LANDFORM AND SOIL ANALYSIS FOR PREDICTING DISTRIBUTION OF PLAGUE RESERVOIRS AND VECTORS IN MAVUMO AREA, LUSHOTO DISTRICT, TANZANIA

BY

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN LAND USE PLANNING AND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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ABSTRACT

A study was carried out in Mavumo area, West Usambara Mountains, Tanzania, to analyse the importance of landform and soil characteristics in predicting the distribution of plague reservoirs and vectors. The main aim was to contribute to information base that would link landscape and ecological factors with the spatial distribution of plague disease in the area so as to provide information to institutions that are dealing with health and land use programmes in Tanzania. Remote sensing and GIS techniques coupled with standard field survey methods were employed to map and analyse the landforms and soils covering an area of 198 km^2. Rodents (plague reservoirs) were trapped in the field based on the mapped landform-soil characteristics, and fleas (plague vectors) were counted from the rodents. The collected data was analysed statistically using Excel and Minitab softwares. Results showed that piedmont-plain, escarpment and plateau are the major landscapes in the study area from which 20 landform units and 13 dominant soil types were identified. The results demonstrated that the very steep complex slopes of the escarpment and the lower slopes of the high and mid slopes of the medium altitude plateaus neighbouring the plateau valley bottoms where water and food are easily accessible had higher abundance (> 40%) of plague reservoirs and vectors. The study showed that there is significant positive correlation ($p < 0.05$) between slope gradient and abundance of both plague reservoirs and vectors. Significant positive correlation ($p < 0.05$) was also observed between plague reservoirs abundance and soil effective depth and copper content. About 99% of the observed variation in the plague reservoirs and vectors occurrence could be explained by their respective models.

DECLARATION

I, **Hussein John Boniface Massawe**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work and that it has neither been submitted nor being concurrently submitted for a degree award in any other institute.

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The above declaration is confirmed

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(Supervisor)

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Prof. B. M. Msanya   **Date**

(Co-supervisor)

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LIST OF ABBREVIATIONS

a.s.l.	=	above sea level
AWC	=	Available Water Capacity
C/N	=	Carbon to Nitrogen ratio
CEC	=	Cation Exchange Capacity
DEM	=	Digital Elevation Model
ESP	=	Exchangeable Sodium Percent
ETM	=	Enhanced Thematic Mapper
FAO	=	Food and Agriculture Organisation of the United Nations
GIS	=	Geographic Information Systems
GPS	=	Global Positioning System
LEPUS	=	Landscape ecological clarification of bubonic plague distribution and outbreaks in the Western Usambara Mountains, Tanzania
NSS	=	National Soil Service
OC	=	Organic Carbon
PBS	=	Percent Base Saturation
r	=	Correlation coefficient
R^2	=	Coefficient of determination
TEB	=	Total Exchangeable Bases
TM	=	Thematic Mapper
URT	=	United Republic of Tanzania
USDA	=	United States of America Departmernt of Agriculture
UTM	=	Universal Transverse Mercator projection

CHAPTER ONE

1.0. INTRODUCTION

1.1. Background Information and Justification

Plague is a zoonotic disease that circulates in small mammals and their fleas (Neerinckx *et al.*, 2010a). In Africa, the disease is mainly transmitted by the bite of infected fleas (Guiguen and Beaucournu, 1979; Laudisoit *et al*., 2007) and rarely by ingestion of infected animals (Dennis *et al*., 1999). Plague endemic areas cover 6 to 7% of the dry land of the earth (Laudisoit, 2009). The World Health Organization (WHO) reports 1,000 to 3,000 human cases of plague every year in at least 38 reported countries (Anisimov *et al.*, 2004). During the period 1954 to 2009, WHO documented 93,116 human cases including 7,430 deaths in 38 countries in Africa, Asia and the Americas (WHO, 2010). The plague endemic regions are found in South America, United States of America, Western Canada, many countries in Africa, the former Soviet Union, the Middle East, Central and Southeast Asia and Indonesia, but not in Australia and Antarctica (Gage and Kosoy, 2005). Globally, most current cases appear in Africa where Madagascar, the Democratic Republic of Congo and Tanzania are the most heavily infected countries (Bertherat *et al.*, 2007). Human plague in Africa has also been documented in Uganda, Algeria, Libya, South Africa, Kenya, Mozambique, Egypt and Botswana (Neerinckx *et al.*, 2010a).

In Lushoto District, Tanzania, human plague was reported for the first time in April 1980 (Kilonzo and Msangi, 1991). By the year 2004, more than 7,600 cases were recorded (Neerinckx, 2006). Reports show that the disease has been able to persist for over 20 years in some villages in the district with some villages appearing to be more affected than nearby villages (Davis *et al.*, 2006; Neerinckx, 2006; van Olmen, 2008). It has not been explained why the plague seems not to spread from the existing foci (Davis *et al.,* 2006; Laudisoit *et al.*, 2009b).

While in the past, plague occurrence was reported in almost across the world, it is now settled in selected areas and is currently distributed in circumscribed foci assumed to be correlated with distributions of dominant reservoirs and vectors and their ecology (Prentice and Rahalison, 2007). Plague foci can be found in a variety of habitats such as grasslands, native forests, high altitude rainforests and rangelands (Dennis *et al*., 1999). Although many natural foci are known, a recent report concluded that the number of people living in plague risk areas remains largely unknown (WHO, 2008). In addition demarcation of the natural plague foci is not yet evident since the plague status in animals (hosts and vectors) is often not known. In his studies on the insights in the ecology of plague, Neerinckx (2010) remarked that only human plague occurrence data are available and in case of human outbreaks, plague is checked in different small mammals (reservoirs) and flea species (vectors). Duplantier *et al.* (2005) noted further that plague foci are not fixed and their distribution can shift in response to changes in environmental conditions (with respect to climate and landscape characteristics including landforms and soils) and distribution of reservoirs and vectors.

Pavlovsky and other Soviet scientists first brought attention to the relationships between landscapes and the geographic distribution and occurrence of various diseases, including plague (Kucheruk, 1960; Pavlovsky, 1966; Rotshild, 1978). Based on these studies, it was noted that distribution and occurrence of zoonotic diseases including plague is limited to certain areas and can be related to landscape factors including elevation, geology and soils (Neerinckx, 2010b). These factors influence the presence, development, reproduction, activity and longevity of vectors and zoonotic reservoirs and their interactions with humans (Meade and Earickson, 2000). Therefore, it is envisaged a study on landscape factors such as landforms and soils with respect to plague reservoirs and vectors might provide insights into the focality of plague and how its spread can be affected by these landscape factors.

As pointed out by Neerinckx (2010), today, a range of tools is available to relate landscape factors to disease occurrence and distribution. Geographic Information System (GIS), Global Positioning System (GPS), remote sensing and spatial statistics are tools mentioned among others to analyse and integrate spatial landscape factors in the study of vector-borne diseases such as plague into research, surveillance and control programmes (Kitron, 1998). In this study GIS was applied to analyse the spatial setting of landforms and soils as predictors of plague reservoirs and vectors.

As pointed out earlier, landscape factors may help to explain the spatial distribution and occurrence of plague disease as was postulated in literature half a century ago (Pavlovsky, 1966; Rotshild, 2001). Neerinckx *et al.* (2010b) observed that the factor of elevation was a good predictor of plague locations in the Usambara Mountains, Tanzania. Heuristic comparisons revealed that calcium and iron enriched environments are associated with plague foci distribution (Liu *et al.,* 2000). An account by Rotshild (2001) demonstrated a close association with patches of repetitively infected rodent colonies (reservoirs) and medium or high concentrations of iron, cobalt and titanium.

According to Neerinckx (2006), about 203 rodent species have been reported to be naturally infected with *Yersinia pestis.* Most rodents use underground burrows for nesting and food storage and provide the rodents with shelter from predators during rodent surface activity (Shenbrot *et al.,* 2002). Therefore, rodent burrows play an important role in the life and survival of the rodents. It is hypothesized that the burrow structure is related to the physical properties of soils (e.g. bulk density and soil texture) and some soil chemical properties (Anderson and Allfred, 1964; Laundré and Reynolds, 1993; Massawe *et al*., 2005). However, so far there is limited comprehensive research that spatially relates soil factors including physical and chemical properties like texture, bulk density, consistence and macro and micronutrients to plague reservoirs and vectors. Spatial analysis of soil physical and chemical properties could be applied to provide insights into the plague foci, particularly with respect to rodents as plague reservoirs.

Worldwide, over 1,500 species of fleas have been identified (Perry and Fetherston, 1997). Studies by Laudisoit *et al.* (2009b) in the West Usambara Mountains, Tanzania, suggest that the fleas are most abundant and diverse on small and medium sized burrowing species. The authors further added that the numbers and types of flea species differ in terms of the range of their hosts (rodents) and habitat properties. Studies conducted by Sharets *et al.* (1958) and Kartman *et al*. (1962) in the USA found that fleas may nestle for some time in the small mammal's burrow which is largely related to soil physical and chemical properties. Modeling approaches have been applied by several scientists in order to understand the plague dynamics. For example Keeling and Gilligan (2000a, b) developed a model focusing on *Y. pestis* infection in humans, *Rattus rattus,* and *Xenopsylla cheopis.* The parameters tested included rat's reproductive rate, rat's carrying capacity, rat's movement, flea's searching efficiency and death rates of fleas among others. The model showed that the high risk infection occurs when there are many infected fleas. This model recreated many of the worldwide dynamics observed in human plague outbreaks but little insight was offered at the smaller scale of enzootic plague in wild rodent communities (Foley *et al.*, 2007).

From the above observations, it is vital to pay attention and research on wide array of landscape conditions including landforms and their associated characteristics and soil physical and chemical properties which may have influence on spatial distribution of major plague reservoirs and vectors in order to provide a broader insight into plague research, surveillance and control programmes. Therefore, this study was conducted to analyse the important factors of landforms and soils at medium scale using spatial tools with respect to plague reservoirs and vectors in order to contribute towards a broader research knowledge base that would likely link landscape ecological factors and explanation of plague foci in Lushoto District, Tanzania.

1.2. Objectives

1.2.1. Main objective

The main objective of this study was to carry out landform and soil analysis using spatial tools with respect to plague reservoirs and vectors in order to contribute to knowledge and information that will help to explain the plague foci behavior in the

Mavumo area, Lushoto District, Tanzania.

1.2.2. Specific objectives

The specific objectives were:

1. To establish detailed spatial distribution of landforms and soils of the study area
2. To stratify landform and soil characteristics in relation to plague vectors and reservoirs
3. To develop spatial model that explains the linkage between landform and soil characteristics and spatial distribution of plague vectors and reservoirs

CHAPTER TWO

2.0. LITERATURE REVIEW

2.1. Basic Definitions and Concepts on Plague and its Environment

2.1.1. Plague epidemiology

Plague is a human disease which results from infection by *Yersinia pestis* bacterium (Neerinckx *et al.,* 2010a). It is a zoonotic disease (i.e. a disease which is primarily of animals but occasionally it can be transmitted to human beings). The causative bacterium of plague (*Yersinia pestis*) was discovered by Yersin while working in Hong Kong in 1894 (Yersin, 1894; Simond, 1898). Transmission of *Y. pestis* to human beings is reported to occur largely but not exclusively from bites by rodent-associated fleas (Drancourt *et al*., 2006). Stenseth *et al*. (2008) noted that the plague patients typically experience a sudden onset of fever, chills, headaches, body aches, weakness, vomiting and nausea after an incubation period of 3-7 days. The researcher also reports that the case-fatality ratio of the disease if not treated varies from 30 to 100%.

It is reported that plague is a disease which primarily affects rodents (Gage and Kosoy, 2005). Fig. 1 shows the assumed natural cycle of plague as summarized by Gage and Kosoy (2005). The disease is thought to exist indefinitely in enzootic cycles that cause little obvious host mortality and involve transmission between partially resistant rodents and their fleas (Eisen *et al.,* 2008). Sometime, the disease spreads from enzootic hosts to more highly susceptible animals (epizootic hosts) often causing rapidly spreading die-offs (Poland *et al*., 1994; Gage and Kosoy, 2005).

During these epizootics, the disease spreads rapidly and human beings are exposed to the disease by the flea bites while they are searching for new hosts. Keeling and Gilligan (2000) partitioned the plague cycle into four stages:

(1) Fleas, feeding on an infected rodent ingest the bacteria causing bubonic plague, and become infectious;

(2) When an infected rodent dies, its fleas leave to search for new host;

(3) The fleas usually find other rodents, infect them, and so, spread the disease in the rodent community;

(4) When the density of rodents is low, the fleas are forced to feed on alternative hosts such as humans, and consequently, a human epidemic could occur.

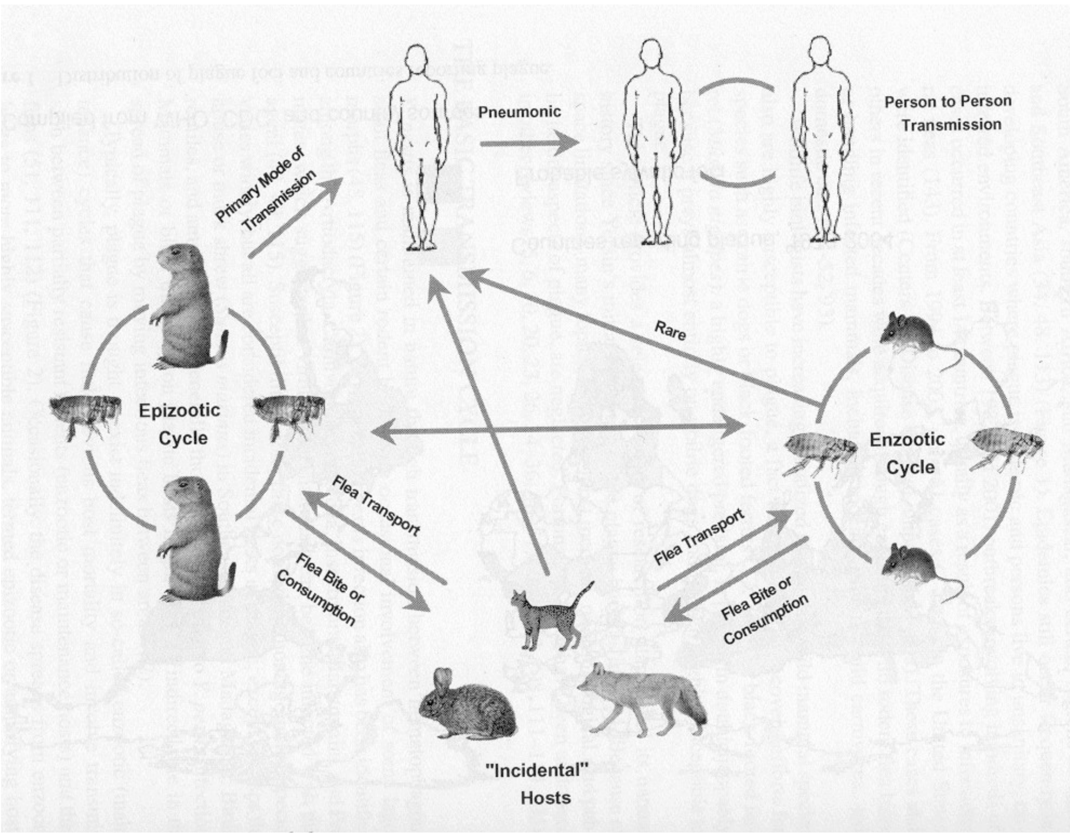


Figure 1: The assumed natural cycle of plague; an enzootic and an epizootic cycle (Gage and Kosoy, 2005)

2.1.2. Plague reservoirs

Haydon *et al*. (2002) defined disease reservoir as one or more epidemiologically connected populations or environments in which the pathogen can be permanently maintained and from which infection is transmitted to the defined target population. The authors further indicated that the existence of a reservoir is confirmed when infection within the target population cannot be sustained after all transmission between target and non-target populations has been eliminated. Many different animal species (mostly wild rodents) are natural reservoirs for plague bacterium (Gage and Kosoy, 2005). Some animal populations are reported to be relatively resistant to the effects of *Y. pestis* infection and serve as the enzootic reservoirs (Dennis and Meier, 1997). Other studies show that some animal species are more susceptible to disease caused by *Y. pestis* and serve as epizootic hosts (Gage, 1998). Examples of reported plague reservoirs include urban and domestic rats, ground squirrels, rock squirrels, prairie dogs, deer mice, field mice, gerbils, voles, chipmunks, marmots, guinea pigs and kangaroo rats (Dennis and Meier, 1997; Gabastou *et al.*, 2000).

2.1.3. Plague vectors

In epidemiology, a vector is an insect or any other living carrier that transmits an infectious agent (Wikipedia.org/wiki/Disease_vector). It is further defined as an organism that carries disease-causing microorganisms from one host to another (http://www.thefreedictionary.com). It is reported that about 70% of emerging infectious diseases imply a vector in their transmission cycle (Gratz, 2006). These vectors can be insects (e.g. mosquitoes, cockroaches, sandflies, fleas, lice, triatomines and midges), acarines (ticks and mites), but also mammals (Jattapalopong *et al.*, 2009). Reports show that the plague causative bacterium is most commonly transmitted between animal reservoirs and humans via bites of infected fleas (Neerinckx, 2010a). Examples of worldwide known major flea vectors as outlined by Perry and Fetherston (1997) include *Xenopsylla cheopis* (the oriental rat flea; occurring in moderate climates), *Oropsylla montanus* (United States), *Nosopsyllus fasciatus* (in temperate climates), *X. brasiliensis* (Africa, India, South America), *X astia* (Indonesia and Southeast Asia) and *X. vexabilis* (Pacific Islands). The most common and efficient flea vector is reported to be *X. cheopis* (Butler, 2009).

