minimum influence because of the lower chance of receiving runoff. However, currently an improvement has been observed in land class three due to improved water channel network facilitating the use of road water runoff generated by roof in the buildup areas in the village.

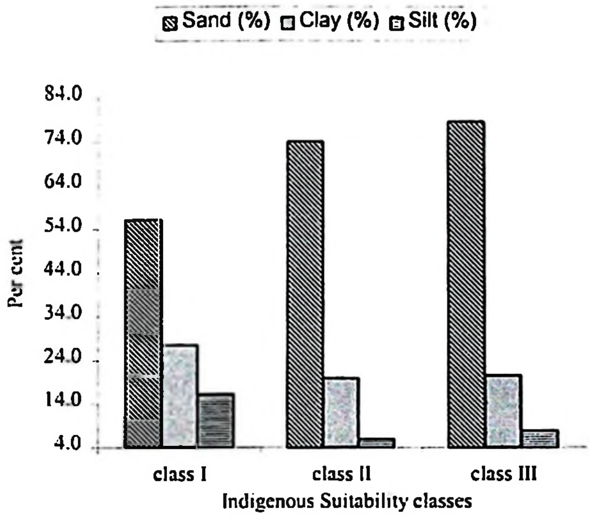


Figure 4.16. Soil particle size distribution in the indigenous suitability classes

Soil pH, electrical conductivity, and contents of soluble salts (Ca, Mg, K and Na) as presented in Figures 4.17, 4.18 and 4.22, respectively, increased from land class three in the tail part to land class one in the head part. This distribution pattern is most probably related to the amounts of water harvested and consequently plant growth and water percolating in the soil. As was observed in the assessment of soil fertility attributes in rainwater runoff, water was found to contain basic soluble salts and high pH (Figures 4.9 and 4.11 – 4.14) when runoff reaches in the lower zone. Obviously, this tends to influence the irrigated soil as well, however, this effect on the soil seems to decrease from class one to class three.

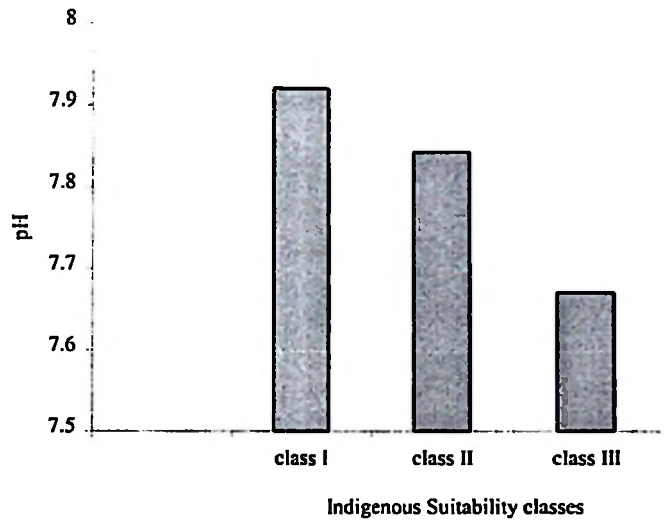


Figure 4.17. Soil pH pattern in the indigenous suitability classes

The pattern distribution of organic carbon and total nitrogen in the three classes (Figures 4.19 and 4.22), respectively, indicate high contents of organic carbon and total nitrogen in the indigenous land suitability class one, decrease in class two and some relatively increase is noted in class three. The relatively high contents of OC could be related with organic matter contained in runoff due to eroded soil surface organic matter. Also, sisal waste could be another contributing factor, as considered by many farmers in the area, to the main source for the soil fertility nutrients. Similar argument about the contribution of sisal waste to plant nutrients for maize crop, was reported by UNIDO and CFC (2001). The similarity of pattern distribution of OC and total N could indicate that probably the source of N is organic matter.

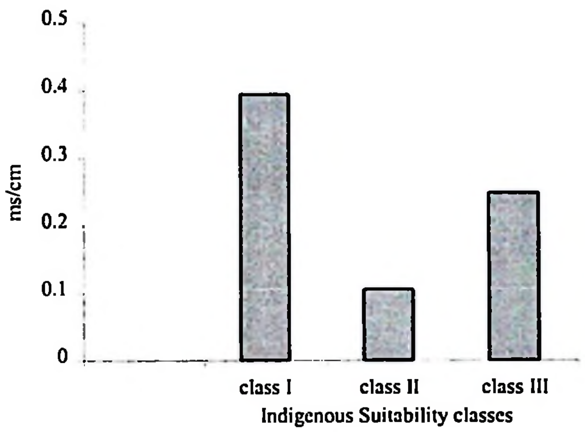


Figure 4.18. Electrical conductivity pattern in the indigenous suitability classes

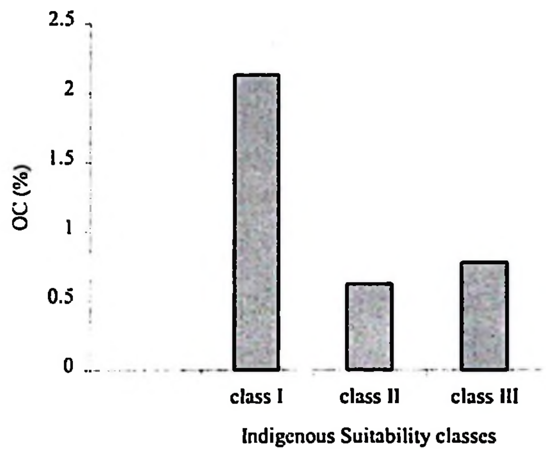


Figure 4.19. Organic carbon pattern in the indigenous suitability classes

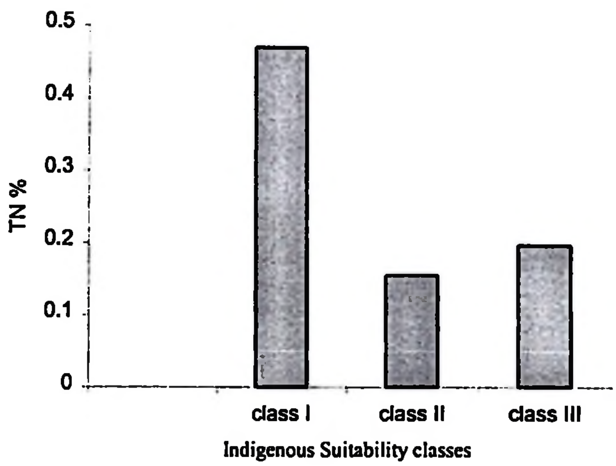


Figure 4.20. Total nitrogen pattern in the indigenous suitability classes

Figure 4.21 presents the extractable phosphorus pattern in the indigenous suitability classes. The results show that, extractable phosphorus tends to increase from the head to the tail part in the lower zone. This pattern could be the influence of RWH practice undertaken in the area. Soil moisture is expected to be high in the runoff receiving area and decreases towards the tail area. Therefore it may be true that the moisture availability facilitate also P availability to plants. Hence, this causing the decrease of P in the soil as the moisture increases.

Figure 4.21. Extractable phosphorus pattern in the indigenous suitability classes

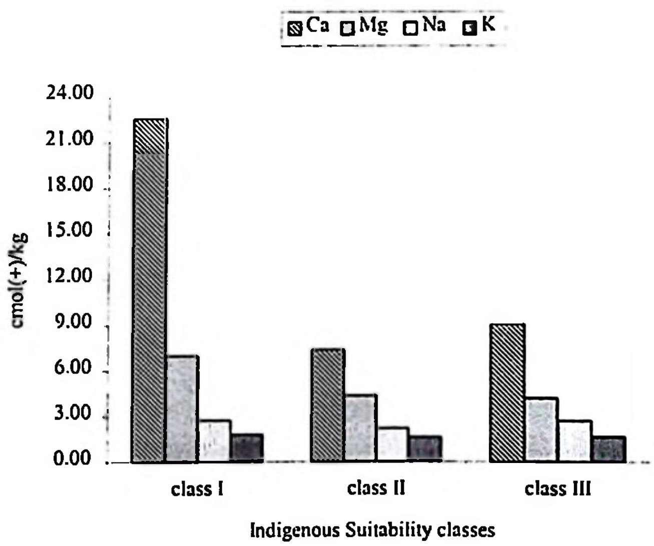


Figure 4.22. Exchangeable bases pattern in the indigenous suitability classes

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

The study attempted to assess the spatial and temporal variability of soil fertility under rainwater harvesting sytems in Makanya river catchment in Same district, Tanzania. On the bases of presented findings, the following conclusions can be drawn.

1. The study portrayed the decrese of K along the toposequence, and low levels of OC and N in the soil. Therefore, it is important to assess soil fertility status and variability in semi-arid areas particularly where there is growing need of RWH systems in order to improve yield in the sustainable way.
2. Spatial pattern distribution analysis has been observed as suitable technique to identify the soil fertility distribution patterns on the terrain. The use of GIS, GPS and Geostatistical analyst was critical in this context because fertility spatial pattern were well portrayed in the maps.
3. It was also observed that, where macro-catchment RWH by diverting runoff techniques is practiced, the distribution pattern of soil fertility in the areas was asociated with water, whereas in the other areas that ultilize side hill sheet or rill, soil fertility pattern distribution is governed by the nature of terrain (slope facet).
4. The fertility status of most of the soils in the study area were low to medium. The contributing parameters to the low fertility status of the soil include: high soil pH (alkaline soil reactions), low total nitrogen and organic matter, caused by low vegetation cover and limited on use of fertilizers and manures.

5. Runoff rainwater had high pH values and high amounts of sodium. Therefore it can be concluded that, in the long run, continuing harvesting the runoff for suplementary irrigation may cause the soil to become sodic and saline as well.

5.2 Recommendations

1. For optimal and sustainable crop production, appropriate soil fertility management packages have to be developed for the study areas, hence, adopted to the whole catchment area with recpect to village location along the toposequence. The use of manure should be incouranged where RWH techniques are practiced.
2. Under RWH systems, the qualities of irrigated water has to be given due consideration when applied or added to soils with high pH (sodic, sodic-saline and saline soils).
3. Most of the land identified by farmers as good quality land was found to have low soil fertility level. Therefore, categorization of soil quality based on farmers knowledge should be applied cautiously. Therefore, it is recommended that, scientific input for the improvement of indigenous classification of soil fertility is proposed, through participatory approach.
4. The soil fertility attributes combined with spatial pattern distribution can be useful in designing soil fertility management practice.
5. Further studies are proposed to investigate more about spatial patterns of soil moiture availability in area (soils) under rainwater harvesting systems, how is

related to soil fertility nutrients spatial pattern distribution in different RWH techniques in semi-arid areas.