2.1.4. Plague foci

Natural foci are places where the plague bacteria can survive in a period without human plague-cases (Duplantier *et al*., 2005, Neerinckx *et al.*, 2008). Natural foci of plague are situated in all continents except Australia, within a broad belt in tropical, subtropical and warmer temperate climates, between the parallels 55° N and 40° S (Laudisoit, 2009). The reported natural plague foci worldwide include Africa (Duplantier *et al*., 2005; Neerinckx *et al.*, 2008), North America (Gage and Kosoy, 2005, Eisen *et al*., 2008), Asia (Liu *et al*., 2000), South America (Rui, 2001) and in Europe (Laudisoit, 2009).

Several studies done on focality of plague report that plague foci are not fixed, and that they can change in response to shifts in factors such as climate, landscape and population dynamics of rodents, fleas and human migrations (Perry and Fetherston, 1997; Gage and Kosoy, 2005; Stenseth *et al*., 2008). Duplantier *et al*. (2005) while writing on the lessons of the Malagasy foci towards global understanding of the factors involved in plague re-emergence commented that re-emergence of human cases of plague after decades of silence does not necessarily mean that plague foci are re-emerging. They further commented that most often, *Yersinia pestis* bacteria have been maintained and circulating at low levels in the rodent populations. Studies conducted have related the plague foci distribution with some landscape factors such as high altitudes in Madagascar and Tanzania (Duplantier *et al*., 2005; Neerinckx *et al.*, 2008), and soil properties in Asia, America and Africa (Liu *et al.*, 2000; Rotshild, 2001; Ayyadurai *et al*., 2008; Neerinckx *et al.,* unpublished).

2.1.5. Landform

According to Buckle (1986), landforms are the results of geomorphic processes shaping the rocks of the earth. According to the author these geomorphic processes include earth movements (faulting, folding, and warping), volcanism, denudation or degradation and deposition or aggradation. Swanson *et al.* (1988) observed that a discussion of effects of landforms on ecosystems is hindered by a lack of concise, widely accepted definitions of key terms and concepts where landform and landscape are often confused.

According to Naveh (1982) landscape commonly refers to the form of the land surface and associated ecosystems at scales of hectares to many square kilometers while landform is usually used at a finer scale and more specifically, such as a landform carved out by a landslide or created by sediment deposition forming a gravel bar. Other authors (Forman and Godron, 1986) commented that landscapes are composed of landforms and ecological units, such as *patches*. FAO (2006) guidelines for soil description defined landform as any physical feature on the earth's surface that has been formed by natural processes and has a distinct shape.

According to FAO (2006), landforms are described foremost by their morphology and not by their genetic origin or processes responsible for their shape. The important factors of landforms are elevation and slope. Important factors of slope are: gradient which is its steepness, aspect which is its direction (where it is facing), shape which refers to its convexity, concavity, complexity or its linearity, length which is its horizontal distance and position which is its relative position along the landscape (Swanson *et al.*, 1988). Global and regional developed soil and terrain (SOTER) database have been used to study landforms of a given area (Van Engelen *et al.*, 2006). SOTER is a land resource information system in which the methodology includes GIS procedures based on identification of areas of land with a distinctive, often repititve, pattern of landform, lithology, surface forms, slope, parent material and soil (Dobos *et al.*, 2005; Huting *et al.*, 2007).

2.1.6. Soil

Soil can be defined as a dynamic natural body on the surface of the earth in which plants grow, composed of mineral and organic materials and living forms (Brady, 1974). Soil Survey Staff (2006) defined soil as a natural body comprised of solids (minerals and organic matter), liquid and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers that are distinguishable from the initial material as a result of additions, losses, transfers and transformations of energy and matter or the ability to support rooted plants in a natural environment.

A modern concept defines soil as a three-dimensional, dynamic, natural body occurring on the surface of the earth that is a medium for plant growth and whose characteristics have resulted from the integrated effect of climate and living matter acting upon parent material, as modified by relief, over periods of time (Gupta, 2001). According to Soil Survey Staff (2006), the upper limit of soil is the boundary between soil and air, shallow water, live plants, or plant materials that have not begun to decompose and that for purposes of classification, the lower boundary of soil is arbitrarily set at 200 cm if the non soil material is not at a shallower depth.

According to FAO (2006), the classification of soils is based on soil properties defined in terms of diagnostic horizons, properties and materials. There are several soil classification systems, but some enjoy worldwide recognition including Soil Taxonomy developed by the USA Department of Agriculture (Soil Survey Staff, 2006), FAO-WRB developed by FAO (FAO, 2006) and FAO-UNESCO soil classification system developed by FAO and UNESCO.

2.1.7. Soil physical properties

The physical properties of a soil are those characteristics which can be seen with the eye or felt between the thumb and fingers. They are the result of soil parent materials being acted upon by climatic factors (such as rainfall and temperature), and affected by topography (slope and direction, or aspect) and life forms (kind and amount, such as forest, grass, or soil animals) over a period of time. Some important physical properties of a soil are colour, texture, structure, consistence, bulk density, porosity and depth (Landon, 1991; Pansu and Gautheyrou, 2006)

2.1.8. Soil chemical properties

As soils are formed during weathering process, some minerals and organic matter are broken down to extremely small particles (Gupta, 2001). Chemical changes further reduce these particles until they cannot be seen with the naked eyes. These particles called colloids are very small; thus, their surface properties are relatively more important than their mass (weight). Because of their large surface-to-mass ratio, soil colloids settle slowly from suspension and have many reactions at their surfaces that determine soil properties. The colloids are primarily responsible for the chemical reactivity in the soil (Brady and Weil, 2002). Important chemical properties which are normally determined in soils are: soil pH (a measure of soil acidity or alkalinity), electrical conductivity - EC (a measure of salinity), cation exchange capacity - CEC (a measure of the quantity of cations that can be adsorbed and held by a soil), organic matter and different elements (macro and micronutrients) which are important for flora and fauna survival in and on the soils (Carter, 1993, Pansu and Gautheyrou, 2006). The nutrients required in large quantities by plants are known as macronutrients. They are N, P, K, Ca, Mg, and S. Micronutrients are the nutrients which are required in small quantities (traces). They are Fe, Zn, Cu, Mn, B, Mo and Cl (Gupta, 2001).

2.1.9. Geographical Information System as a spatial tool for modeling landscape factors

Geographic Information System (GIS) is any system that captures, stores, analyses, manages, and presents data that are linked to location. It merges cartography, statistical analysis, and database technology. GIS applications are tools that allow users to create interactive queries, analyse spatial information, edit data, maps, and present the results of all these operations (De By, 2004).

Several studies have been carried out using GIS as a spatial tool for modeling landscape factors. GIS was used to describe the spread of Dengue fever in French Guyana where spatial and temporal patterns of the disease were analysed. The distances between the houses was calculated and compared with confirmed cases of Dengue fever. Spatial outbreaks seemed to appear at some fixed distances: the most nearest neighbouring houses (Tran *et al*., 2004). The distribution of gastrointestinal infections with respect to drinking water supply structures was analysed in a GIS in the German (Dangendorf *et al*., 2002). The analysis revealed spatial variation in the incidence of diarrhoeal illnesses and a trend of positive linkage between disease incidence and amount of groundwater was found in this study.

2.2. Potential Plague Reservoirs and Vectors

2.2.1. Plague ecology

Plague ecology is still mysterious. The disease is reported to be characterized by geographical foci from which it re-emerges after a number of quiescent years (Bertherat *et al.,* 2007; Ayyadurai *et al.,* 2008; Neerinckx *et al.,* 2008). In Boteti sub-district, Botswana, plague was reported to re-emerge in 1989 after a silent period of more than 35 years (Kumaresan *et al.*, 1991). Another report shows that in the port of Mahajanga, Madagascar in 1991 plague reappeared after a silence of over 60 years (Boisier *et al.*, 1997). In Zambia, McClean (1995) reported that plague resurfaced in 1991 and 1993 at Chitokoloki Mission after a period of about 40 years. Bertherat *et al.* (2007) reported that in Oran, Algeria, plague reappeared in June 2003, while the last recorded incidence was in 1950. Another report by Makundi *et al.*, (2008) indicates that in Mbulu district, Tanzania, plague reappeared in 2007 after a period of silence of almost 30 years. Laudisoit (2009) when researching in Lushoto, Tanzania, remarked that plague re-emergence seemed linked with climatic factors to some extent, but the number of plague cases was prone to an extreme inter-annual and inter-locality variation and seemed unpredictable.

What limits the geographic distribution of the disease causing organism is also unclear. Pollitzer (1954) and Eisen *et al*. (2008) reported that plague bacterium is endemic west of the 100th meridian in the United States, but not in eastern states despite several known introductions. It was further observed that some foci may become quiescent, others may appear, and, even at a local scale, within a known focus, some villages may be affected while others never get plague (Laudisoit *et al.*, 2007; Neerinckx *et al.*, 2008)

2.2.2. Potential plague reservoirs

Plague is primarily a disease of rodents (Gage and Kosoy, 2005). The infection is maintained in natural foci of the disease in wild rodent colonies through transmission between rodents by their flea ectoparasites (Gratz, 1999). The circulation of *Y. pestis* has been detected in more than 200 species of wild rodents living in natural plague foci (Anisimov, 2002). Many species of rodents and other small mammals are susceptible to infection but are only occasionally infected and are not necessarily important reservoirs of infection (Gratz, 1999). Studies show that domestic rats are the most important reservoirs for the plague bacillus, but field mice, cats, chipmunks, prairie dogs, rabbits and squirrels can be important animal reservoirs as well (Bizanov and Dobrokhotova, 2007). Modelling studies done by Keeling and Gilligan (2000a, b) suggested that plague can persist in small rat subpopulations for indefinite periods and serve as sources of infection for later outbreaks. Table 1 shows plague reservoirs and vectors in Bolivia, Brazil, Ecuador, United States and Peru as summarized by Ruiz (2001) while Table 2 shows diversity of some rodents, insectivores and small carnivores and the involvement of each small mammal in the plague cycle as potential carriers of the disease in the Democratic Republic of Congo (DRC), Kenya, Tanzania and Uganda (Laudisoit, 2009).

2.2.3. Potential plague vectors

As it has been pointed out earlier, plague is transmitted from one reservoir to another and to humans mainly through flea bites (Barnes, 1982). In continental East African regions, the major rodent flea vectors responsible for *Y. pestis* transmission are *Xenopsylla brasiliensis* and *Xenopsylla cheopis* (Pollitzer, 1954; Dennis *et al.*, 1999) commonly found in domestic environment. *X. cheopis* is the predominant vector in North Africa, Kenya, Senegal and Madagascar, and *X. brasiliensis* in East and Southern Africa (Davis, 1953). *Dinopsyllus lypusus, Dinopsyllus ellobius, Ctenophthalmus calceatus* and other members of those two genera are cited as potential vectors in sylvatic and wild environment (Devignat, 1949; Heisch, 1952).

Table 1: Plague in the Americas: reservoirs and vectors

Country	Reservoirs	Vectors
Bolivia	*Akodon* sp	*Xenopsylla cheopis*
	Rattus rattus	*Pulex irritans*
Brazil	*Akodon* sp	*X. cheopis*
	Oryzomys sp	
	Callomys sp	
	Bolomy sp	
	Monodelphis deomestica	
Ecuador	*R rattus*	*P. irritans*
	R. norvegicus	
	R. alexandrinus	
	Akodon mollis	
	Oryzomys sp	
	Phyllotis sp	
	Scirurus stramineus	
United States	*Marmot* (*Cynomys* sp)	*Orchopeas sexdentatus*
	Rabbits	*Oropsylla montana*
	Rats (*Dipodomys* sp)	*Haplosyllus* sp
	Mice (*Peromyscus* sp)	*Diamanus* sp
	Terrestrial squirrel (*Citellus* sp)	*Thrasis* sp
Peru	*Akodon* sp	*X. cheopis*
	Oryzomys sp	*Polygenes* sp
	Sigmodon sp	*Tiamastus* sp
	Phyllotis sp	*P. irritans*
	R. rattus	
	Cavia porcellus	

Source: Ruiz (2001)

Table 2: Diversity of some reservoirs in the Democratic Republic of Congo (D), Kenya (K), Tanzania (T) and Uganda (U)

Reservoir	**D**	**K**	**T**	**U**	**Reservoir**	**D**	**K**	**T**	**U**
Acomys sp.		1			*Mastomys coucha*	1	1	1	
Acomys spinosissimus			x		*Mastomys natalensis*	1	1	1	1
Aethomys chrysophilus	x		x		*Microgale fotsifotsy*				
Aethomys kaiseri		1			*Microgale talazac*				
Aethomys namaquensis					*Mus alexandrinus*	x			
Arvicanthis abyssinicus	1	1	1	1	*Mus decumanus*	x			
Arvicanthis nairobe			x		*Mus minutoides*	1		x	1
Arvicanthis niloticus	x	1	1		*Mus musculus*	x	x	x	
Brachytarsomys bastardi					*Nesomys rufus*				
Calomys goslingi		x			*Oenomys hypoxanthus*	1	x		x
Canis familiaris			1		*Oryzoryctes hova*				
Claviglis murinus	x				*Otomys angoniensis*		1	1	
Cricetomys gambianus	x	x	1		*Otomys denti*			1	
Crocidura flavescens		x			*Otomys irroatus*	1			
Crocidura hirta			x		*Otomys spp.*			1	
Crocidura sp.	x		x		*Otomys tropicalis*	x			
Dasymys incomtus	x	x			*Paraxerus ochraceus*		x		
Dendromus haymani	x		x		*Paraxerus vexillarius*			x	
Dendromus isignis	x				*Pelomys campanae*	x			
Dendromus mesomelas	x				*Pelomys fallax*	x	1	1	
Dendromus sp.			x		*Pelomys luluae*	x			
Desmodillus auricularis					*Pelomys minor*	x			
Elephantulus sp.		x			*Petrodromus spp.*			x	
Eliurus myoxinus					*Petrodromus tetradactylus*		1		
Felis catus			x		*Praomys delectorum*		x	x	
Felis lybica			1		*Praomys jacksoni*	x	x	x	
Felis silvestris catus			x		*Praomys stella*		x		

Genetta tigrina		x			*Rattus norvegicus*	1	1	1	
Genomys sp.	x				*Rattus rattus*	1	1	1	1
Grammomys dolichurus		1	1		*Rhabdomys pumilio*		1		
Grammomys drias	x				*Saccostomus campestris*	x	x	x	
Grammomys nairobe			1		*Saccostomus cricetulus*				x
Grammomys surdaster	x				*Saccostomus isiolae*		x		
Graphiurus murinus		x	x		*Saccostomus mearnsi*			x	

Source: Laudisoit (2009).

Note: The involvement of each small mammal in the plague cycle as potential carriers of the disease is indicated as 1 for species found infected or seropositive and as X, for species present with no records (or unknown) of seropositivity**.**

Some of the fleas which are important vectors of plague worldwide as outlined by Perry and Fetherston (1997) and Gratz (1999) are summarized in Table 3. Also Table 4 shows diversity of some fleas in the DRC, Kenya, Tanzania and Uganda with an indication of their involvement as plague vector. *Pulex irritans* fleas have been observed to have a wide host range, feeding also on rodents and human beings (Gabastou *et al*., 2000). These fleas are considered a possible or probable vector of plague in Angola (Beaucournu *et al.*, 1993), Brazil (Karimi *et al.*, 1974), Burundi (Beaucournu and Guigen, 1979), the DRC (Shyu and Hsu, 1991), Iran (Baltazard *et al.*, 1960), Iraq (Baltazard and Seydian, 1960) and Tanzania (Kilonzo, 1980).