REFERENCES

Agromisa Foundation (1997). *Water harvesting and soil moisture retention.* CTA, Wegeningen, The Netherlands. 92 pp.

Aronoff, S. (1989). *Geographic Information Systems: A management perspective.* WDL Publisher, Ottawa. 294pp.

Arshad, M. A., and Coen, G. M. (1992). Characterization of soil quality: physical and chemical criteria. *American Journal of Alternative Agriculture* 7: 12 – 16.

Barrows, H. L. and Kilmer, V. J. (1963). Plant nutrients losses from soil by water erosion. *Advanced Agronomy* 15: 303 – 316.

Boers, Th M. and Ben-Asher, J. (1982). A review of rainwater harvesting. *Agricultural Water Management* 5: 145-158.

Bremner, J. M. (1996). Total nitrogen. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 1085-1122.

Bwana, T. N. (2003). Assessment of in-situ rainwater harvesting techniques for improving smallholder maize production in semi-arid areas of Morogoro, Tanzania. Unpublished Dissertation for Award of MSc Degree at Sokoine University of Agriculture, Morogoro, Tanzania, pp. 30-33.

Carter, S. E. and Murwira, H. K. (1995). Spatial variability in soil fertility management and crop response in Mutoko communal area, Zimbabwe. *AMBIO* 22 (2): 77 – 84.

Chuma, E., Mombeshora, B. G., Murirwa, H. K. and Chikuvire, J. (2000). The dynamics of soil fertility management in communal areas of Zimbabwe. In: *Nutrients on the move. Soil fertility dynamics in African farming systems.* (Edited by Hilhorst, T. and Muchena, F. M.) International Institute of Environment and Development, London. pp. 45-64.

De Pauw, E. (1984). *Soils, physiography and agroecological zones of Tanzania.* Crop Monitoring and Early Warning Systems Project, FAO and GoT, Dar es salaam.

Dobermann, A., Goovaerts, P. and George, T. (1995). Source of soil variation in an acid Ultisol of the Philippines. *Geoderma* 68: 173-191

Environmental Systems Research Institute (1996). ESRI *Arc View GIS.* The Geographic Information System for Everyone. ESRI, Redlands, USA. 340pp.

Environmental Systems Research Institute (1996). ESRI Arc View GIS. *Spatial Analyst.* ESRI, Redlands, USA. 148pp.

Environmental Systems Research Institute (2001). ESRI *ArcGIS Geostatistical Analyst.* ESRI, Redlands, USA. 300pp.

EUROCONSULT (1989). *Agricultural Compendium for Rural Development in the Tropics and Subtropics.* Elsevier Science Publiushers. Amsterdam. 740pp.

FAO (1985). *Guidelines: Land evaluation for irrigated agriculture.* FAO Soils Bulletin No. 55. 231pp.

FAO (1991). *Water harvesting.* A manual for the design and construction of water harvesting schemes for plant production. 133pp.

FAO (1994). *Water Harvesting for improved Agricultural production.* Proceedings of the FAO Expert consultation. FAO, Roma. No. 3: 424pp.

FAO (2000). Manual of integrated soil management and conservation practices. *Land and Water Bulletin* 8. FAO, Roma, Italy. 214pp.

Gee, G. W. and Bauder, J. W. (1986). Particle Size Analysis. In: *Methods of Soil Analysis* Part I (Edited by Klute, A.). Soil Science Society of America, Inc. USA. pp. 404-408.

Gowing, J. W., Mahoo, H. F., Mzirai, O. B. and Hatibu, N. (1999). Review of Rainwater Harvesting Techniques and Evidence for their Use in Semi-Arid Tanzania. *Tanzania Journal of Agricultural Science* 2: 171-180.

Halvorson, J. J., Smith, J. L. and Rapendick, R. I. (1997). Issues of scale for evaluating soil quality. *Journal of Soil and Water Conservation* 1997: 26 – 30.

Hartsock, N. J., T. G. Mueller, G. W. Thomas, R. I. Barnhisel, K. L. Wells and S. A. Shearer (2000). Soil Electrical Conductivity Variability. In: Proc. 5th International conference on precision Agriculture. (Edited by. Robert, P. C *et al.*). [http:/www.bae.uky.edu/precag/PrecisionAg/Reports/Soil_EC_Var.htm] site visited on 26/7/2002.

Hatibu , N and Mahoo, H (1999). Rainwater technologies for agricultural production: A case of Dodoma, Tanzania. In: Conservation tillage with animal traction. *A resource book of the Animal Traction Network for Eastern and Southern Africa* (ATNESA). (Edited by Kaumbutho, P. G. and Simalenga, T.E.). Harare. pp 161-170.

Hatibu, N. (September 2003). Rainwater Management: Strategies for Improving Water Availability and Productivity in Semi-arid and Arid Areas. [http://www.iwmi.cgiar.org/home/rainwater.htm] site visited on 25/9/2003.

Hatibu, N. and Mahoo H. (2000). *Rainwater Harvesting for Natural Resources Management.* A planning guide for Tanzania. Sida's Regional Land Management Unit, Nairobi, Kenya. 144pp.

Hatibu, N., Kayombo, B., Mahoo, H., Ellis-Jones, J., Senkondo, E. M. and Simalenga, T. E. (1993). Evaluation and promotion of rainwater harvesting in semi-arid areas of Tanzania research project. *Rapid rural appraisal of Mwanga District.* pp. 52.

Hilhorst, T., Muchena, F., Defoer, T., Hassink, J., Jager, A., Smaling, E. and Toulmin, C. (2000). Managing Soil Fertility in Africa: diverse settings and changing practice. In: *Nutrients on the move. Soil fertility dynamics in African farming systems.* (Edited by Hilhorst, T. and Muchena, F. M.) International Institute of Environment and Development, London. pp. 1-28.

Hulugalle, N. R. (1990). Alleviation of soil constraints to crop growth in the upland alfisols and associated soil groups of the west African Sudan Savannah by tied-risges. *Soil and Tillage Research* 18: 231 – 248.

James, L. G. (1988). *Principles of Farm Irrigation System Design.* Washington State University. John Wiley & Sons, New York. pp 385-411.

Johnston, K., Hoef. J. M., Krivoruchko, K. and Lucas, N (2001). *Using ArcGIS. Geostatistical Analyst.* Environmental Systems Research Institute (ESRI), Redlands, USA. 300pp.

Kuo, S. (1996). Phosphorus. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 869-920.

Kuzyakova, I. F., Romanenkov, V. A. and Kuzyakov, Y. V. (2001). Application of Geostatistics in Processing the Results of Soil and Agrochemical studies. *Eurasian Soil Science*, Vol. 34, No 11: 1219-1228.

Lamers, J. P. A., Feil, P. R. and Buerkert, A. (2002). Spatial crop growth variability in Western Niger: the knowledge of farmers and research. [http: www.nuffic.nl/ciran/ikdm/3-3/articles/lamers.html] site visited on 26. 07. 2002.

Land Resources Development Centre (LRDC) (1987). *Tanzania: Profile of Agricultural Potential*. NRI, London. 26 pp.

Landon, J. R. (1991). *Booker Tropical Soil Manual*. A Hand Book for Soil Survey and Agricultural Land Evaluation in the Tropics and Sub-Tropics. Longman. New York. 450pp.

Laurin, R. and Thompson, D. (1992). *Fundamentals of Spatial Information Systems*. The APIC Series Number 37. Academic Press Ltd, London. 680pp.

Ley, G. J. (1990). Tillage and water management in southern highlands of Tanzania. *Preceedings of the First Annual Conference, SADC-L and WMRP*. October 1990, Gaborone Botswana, pp 225 – 233.

Lompo, F., Bonzi, M., Zougmor'e, R., and Youl, S. (2000). Rehabilitating Soil Fertility in Burkina Faso. In: *Nutrients on the move. Soil fertility dynamics in African farming systems*. (Edited by Hilhorst, T. and Muchena, F. M.) International Institute of Environment and Development, London. pp. 103-118.

Mallarino, A. (1998). Using precision agriculture to improve soil fertility management and on-farm research [http: www.ent.iastate.edu/ipm/icm/1998/4-9-1998/fertman.htm] site visited on 26/ 07/ 2002.

Martinez, L. J. and Zinck, J. A. (1994). Modelling spatial variations of soil compaction in Guaviare colonization area, Colombian Amazonia. *ITC Journal* 3: 252 - 263.

Mbuvi, J. P., Kironchi, G. and Mainga, P. M. (1997). Technical Note. Effect of topography and climate on soils of the northern slopes of Mount Kenya. *ITC Journal* 2: 154-159.

Melatic, J. T. and Hutchings, T. B. (1996). Selection and classification of irrigable land. In: *Irrigation of Agricultural Land*. (Edited by Hagan, L. M., Haise, H. R., and Edminster, T. W.). American Society of Agronomy. Madison, Wisconsin, USA. pp. 125-171.

Metternicht, G. and Zinck, A. (1996). Modelling salinity-alkalinity classes for mapping salt-affected topsoils in the semiarid valleys of Cochabamba, Bolivia. *ITC Journal* 2: 125 – 135.

Mueller, T. G., Wells, K. L., Thomas, G. W., Barnhisel, R. I., Hartsock, N. J., Shearer, S. A., Kumar, A. and Dillon, C. R. (2000). Soil Fertility Map Quality: Case Studies in Kentucky. In: Proc. 5th International conference on precision Agriculture. (Edited by. Robert, P. C *et al.*). [http:/www.bae.uky.edu/precag/PrecisionAg/Reports/Soil_fertility_map_quality.htm] site visited on 14/9/2002.

Nelson, D. W. and Sommers, L. E. (1996). Total Carbon, Organic Carbon and Organic Matter. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 961-1010.

Neue, H. U. and Snitwongse, M. R. (1988). *Nitrogen levels and N fertilizer management in lowland rice fields*. IRRI technical paper no. 28, Los Bonas, Philippines. pp 26.

Ngailo, J. A., Shaka, J. M., Kiwelu, A., and Msangi, A. (1994). *Soils of Maswa District and their sustainability for cultivation of maize, rice, cotton, sorghum, cassava, and extensive grazing*. Ministry of agriculture. Reconnaissance soil survey. Nation Soil Service ARI Mlingano, Tanga, Tanzania. Report no. 6, 64pp.

Nyambilila, A. (2003). Assessment of fertility status of soils of rice growing area of Same district, Kilimanjaro region, Tanzania. Unpublished Dissertation for award of MSc degree at Sokoine University of Agriculture, Morogoro, Tanzania, pp. 34-41.