Table 3: Some important vectors of plague

Flea	Remarks
Xenopsylla cheopis	• the most important vector of plague • most commonly parasitizes *Rattus* species but is frequently found on other rodent species in and around houses • oriental in origin but currently its presence is nearly worldwide in moderate climates
Xenopsylla astia	• a parasite of both gerbils and rats
Xenopsylla brasiliensis	• native to all Africa south of the Sahara • most common vector in some areas, often more common than *X. cheopis*
Nosopsyllus fasciatus	• one of the most prevalent fleas in Europe • parasite of commensal rats
Monopsyllus anisus	• is the common rat flea of temperate East Asia
Leptopsylla segnis	• the mouse flea, is generally abundant on rats than on mice
Ctenocephalides felis	• the cat flea • completely cosmopolitan in its distribution
Pulex irritans	• worldwide in its distribution • wide range of hosts: it is found in the wild on foxes, badgers, ground squirrels, guinea pigs and rats as well as domestically on pigs, goats, dogs, cats and humans • often found in high densities in habitations

Source: Compiled from Perry and Fetherston (1997) and Gratz (1999)

Table 4: Diversity of fleas in the Democratic Republic of Congo (D), Kenya (K), Tanzania (T) and Uganda (U)

Fleas	D	K	T	U	Fleas	D	K	T	U
Afristivalius torvus	x		x		*Hypsophthalmus campestris*	x		x	
Chiastopsylla rossi			x		*Leptopsylla aethiopica*	1	x	x	x
Ctenocephalides canis		x	x		*Nosopsyllus fasciatus*		x	x	
Ctenocephalides felis strongylus	1	x	x	x	*Nosopsyllus incisus*	x	x	x	x
Ctenophtalmus calceatus spp.	1	x	x	x	*Pulex irritans*	x	x	x	x
Ctenophtalmus devignati	x				*Tunga penetrans*	x	x	x	x
Ctenopthalmus evidens	x				*Xenopsylla brasiliensis*	1	x	x	x
Ctenophthalmus eximius			x	x	*Xenopsylla cheopis*	1	x	x	x
Ctenophthalmus leptodactylus			x		*Xenopsylla debilis*		x	x	
Ctenophthalmus kemmelberg			x		*Xenopsylla hipponax*	x			
Ctenophthalmus teucqae			x		*Xenopsylla humilis*		x	x	
Ctenophthalmus cophurus		x	x		*Xenopsylla nilotica*			x	
Ctenophtalmus luberensis	x				*Xenopsylla nubica*	x	x	x	x
Ctenophtalmus phyris	x			x	*Xenopsylla philoxera*			x	
Dinopsyllus ellobius	x				*Xenopsylla syngenis*	x		x	
Dinopsyllus grypurus			x		*Xenopsylla torta*	x			
Dinopsyllus lypusus	1	1	x	x	*Xenopsylla versuta*		x	x	x
Dinopsyllus longifrons			x		*Xiphiopsylla hyparetes*	x	x	x	
Dinopsyllus titan			x		*Xiphiopsylla lippa*	x		x	
Echidnophaga gallinacea	x	x	x	x					

Source: Laudisoit (2009)

Note: The involvement of each species as plague carrier is indicated as 1, for species found infected or x, for species present with no evidence of plague

2.3. Landforms and Soils with Respect to Plague Reservoirs and Vectors

2.3.1. Landforms with respect to plague reservoirs and vectors

Elevation and aspect are environmental gradients that have been widely recognized in mapping and in gradient analysis of patterns of living organisms across landscapes (Swanson *et al.*, 1988). Such studies include those done in the Arctic (Billings, 1973), Mountain region in the Central Appalachians, US (Hack and Goodlett, 1960) and in Santa Catalina Mountains, Arizona (Whittaker and Niering, 1965). Implicit in the relations between patterns of living organisms and landforms were found to be the influences of elevation and aspect on solar energy and water regimes at patches within complex ecosystems (Swanson *et al.,* 1988). Solar energy and water regimes are important factors affecting food availability and habitat microclimate in many organisms including the reservoirs and vectors of plague. Forman and Godron (1986) reported that landforms may delimit the ranges of some vertebrates. The authors added that gullies, streams, and cliffs may form physical barriers to movement, or they may act as convenient, but passable, features to mark the boundaries between home ranges of neighbouring animals. In a study done in the Blue Mountains of Oregon, cliff faces and associated talus slopes have been observed to form habitats at several scales for a community of small mammals and birds in semiarid landscapes (Maser *et al.*, 1979).

In another study, slope gradient and slope curvature (shape) were found to influence hydrology and sediment sorting in soil (Hall and Olsen, 1991) which in turn affected digging for the burrowing small mammals in Colorado (Fitzgerald *et al*., 1994). In a study done in the City of Boulder Open Space and Mountain Parks, it was also found that slope aspect and consequent insolation influences soil temperature and hibernation timing in the Preble's meadow jumping mice (*Zapus hudsonius preblei*) (Cranford, 1978).

Adult fleas live exclusively as parasites of warm blooded animals, especially mammals (Valent BioSciences, 2001). As it was shown earlier, fleas are ectoparasites and therefore, their lives are associated with their hosts. In a study done in Boulder County, Colorado by Brinkerhohoff (2008) to determine how prevalence, abundance and species assemblages of fleas vary by habitat association, it was found that skunks sampled from foothills habitats carry significant richer flea species assemblages than those sampled in the grassland habitats. Skunks from foothills habitats were also found to carry fleas typically associated with rodents. From the literature search, it can be concluded that inadequate research has been done in Africa to relate the distribution of small mammals and fleas with landforms.

2.3.2. Soils with respect to plague reservoirs and vectors

In plague studies, the ecological importance of edaphic factors is vital in understatnding the disease dynamics (Hubert *et al.*, 1977). Most studies on disease ecology have attempted to examine the surface landscape connectivity (Kucheruk, 1965; Ostfeld *et al.*, 2005; Wilcox and Colwell, 2005) but have so far not adequately considered the soil component (Laudisoit, 2009). Some studies suggest that soil physical properties are important factors influencing rodents which are plague reservoirs. Shenbrot *et al.* (2002) reported that rodent burrows have relatively stable microclimate which provides protection, shelter, nesting and food storage for the small animals. The burrow structure has been observed to be related to the physical properties of the soils in which they are constructed (Anderson and Allfred, 1964; Laundré and Reynolds, 1993). Some studies show that the most complex burrows occur in hard - clay and silt - soils, while the simplest burrows are found in sandy soils

(Shenbrot *et al*., 2002). In Tanzania, a study by Massawe *et al*. (2005) aimed to investigate the role of soil on population, abundance and distribution of rats (*Mastomys natalensis*) which is one of the plague reservoirs revealed that soil texture was an important influencing factor. The researchers suggested that *M. natalensis* prefers loam-textured soils with a high percentage of sand which are probably better than clay soils for burrowing and nesting, particulary in the rainy season. In a study done in South Africa by Jackson *et al.* (2008), the size distribution of sand particles influenced the density and compactability of the soil, and both were positively correlated with the presence of golden moles. These soil characteristics are thus vital in understanding and describing the distribution of the rodents.

Small mammals living in the burrows are associated with fleas which spend a part or all of their life time feeding and nesting with the burrowing animals (Shenbrot *et al.*, 2002; Laudisoit, 2009). Observations from studies conducted in the USA have shown that fleas can survive in the rodent burrows for a long time even without the rodents' presence and still remain infectious. In another study, infected prairie dog fleas (*Oropsylla labis* and *O. tuberculata cynomuris*) were recovered from burrows in Colorado for a period more than one year after their hosts had perished from plague (Kartman *et al*., 1962).

The relationship between the cost of digging a burrow and soil hardness is regarded as one of the most important factors affecting burrowing efficiency in subterranean rodents (Luna and Antinuchi, 2006). For example, the digging metabolic rate (DMR) for *Ctenomys talarum (Ctenomyidae)* was found to be 295.9% higher than the resting metabolic rate when digging through relatively soft soil (Luna *et al.,* 2002). The proportions of the various particle size classes within sand samples determine its properties, such as potential compactability and drainage (Brady and Weil, 2002). Poorly graded soils do not compact significantly whereas well-graded soils compact more readily due to the availability of particles of various sizes to interlock with one another (Jackson *et al*., 2008). The analysis of particle size distribution could thus yield valuable insights into the factors affecting soil suitability for the burrowing plague reservoirs and their associated vectors.

Researches done worldwide suggest that soil chemical properties have an influence in spatial distribution of plague vectors and reservoirs which define plague foci. In the studies done in the Altay Mountains and Kyzyl Kum Desert (in Uzbekistan) and in the Caspian lowlands, Rotshild (2001) reported that occurrence of plague epizootics were correlated with soils which have medium or high concentration of iron, cobalt, and titanium, and low concentrations of copper, nickel, and vanadium. Observation by Liu *et al.* (2000) showed that the distribution of plague foci in China is correlated with calcium and iron enriched soil environments. The distribution of plague foci could, according to Tan *et al.* (2002) be closely related to calcium- and iron-enriched soils due to the known role of these elements in *Y. pestis* virulence (Avanyan and Gubina, 1961; Straley and Bowmer, 1986).

2.4. Spatial Modeling of Landscape Factors with Respect to Disease Vectors and Reservoirs

Geographic Information System (GIS) has been used in identifying environmental risk factors associated with vector-borne diseases. Glas *et al.* (1995) tested 53 environmental variables on the risk of Lyme disease infections. The analysed risk factors included the distances to forest edges, steepness of slopes, distances to watersheds, streams and elevation. The risk of Lyme disease decreased with increasing distance from forest edge and increased with increasing slopes steepness. The authors observed that distances from streams were not related to changes in disease beaviour (Glas *et al.,* 1995). GIS was also used to describe the spread of Dengue fever in French Guyana where spatial and temporal patterns of the disease were analysed. In this study the distances between the houses were calculated and compared with confirmed cases of Dengue fever. The results showed that spatial outbreaks of the disease seemed to appear at some fixed distances which were equivalent to the most nearest neighbouring houses (Tran *et al*., 2004).

The distribution of gastrointestinal infections with respect to drinking water supply structures was analyzed in a GIS in the Rhine-Berg District, Germany (Dangendorf *et al*., 2002). A trend of positive linkage between disease incidence and amount of groundwater which according to Swanson *et al.* (1988) is influenced by slope curvature was found (Dangendorf *et al*., 2002).

In Northern Thailand the influence of agricultural and forested landscape structures on species of malaria vector (female Anopheles genus mosquito) density and diversity was studied by Overgaard *et al*. (2003). Results showed that some species were positively related to forest mean patch size, various water and paddy field landscape metrics and negatively related to landscape diversity. It was observed that forest fragmentation resulting from human activities may increase landscape heterogeneity, which may result in a reduction in species diversity (Overgaard *et al*., 2003).

2.5. Spatial Modeling of Landforms and Soil Properties with Respect to Plague Reservoirs and Vectors

Several studies have described modeling approaches to plague dynamics. A model of vector borne plague was developed by Keeling and Gilligan (2000a, b) focusing on *Y. pestis* infection in humans, *R. rattus*, and *X. Cheopis.* The model parameters tested included rat's reproductive rate, probability of inherited resistance, rat's carrying capacity, death rate of rats, transmission rate (infectious period), probability of recovery, movement rate of rats, fleas searching efficiency, flea's reproductive rate, death rate of fleas, mean flea's carrying capacity per rat, movement rate of fleas, reproductive rate of humans, death rate of humans, transmission rate to humans (infectious period) and probability of recovery. From the model it was observed that the real danger to humans occurs when there are many infected fleas, but few rat hosts. In this model, landscape factors such as soils and landforms were not considered.

In another study by Foley *et al.* (2007), the traditional vector SIRS (susceptible infective resistant susceptible) models were extended to create a flexible matrix-based community vector SIRS framework, which was used to investigate multiple interacting rodent hosts and flea vectors of plague in the Western United States. The parameters used in this model included number of host species in the community, number of vector species in the community, vector of host-carrying capacities, composite carrying capacity parameter, species specific host population size, Malthusian parameter for host and fleas, vector of host maximum birth rates, vector of flea mean daily hatch rates, amplitude and peak dates of flea hatches, and vector of environmental stochasticity affecting hosts. Sensitivity analysis indicated that the model was sensitive to flea attack rate, host recovery rate, and rodent host carrying capacity but relatively insensitive to changes in the duration of latent infection in the flea, host and vector competence, flea recovery from infection, and host mortality attributable to plague. Again, in this model no landform and soil factors were included.

Most of the modeling studies have concentrated on plague occurrence relations with climatic factors and less attention has been given to plague reservoirs and their associated vectors with landscape factors such as landform and soils. For example, a national update paper of modeling relationships between climate and frequency of human plague cases in the Southwestern U.S found that precipitation, temperature, humidity, land cover, vegetation, and altitude are important factors to be analyzed in an early warning system (Enscore *et al*., 2002). This update paper mentioned only altitude as among important factors to be analysed in early warning system among the landforms and soil factors.

CHAPTER THREE

3.0. MATERIALS AND METHODS

3.1. Description of the Study Area

Location

The study area is located in the Western Usambara Mountains, Lushoto District, Tanzania (Fig. 2). The geographical location is between latitudes $4^0$36’48.647”S to $4^0$42’47.509”S and longitudes $38^0$18’20.538”E to $38^0$08’36.723”E. The altitude of the area ranges from 418 m in the plains to 2273 m above sea level in the summits of the dissected plateau ridges.

Geomorphology

The Western Usambara Mountains were formed by block-faulting of Precambrian crystalline rocks 180-290 million years ago (Hamilton, 1989; Griffiths, 1993). The successive processes of erosion and uplift and reactivation of the faults are the major processes that have shaped the present landscape (ww.easternarc.org). It is predominantly characterised by slopes that are gently undulating to steep, and are intersected at their base by narrow flat and broad U-shaped valleys. The slopes are also cut by numerous gullies. Some of these gullies carry permanent streams, while the rest carry water only during the wet season. The rocks of the West Usambara Mountains are assigned to the Usagaran System. The rocks have been subjected to several periods of metamorphism and migmatization. They represent a thick series of highly metamorphosed calc-argillaceous and calcareous sediments, with minor carbonaceous beds and with intercalated igneous rocks. Minor intrusions of gabbro, serpentinite, pyroxenite and anorthosite have been affected by phases of movement

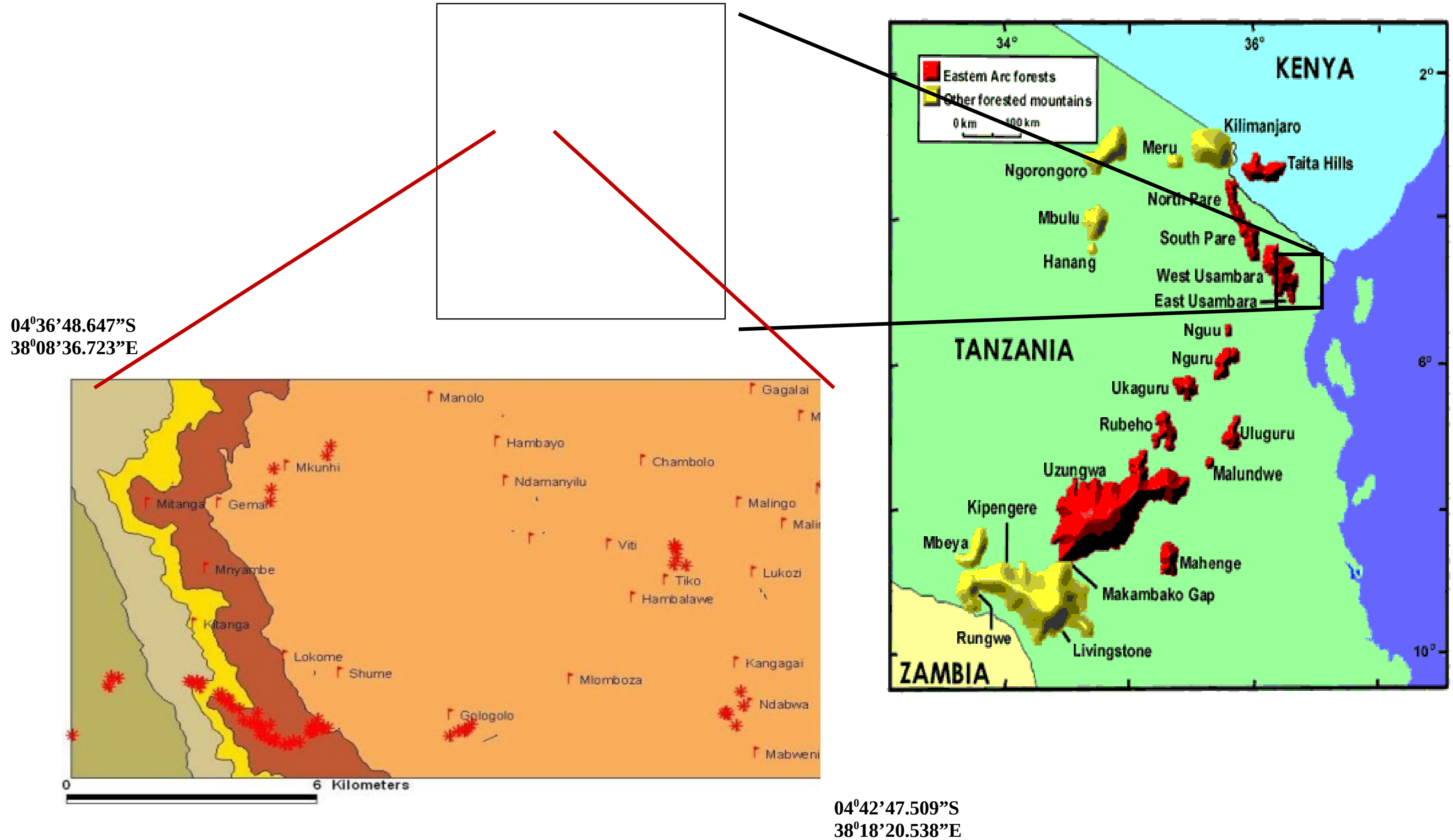


Figure 2: Location map of the study area

and metamorphism (Bagnall, 1963; Muhongo and Lenoir, 1994; Maboko and Nakamura, 2002). Due to complex movements and erosion which have affected the landscape, rock outcrops occur in many places including the escarpment and summits of ridges. However, the geological sequence of the rocks tends to be rather uniform (Mutakyahwa *et al*., 2003). The most common parent materials of the soils observed today include (acid) gneiss, pyroxene and hornblende granulites (Halperin, 2002). Bauxite deposits have been observed in many places in the study area (Mutakyahwa *et al*., 2003).

Soils

Soils of the study area are mainly clays, sandy clays and sandy clay loams, varying in colour from red through grey-brown to black, characterized by low pH values and rich in iron, manganese and magnesium. According to Neerinckx (2006), the dominant soils on the slopes are characterised by an argic horizon, often strongly eroded; and thus acidic (Acrisols, Acric Ferralsols, Lixisols and Alisols). Besides, less eroded younger soils (Luvisols and Lixisols) can be found. On the valley bottoms, dominant soils are under influence of a fluctuating groundwater table (Fluvisols and Gleysols), while the hill tops are characterised by superficial soils where an abundance of rock and petro-plinthic outcrops, rich in iron, are present (Neerinckx, 2006).