Parr, J. F., Papendick, R. I., Hornick, S. B., and Meyer, R. E. (1992). Soil quality: attributes and relationship to alternative and sustainable agriculture. *American Journal of Alternative Agriculture* 7: 5 – 11.

Patel, R. M., Prasher, S. O. and Bonnell, R. B. (2000). Effects of water table depth, irrigation water salinity, and fertilizer application on root zone salt buildup. *Canadian Agricultural Engineering* 42(3): 111 – 115.

Pearson, C. J., Norman, D. W. and Dixon, J. (1995). Sustainable dryland cropping in relation to soil productivity. *FAO Soil Bulletin* 72. FAO Italy. 146pp.

Pierce, F. J., Larson, W. E., Dowdy, R. H., and Graham, W. A. P., (1983). Productivity of soils: Assessing long-term changes due to erosion. *Journal of Soil and Water Conservation*, 1983: 39 – 44.

Pieri, C. and Steinar, K. G. (1997). The role of soil fertility in sustainable agriculture with special reference to sub-Saharan Africa. *Agriculture and Rural Development* 4(1): 22-25.

Ponamperuna, F. N. (1975). *Chemical kinetics of wetland rice soils relative to soil fertility.* In Wetland soils: Characterisation, classification and utilization. IRRI, Los Bonas, Philippines. pp 109 – 122.

Rhoades, J. D. (1996). Salinity: Electical Conductivity and Total Dissolved Solids. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 417-436.

Rwehumbiza, F. B. R., Hatibu, H. and Machibya, M. (1999). Land characteristics, run-off and potential for rainwater harvesting in semi-arid areas of Tanzania. *Tanzania Journal of Agricultural Science* 2(2): 141 – 149.

Sauer, T. J., Daniel, T. C., Jr., Moore, P. A., Coffey, K. P., Nichols, D. J., and West, C. P. (1999). Poultry Litter and Grazing Animal Waste Effects on Runoff Water Quality. *Journal of Environmental Quality* 28(3): 860 – 865.

Senkondo, E. M. M., Mdoe, N. S. Y., Hatibu, N., Mahoo, H. and Gowing, J. W. (1999). Factors affecting the adoption of rainwater harvesting technologies in Western Pare Lowlands of Tanzania. *Tanzania Journal of Agricultural Science* 1(1): 81 - 89.

Smaling, E. M. A. and Fresco, L. O. (1993). A decision-support model for monitoring nutrient balance under agricultural land use (NUTMON). *Elsevier Science Publishers B. V., Amsterdam. Geoderma*, 60 (1993): 235 – 256.

Smaling, E. M. A., Stoorvogel, J. J. and Windmeijer, P. N. (1993). Calculation of soil nutrient balances in Africa at different scales, II – District scale. *Fertiliser Research* 35: 237 – 250.

Smith, J. L., Halvorson, J. J. and Papendick, R. I. (1993). Using multiple-variable indicator kriging for evaluating soil quality. *Soil Sc. Soc. Am. Journal*, 57: 743 – 749.

Soil-Water Management Research Group (SWMRG) (2001). *Assessment of RWH Demand and Efficacy. Final Technical Report. Annex D*, 39pp.

Stocking, M. (1994). Soil Erosion and Conservation: A Place for Soil Science? In: *Soil Science and Sustainable Land Management in the Tropics*. (Edited by Syers, J. K. and Rimmer, D. L.) CAB International, Wallingford, UK. pp. 40 - 58.

Stoorvogel, J. J. and Smaling, E. M. A. (1990). *Assessment of soil nutrient depletion in sub-Saharan Africa 1983 – 2000. Report 28*, The Winand Staring Centre for Integrated Land, Soil and Water Rsearch (SC-DLO), Wageningen.

Sumner, M. E. and Miller, W. P. (1996). Cation Exchange Capacity and Exchangeable Coefficients. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 1201-1232.

Thomas, G. W. (1996). Soil pH and Soil Acidity. In: *Methods of Soil Analysis*. Part 3. Chemical Methods. (Edited by Sparks, D. L., Page, A. L., Helmke, P. A., Loeppert, R. H., Soltanpour, P. N., Tabatabai, M. A., Johnston, C. T. and Sumner, M. E.) American Society of Agronomy and Soil Science of America, Inc., Madison, Wisconsin. pp. 475-490.

Uboldi, J. A. and Chuvieco, E. (1997). Technical note. Using remote sensing and GIS to assess current land management in the valley of the Colorado river, Argentina. *ITC Journal* 2: 160-165.

United Nations Industrial Development Organization (UNIDO) and Common Fund for Commodities (CFC) (2001). *Past Research Results and Present Production Practices in East Africa*. Present status, problems, opportunities and future prospects. Common Fund for Commodities. Technical paper No. 8. SISAL, Vienna. pp. 96-97.

United States Department of Agriculture (USDA) (1975). *Soil Taxonomy*. A basic system of soil classification for making and interpreting soil survey. Soil survey staff. Soil conservation services. Washington, DC.

APPENDICES

Appendix 1: Questionnaire 1

A sample of household questionnaire for soil fertility and fertility management strategies on the Makanya catchment –WPLL.

SECTION A: *Background information*

A1. Gender of household head:

A2. Age group:

i. 18 – 25
ii. 25 – 35
iii. 35 – 50
iv. 50 - 90

A3. Place of birth:

A4. Tribe:

A5. Place of usual residence:

A6. Years spent in this village:

A7. Highest level of education:

A8. Marital status:

A9. Number of dependants:

SECTION B: *Rainwater harvesting*

B1. Do you practice RWH?

B2. If yes, when did you start RWH?

B3. How much of your cultivated land is under RWH?

B4. What type of RWH are you using?

i. In-situ RWH
ii. Micro-catchment system
iii. Macro-catchment RWH.

B5. Is rainwater harvesting sufficient?

SECTION C: *Land use and land tenure*

C1. Do you own land for agricultural use?

C2. If C1 is yes, how did you get it?

i Purchased,
ii Rented
iii Inherited?

C3. How long have you possessed the land?

C4. Do you keep any livestock?

If yes, what type?

C5. Are you cultivating all your land?

C6. If not, how much land you cultivate per season (acres)?

C7. Reasons for reducing cultivated land?

i Long travelling distance to plot(s)
ii Reduced production
iii High input
iv Erosion
v Water shortage

C8. Are all your plots in one unit?
C9. Is your farming land enough?
C10. If not, what is your plan?

C11. What are current crops?
C12. What were your previous crops?
C13. Reasons for changing your previous crops?
C14. Do you plan to change your present crop?
C15. What kind of crops do you want to opt? Reasons:

SECTION D: *Soil erosion*
D1. Do you experience soil erosion on your land?

D2. Which features lead you to believe that such a problem exists?
D3. Do you use any measures to control erosion?
D4. Which measure do you use?
i Mulching
ii Crop residues
iii Crop rotation
iv Contour farming
v Terracing
vi Planting trees
vii Agro-forestry
viii Fallow
ix Others (specify)

SECTION E: *Soil fertility*
E1. Do you experience soil fertility changes on your farm?
E2. If yes, is it positive or negative?.
E3. What features lead you to believe that such fertility depletion or enrichment exists?
E4. If soil fertility increasing or decreasing, what are the major reasons?
E5. Do you use management practices to maintain or enrich soil fertility on your farm?
E6. Which of the following practices do you use?
i Fertilizer application
ii Manuring
iii Inter-cropping
iv Mulch or compost application
v Agroforestry
vi Crop residue application
vii Fallowing.
viii Others (specify)

E7. If you practice fallow, how long do you fallow?

Appendix 2: Questionnaire 2

A sample of household farmer questionnaire for farmyard manure use and management in Makanya village.

Name of household____________________ Date______________

Village________________ Ward____________ Division______________

A: BACKGROUND INFORMATION

Residence	Reasons for immigration

Residence: 1= I was born here, 2= Immigrated here
Reasons for immigration: 1= Searching for agricultural land where RWH is applicable, 2= I was accompanied with my parents, 3= Looking for green pasture, 4= Appointment transfer

B: RAINWATER HARVESTING AND SOIL FERTILITY

Do you harvest rainwater? 1= Yes, 2= No	

Q1: Crop fields, RWH and crop management

Crop fields	RWH categories	Indigenous land suitability classes	Soil fertility management strategies (a case of depletion)

RWH categories: 1= In-situ RWH, 2= Micro-Catchment RWH, 3= Macro-Catchment RWH
Soil fertility management strategies: 1= Application of inorganic fertilisers, 2= Application of farmyard manure, 3= Inter-cropping (legumes and cereals), 4= Application of mulch and farmyard manure, 5= Agro-forestry, 6= Application of crop residues, 7= Fallowing
Indigenous land suitability class: 1= class 1, 2= class 2, 3= class 3

Q2: For the past ten years, did you experience any soil fertility changes in your fields?

(____)

1= Yes, 2= No. If yes, what happened (_____) 1= enrichment, 2= depletion
If no, what are features lead you to believe that:

a)____
b)____
c)____

Q3: If inorganic fertilisers were applied, which types were applied? ________________
____

Q4: Do you own any livestock? (______) 1= Yes, 2= No. If yes, what type do you own?
1= cattle: total number____________
2= goats: total number ____________
3= sheep: total number ____________
4= chicken: total number ____________

Q5: If you are a livestock keeper, how do you use the farmyard manure produced by the animals or livestock. (______)
1= for sale
2= applied in the fields
3= given as an offer
4= Not used anyhow

Q6: If you are not using farmyard manure, then give the reasons for not using farmyard manure?
a)____
____

b)____
c)____

Q7: If you sell or give it to somebody as an offer, where is taken to: (___)
1= Tae 2= Mwembe 3. Bangalala 4= Chome 5= Vudee 6= other places:________

Q8: If farmyard manure is not used anyhow, where is it finally taken to?
a)____
____

b)____
c)____

Q9: If you are not a livestock keeper, and you are applying farmyard manure, where and how do you get it?
1 = purchasing 2. Offered 3. Collected from grazing area 4.________________________

Q10: If you are buying, offered or collected from grazing area, which area you're getting it from?
________________________________.

Q11: Give reasons for not using both inorganic fertilisers and farmyard manure?

a) ____

b) ____

c) ____

Thank you very much for your cooperation.

Appendix 3: Spatial and temporal soil fertility status in Makanya village:

Appendix 3a. Spatial and temporal soil fertility status in the crop fields of Mr. E. Mnyuku

Sample Id	OC (%)	%TN	Extractable P(mg/kg)	pH	EC	Exch. Bases (cmol(+)/Kg)				SOIL TEXTURE			
						Ca	Mg	Na		Sand (%)	Clay (%)	Silt (%)	Text class
i Short rains (vuli) 2002													
Mnyuku 23-25	1.79	0.42	48.52	8.1	0.3	21.6	6.78	3.13	2.4	56.0	31.0	13.0	SCL
Mnyuku 1-2	2.28	0.46	45.66	7.9	0.5	19.9	5.94	3.40	2.8	63.0	22.4	14.6	SCL
Mnyuku 6-8	2.34	0.50	42.47	8.0	0.4	24.8	7.49	2.04	1.7	50.7	31.7	17.6	SCL
Mnyuku 15-17	2.18	0.46	42.80	8.0	0.4	22.2	6.75	2.58	1.4	59.5	31.9	8.6	SCL
Mnyuku 3-5	2.38	0.56	39.95	7.9	0.5	24.4	7.06	2.58	2.0	50.7	29.9	19.4	SCL
Mnyuku 32-34	1.83	0.45	61.14	8.1	0.3	20.8	6.62	2.85	1.5	65.6	24.6	9.8	SCL
Mnyuku 26-28	1.97	0.42	43.57	8.1	0.3	20.5	6.44	2.58	1.7	58.7	27.5	13.8	SCL
Mnyuku 21-22	2.42	0.48	43.57	8.0	0.4	23.9	7.52	3.40	2.4	51.8	27.5	20.6	SCL
Mnyuku 12-14	2.26	0.43	56.04	8.0	0.3	21.6	6.54	2.85	1.4	59.5	24.1	16.4	SCL
Mnyuku 9-11	1.83	0.15	41.50	8.0	0.3	18.4	5.67	2.58	1.2	64.8	22.4	12.8	SCL
Mnyuku 29-31	2.18	0.46	48.50	8.1	0.3	23.5	7.52	3.13	1.7	59.5	25.8	14.7	SCL
Mnyuku 18-20	2.20	0.42	46.70	8.1	0.4	22.0	6.73	3.13	2.1	57.0	27.5	15.5	SCL
Mean	2.14	0.44	46.70	8.0	0.4	22.0	6.75	2.85	1.8	58.1	27.2	14.7	SCL
ii. Long rains (masika) 2003													
•	2.69	0.55	47.07	7.8	0.5	26	8.07	3.94	2.6	46.7	32.7	20.6	CL
Mnyuku 15-17	2.18	0.43	49.78	7.9	0.5	22.7	7.32	1.22	1.5	60.4	24.1	15.5	SCL
Mnyuku1-2	2.24	0.46	44.88	7.9	0.5	21.8	6.55	3.13	1.8	57.0	29.2	13.8	SCL
Mnyuku 24-25	2.36	0.46	47.87	7.9	0.4	22.3	7.14	2.85	1.8	53.6	31.0	15.5	SCL
Mnyuku 3-5	2.30	0.48	45.71	8.0	0.4	25.7	7.32	3.67	2.0	47.2	31.0	21.8	SCL
Mnyuku 6-8	2.44	0.50	47.07	8.0	0.3	25.1	8.11	3.40	2.0	43.7	34.4	21.9	C L
Mnyuku 32-34	2.44	0.49	56.80	7.8	0.5	22.7	6.68	2.58	1.4	65.6	22.4	12.0	SCL
Mnyuku 29-31	2.52	0.48	43.57	7.9	0.4	19.7	5.93	2.85	1.5	62.2	22.4	15.5	SCL
Mnyuku 12-14	1.72	0.39	66.82	8.0	0.3	19.9	5.74	2.58	1.4	61.3	21.1	17.6	SCL
Mnyuku 26-28	0.64	0.48	50.32	8.0	0.3	19.2	5.98	2.85	1.7	59.5	24.6	15.8	SCL
Mnyuku 18-20	1.99	0.46	45.91	8.1	0.3	23.6	7.79	1.76	2.3	56.0	31.7	12.3	SCL
Mnyuku 9-11	2.03	0.48	42.29	7.9	0.4	22.2	7.0	2.04	1.2	61.3	25.8	12.9	SCL
Mean	2.13	0.47	49.01	7.9	0.4	22.6	6.97	2.74	1.8	56.2	27.5	16.3	SCL

KEY: C: Clay, SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Appendix 3b. Spatial and temporal soil fertility status in the crop fields of Mr. A. Simba

Sample Id	OC (%)	%TN	Extractable P(mg/kg)	pH	EC	Exch. Bases (cmol(+)/Kg)				SOIL TEXTURE			
						Ca	Mg	Na	K	Sand (%)	Clay (%)	Silt (%)	Text class
i. Short rains (vuli) 2002													
Simba 4-5	0.66	0.22	57.07	7.8	0.19	11.2	6.64	2.85	3.27	69.0	22.4	8.6	SCL
Simba 8-9	0.72	0.21	55.19	7.7	0.26	7.28	5.09	2.04	2.18	75.9	13.8	10.3	SL
Simba 1	0.59	0.18	67.64	7.8	0.20	5.78	3.78	2.85	3.11	75.4	15.5	9.2	SL
Simba 21-22	0.59	0.15	66.00	7.7	0.12	8.55	4.73	2.31	2.18	75.9	17.2	6.9	SL
Simba 14	0.74	0.18	65.19	7.7	0.20	8.18	4.44	2.85	2.80	74.2	22.9	2.9	SCL
Simba 2-3	0.62	0.15	59.51	7.7	0.22	6.93	4.11	2.31	2.33	77.1	19.4	3.5	SL
Simba 10-11	0.72	0.15	53.83	7.9	0.11	7.11	4.65	1.76	2.02	58.7	27.5	13.8	SCL
Simba 17-18	0.74	0.21	56.00	7.9	0.15	8.70	4.52	1.76	2.02	70.8	20.6	8.6	SCL
Simba 19-20	0.66	0.17	57.35	7.8	0.14	7.92	4.33	2.04	2.02	72.5	20.6	6.9	SCL
Simba 15-16	0.64	0.21	64.91	7.5	0.14	6.94	4.27	2.04	1.87	77.6	18.9	3.4	SL
Simba 12-13	0.53	0.17	56.53	7.8	0.16	5.57	3.72	2.04	2.02	75.4	17.2	7.4	SL
Simba 6-7	1.01	0.24	66.55	7.6	0.33	9.75	6	3.67	2.80	63.0	27.5	9.4	SCL
Mean	0.69	0.19	60.48	7.7	0.19	7.83	4.69	2.38	2.39	72.1	20.3	7.6	SCL
ii. Long rains (masika) 2003													
Simba 19-20	0.74	0.15	58.16	7.7	0.09	8.89	4.8	2.04	1.71	72.5	21.1	6.4	SCL
Simba 15-16	0.70	0.17	51.12	7.7	0.10	6.44	3.75	1.76	1.09	75.9	19.4	4.7	SL
Simba 1	0.39	0.14	47.87	7.9	0.06	6.28	3.89	1.76	1.56	78.9	17.6	3.5	SL
Simba 2-3	0.64	0.14	50.32	7.8	0.11	6.65	3.87	2.31	1.87	75.9	19.4	4.7	SL
Simba 14	0.62	0.17	60.05	7.6	0.10	7.88	4.01	2.85	2.49	71.8	20.6	7.5	SCL
Simba 21-22	0.57	0.14	63.03	7.7	0.13	6.95	4.02	2.58	2.02	75.9	17.2	6.9	SL
Simba 10-11	0.51	0.14	46.26	8.2	0.08	8	4.02	2.04	1.25	77.1	17.2	5.7	SL
Simba 17-18	0.72	0.2	50.58	7.9	0.15	5.6	4.33	1.49	1.09	72.5	20.6	6.9	SCL
Simba 12-13	0.47	0.17	47.07	7.8	0.08	6.16	4.01	2.04	1.40	77.1	15.8	7.0	SL
Simba 8-9	0.57	0.18	51.12	8.1	0.09	7.46	4.89	2.31	1.40	74.2	22.9	2.9	SCL
Simba 6-7	0.92	0.15	56.28	7.9	0.19	10.2	5.96	2.58	2.02	64.8	25.8	9.4	SCL
Simba 4	0.62	0.13	49.78	7.9	0.10	7.77	4.62	2.58	1.56	71.8	22.4	5.8	SCL
Mean	0.62	0.16	52.64	7.8	0.11	7.35	4.35	2.20	1.62	74.0	20.0	6.0	SL

KEY: C: Clay, SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Appendix 3c. Spatial and temporal soil fertility status in the crop fields of Mr. J. Elinazi