Population

Lushoto District has a total population of 419,970 inhabitants of whom 54.3% are women (URT, 2002). The district is densely populated with an annual growth rate of

2.8% and a density of 102 inhabitants per km^2 reaching 120 persons per km^2 in some places. The inhabitants belong to three major tribes or ethnic groups: the Wasambaa who constitute the largest group (78.3%), followed by the Wambugu (10%), and the Wapare (5%). The remaining 5% are immigrants from diverse origins in other regions (Laudisoit, 2009).

Climate

The rainfall in the area has a bimodal pattern with short rains starting in October to December and long rains from March to June with a peak in April. The mean annual rainfall ranges between 600 and 2,000 mm per annum. The mean annual temperature varies with altitude: at 800 m a.s.l. the mean annual temperature is 25-27°C and on the plateau at 1,500-1,800 m a.s.l. the mean annual temperature range is between 17 and 18°C (Neerinckx, 2010). The mean annual relative humidity of the study area is 70%. Major portion of the study area which is covering the plateau and the escarpment is located in humid cold agro-ecologica zone while the portion which covers the piedmont-plain is located in dry-warm area (Neerinckx, 2006).

Vegetation and landuse

Originally, the West Usambara Mountains were almost entirely covered with natural forests (Van Olmen, 2008). There were two main types of vegetation: the Camphor-Podo type which is a montane rain forest of sparse camphor (*Ocotea usambarensis*) with some Podo (*Podocarpus usambarensis* and *Podocarpus pensiculy*) and the Cedar forest type which is a montane dry forest and is described as mainly cedar (*Juniperus procera*) with a thick shrub under storey (Kiboga, 2005). The interactions of climate, topography and human interventions, have led to a landscape that exists today of mostly agricultural fields, some of them bordering reforested areas and timber plantations (Debien, 2009), and primary rainforest in the Forest Reserves of amongst others Shume-Magamba forests (Johannson, 2001). According to Hubeau (2010), the vegetation of the natural forest is *Camphor-Podo* vegetation type which is a montane and afro-montane rain forest vegetation. The forest is composed of camphor (*Ocotea usambarensis*) with podo (*Podocarpus usambarensis* and *Podocarpus pensiculi*) and an undergrowth of *Lansthus cirumilee* and other shrubs. Associated species are *Parinari excelsa, Pygeum Africanum, Ficalhoa laurifolie, Polycas* spp., *Macarange kilimandscharica, Chrysophylum* spp., *Olea hochstetteri* and *Cassipourea* spp. (Hubeau, 2010). The major species of the plantations are cedar (*Juniperus procera*), cypress (*Cupressus Lusstanica*), *Pinus petula* and *Pinus radiate* (Masunga, 2009).

Smallholder farming is the main economic activity for the majority of households on which more than 90% of the population depends (Lyamchai *et al.,* 1998; Tenge, 2005). Most cultivation takes place on the slopes on which land degradation processes including soil erosion is severe. The valley bottoms are intensively used for vegetable production where water from furrow irrigation is for production of horticultural crops. The dominant land uses include subsistence and cash crop agriculture (covering 58% of the area), orchards and commercial plantations (11%), indigenous protected forest reserves (16%), and pastures (15%) (Shemdoe, 2002). The main cash crops are vegetables, fruits and irish potatoes, while maize (*Zea mays),* cassava (*Manihot esculenta),* beans (*Phaseolus lunatus*) and potato (*Solanum tuberosum*) are the main food crops (Kamugisha *et al.*, 2007; Neerinckx, 2010).

3.2. Methodology

3.2.1. Pre-field work

3.2.1.1. Collection of materials and available information

Before going to the field, acquisition of remote sensing materials was done. The materials collected included aerial photographs of scale 1:30,000 (run numbers 1748-1752, 1717-1722, 1661-1668, 1640-1647, 3397-3400, 4146-4149, 4090-4094) taken on 7 August, 1996 and orthophoto maps of scale 1:54,000 (run numbers 9480410, 9480400, 9470410, 9470400) of 1996. Other materials collected included topographic maps at the scale of 1:50,000; Mkomazi sheet No. 109/1 and Mlalo sheet No. 109/2 (Survey and Mapping Division, 1970) and the geological map of Lushoto at the scale of 1:125,000: Quarter degree sheet No. 109 (Geological Survey Division, 1963). Various satellite imagery (Landsat TM and Landsat ETM) retrieved on 11 January 1973; 02 February 1987, 25 October 1999, 06 February 2003 and 08 January 2008 were also obtained at this stage.

Review of reports and dissertations of previous studies was also done. These reports included those done by Kilonzo and Msangi (1991), Davis *et al.* (2006), Neerinckx (2006), van Olmen (2008), Debien (2009) and Laudisoit (2009). Published research materials and reports from other parts of the world on the subject matter were searched from the internet and libraries at Sokoine University of Agriculture (SUA) and Lushoto district headquarters.

3.2.1.2. Data interpretation and preparation of base maps

In this phase analysis of acquired remote sensing materials was done in order to obtain landform map for field mapping. Stereoscopic and visual analysis of aerial photographs and orthophoto maps was done in the Remote Sensing and GIS laboratory of Sokoine University of Agriculture. In this exercise landform characteristics including elevation, slope shape, slope gradient and slope aspect were identified and mapped using ArcView GIS 3.2 software. Others included landuse and vegetation. Other elements were derived from the analysis of topographic maps and geological maps. The map elements obtained above were integrated in GIS environment to produce base maps of the study area with details on landforms and their associated characteristics for field use and further analysis. The base maps produced included contour, landform, landuse, geology and digital elevation model.

3.2.2. Field work

3.2.2.1. Landform and soil survey

A combination of both free survey and transect observations were used in the field to collect data on landforms and soils related properties in accordance with procedures outlined by Dent and Young (1981). In addition to soil identification in the field, landform features mapped during interpretation phase (section 3.2.1.2) were confirmed. The base maps were also used to plan and guide the location of transects and site for soil observation and sampling.

Along the transect and on each identified landform unit, soil observations by augering were made to a maximum depth of 1.5 m or to a limiting layer to identify soil properties. At each observation site, data on landform and soil morphological characteristics were recorded. Each observation site was geo-referenced using Global Positioning System (GPS) (model OREGON 400t). The survey was done at an observation intensity of 2 mini-pits per square km and 8 auger holes per square km. Fig. 3 shows location of observation points on selected transects in the study area. Landform units similar in parent material, relief, topography and soil morphological characteristics were considered to be similar and were accorded a similar mapping unit. In this way, twenty mapping units describing the homogeneous landform and soil characteristics were identified.

3.2.2.2. Field characterisation of soils

Based on the delineated mapping units and field soil morphological and physical characteristics, locations for representative soil profile pits were identified and fully geo-referenced. Soil profile pits were dug to a depth of 2 m or to a limiting layer. The soil profile pits were studied and described according to FAO Guidelines for Soil Description (FAO, 2006).

Site characteristics including slope gradient, slope type, slope length, rock outcrops, stoniness, erosion, natural drainange, natural vegetation and landuse were recorded. Soil profile morphological characteristics studied included soil colour, texture, consistence, structure, porosity, effective depth, presence or absence of cutans, mottles, concretions and type of primary minerals and rock fragment. Soil colour was determined by Munsell soil colour charts (Munsell Colour Co., 1992).

3.2.2.3. Soil sampling

In each soil profile pit, bulk and undisturbed soil samples were taken from designated natural horizon for physical and chemical analysis in the laboratory.

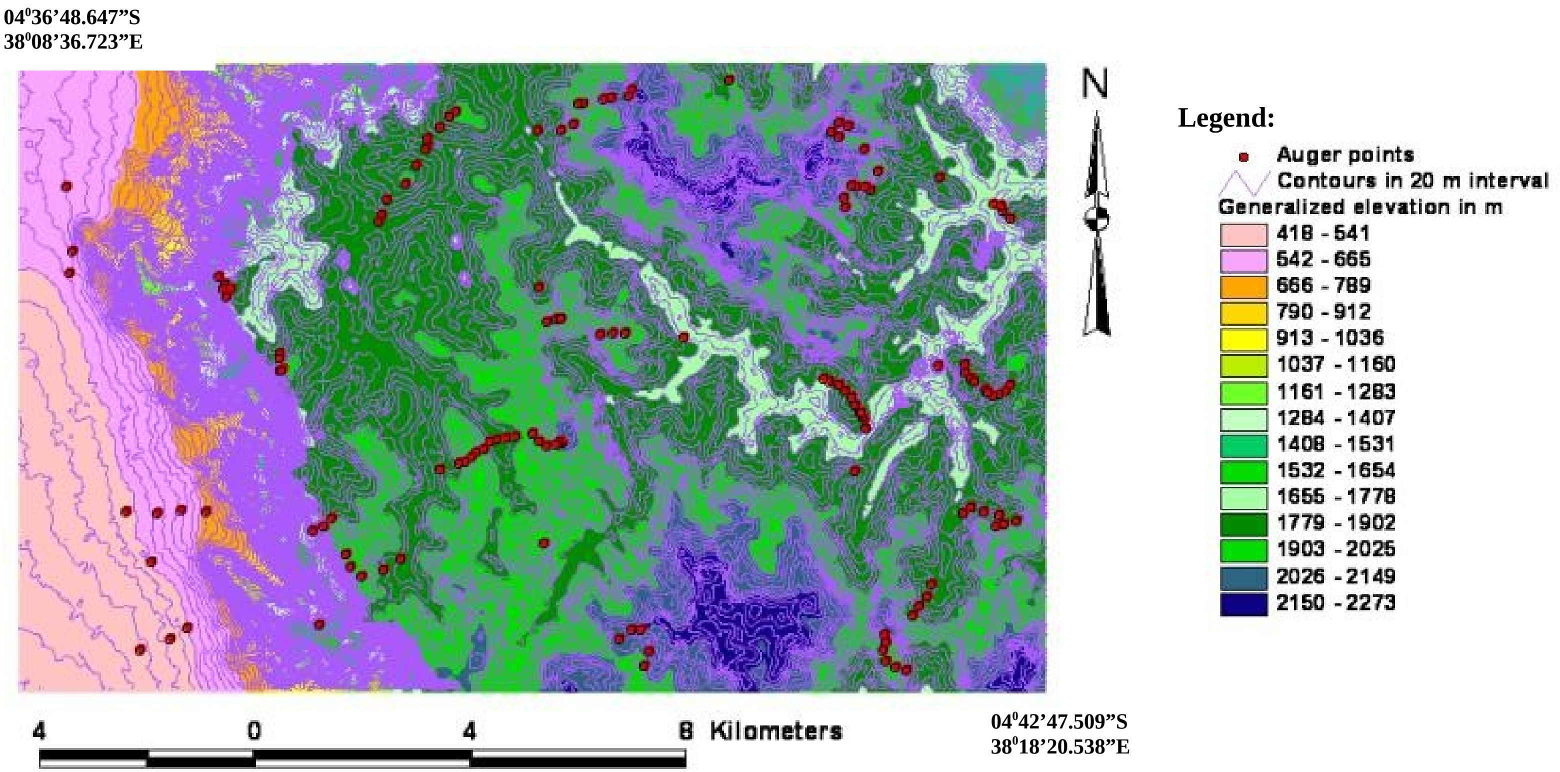


Figure 3: Location of observation points on some selected transects in the study area

3.2.2.4. Trapping of rodents and fleas

Trapping of rodents (plague reservoirs) was conducted twice between December 2009 and January to March 2010. Trapping was done in three distinctive major landscapes: piedmont-plain, escarpment and plateau. Different sites were chosen in each major landscape depending on the variability of the landform features and soil characteristics such as slope gradient, slope aspect, slope shape, elevation, rock outcrops and fissures, soil depth, structure, wetness and hardness or compaction. Other factors which were considered include vegetation and land use, frequency of plague occurrence and traps security. Sherman traps (H.B. Sherman Traps Inc., Tallahassee, FL, U.S.A.) were used to trap the animals. Peanut butter mixed with maize bran was used as bait. A total of 100 traps were used per site in 10 lines, each with 10 trapping stations placed 10 m apart and left open during the day and night for two consecutive days as outlined by Mulungu *et al.* (2008). Traps were inspected every morning where those with catches were replaced by spare traps and bait. The trapped rodents were counted and recorded as plague reservoirs in the respective mapping units. The rodents were further made unconscious by using chloroform and with the help of ethanol fleas were brushed off and collected from the rodents' bodies. Collected fleas were counted and recorded as plague vectors in the respective mapping unit.

3.2.3. Post-field work

3.2.3.1. Laboratory soil analysis

The disturbed soil samples were air-dried and ground to pass through 2 mm sieve to obtain the fine earth fractions for chemical and physical determinations. Undisturbed core samples were used for the determination of bulk density and moisture retention characteristics. In order to express the results of the soil analysis on oven-dry soil weight, the moisture correction factor (MCF) for each soil sample was calculated after determination of the moisture content of the respective soil samples. The moisture content was determined by the use of oven dry method (Hamazaki and Paningbatan, 1988) where the soil sample was weighed in a tare tin, oven-dried overnight at 105^0C, cooled in a desiccator and weighed again with the tare tin.

Moisture content was calculated by the formula:

$$\text{Moisture content } (\%) = \frac{\text{A} - \text{B}}{\text{B} - \text{Tare tin weight}} \text{ X } 100$$

Where: A= weight of soil sample+tared tin (g)

B= weight of oven-dried soil+tared tin

Moisture correction factor was calculated by the formula:

$$\text{Moisture correction factor (mcf)} = \frac{100 + \%\text{ moisture content}}{100}$$

Soil texture was determined by hydrometer method using calgon (5%) as a dispersing agent (NSS, 1990) while water dispersible silt and clay was determined by both pipette and hydrometer methods (NSS, 1990). Bulk density was determined according to core sample method (Blake and Hartge, 1986). Soil moisture retention characteristics were studied using sand kaolin box for low suction values and pressure membrane apparatus for higher suction values (NSS, 1990). The soil pH was determined potentiometrically in water and in 1N KCl at the ratio of 1:2.5 soil-water and soil-$CaCl_2$ as described by McLean (1982) while electrical conductivity (EC) was determined by conductivity meter in a 1:2.5 soil-water suspension following a method by Rhoades (1982). Organic carbon was determined by the Walkley and Black wet oxidation method as outlined by Nelson and Sommers (1982). Percent organic matter was calculated by multiplying percent organic carbon by 1.72. The total nitrogen in the soil samples was determined by Kjeldahl method (Bremner and Mulvaney, 1982) while the carbon/nitrogen ratio (C/N ratio) was obtained arithmetically by dividing samples calculated percent organic carbon by its calculated percent total nitrogen. Available phosphorus was extracted by Bray and Kurtz-1 method (Bray and Kurtz, 1945) for soils with pH_{water} less than 7 and Olsen method for soils with pH_{water} above 7 and determined spectrophotometrically (Murphy and Riley, 1962; Watanabe and Olsen, 1965). Cation exchange capacity of the soil (CEC_{soil}) and exchangeable bases were determined by saturating soil with neutral 1M NH_4OAc (ammonium acetate) and the adsorbed NH_4^+ were displaced using 1M KCl and then determined by Kjeldahl distillation method for the estimation of CEC of the soil. Cation exchange capacity of clay (CEC_{clay}) was calculated by multiplying CEC_{soil} by 100 and dividing by percent clay of the soil sample. The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+, K^+) were determined by atomic absorption spectrophotometer (Thomas, 1982). The total exchangeable bases (TEB) were calculated arithmetically as a sum of the four exchangeable bases (Ca^{2+}, Mg^{2+}, Na^+ and K^+) for a given soil sample. Total exchangeable acidity was determined for soil samples with pH_{water} below 5.0 by percolating soil sample with 1 M KCl solution and then titrating with sodium hydroxide. A second titration with HCl after addition of sodium fluoride was used to obtain the exchangeable aluminium as described in the National Soil Service Soil Laboratory manual (NSS, 1990). From these samples; effective cation exchange capacity of the soil sample ($ECEC_{soil}$) was calculated arithmetically as a sum of total exchangeable bases (TEB) and total exchangeable acidity. For the same samples; effective cation exchange capacity of the clay ($ECEC_{clay}$) was calculated by multiplying $ECEC_{soil}$ by 100 and then divided by percent clay content of the soil sample. The other arithmetically derived parameters were the exchangeable sodium percent (ESP) and the percent base saturation (PBS). ESP was calculated by multiplying exchangeable sodium by 100 and then divided by CEC_{soil} while the PBS was calculated by multiplying the total exchangeable bases (TEB) by 100 and then divided by CEC_{soil} of the respective soil samples. Diethylenetriaminepenta-acetic acid (DTPA) was used to extract four micronutrients: iron, manganese, copper and zinc as outlined in Moberg (2000).