Sample Id	OC (%)	%TN	Extractable P (mg/kg)	pH	EC	Exch. Bases (cmol(+)/Kg)				SOIL TEXTURE			
						Ca	Mg	Na	K	Sand (%)	Clay (%)	Silt (%)	Text class
i Short rains (vuli) 2002													
James 23-24	1.15	0.32	58.63	7.4	0.62	14.42	3.35	2.31	2.02	70.1	22.4	7.6	SCL
James 5-6	0.94	0.22	56.29	7.5	0.30	8.80	3.66	2.04	1.56	77.1	17.2	5.7	SL
James 21	0.82	0.20	49.55	7.6	0.18	8.15	3.49	2.31	1.56	75.9	17.2	6.9	SL
James 11	0.47	0.18	72.77	7.4	0.12	6.00	3.24	1.76	1.40	78.9	17.6	3.5	SL
James 15-16	0.64	0.22	87.11	7.0	0.29	8.59	4.20	2.31	1.40	73.6	18.9	7.5	SL
James 19-20	0.64	0.15	65.89	6.8	0.22	6.38	3.52	2.04	1.25	75.9	18.9	5.2	SL
James 2	0.57	0.10	83.32	7.6	0.13	8.39	4.18	2.04	1.40	73.6	18.9	7.5	SL
James 12	0.47	0.11	69.54	7.1	0.17	6.64	3.51	1.49	1.09	78.9	15.5	5.6	SL
James 17-18	0.72	0.13	80.41	7.2	0.26	7.76	3.83	2.85	1.71	54.2	20.6	25.1	SCL
James 9-10	0.59	0.17	55.52	7.0	0.13	6.43	3.39	2.04	0.93	75.4	18.9	5.7	SL
James 4	1.38	0.31	72.89	7.2	0.51	10.65	3.50	2.04	1.40	73.6	18.9	7.5	SL
James 13-14	0.57	0.15	67.70	7.2	0.16	5.40	2.82	2.31	1.25	75.4	17.2	7.4	SL
James 7-8	1.03	0.22	56.80	6.8	0.39	7.78	3.84	2.58	1.25	73.6	20.6	5.8	SCL
James 22	0.60	0.15	66.41	7.3	0.08	5.64	3.34	2.31	1.25	78.9	15.5	5.6	SL
Mean	0.76	0.19	67.34	7.2	0.25	7.93	3.56	2.17	1.39	73.9	18.5	7.6	SL
ii. Long rains (masika) 2003													
James 1-2	0.57	0.16	70.17	7.3	0.3	7.71	3.97	2.31	1.32	74.5	18.1	7.5	SL
James 7-8	1.33	0.29	80.14	6.9	0.6	12.4	3.78	2.58	2.02	61.3	22.9	15.8	SCL
James 9-10	0.80	0.17	62.77	7.3	0.2	7.89	3.81	2.58	1.25	77.1	17.2	5.7	SL
James 13-14	0.55	0.15	66.66	7.2	0.2	6.99	3.74	2.85	1.56	75.4	19.4	5.3	SL
James 22	1.07	0.22	53.70	8.2	0.2	9.74	3.72	3.94	3.11	74.2	19.4	6.4	SL
James 21	0.64	0.20	53.95	6.7	0.2	7.62	2.96	1.76	1.25	75.4	17.2	7.4	SL
James 17-18	0.51	0.15	121.39	6.9	0.1	6.96	3.91	2.58	1.09	70.1	22.4	7.6	SCL
James 12	0.51	0.15	70.82	7.3	0.1	5.45	3.14	1.76	1.09	78.9	15.5	5.6	SL
James 15-16	0.57	0.17	50.84	6.4	0.4	9.01	4.95	2.04	0.93	70.1	22.4	7.6	SCL
James 3-4	0.88	0.18	57.84	7.0	0.4	8.07	3.58	2.58	1.25	75.4	17.2	7.4	SL
James 5-6	0.64	0.18	81.71	7.2	0.2	6.39	4.01	2.31	1.25	75.4	17.2	7.4	SL
James 19-20	0.68	0.18	61.21	7.3	0.2	8.17	3.67	2.31	1.40	71.8	21.1	7.0	SCL
James 23-25	0.92	0.22	66.93	7.3	0.2	11.8	4.44	2.58	1.87	69.0	24.1	6.9	SCL
James 11	0.64	0.17	65.38	7.2	0.2	9.97	4.98	3.13	2.65	77.1	17.2	5.7	SL
Mean	0.74	0.19	68.82	7.2	0.2	8.44	3.9	2.52	1.57	73.3	19.4	7.4	SL

KEY: C: Clay, SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Appendix 4: Some chemical properties of rainwater runoff on the Makanya river catchment

						Base content in solution (cmol(+)/l)			
Rain season	Sample Id	Village	Field date	pH	EC (mS/cm)	Ca	Mg	K	Na
Vuli 2002-3	Makanya bridge	Makanya	01.11.02	8.1	0.70	0.13	0.15	0.04	0.41
	Makanya	Makanya	20.11.02	8.3	0.36	0.06	0.08	0.02	0.20
	Makanya	Makanya	22.12.02	8.0	0.34	0.04	0.08	0.02	0.22
	Makanya	Makanya	31.12.02	8.3	1.02	0.12	0.30	0.05	0.55
	Makanya	Makanya	02.01.03	8.6	0.74	0.06	0.15	0.02	0.37
	Mean			8.3	0.6	0.1	0.2	0.0	0.4
Vuli 2002-3	Kimunyu	Mgwasi	01.11.02	8.4	0.55	0.05	0.11	0.02	0.38
	Mwembe	Mgwasi	20.11.02	7.9	0.25	0.03	0.05	0.01	0.12
	Mwembe	Mgwasi	22.12.02	8.0	0.30	0.02	0.05	0.01	0.24
	Mwembe	Mgwasi	31.12.02	8.7	1.22	0.06	0.26	0.01	0.74
	Mwembe	Mgwasi	02.01.03	8.5	0.73	0.04	0.15	0.01	0.40
	Mean			8.3	0.61	0.04	0.12	0.01	0.38
Vuli 2002-3	Mwembe natural forest	Mwembe	2002	8.7	1.06	0.07	0.34	0.01	0.39
Vuli 2002-3	Tae	Tae	13.10.02	8.2	0.13	0.00	0.02	0.00	0.12
	Tae Malewa stream	Tae	16.10.02	8.3	0 16	0.01	0.04	0.00	0.09
	Tae	Tae	31.12.02	8.4	0.34	0.02	0.11	0.00	0.10
	Mean			8.3	0.21	0.01	0.06	0.00	0.10
Kipupwe 2003	W1	Tae	18.03.03	8.2	0.14	0.01	0.03	0.00	0.07
Masika 2003	W3	Makanya	02.04.03	8.4	0.98	0.07	0.14	0.02	0.54
	W4	Makanya	02.04.03	8.1	0.33	0.04	0.07	0.02	0.18
	W5	Makanya	02.04.03	8.3	0.93	0.07	0.14	0.02	0.41
	W9	Makanya	05.04.03	8.1	0.30	0.03	0.06	0.02	0.14
	W7	Makanya	05.04.03	8.0	0.26	0.03	0.06	0.02	0.15
	W8	Makanya	05.04.03	8.0	0.29	0.04	0.06	0.02	0.14
	W11	Makanya	07.04.03	7.1	0.99	0.31	0.26	0.15	0.25
	W12	Makanya	07.04.03	8.2	0.82	0.11	0.15	0.03	0.52
	W13	Makanya	07.04.03	7.4	1.23	0.35	0.32	0.14	0.26
	W14	Makanya	07.04.03	8.1	0.81	0.14	0.20	0.04	0.49
	W2	Makanya	24.03.03	7.8	0.66	0.18	0.27	0.08	0.46
	Mean			7.9	0.69	0.13	0.16	0.05	0.32
Masika 2003	W10	Mgwasi	07.04.03	8.5	1.66	0.13	0.27	0.03	1.09
	W6	Mgwasi	05.04.03	8.1	0.16	0.01	0.04	0.00	0.06
	Mean			8.3	0.91	0.07	0.15	0.01	0.57
Masika 2003	W15	Tae	24.04.03	8.1	0.14	0.01	0.03	0.00	0.06

Appendix 5: Guide to soil fertility ratings (Landon, 1991)

(i) Organic matter and total nitrogen

		Very low	Low	Medium	High	Very high
Organic matter	%	<1.0	1.0 – 2.0	2.1 – 4.2	4.3 – 6.0	>6.0
Organic C	%	<0.60	0.60-1.25	1.26-2.50	2.51-3.50	>3.50
Total N	%	<0.10	0.10 – 0.20	0.21-0.50	0.51-1.00	>1.0.00

C/N ratios indicate the quality of the organic matter:

- C/N 8-13: good quality
- C/N 14 –20: moderate quality
- C/N >: 20 poor quality

(ii) Soil reaction

Soil reaction (pH H_2O) is classified as follows:

Extremely acid -	pH below 4.5
Very strongly acid	pH 4.5 to 5.0
Strongly acid	pH 5.1 to 5.5
Medium acid	pH 5.6 to 6.0
Slightly acid	pH 6.1 to 6.5
Neutral	pH 6.6 to 7.3
Mildly alkaline	pH 7.4 to 7.8
Moderately alkaline	pH 7.9 to 8.4
Strongly alkaline	pH 8.5 to 9.0
Extremely alkaline	pH above 9.0

(iii) Available phosphorus

		Low	Medium	high
Avail. P (Bray I	mg/kg	<7	7-20	>20
Avail. P (Olsen)	mg/kg	<5	5-10	>10

Available phosphorus is determined by the Bray I method if the pH in H_2O of the soil is less than 7.0 In soils with a pH in H_2O of more than 7.0, the Olsen method is used.

(iv) (iv) Cation Exchange Capacity (CEC)

		Very low	Low	Medium	High	Very high
CEC	Me/100g	<6.0	6.0 12.0	12.0 – 25.0	25.0 –40.0	> 40.0

CEC is determined using IM ammonium acetate in soils with pH < 7.5; In soils with pH > 7.5 CEC is determined using IM sodium acetate.

(v) Exchangeable calcium

		Very low	Low	Medium	High	Very high
Ca (Clayey soils, rich in 2:1 clays)	me/100g	<2.0	2.0-5.0	5.1-10.0	10.1-20.0	>20.0
Ca (Loamy soils)	me/100g	<0.5	0.5-2.0	2.1-4.0	4.1-6.0	>6.0
Ca (Kaolinitic and sandy soils)	me/100g	<0.2	0.2-0.5	0.6-2.5	2.6-5.0	>5.0

(vi) Exchangeable magnesium

		Very low	Low	Medium	High	Very high
Mg (Clayey soils)	me/100g	<0.3	0.3-1.0	1.1-3.0	3.1-6.0	>6.0
Mg (Loamy soils)	me/100g	<0.3	0.3-0.7	0.8-2.0	2.1-4.0	>4.0
Mg (Sandy soils)	me/100g	<0.2	0.2-0.5	0.6-1.0	1.1-2.0	>2.0

(vii) Exchangeable potassium

		Very low	Low	Medium	High	Very high
K (Clayey soils)	me/100g	<0.20	0.20-0.40	0.41-1.20	1.21-2.00	>2.00
K (Loamy soils)	me/100g	<0.13	0.13-0.25	0.26-0.80	0.81-1.35	>1.35
K (Sandy soils)	me/100g	<0.05	0.05-0.10	0.11-040	0.41-0.70	>0.70

(viii) Exchangeable sodium

		Very low	Low	Medium	High	Very high
Na	Me/100g	<0.10	0.10-0.30	0.31-0.70	0.71-2.00	>2.00

More important than the absolute level of exchangeable Na is the Exchangeable Sodium Percentage (ESP) calculated by dividing exchangeable Na by CEC (x 100). ESP values are a measure of the sodicity of the soil.

(ix) Soil sodicity

	Non-sodic	Slightly sodic	Moderately sodic	Strongly sodic	Very strongly sodic	Extremely sodic
ESP	0-5	6-10	11-15	16-25	26-35	>35

ESP – Exchangeable Sodium Percentage (average over the root zone)

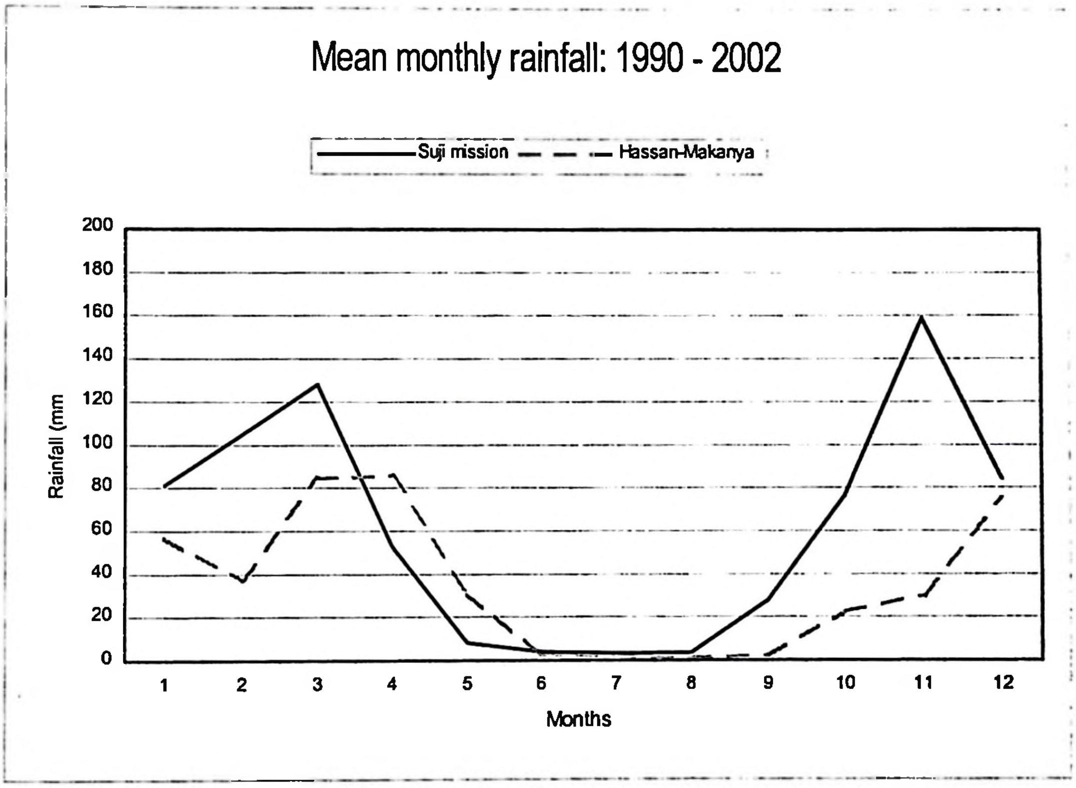
(x) Soil salinity

	Non-saline	Slightly saline	Moderately saline	Strongly saline
Ece mS/cm	0-4	5-8	9-15	>15

ECe – Electrical conductivity of the soil saturation extract (average over the root zone).

(xi) Base saturation

	Very low	Low	Medium	High	Very high
Base saturation %	<20	20-40	41-60	61-80	>80



Appendix 6: Rainfall data in the study area

Appendix 7: Soil sampling distribution in RWH systems

Appendix 7.1. Mwembe village soil sample GPS points

Point Id	X-coord	Y-coord	Farmer name	RWH system
MW1	370656	9537021	Omari Mrutu	Road rainwater (Micro-catchment)
MW2	370870	9537091	Omari Mlekea	Micro-catchment
MW3	371231	9539427	Janet Marko	Micro-catchment
MW4	370935	9539439	Abdalla Kadufa	In-situ
MW5	371763	9540579	Walter Mjema	Macro-catchment "*ndiva*"
MW6	371674	9540639	Walter Mjema	In-situ
MW7	372064	9540454	Shabani Kila	Micro-catchment
MW8	371821	9539782	Solomon Ramadhan Mkumbwa	In-situ
MW9	371645	9539750	Daudi Abdalla	Micro-catchment
MW10	371498	9539850	Elibariki Mchani	In-situ
KISIMA	371337	9539285	Kisima	

Appendix 7.2. Tae village soil sample GPS points

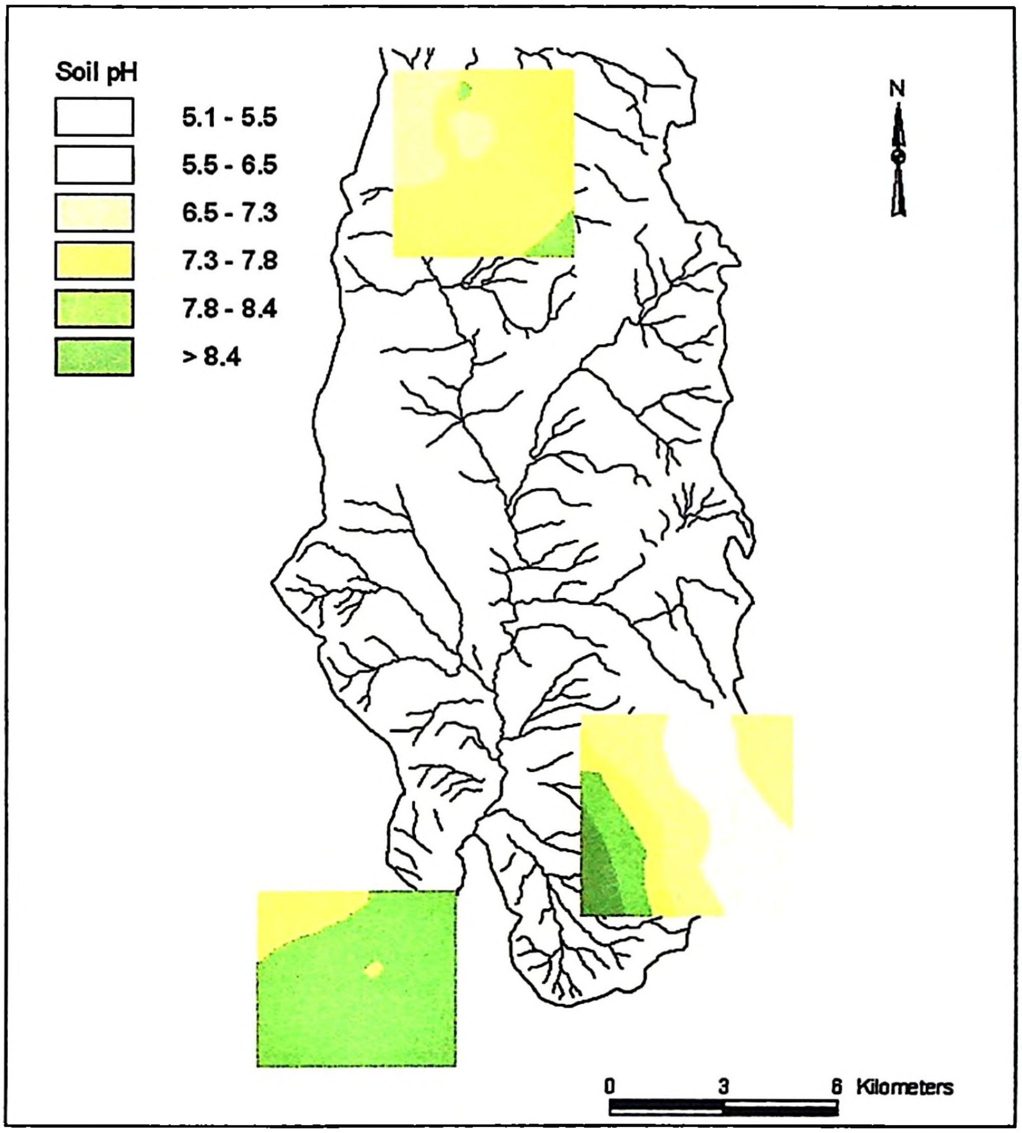
Point_Id	X-coord	Y-oord	RWH system
Tae1	376584	9520406	In-situ
Tae2	377226	9520098	In-situ
Tae3	377503	9520216	In-situ
Tae4	377885	9520335	In-situ
Tae5	378605	9522648	Macro-catchment "*ndiva*"
Tae6	379048	9522789	Macro-catchment "*ndiva*"
Tae7	378862	9521310	In-situ
Tae8	378071	9520168	In-situ
Tae9	377313	9520719	Macro-catchment "*ndiva*"
Tae10	377687	9520590	Macro-catchment "*ndiva*"
Tae11	377809	9521142	Macro-catchment "*ndiva*"
Tae12	377434	9521376	Macro-catchment "*ndiva*"
Tae13	376964	9521999	Macro-catchment "*ndiva*"