3.2.3.2. Landform characteristics for prediction of plague reservoirs and vectors

The landform characteristics which were hypothesized to have influence on distribution of plague reservoirs and vectors in this study were elevation, slope shape, gradient and slope aspect. These characteristics were determined from digital elevation model (DEM) of the study area with a pixel size of 20 m by 20 m. The DEM was generated by digitizing 20 m interval contours from 1:50,000 topographic maps of the study area in ArcView GIS 3.2 software. The calculations were done in two steps: (a) conversion of segment contour map into raster formart and (b) contour interpolation by linear distance method. In the first operation the raster map is obtained by georeferencing in which the pixel size, the number of lines and columns and the minimum and maximum X and Y coordinates of the map are defined. The obtained raster map contains elevation values for those pixels covered by contour lines. In the second operation, elevation values for each undefined pixel in between the rasterised contour lines were calculated using “linear distance method” to obtain height values for the undefined pixels. All these were done in ArcView GIS 3.2 software. The digital elevation model was used to create landform feature maps including generalized elevation map, slope curvature (shape), slope gradient and slope aspect.

3.2.3.3. Spatial prediction of plague reservoirs and vectors

A stepwise multiple linear regressions were employed using Minitab (2004) statistical package to obtain landform-soil models for predicting spatial distribution of plague reservoirs and vectors abundance as shown in equation (1).

$$\mathbf{Y = a + b_1X_1 + b_2X_2 + \ldots\ldots. + b_nX_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(1)}$$

Where: **Y** = predicted spatial distribution of plague reservoirs or vectors,

$\mathbf{X_1, X_2, X_n}$ = landform-soil spatial attributes,

$\mathbf{a, b_1, b_2, b_n}$ = parameter coefficients (estimates).

Landform and soil attributes created in sections 3.2.3.1 and 3.2.3.2 respectively were fitted in the landform-soil models to spatially predict abundance of plague reservoirs and vectors distribution. The models predicted values were validated by linear regression analysis between model predicted and the actual recorded plague reservoirs and vectors abundance.

3.2.3.4. Classification of soils

Using field and laboratory data, the soils were classified to level-2 of the FAO World Reference Base (FAO, 2006) and to subgroup level of the Soil Taxonomy (Soil Survey Staff, 2006)

3.2.3.5. Statistical analysis

Qualitative assessment and descriptive statistical analysis were widely employed in the exploratory analysis of plague reservoirs and vectors abundance and related factors of landform and soil. This included the estimation of means and standard deviations of some critical variables of the study. Wherever it was applicable the degree of association between variables was measured by linear regression and calculation of the Pearson correlation coefficient R. Level of significance (P) at 0.05 was used.

CHAPTER FOUR

4.0. RESULTS AND DISCUSSION

4.1. Spatial Distribution of Landforms and Soils

4.1.1. Landform features

Figures 4 and 5 present the major landscapes and their associated landform features in the study area. Tables 5 and 6 present summary description of the landform units and their associated relief types, slope facets, intensity of dissection and dominant slopes in degrees. Maps of slope shape, slope gradient and the slope aspect of the study area are presented in Fig. 6, 7 and 8 respectively. These results show that the study area displays marked variation in altitude range, relief and intensity of dissection. Van Engelen *et al*. (2006) when preparing soil and terrain database of Central Africa used landform parameters such as altitude, slope gradient and relief intensity which are also used in this study. On the basis of these characteristics the study area has been classified into three major landform units namely piedmont-plain, escarpment and plateau. This classification is in accordance with the Guidelines for Soil Description (FAO, 2006).

The piedmont-plain consists of undulating to rolling relief. Its main salient features comprised the footridges, upper sloping interfluves, colluvio-alluvial fans and the lower sloping interfluves. The footridges are strongly dissected slope complexes constituting the narrow ridge summits and slopes with slope gradients ranging from 15 to 30 degrees. The upper sloping interfluves are moderately dissected complex slopes with gradients ranging dominantly from 10 to 14 degrees. The colluvial-alluvial fans have complex slopes and their dominant slope gradients range from 6 to 10 degrees. The lower sloping interfluves are slightly dissected, with complex slopes

Piedmont-plain Escarpment Plateau

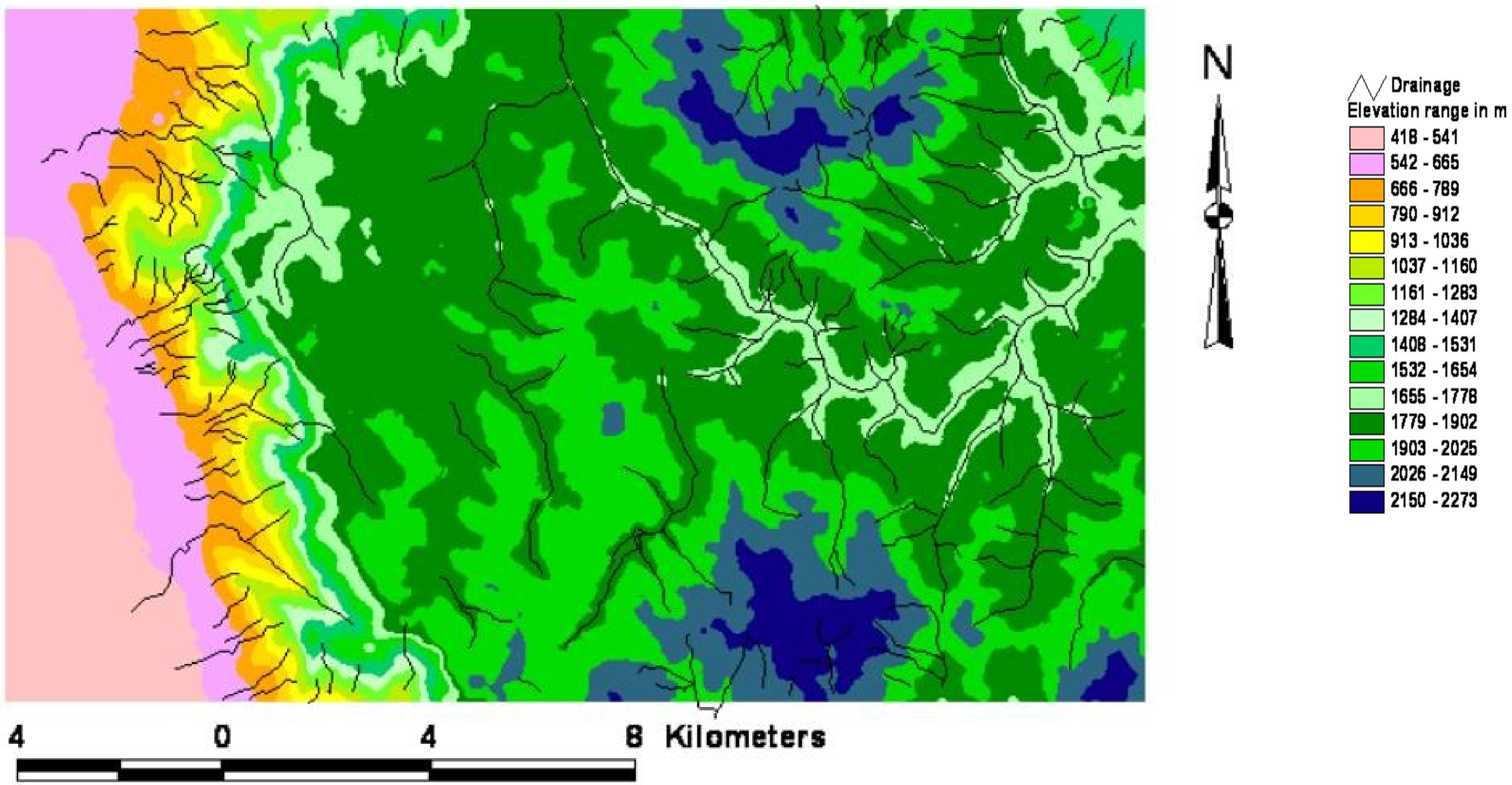
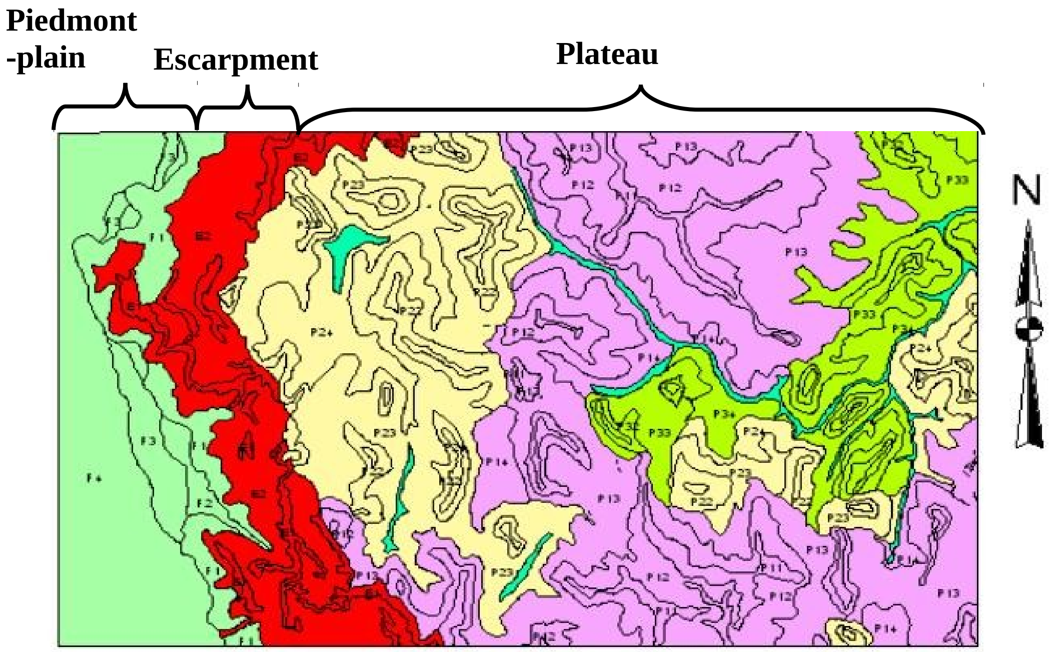


Figure 4: Generalised elevation map depicting the major landscapes and their intensity of dissection in the study area.



Key: Landform features

F1	Foot ridges
F2	Upper sloping interfluves
F3	Colluvial/alluvial fans
F4	Lower sloping interfluves
E1	Rock outcrops and cliffs
E2	Very steep complex slopes
P11	Crest of high altitude plateau
P12	Upper slopes of high altitude plateau
P13	Mid slopes of high altitude plateau
P14	Lower slopes of high altitude plateau
P21	Crest of medium altitude plateau
P22	Upper slopes of medium altitude plateau
P23	Mid slopes of medium altitude plateau
P24	Lower slope of medium altitude plateau
P31	Crest of low altitude plateau
P32	Upper slopes of low altitude plateau
P33	Mid slopes of low altitude plateau
P34	Lower slopes of low altitude plateau
P4	Plateau valley bottoms

Figure 5: Major landscape units and their associated landform features

Table 5: Salient landform features in the study area: Piedmont-plain, Escarpment and High altitude plateau

Major landscape	Map unit	Landform features	Slope facets	Dominant slope gradient (degrees)	Lithology	Intensity of dissection
Piedmont-plain (418 - 800 m asl)	F1	Foot ridges	Slope facets complex and rock outcrops	15 - 30	Undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites	Strongly dissected
	F2	Upper sloping interfluves	Slope facets complex	10 - 14	Colluvio-alluvium derived from undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites	Moderately dissected
	F3	Colluvial/alluvial fans	Slope facets complex	6 - 10	Colluvio-alluvium derived from undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites	Moderately dissected
	F4	Lower sloping interfluves	Slope facets complex	1 - 7	Colluvio-alluvium derived from yellow to grey sands, duricrust calcareous and secondary limestone rocks	Slightly dissected
Escarpment (800 - 1680 m asl.)	E1	Rock outcrops and cliffs	Rockland	50 - 72	Undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites	Strongly dissected
	E2	Very steep complex slopes	Slope facets complex and rock outcrops	15 - 45	Colluvio-alluvium derived from undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites	Strongly dissected
High altitude plateau (ridges with peaks >2000 m asl)	P11	Ridge rest	Convex slopes and rock outcrops	1 - 6	Pyroxene, hornblende and khondalites	Moderately dissected
	P12	Upper slopes	Slope facets complex	50 - 70	Pyroxene, hornblende and khondalites	Strongly dissected
	P13	Mid slopes	Slope facets complex	30 - 55	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected
	P14	Lower slopes	Slope facets complex	15 - 30	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected

Table 6: Salient landform features in the study area: Medium and Low altitude plateaus

Major landscape	Map unit	Landform features	Slope facets	Dominant slope gradient (degrees)	Lithology	Intensity of dissection
Medium altitude plateau (ridges with peak between 1900-2000 m asl)	P21	Ridge crest	Convex slopes	1 - 6	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Moderately dissected
	P22	Upper slopes	Slope facets complex	30 - 60	Residium (insitu weathering of undifferentiated rocks dominated by distinctive bands of hornblende, pyroxene, biotite, garnet and leucocratic quartzo-feldspathic granulites)	Strongly dissected
	P23	Mid slopes	Slope facets complex	25 - 40	Colluvio-alluvium derived from pyroxene, hornblende and khondalite rocks	Strongly dissected
	P24	Lower slope	Slope facets complex	12 - 25	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected
Low altitude plateau (ridges with peaks <1900 m asl)	P31	Ridge crest	Convex slopes	1 - 6	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Moderately dissected
	P32	Upper slopes	Slope facets complex	25 - 50	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected
	P33	Mid slopes	Slope facets complex	18 - 30	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected
	P34	Lower slopes	Slope facets complex	8 - 25	Residium (insitu weathering of pyroxene, hornblende and khondalite rocks)	Strongly dissected

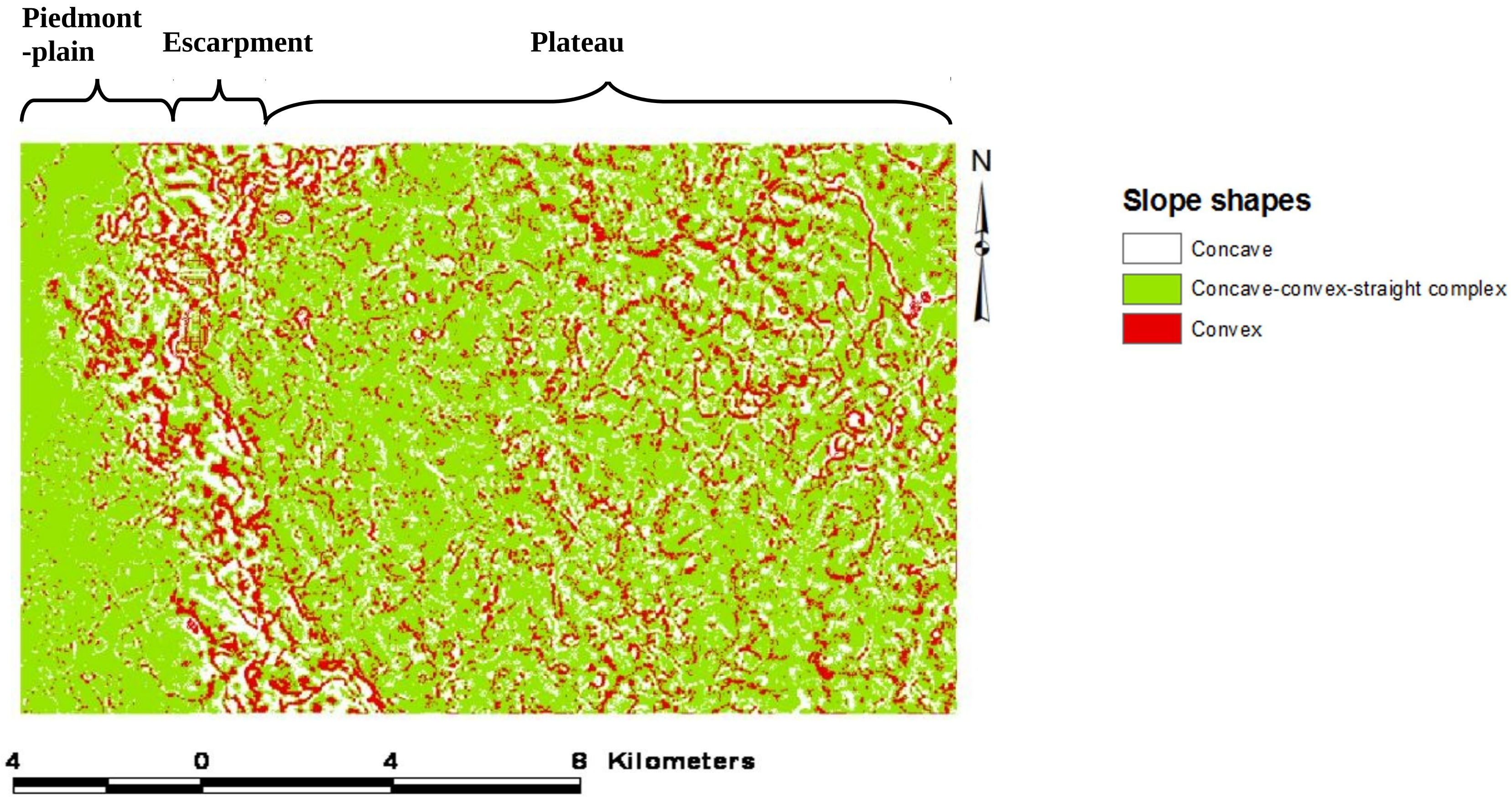


Figure 6: Slope shape map

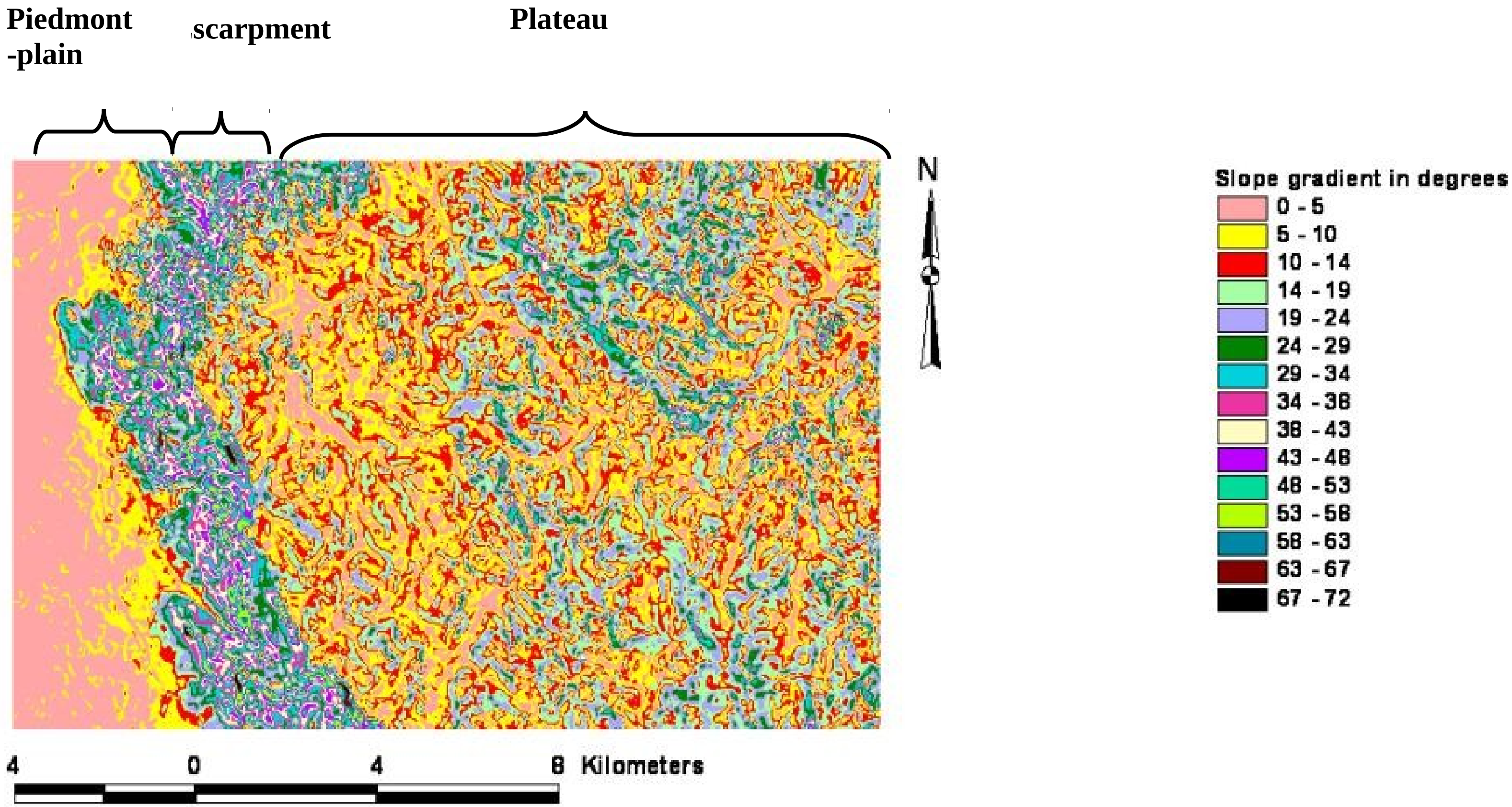


Figure 7: Slope gradient map

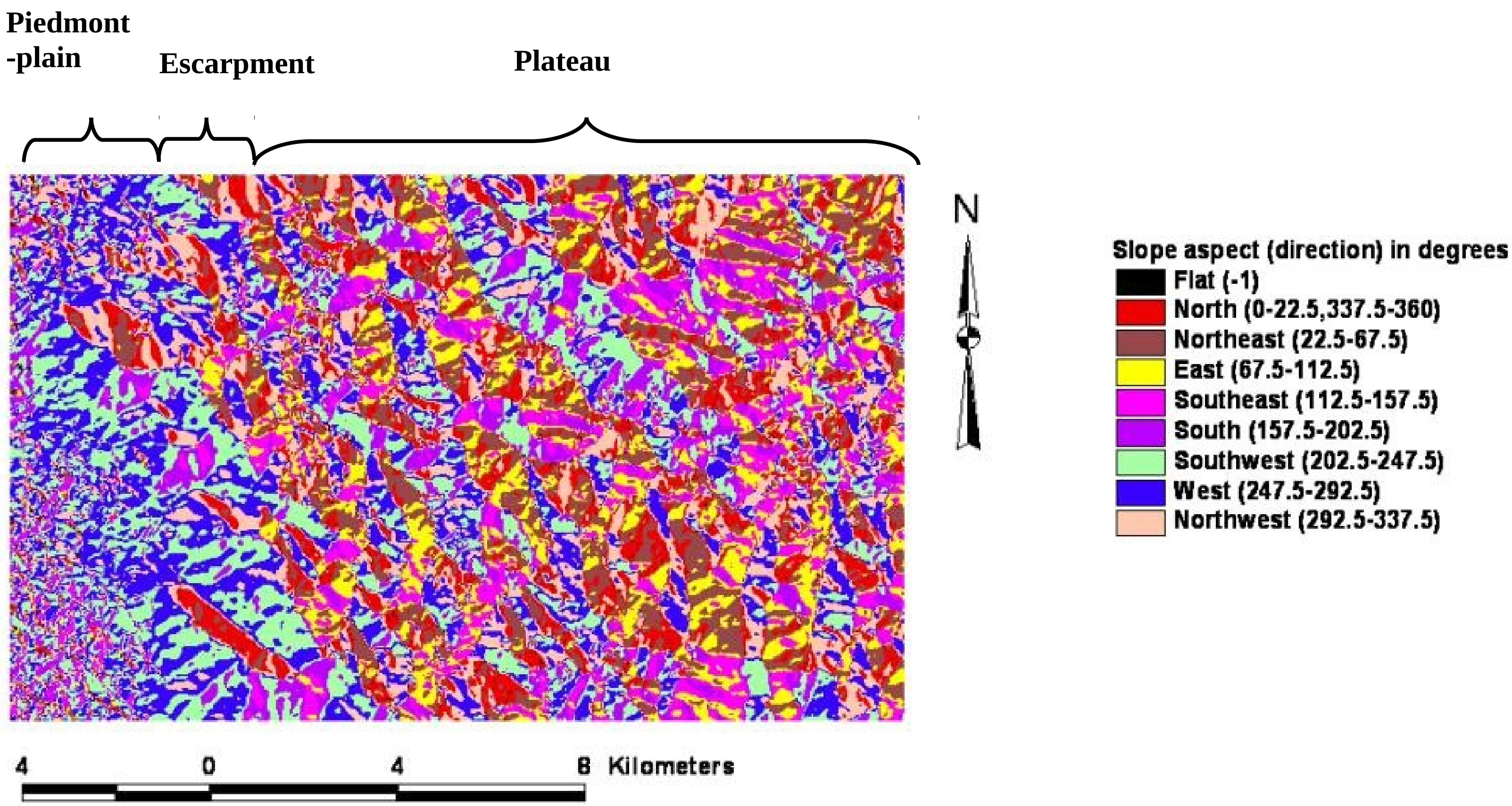


Figure 8: Slope aspect map

and dominant slope gradients ranging from 1 to 7 degrees. Generally, the piedmont-plain varies in elevation from 418 m in the lower sloping interfluves to approximately 800 m asl in the summits of the footridges. Majority of the slopes in the piedmont-plain face southward direction (157.5 - 202.5 compass degrees). Msanya *et al.* (2003) when working in Morogoro Urban, Tanzania found that the topography of the area was a mixture of flat and almost flat to undulating slopes (0.5-6%) and that piedmont was situated at an altitude range of 520-600 m.a.s.l. These features have been observed in the Piedmont-plain of the study area.

The escarpment is comprised of steep complex slopes, rock outcrops and cliffs. Generally, the escarpment lies between 800 and 1680 m asl adjacent to the plateau. The dominant slope gradients of the rock cliffs range between 50 and 72 degrees (very steep). The steep complex slopes constitute the V-shaped valleys, cliffs, canyons, gullies and steep sloping interfluves. The dominant slope gradient of this unit is between 15 and 45 degrees. Majority of the slopes of the escarpment are facing south-west (202.5 - 247.5 degrees) and west (247.5 - 292.5 degrees) direction.

The plateau occupies the highest elevation ranging from 1680 near the escarpment to the highest peak which stands at 2273 m above sea level. The salient features of this landform unit include: high altitude plateau, medium altitude plateau, low altitude plateau and the plateau valley bottoms. The high altitude plateaus have their ridge peaks at elevations greater than 2000 m asl; while medium altitude plateau are positioned on ridge peaks between 1900 and 2000 m asl. The low altitude plateaus have their ridge peaks at an elevation below 1900 m asl.

The plateau landscape includes four relief types i.e. narrow ridge crests (summits), upper slopes, mid slopes and lower slopes. The ridge crests (summits) are convex, moderately dissected and have dominant slope gradient ranging from 1 to 6 degrees. Rock outcrops occur in some places. The upper slopes are a complex of slope facets, which are strongly dissected and having dominant slopes ranging from 50 - 70 degrees (in high altitude plateau), 30 - 60 degrees (in medium altitude plateau and 25 - 50 degrees (in low altitude plateau).

The mid slopes are a complex of strongly dissected slope facets with dominant slope gradients ranging from 30 to 55 degrees (in high altitude plateau), 25 to 40 degrees (in medium altitude plateau) and 18 to 30 degrees (in low altitude plateau). The lower slopes are also a complex of strongly dissected slope facets with dominant slope gradients ranging from 15- 30 degrees (in high altitude plateau), 12 - 25 degrees (in medium altitude plateau) and 8 - 25 degrees (in low altitude plateau).

Most of the slopes are facing north-east (22.5 - 67.5 degrees) and south-east (112.5 - 157.5 degrees) in the plateau landscape. The plateau valley bottoms constitute the low lying elongated areas between alternating ridges of the plateau landscape. They are U-shaped broad valley flats with 1 - 2 degrees slope gradients.

4.1.2. Soil types and their salient characteristics

4.1.2.1. Soil physical and morphological properties

Somesoil physical properties of selected landform units of Mavumo area are presented in Table 7. A major part of the piedmont-plain has soils which are very

Table 7: Selected soil physical properties on selected landform units

Map unit	Effective soil depth (cm)	Moist colour		Structure grade		% sand		% silt		% clay		Textural class	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
F2	30	black	nd	moderate	nd	67	nd	8	nd	25	nd	SCL	nd
F3	90	very dark brown	dark reddish brown	single grain	weak	88	80	2	4	10	16	LS	SL
F4	200	dark brown	very dark brown	weak	weak	72	64	8	22	20	14	SCL	SL
E2	120	very dark brown	yellowish red	moderate	moderate	57	56	14	16	29	29	SCL	SCL
P13	140	dark reddish brown	dark reddish brown	weak	moderate	41	26	12	4	47	70	C	C (HC)
P14	200	dark red	dark red	weak	weak	42	27	2	2	56	71	C	C (HC)
P21	63	dark brown	dark brown	weak	moderate	42	45	12	10	46	45	C	SC
P22	75	very dark brown	yellowish red	weak	moderate	58	48	8	4	34	48	SCL	SC
P23	170	very dark brown	dark reddish brown	moderate	moderate	39	33	8	2	53	65	C	C (HC)
P24	80	very dark brown	yellowish red	weak	moderate	54	44	11	17	35	39	SCL	CL
P31	75	brown	dark reddish brown	weak	moderate	36	26	18	19	46	55	C	C
P32	90	dark reddish brown	nd	weak	nd	62	nd	3	nd	35	nd	SCL	nd
P33	90	very dark brown	dark reddish brown	weak	moderate	51	35	16	7	33	58	SCL	C
P34	110	very dark brown	dark reddish brown	weak	moderate	60	33	13	1	27	66	SCL	C (HC)
P4	200	black	very dark gray	weak	weak	49	45	20	8	31	47	SCL	SC

Key:

F2 = upper sloping interfluves;
F3 = colluvial/alluvial fans;
F4 = lower sloping interfluves;
E2 = very steep complex slopes;
P13= mid slopes of high altitude plateau;
P14 = lower slopes of high altitude plateau;
P21 = ridge summits of medium altitude plateau;
P22 = upper slopes of medium altitude plateau;
P23 = mid slopes of medium altitude plateau;
P24 = lower slopes of medium altitude plateau;
P31= ridge summits of low altitude plateau;
P32 = upper slopes of low altitude plateau;
P33 = mid slopes of low altitude plateau;
P34 = lower slopes of low altitude plateau.
P4 = plateau valley bottom
nd = not determined

deep (over 200 cm), well drained, dark brown, sandy loams with dark yellowish brown, sandy loam top soils. Stratification is observed in some parts especially in the lower sloping interfluves due to cyclic depositions of materials of diverse origin (Msanya *et al*., 2001).

The alluvio-colluvial fans and the upper slopping interfluves are comprised of a complex of deep soils (up to 120 cm), well drained, dark reddish brown, sandy clay loams with dark reddish brown, sandy clay loam top soils in places and very shallow soils (less than 22 cm), well drained, black, sandy clay loams seated on sediments of colluvio-alluvium rock fragments. The foot ridges are covered by pockets of very shallow soils and rock outcrops.

Generally, the escarpment is predominantly rocky with few pockets of deep and shallow, predominantly gravelly sandy clay loam soils derived from erosion and deposition. This could be explained by the nature of the escarpment which is characterized by very steep complex slopes.

Kimaro *et al.* (2009) reported that soil flux is directly proportional to the slope gradient and that erosion and deposition are also proportional to the slope gradient change. This implied that erosion occurs at the convexities, while deposition takes place at the concavities. The soils are well to somewhat excessively drained, yellowish red, gravelly sandy clay loams with very dark brown, gravelly sandy clay loam top soils.

The high altitude crests and upper slopes are dominantly covered by rock outcrops and pockets of very shallow soils. The mid slope soils are very deep, well to excessively drained, dark reddish brown clays with dark reddish brown clay topsoils while the lower slope soils are very deep, well to excessively drained, dark red clays with dark red clay topsoils. The lower slopes are having more clay content (56% top soils, 71% sub soils) comparing to mid slopes (47% top soils, 70% sub soils). The presence of soils with more clay on the lower slopes could be explained by the accumulation of finer soil materials removed from higher elevations through mud flow. Sorensen and Kaaya (1998) and Kimaro (2003) made similar observations for soils of Uluguru Mountains.

On the medium altitude plateau crests, the soils are deep, well drained, dark brown, gravelly sand clays, with dark brown, clay topsoils while those of the upper slopes are moderately deep, well to excessively drained, yellowish red, sandy clays with dark brown, sandy clay loam topsoil. The soils of the mid slopes are very deep, well drained, dark reddish brown clays with very dark brown, clay top soils while those of the lower slopes are moderately deep, well to excessively drained, yellowish red clay loams with very dark brown, sandy clay loam topsoils. The subsoils are having more clay than the topsoils as a result of pedogenic processes (FAO, 2006). The lower slopes are moderately deep as a result of poor agronomic practices leading to topsoil loss through tillage and runoff induced erosions. The lower slopes are intensively used for annual crop production.

On the low altitude plateau, the soils of the crests are very deep, well drained, dark reddish clays with brown, clay topsoils while those of the upper slopes are shallow, well drained, dark reddish brown gravelly sand clay loams seated on a dominantly rocky horizon with pockets of soil which is dark reddish brown gravelly sand clay. The soil difference could be attributed to the topsoil losses in the upper slopes due to poor conservation practices and accelerated soil erosion due to steep slopes. The mid slopes have soils which are deep, well drained, dark reddish brown gravelly clays with very dark brown, sandy clay loam topsoils while the lower slope soils are deep, well drained, dark reddish brown clays with very dark brown, sand clay loam topsoils.