Appendix 7.3. Makanya village soil sample GPS points

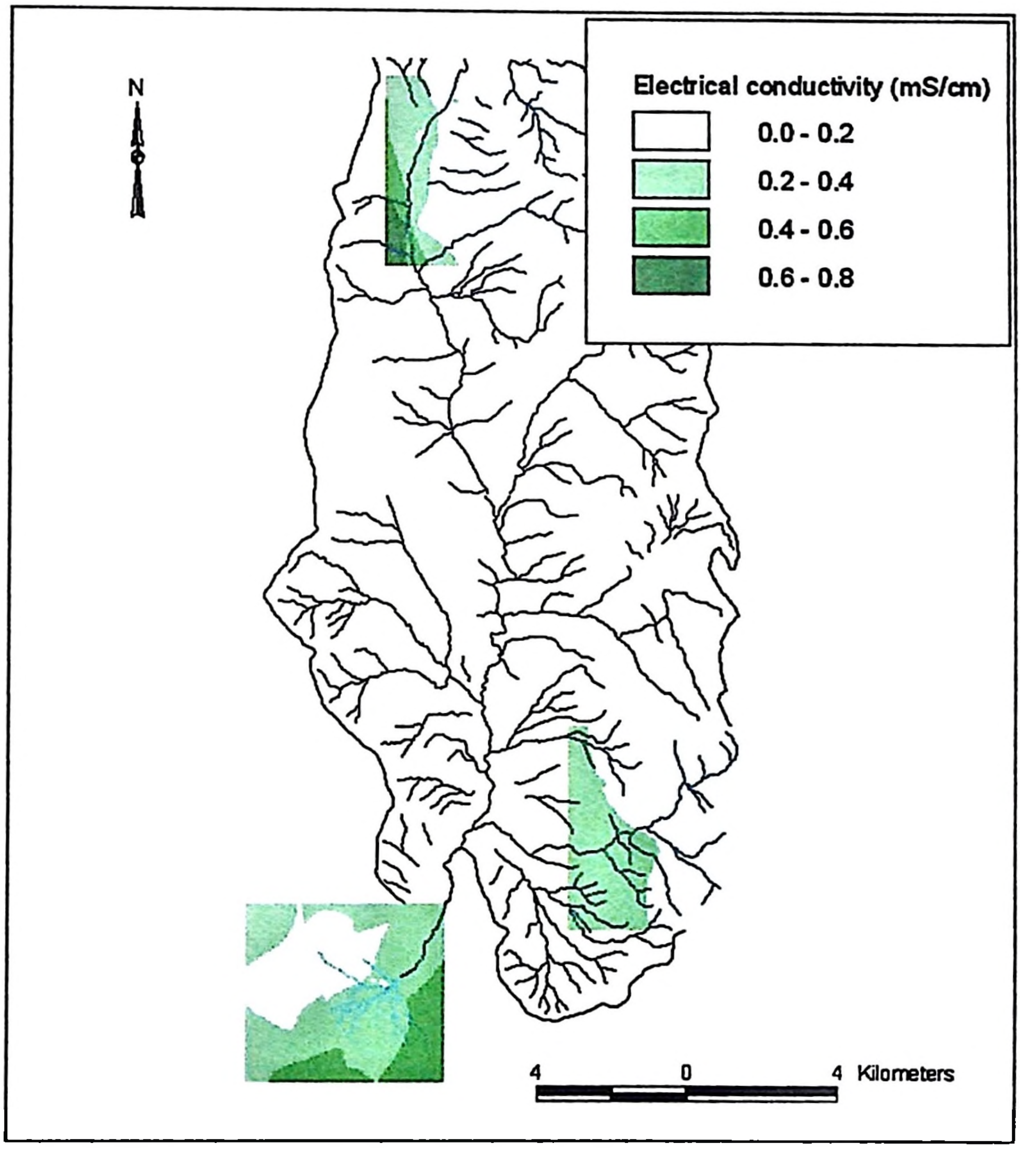
Sample Id.	X-coordinate	Y-coordinate	RWH system
Shabani Bakari	370092	9517167	Macro-catchment
Fatuma Hussen	370157	9517189	Macro-catchment
Tusu Juma I	370266	9517009	Macro-catchment
Majid Sengasu	369965	9517132	Macro-catchment
Tusu Juma II	370146	9517126	Macro-catchment
Mnyuku	370499	9516740	Macro-catchment
Simba	369643	9517218	Macro-catchment
James	367055	9518462	In-situ and Micro-catchment

Appendix 8: Maps of some of the soil fertility attributes in the study area

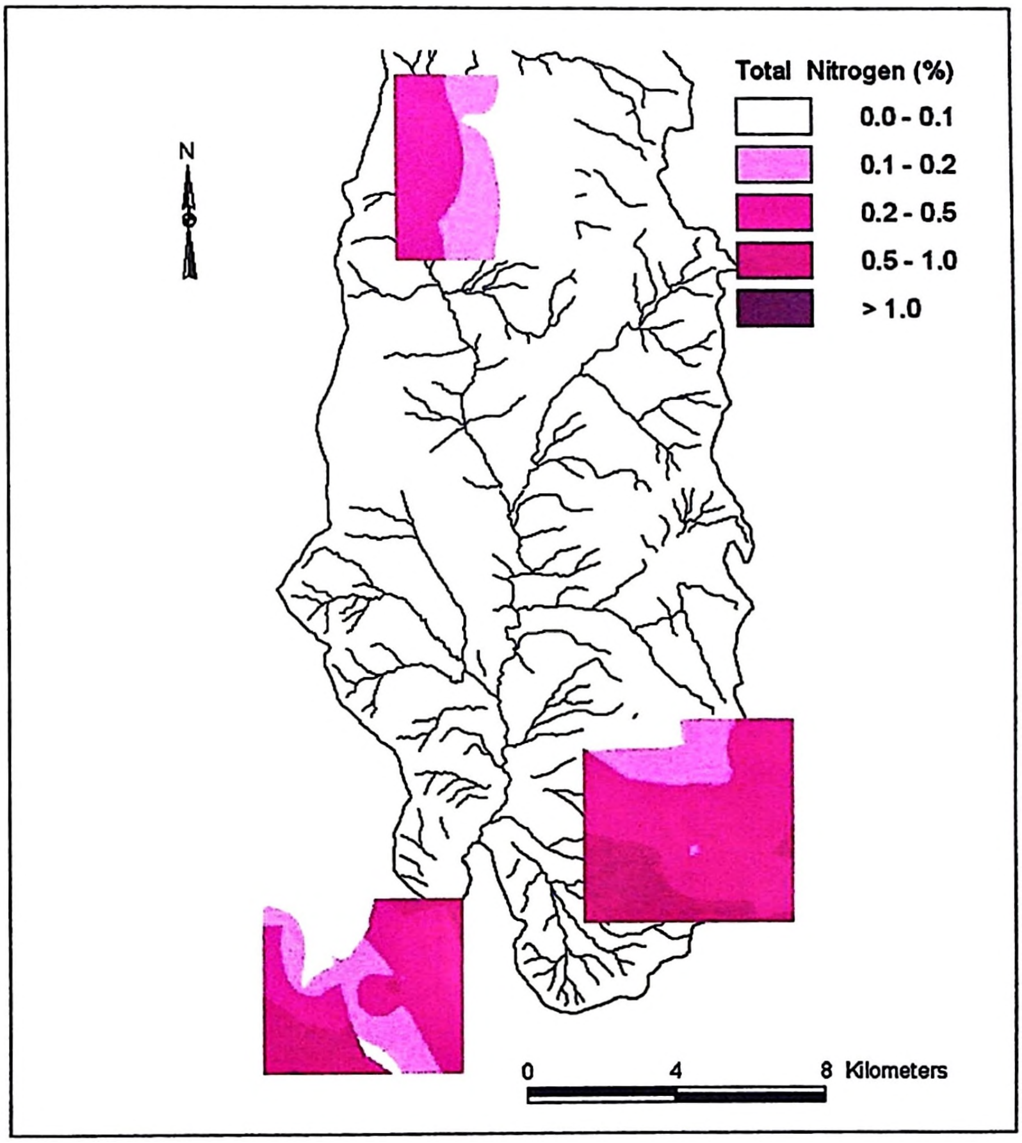
(a) Soil pH map of the study area



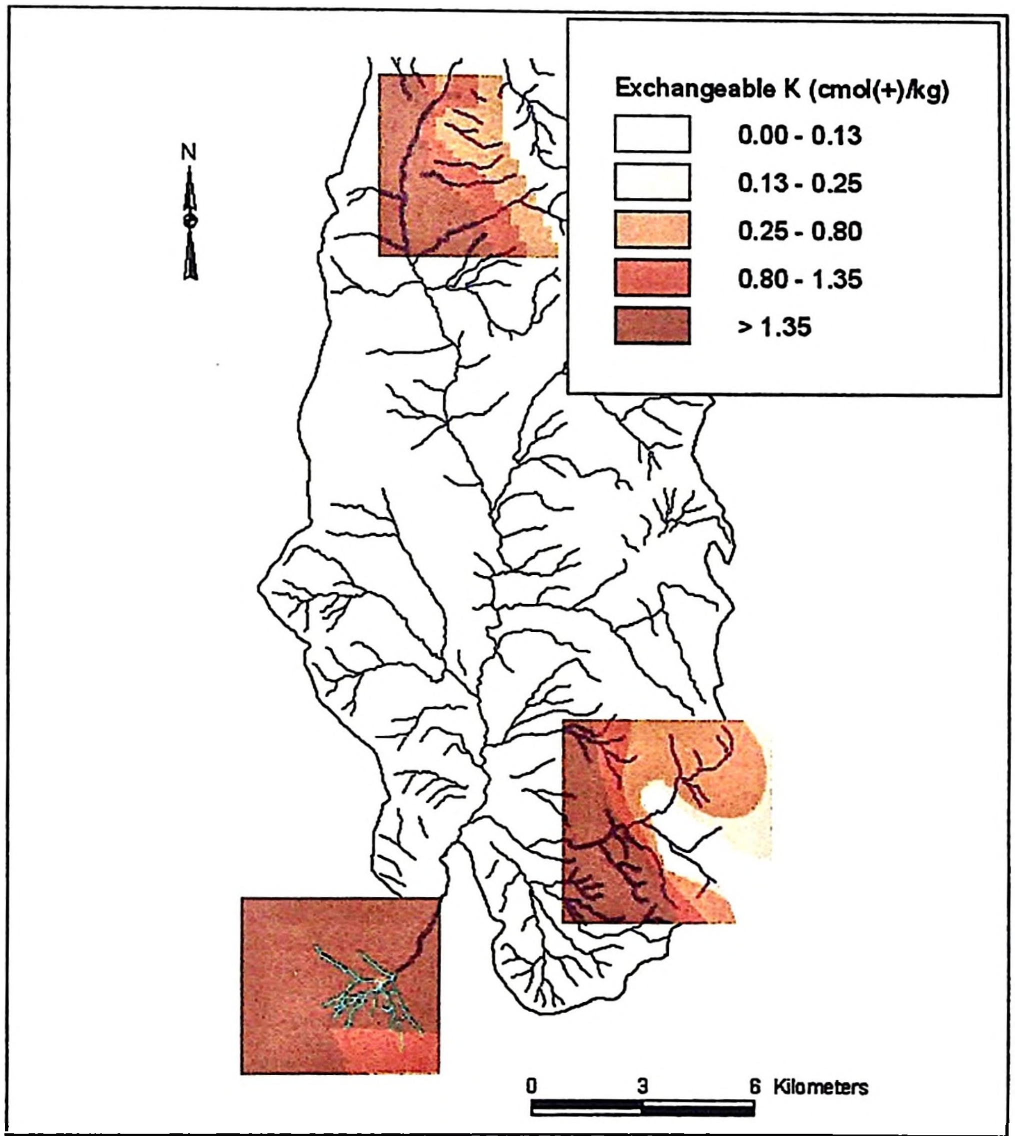
(b) Electrical conductivity map of the study area