In the plateau valley bottoms, the soils are stratified; very deep, poorly to imperfectly drained, very dark grey clays with black, clay loam topsoils. The soils are stratified as a result of cyclic deposition of materials of diverse origin (Msanya *et al*., 2001)

4.1.2.2. Soil chemical properties (macro and micronutrients)

Table 8 presents selected soil chemical properties while Table 9 presents micronutrient levels of selected landform units. The soils formed on the piedmont plains are generally alkaline with pH values varying from 7.4-8.6. This could be attributed to high levels of the exchangeable bases especially Ca and Mg observed in this unit (Meliyo *et al*., 2001). The electrical conductivity (EC) of the profiles ranges from 0.06 to 0.28 $mScm^{-1}$ implying that soluble salts are at very low levels in these soils (Landon, 1991). The available P (Olsen method) is generally high in topsoils and subsoils throughout the piedmont plain which could be attributed to the soil parent materials (Kimaro, 2003). Generally, OC and TN are rated very low to low throughout (<1.03% and <0.12% respectively). The CEC values are rated

Table 8: Selected soil chemical properties on selected landform units

Map unit	pH (water)		EC (mS/cm)		Organic Carbon (%)		Total N (%)		Bray P (mg/kg)		CEC (cmol(+)/kg)	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
F2	7.9	7.9	0.06	0.12	0.89	0.78	0.06	0.08	20.23	13.94	10.44	15.07
F3	7.9	nd	0.14	nd	2.88	nd	0.12	nd	23.19	nd	23.04	nd
F4	7.9	8.1	0.12	0.12	0.63	0.51	0.16	0.06	39.13	12.23	16.84	14.30
E2	7.5	7.6	0.12	0.06	4.70	0.90	0.42	0.05	16.49	11.69	23.23	8.76
P13	6.7	4.4	0.11	0.35	3.79	1.15	0.33	0.07	5.11	4.62	19.96	13.59
P14	5.0	4.4	0.04	0.05	1.25	0.86	0.09	0.06	4.36	53.09	11.95	13.00
P21	6.0	5.3	0.08	0.04	5.90	2.02	0.41	0.11	9.32	15.16	27.37	15.37
P22	4.7	4.4	0.07	0.06	4.94	1.57	0.30	0.09	13.18	10.85	12.15	8.13
P23	6.0	4.8	0.07	0.08	3.73	1.26	0.24	0.09	3.93	3.45	18.40	12.89
P24	6.5	5.8	0.09	0.06	3.71	0.47	0.30	0.05	3.59	7.40	18.76	11.16
P31	5.9	4.7	0.11	0.06	6.21	2.11	0.46	0.09	7.19	5.70	25.50	14.42
P32	4.8	nd	0.04	nd	2.23	nd	0.17	nd	5.79	nd	11.76	nd
P33	6.6	6.3	0.10	0.07	6.27	2.26	0.44	0.22	5.41	8.77	24.99	18.32
P34	7.6	6.8	0.23	0.09	1.92	1.19	0.51	0.06	24.71	4.05	29.31	10.70
P4	6.2	5.6	0.14	0.06	6.29	1.11	0.49	0.09	21.73	5.28	35.99	14.77

Key:
F2 = upper sloping interfluves;
F3 = colluvial/alluvial fans;
F4 = lower sloping interfluves;
E2 = very steep complex slopes;
P13= mid slopes of high altitude plateau;
P14 = lower slopes of high altitude plateau;
P21 = ridge summits of medium altitude plateau;
P22 = upper slopes of medium altitude plateau;
P23 = mid slopes of medium altitude plateau;
P24 = lower slopes of medium altitude plateau;
P31= ridge summits of low altitude plateau;
P32 = upper slopes of low altitude plateau;
P33 = mid slopes of low altitude plateau;
P34 = lower slopes of low altitude plateau.
P4 = plateau valley bottom
nd = not determined

Table 9: Micronutrient levels of selected landform units

Map unit	Extractable Fe (mg/kg)		Extractable Mn (mg/kg)		Extractable Cu (mg/kg)		Extractable Zn (mg/kg)	
	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
F2	16.3	2.1	80.07	26.21	1.98	1.09	0.20	0.16
F3	13.2	7.0	35.98	52.9	1.07	2.1	0.56	0.6
F4	13.1	4.0	93.52	36.12	2.28	1.32	1.20	0.35
E2	42.5	6.8	266.28	5.81	2.18	0.89	2.78	0.08
P13	30.2	21.1	237.89	1.73	2.19	1.29	2.86	0.33
P14	21.0	17.1	129.63	98.09	5.82	4.06	0.22	0.18
P21	150.7	175.0	26.55	0.60	0.65	1.34	1.31	0.26
P22	231.4	70.4	40.76	3.42	0.76	0.25	0.70	0.23
P23	31.6	22.4	83.76	9.58	5.17	4.80	0.87	0.26
P24	37.0	27.9	174.14	0.59	1.89	3.36	1.72	0.37
P31	81.6	92.8	247.22	4.31	6.15	6.09	3.74	0.20
P32	63.4	nd	103.15	nd	4.06	nd	0.66	nd
P33	30.0	58.0	173.01	10.55	2.19	7.21	2.12	0.33
P34	26.1	31.6	91.59	0.90	1.97	3.86	4.28	0.29
P4	320.9	222.5	35.91	9.01	5.94	6.03	19.60	0.21

Key:
F2 = upper sloping interfluves;
F3 = colluvial/alluvial fans;
F4 = lower sloping interfluves;
E2 = very steep complex slopes;
P13= mid slopes of high altitude plateau;
P14 = lower slopes of high altitude plateau;
P21 = ridge summits of medium altitude plateau;
P22 = upper slopes of medium altitude plateau;
P23 = mid slopes of medium altitude plateau;
P24 = lower slopes of medium altitude plateau;
P31= ridge summits of low altitude plateau;
P32 = upper slopes of low altitude plateau;
P33 = mid slopes of low altitude plateau;
P34 = lower slopes of low altitude plateau.
P4 = plateau valley bottom
nd = not determined

medium in a major part of the piedmont plain. This could probably be attributed to the type of clay minerals present in the soil as the levels of soil organic matter which also affect CEC levels, are very low (Meliyo *et al*., 2001; Msanya *et al*., 2007). The levels of DTPA extractable Fe, Zn, Mn and Cu content (Table 8) are generally higher than the critical levels established by Sims and Johnson (1991). This could be attributed to the richness of these micronutrients in the soil parent materials.

The soils in the escarpment are slightly alkaline having pH of 7.5 - 7.6 with very low EC ranging from 0.07 to 0.2 $mScm^{-1}$. Available P (Olsen) is rated high (16.49 mg/kg in the topsoil and 11.69 mg/kg in the subsoil) most probably reflecting the nature of the parent materials. The OC and TN levels on the topsoils are generally high (4.70 and 0.42 respectively). The CEC levels are medium in the topsoils (23.23 cmol(+)/kg) and low (8.76 cmol(+)/kg) in subsoil corresponding to the levels of soil organic matter. Iron content is high throughout with topsoils having higher levels than the subsoils. The same trend is observed for Mn, Cu and Zn levels where the levels in the topsoils are higher than those in the subsoils. The high contents of the soil micronutrients in this unit could be attributed to the soil parent material.

Soils formed in high altitude plateau are highly weathered. Their pH is very strongly acidic throughout (pH of 5.0 in the topsoil and 4.4 in the subsoil). This could be explained by low levels of exchangeable bases due to leaching (Kimaro, 2003). The EC levels are very low. The available P (Bray and Kurtz I) is low in both the mid and lower slopes most probably due to P-fixation as a result of low pH values. There is a negative correlation between soil pH and P-retention (Msanya *et al*., 2007). OC in the mid slopes is rated high and medium in the lower slopes most probably due to low decomposition rates as a result of unfavourable pH levels for microbial activities as well as high rainfall and cold climatic conditions which slow down biological degradation of soil organic matter (Meliyo *et al*., 2001). The TN levels are generally low while the CEC values for both lower and upper slopes are rated medium throughout. In these soils, the levels of Fe and Cu are above the critical values. No trend is observed with soil depth for both Fe and Cu in lower slopes but in mid slopes the levels decrease with soil depth. The Mn levels are also higher than critical values in both mid and lower slopes but the levels decrease with soil depth. Soil Zn levels are within the critical levels in the lower slopes, while the topsoils in mid slope have values above the critical level and the subsoils have values within the critical levels. These high levels could be attributed to the high contents of these elements in the parent materials.

Soils formed on the medium altitude plateau have pH values ranging from very strongly acidic to medium acidic due to excessive leaching of exchangeable bases. The EC for these soils is very low indicating that there is no salinity problem in the soils (Landon, 1991). The available P (Bray-Kurtz) levels are low in the lower slopes and broad crests ranging between 3 and 4 mg/kg while those for upper slopes and mid slopes are rated medium with their values ranging between 9 and 15 mg/kg. The OC for topsoils is high throughout medium altitude plateau (ranging from 3.5 to 5.9%) and low to very low in the subsoils. Consequently, the soils are having TN levels which are high to medium in the topsoils and low to very low in the subsoils. The CEC levels of the soils are generally medium to high ranging from 12.15 to 27.37 cmol(+)/kg in the topsoils and 8.13 to 15.37 cmol(+)/kg in the subsoils. This could be attributed to the high levels of organic matter present in these soils. The soil

Fe and Cu values are higher than critical levels throughout in the soils formed on the medium altitude plateau while Zn levels fall within critical range as established by Sims and Johnson (1991). Mn is high throughout the soil depth in the upper and mid slopes while in the crests and lower slopes the levels are above critical levels in the topsoils and below critical levels in the subsoils.

Soils formed on the low altitude plateau have pH values ranging from very strongly to medium acidic in both topsoils and subsoils of the crest, upper and mid slopes due to leaching of exchangeable bases. The soils of the lower slopes are mildly alkaline throughout the profile and consequently have higher available P (Olsen) values compared to the low available P (Bray-Kurtz I) of the crest, upper and mid slopes. The EC levels are low throughout. The OC levels in summits and mid slope topsoils are generally high with medium levels of TN. The soils on the upper slopes were found to have medium levels of OC and low levels of TN and CEC throughout the profile. The lower slopes were found to have medium levels of OC and correspondingly high levels of TN and CEC in the topsoils. The levels of CEC in the summits (14.42 cmol(+)/kg) and the mid slopes (18.32 cmol(+)/kg) are rated medium. These levels of CEC could be attributed to the high soil OC in these areas (Meliyo *et al*., 2001; Msanya *et al*., 2007). The Fe, Mn and Cu levels are higher than the critical value throughout the profile depths of soils formed on the low altitude plateau. Zn levels are above the critical levels in topsoils of the crests, mid and lower slopes, while their subsoils have levels falling within the critical range. The soils in the plateau valley bottoms are slightly acidic with pH values ranging from 6.2 in the topsoils to 5.6 in the subsoils. The valley bottoms are intensively used for vegetable production in which different organic and inorganic materials are applied as fertilizers, herbicides and pesticides. The application of these materials could be an explanation of high levels of available P, OC, N and CEC observed in the topsoils (Table 8). The Fe, Cu, Mn and Zn levels of the valley bottom soils were also observed to be above the critical range (Table 9). This could be attributed to the nature of parent materials and to inorganic pesticides applied in this unit.

4.1.2.3. Dominant soil types

The dominant soil types on different landforms in the study area are summarized in Table 10 and Fig. 9. The cross sections depicting their spatial distribution, position on the landscape and their key salient features are presented in Fig. 10 and 11. The soils of the piedmont-plain are dominantly complexes of **Lithic Leptosols** and rock outcrops on footridges, **Mollic Leptosols** and **Cutanic Luvisols** on the upper slopping interfluves, **Haplic Umbrisols** on colluvio-alluvial fans and **Fluvic Cambisols** and **Mollic Fluvisols** on the lower sloping interfluves. The dominant soils of the escarpment are a complex of **Mollic Leptosols**, rock outcrops, **Lithic Leptosols, Cutanic Luvisols** and **Haplic Cambisols** on the steep complex slopes (steep sloping interfluves, V-shaped valleys, canyons and cliffs). A significant portion of the escarpment (about 21%) is occupied by rock outcrops and cliffs. Slope gradient is the main factor that has influenced the salient features observed in this landscape. Mass movements, particularly landslides and rock falls are the dominant processes that had profound influence in shaping the landscape and soil profile development and variation in soil types. Kimaro (2003), Msanya *et al*. (2003) and Kimaro *et al.* (2009) reported remarkable effects of geomorphological processes including water erosion and mass movement on the evolution of landforms and soil profile development in the Uluguru Mountains, Tanzania. Based on topographic

Table 10: Dominant soil types on different landforms in the study area

Landform features	Landform unit	Dominant soils	Areal extent (ha)
Foot ridges	F1	Rock outcrops and Lithic Leptosols	680
Upper sloping interfluves	F2	Mollic Leptosols (Epieutric, Humic) and Cutanic Luvisols (Chromic, Hypereutric)	158
Colluvial/alluvial fans	F3	Haplic Umbrisols (Chromic, Arenic, Endoeutric) and Lithic Leptosols	300
Lower sloping interfluves	F4	Fluvic Cambisols(Hypereutric) and Mollic Fluvisols (Hypereutric)	1767
Rock outcrops and cliffs	E1	Rock outcrops, cliffs and Regosols	500
Very steep complex slopes	E2	Haplic Cambisols (Hypereutric, Humic), Lithic Leptosols, Cutanic Luvisols	1843
Crest of high altitude plateau	P11	Rock outcrops and Lithic Leptosols	497
Upper slopes of high altitude plateau	P12	Haplic Regosols and rock outcrops	2166
Mid slopes of high altitude plateau	P13	Cutanic Acrisols (Epiclayic, Profondic, Humic) and Haplic Regosols	3664
Lower slopes of high altitude plateau	P14	Cutanic Vetic Acrisols (Profondic, Hyperdystric, Humic) and Cutanic Acrisols (Epiclayic, Profondic, Humic)	772
Crest of medium altitude plateau	P21	Cutanic Alisols (Profondic, Hyperdystric, Humic) and rock outcrops	186
Upper slopes of medium altitude plateau	P22	Ferralic Cambisols (Chromic, Hyperdystric, Humic)	892
Mid slopes of medium altitude plateau	P23	Cutanic Acrisols (Epiclayic, Hyperdystric, Humic) and Ferralic Cambisols (Chromic, Hyperdystric, Humic)	2687
Lower slope of medium altitude plateau	P24	Cutanic Alisols (Chromic, Profondic, Humic) and Cutanic Acrisols (Epiclayic, Hyperdystric, Humic)	1339
Crest of low altitude plateau	P31	Cutanic Alisols (Hyperdystric, Humic, Abruptic) and few rock outcrops	60
Upper slopes of low altitude plateau	P32	Haplic Regosols and Cutanic Alisols (Profondic, Hyperdystric, Humic)	241
Mid slopes of low altitude plateau	P33	Cutanic Alisols (Chromic, Humic, Abruptic) and Luvic Ferralic Phaeozems (Chromic, Epiclayic, Abruptic)	1033
Lower slopes of low altitude plateau	P34	Luvic Ferralic Phaeozems (Chromic, Epiclayic, Abruptic) and Cutanic Acrisols (Epiclayic, Hyperdystric, Humic)	702
Plateau valley bottoms	P4	Mollic Gleyic Fluvisols (Epiclayic, Orthoeutric, Humic)	354