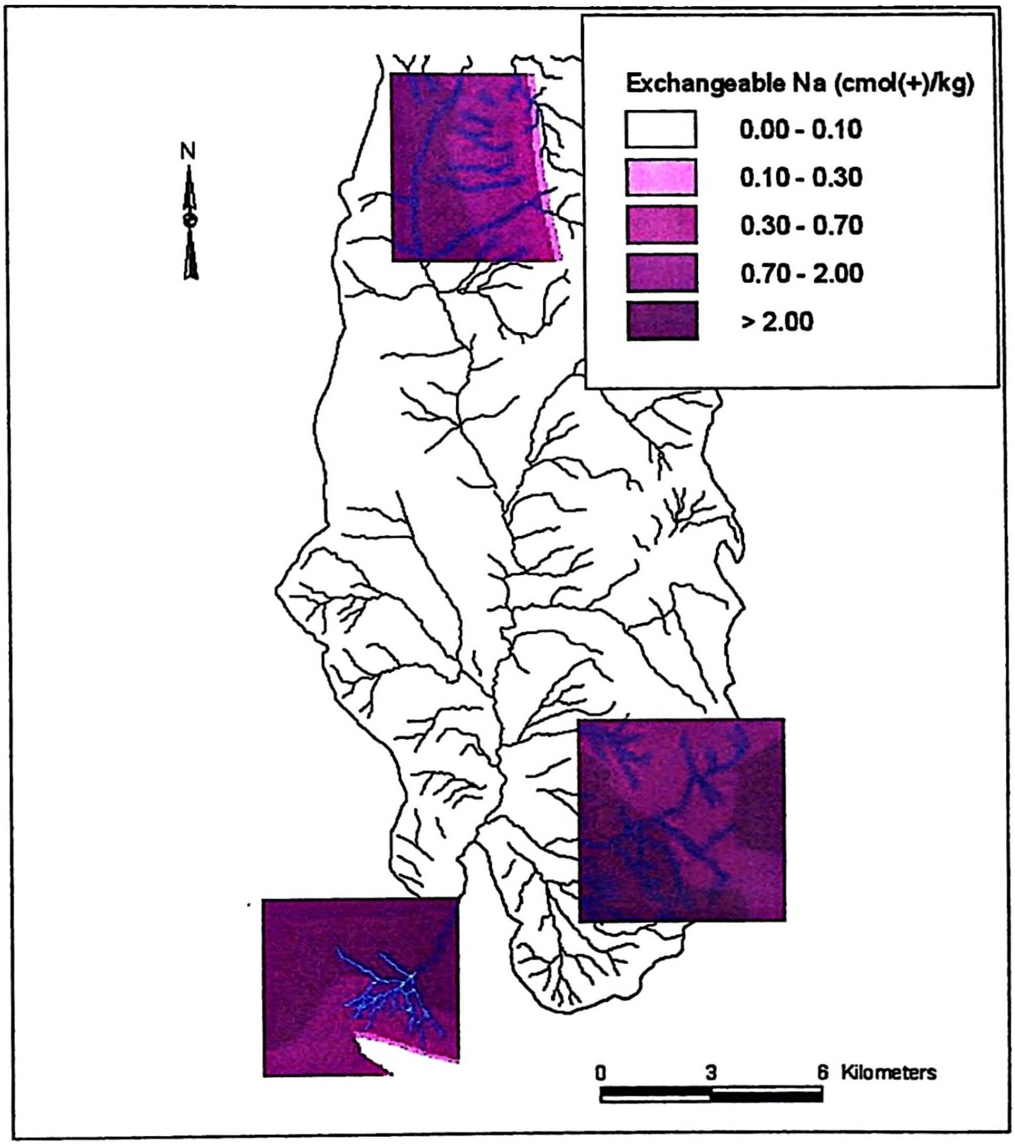
(c) Total nitrogen map of the study area



(d) Extractible potassium map of the study area



(e) Extractable sodium map of the study area



Appendix 9: Some of the properties of the soils on the Makanya river catchment

Appendix 9.1. Some of the properties of the soils from the crop fields at the lower zone of the catchment (Makanya village)

	Particle size distribution									Exch. Bases (cmol(+)/Kg)				GPS coordinate (m)	
Sample Id	Sand (%)	Clay (%)	Silt (%)	Soil texture	pH	EC (mS/cm)	OC (%)	% TN	Extractable P(mg/kg)	Ca	Mg	Na	K	X	Y
Shabani Bakari	52.5	34.4	13.1	SCL	8.19	0.25	1.58	0.25	39.49	19.26	7.93	3.4	2.02	370 092	9 517 167
Fatuma Hussen	59.5	25.8	14.7	SCL	8.09	0.32	1.72	0.45	81.16	19.39	5.93	3.1	2.65	370 157	9 517 189
Tusu Juma I	52.5	19.4	28.2	L	8.30	0.16	0.94	0.15	52.76	12.45	4.08	2.5	1.09	370 266	9 517 009
Majid Sengasu	63.0	29.2	7.7	SCL	8.08	0.18	0.98	0.13	46.70	13.53	6.56	2.8	1.87	369 965	9 517 132
Tusu Juma II	72.5	21.1	6.4	SCL	8.35	0.14	0.92	0.22	56.28	12.67	5.38	2.0	1.40	370 146	9 517 126
Mnyuku	56.2	27.5	16.3	SCL	7.92	0.40	2.13	0.47	49.01	22.57	6.97	2.7	1.80	370 499	9 516 740
Simba	74.0	20.0	6.0	SL	7.84	0.11	0.62	0.16	52.64	7.35	4.35	2.2	1.62	369 643	9 517 218
James	78.6	20.7	7.9	SL	7.67	0.25	0.78	0.20	73.83	8.99	4.18	2.6	1.67	367 055	9 518 462
Mean	63.6	24.8	12.5	SCL	8.06	0.23	1.21	0.25	56.48	14.53	5.67	2.7	1.76		

KEY: C: Clay, L: Loamy SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Appendix 9.2. Some of the properties of the soils from the crop fields at the mid zone of the catchment (Mwembe village)

Sample Id	Particle size distribution			Soil texture	pH	EC (mS/cm)	OC (%)	% TN	Extractable P(mg/kg)	Exch. Bases (cmol(+)/Kg)				GPS coordinate (m)	
	Sand (%)	Clay (%)	Silt (%)							Ca	Mg	Na	K	X	Y
Mwembe 3	45.4	40.5	14.1	C	7.75	0.28	2.42	0.35	36.24	20.95	9.83	2.04	1.09	371 231	9 539 427
Mwembe 10	69.0	20.6	10.3	SCL	7.51	0.20	1.21	0.24	51.63	10.83	5.19	2.58	1.56	371 498	9 539 850
Mwembe 7	63.9	29.2	6.9	SCL	7.6	0.15	0.86	0.18	40.31	11.75	4.22	2.04	1.56	372 064	9 540 454
Mwembe 2	65.6	31.7	2.7	SCL	7.42	0.15	0.98	0.21	57.07	9.38	4.29	3.13	2.18	370 870	9 537 091
Mwembe 1	59.5	31.7	8.8	SCL	7.68	0.68	1.79	0.28	43.01	19.03	3.61	3.94	2.80	370 656	9 537 021
Mwembe 5	80.6	12.0	7.3	SL	8.25	0.16	0.55	0.15	79.25	9.52	3.46	3.13	1.25	371 763	9 540 579
Mwembe 9	67.3	27.5	5.2	SCL	6.9	0.08	0.84	0.22	19.20	6.74	3.06	2.31	0.47	371 645	9 539 750
Mwembe 8	74.2	22.4	3.4	SCL	6.9	0.05	0.64	0.08	6.75	4.73	3.53	1.76	0.31	371 821	9 539 782
Mwembe 6	79.4	12.0	8.6	SL	7.12	0.10	0.72	0.15	32.19	4.41	3.08	1.76	0.62	371 674	9 540 639
Mwembe 4	57.0	32.7	10.3	SCL	6.82	0.16	1.50	0.32	29.49	8.67	3.17	2.58	2.02	370 935	9 539 439
Mean	66.2	26.0	7.8	SCL	7.40	0.20	1.15	0.22	39.51	10.60	4.34	2.53	1.39		

KEY: C: Clay. L: Loamy SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Appendix 9.3. Some of the properties of the soils from the crop fields on the upper zone of the catchment (Tae village)

Sample Id	Particle size distribution			Soil texture	pH	EC (mS/cm)	OC (%)	% TN	Extractable P(mg/kg)	Exch. Bases (cmol(+)/Kg)				GPS coordinate (m)	
	Sand (%)	Clay (%)	Silt (%)							Ca	Mg	Na	K	X	Y
Tae 5	73.6	17.6	8.8	SL	5.22	0.11	0.72	0.15	67.36	2.37	1.34	1.7	0.78	378 605	9 522 648
Tae 13	52.5	36.1	11.4	SC	6.8	0.05	1.70	0.24	0.00	9.61	5.32	0.9	0.00	376 964	9 521 999
Tae 11	70.1	22.4	7.6	SCL	6.64	0.08	2.07	0.35	7.03	9.87	5.15	1.2	0.00	377 809	9 521 142
Tae 4	56.0	27.5	16.5	SCL	6.6	0.10	0.72	0.48	9.20	10.08	3.20	1.4	0.04	377 885	9 520 335
Tae 3	64.8	24.1	11.1	SCL	6.72	0.07	1.46	0.28	4.33	10.95	5.23	1.2	0.00	377 503	9 520 216
Tae 8	68.3	20.6	11.0	SCL	6.33	0.08	1.99	0.38	9.87	9.66	4.30	1.4	0.00	378 071	9 520 168
Tae 7	75.9	13.8	10.3	SL	6.26	0.08	1.60	0.38	14.61	6.43	3.73	2.0	0.19	378 862	9 521 310
Tae 9	69.0	22.9	8.1	SCL	6.79	0.19	1.91	0.36	7.03	8.60	4.52	1.7	0.03	377 313	9 520 719
Tae 6	63.0	28.2	8.8	SCL	6.99	0.10	2.01	0.36	7.98	7.40	2.67	2.0	0.56	379 048	9 522 789
Tae 2	60.4	33.4	6.1	SCL	6.77	0.10	2.36	0.39	28.13	14.11	4.23	2.5	1.56	377 226	9 520 098
Tae 12	71.8	18.9	9.2	SL	7.08	0.16	1.87	0.35	6.50	11.67	5.66	2.0	0.00	377 434	9 521 376
Tae 1	73.6	15.5	10.9	SL	7.75	0.33	3.16	0.55	**203.42**	19.23	5.64	3.6	2.65	376 584	9 520 406
Tae 10	71.8	21.1	7.0	SCL	6.75	0.05	3.72	0.08	7.98	8.88	4.50	1.7	0.00	377 687	9 520 590
Mean	67.0	23.2	9.8	SCL	6.67	0.12	1.95	0.33	14.17	9.91	4.27	1.8	0.45		

KEY: C: Clay, L: Loamy SCL: Sandy Clay Loam, SL: Sandy Loam, SC: Sandy Clay

Note: Bolded figure is taken as an outlier