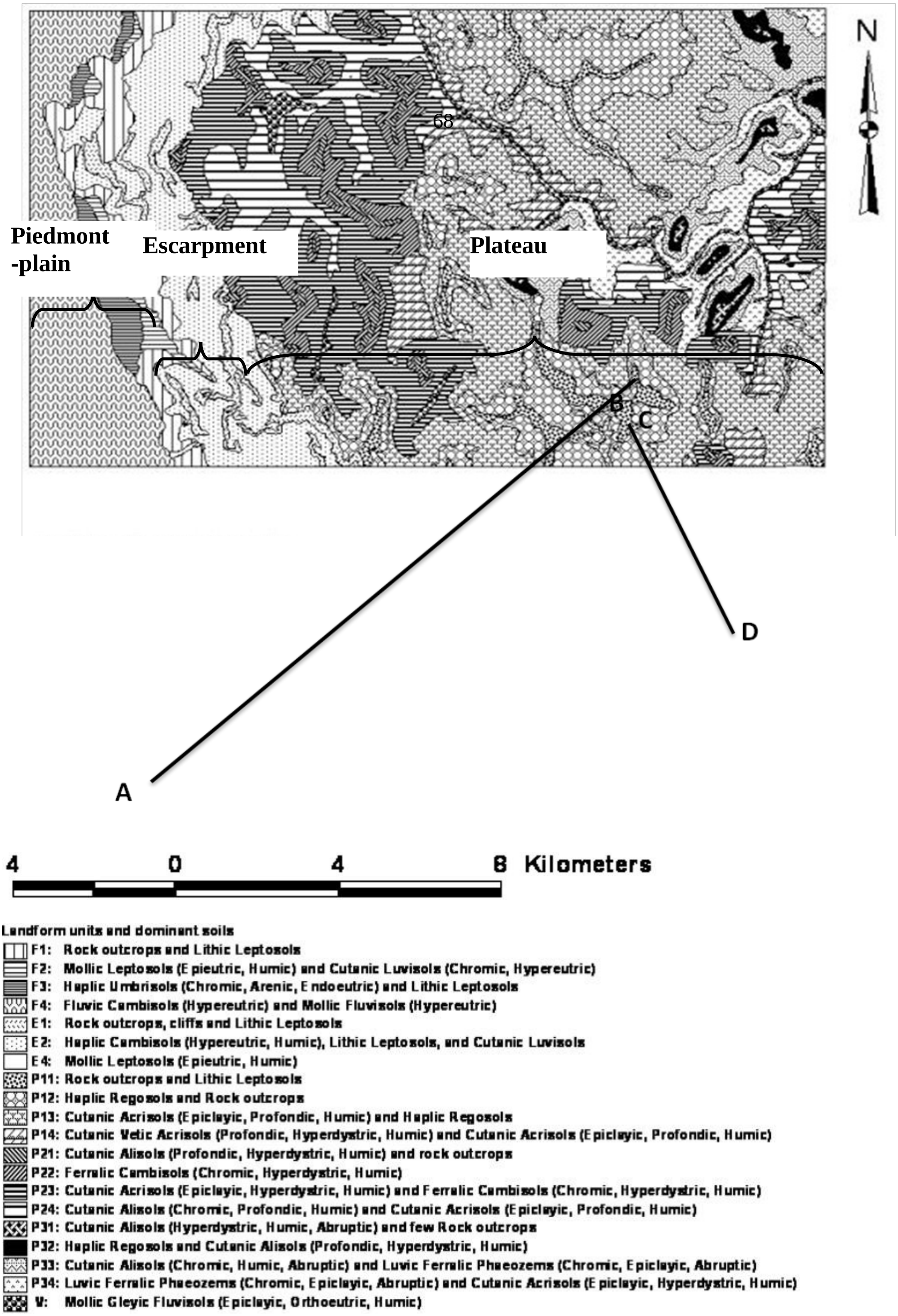
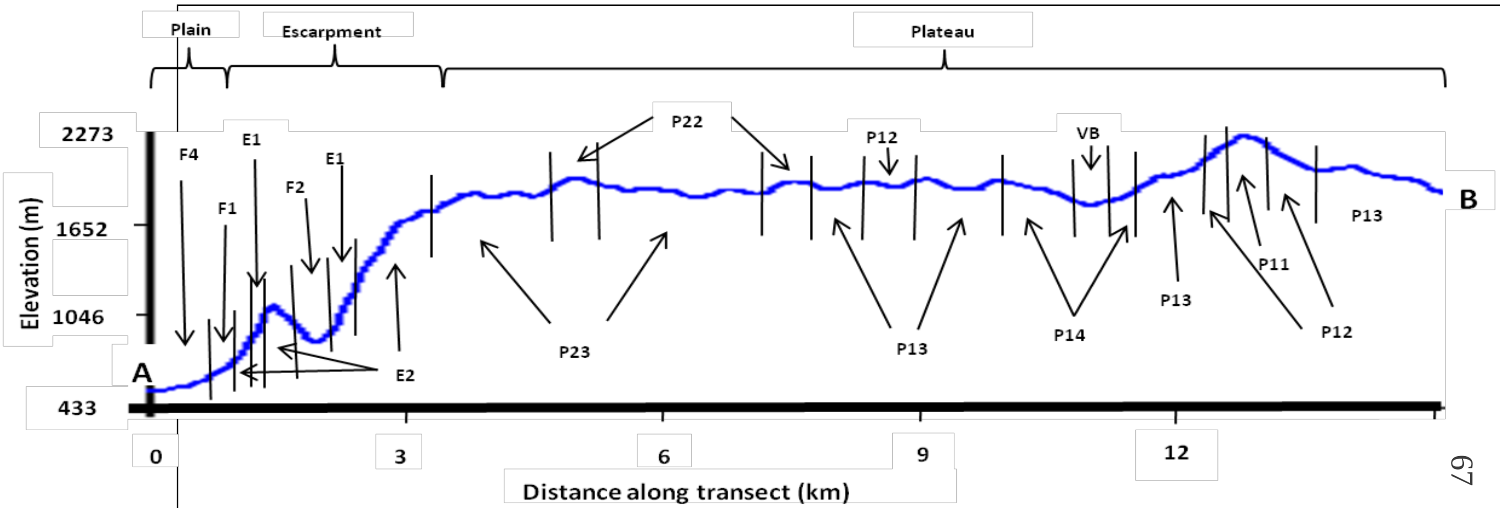
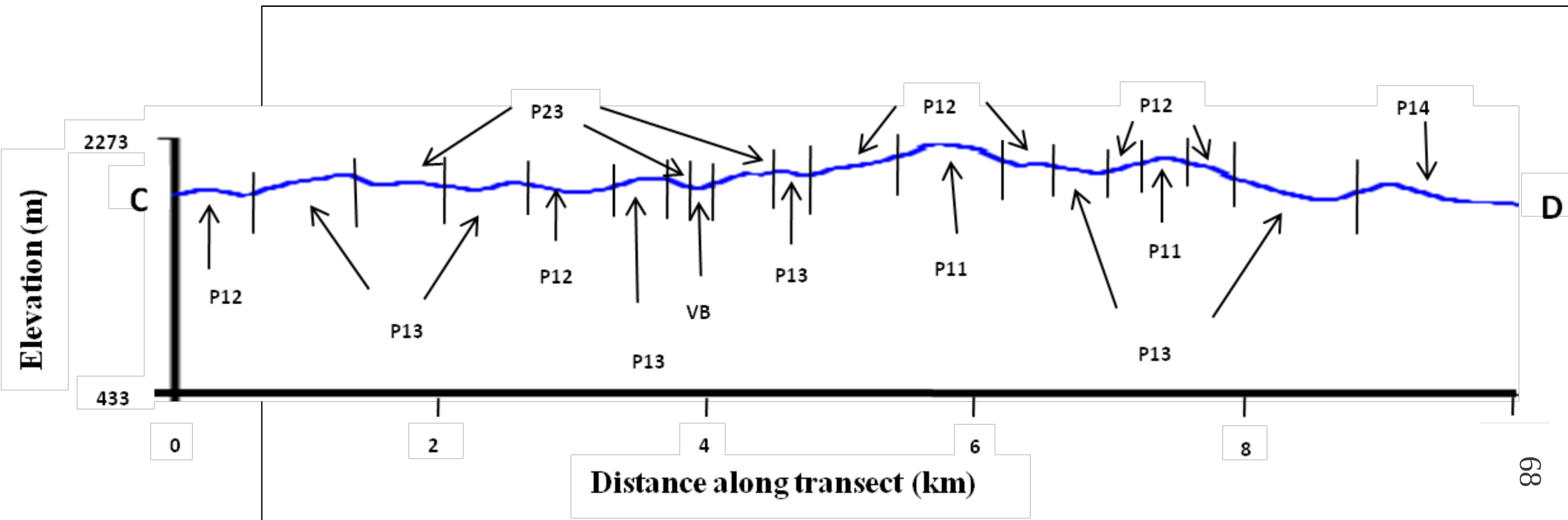


Figure 9: Landform-soil map with dominant soil types



Map unit	Landform features	Dominant soil type
F4	Lower sloping interfluves	Fluvic Cambisols(Hypereutric) and Mollic Fluvisols (Hypereutric)
F1	Footridges	Rock outcrops and Lithic Leptosols
E2	Very steep complex slopes	Haplic Cambisols (Hypereutric, Humic), Lithic Leptosols, Cutanic Luvisols
E1	Rock outcrops and cliffs	Rock outcrops, cliffs and Regosols
F3	Colluvial/alluvial fans	Haplic Umbrisols (Chromic, Arenic, Endoeutric) and Lithic Leptosols
P23	Mid slopes of medium altitude plateau	Cutanic Acrisols (Epiclayic, Hyperdystric, Humic) and Ferralic Cambisols (Chromic,
P22	Upper slopes of medium altitude plateau	Ferralic Cambisols (Chromic, Hyperdystric, Humic)
P13	Mid slopes of high altitude plateau	Cutanic Acrisols (Epiclayic, Profondic, Humic) and Haplic Regosols
P12	Upper slopes of high altitude plateau	Haplic Regosols and rock outcrops
P14	Lower slopes of high altitude plateau	Cutanic Vetic Acrisols (Profondic, Hyperdystric, Humic) and Cutanic Acrisols (Epicla
V	Valley bottom	Mollic Gleyic Fluvisols (Epiclayic, Orthoeutric, Humic)
P11	Ridge crest of high altitude plateau	Rock outcrops and Lithic Leptosols

Figure 10: Salient landform-soil features along cross-section A-B of Figure 9



Map unit	Landform features	Dominant soil type
P12	Upper slopes of high altitude plateau	Haplic Regosols and rock outcrops
P11	Ridge crest of high altitude plateau	Rock outcrops and Lithic Leptosols
P13	Mid slopes of high altitude plateau	Cutanic Acrisols (Epiclayic, Profondic, Humic) and Haplic Regosols
P14	Lower slopes of high altitude plateau	Cutanic Vetic Acrisols (Profondic, Hyperdystric, Humic) and Cutanic Ac
P33	Mid slopes low altitude plateau	Cutanic Alisols (Chromic, Humic, Abruptic) and Luvic Ferralic Phaeozer
P34	Lower slopes of low altitude plateau	Luvic Ferralic Phaeozems (Chromic, Epiclayic, Abruptic) and Cutanic Ac
VB	Valley bottom	Mollic Gleyic Fluvisols (Epiclayic, Orthoeutric, Humic)

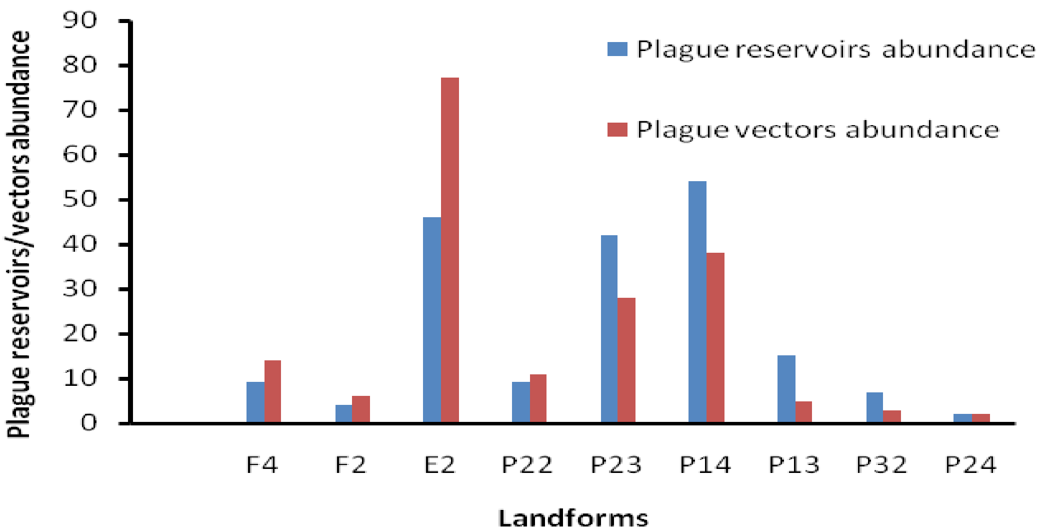
Figure 11: Salient landform-soil features along cross-section C-D of Figure 9

differentiation the plateau landscape was divided into three topographic levels namely high, medium and low altitude plateaus as discussed in section 4.1.1. The soils of the high altitude plateau are dominantly **Regosols, Lithic Leptosols** and rock outcrops on the ridge crests and upper slopes while **Cutanic Acrisols** are dominant on the mid and lower slopes. In the medium altitude plateau, the dominant soils are complexes of **Cutanic Alisols** on the ridge crests and lower slopes, **Ferralic Cambisols** on the upper slopes and **Cutanic Acrisols** and **Ferralic Cambisols** on the mid slopes. In the low altitude plateau, the dominant soils of the ridge crests, upper and mid slopes are complexes of **Cutanic Alisols** and **Haplic Regosols**. **Luvic Ferralic Phaeozems** are commonly found on the lower slopes. The dominat soils of the elongated U-shaped plateau valley bottoms alternating with ridges in the plateau landscape are **Mollic Fluvisols**. Neerinckx (2006) reported **Haplic Alisols** on mid slopes, **Xanthic-Hyperdystric Acrisols** and **Acric Ferrasols** on middle upper slopes and **Epigleyic Fluvisols** on valley bottoms in Gologolo village in the study area. The author concluded further that the soil types in the study area (i.e. in the studied landscape particularly the plateau are distributed uniformly: shallow soils and rock outcrops on ridge summits, strongly weathered soils on slopes and **Fluvisols** on the valley bottoms. This trend is confirmed by this study. A study by Meliyo *et al.* (2001) reported that **Haplic Acrisols** were the dominant soil types on complex slopes and ridge summits in the plateau landscape in Lushoto district, Tanzania. In the Uluguru Mountains, Kimaro *et al.* (2001) reported similar results that **Leptosols** and **Regosols** were commonly observed on strongly dissected ridge crests and slopes.

4.2. Influence of Landform and Soil Characteristics on the Abundance and Distribution of Plague Reservoirs and Vectors Distribution in the Study Area

4.2.1. Abundance of plague reservoirs and vectors in selected landforms

Fig. 12 presents plague reservoirs and vectors abundance trapped on different landform units. The results indicate relatively high abundance in the lower slopes of high altitude plateau (map unit P14) and in the midslopes of medium altitude plateau (map unit P23). These units are bordering the valley bottoms which are commonly cropped continuously due to availability of water. The high number of plague reservoirs (rodents) trapped could be attributed to easy water and food accessibility.



Key
F4 = Lower sloping interfluves of piedmont-plain; F2 = Upper sloping interfluves of piedmont plain
E2 = Very steep complex slopes of the escarpment; P22 = Upper slopes of medium altitude plateau
P23 = Mid slopes of medium altitude plateau; P14 = Lower slopes of high altitude plateau
P13 = Mid slopes of high altitude plateau; P32 = Upper slopes of low altitude plateau
P24 = Lower slopes of medium altitude plateau

Figure 12: Field observed abundance of plague reservoirs and vectors in selected landforms

These results are supported by Gratz (1999) who reported that burrowing small mammal species are commonly found in large numbers near sources of food and water, such as refuse and drainage ditches, streams or sewers. These results are also in line with the observation that rodents are oriented towards a habitat capable of supplying their food (Monadjem and Perrin, 1998). The soils of the two units are highly weathered (dominantly **Acrisols**) with pH values between 5 and 6 (Table 8). They are also characterised by high micronutrient levels with iron ranging from 21 to 32 mg/ kg, manganese from 84 to 130 mg/kg, copper from 5 to 6 mg/kg and zinc from 0.22 to 0.87mg/kg (Table 9). However, no clear influences of these soil properties were established to the ecology of the plague reservoirs and vectors.

The abundance of the plague reservoirs is also relatively high in the escarpment (map unit E2) (Fig. 12). This could be explained by the nature of the escarpment which is characterised by many rock caves, canyon, and fissures which provide favourable microclimate for plague reservoirs' survival, especially hide outs from surface predators and rainfall (Maser *et al*., 1979; Forman and Godron, 1986). These results are also in line with the observation that rodents are oriented towards a habitat with fewer predators (Monadjem and Perrin, 1998). The soils of the escarpment are relatively young (dominantly **Haplic Cambisols** and **Lithic Leptosols**) with relatively higher pH (7.5) as shown in Table 8 and higher levels of micronutrients (iron = 42 mg/kg, manganese = 266 mg/kg, copper = 2 mg/kg and zinc = 3 mg/kg as shown in Table 9. No clear interactions were deduced between these soil properties and the ecology of the plague reservoirs and vectors suggesting that the landform features (caves, canyon and fissures) as discussed above in this paragraph may be the major explanation of plague reservoirs' higher abundance in the escarpment. The low abundance of plague reservoirs in other landform units could be attributed to poor accessibility to water and food (Mulungu *et al*., 2008). In the piedmont-plain, the area is hot and dry except during rainy season. The major land use in this unit is grazing and charcoal burning with no crop cultivation. The area is generally non-inhabited. The rest of the selected map units in the plateau are relatively far away from the wet valley bottom and thus are seasonally wet and cropped. Therefore, the accessibility to water and food for the plague reservoirs in these landforms is limited resulting to their low populations. Duesser and Shugart (1978) and Isabirye-Basuta and Kasenene (1987) reported that the abundance and distribution of the small mammals depend mainly upon the nature and density of vegetation which, in turn influences food and shelter availability.

4.2.2. Influence of landform characteristics

Table 11 presents some landform characteristics that are considered to influence plague reservoirs and vectors abundance in the study area. These characteristics appear to vary widely on the different landforms in the study area. The results show that slope gradient was highly correlated with both plague reservoirs abundance ($r = 0.73$) and vectors abundance ($r = 0.74$) at $P = 0.05$ repectively. The relative high abundance of plague reservoirs observed on the steep slopes in the area could be attributed to the presence of features like fissures and caves. These features are dominant on the steep slopes of the escarpment and upper slopes of the plateau landscapes. As it has been observed in previous studies, these features provide a better nesting and foraging micro-environment for the plague reservoirs (small mammals) and their associated plague vectors (fleas) (Maser *et al*., 1979; Forman and Godron, 1986).

Table 11: Correlations between landform characteristics and abundance of plague reservoirs and vectors

	Plague reservoirs abundance		Plague vectors abundance	
Parameter	**Pearson correlation**	**P - value**	**Pearson correlation**	**P - value**
Elevation (m)	0.335	0.378 NS	0.138	0.717NS
Slope gradient (degrees)	0.727	0.025*	0.741	0.012*
Slope aspect (degrees)	0.538	0.135 NS	0.105	0.783 NS

NS = not significant. * = significant

High slopes have been recorded to cause rock instability resulting to fissures and caves (Gian, 1988; Wen-bin and Wei-jian, 2010). The stability of a rock in a sloping area is controlled by local geological conditions, shape of the overall slope and local ground water conditions. Haek and Bray (1999) report that saturated slope will fail if it is at an angle greater than 64 degrees. The dominant slopes in the escarpment of the study area are ranging from 50 to 72 degrees making it possible for the rocks to fall and crack along the weak lines resulting to fissures and caves from where they have been detached. Similarly significant correlation was observed between plague reservoirs abundance and the slope aspect (r = 0.54). The rocky and steeply sloping escarpment, in which relatively high abundance of plague reservoirs was observed, is dominantly facing south-west. This is in line with results by Prior and Weatherhead (1996) in Ontario, USA, where they observed that black rat hibernaculars tended to be situated on relatively rocky and sloping hillsides that faced south-south-east direction.

Statistically, there was no correlation between elevation and the abundance of both plague reservoirs and vectors, but generally the trend is apparent as depicted in Fig. 12. Corominas (2004) observed that small mammals increased with altitude in the forest habitat of the Natural Park and Reserve of Barcelona, but Mena and Vazquez-Domınguez (2005) observed that small mammals were not always linearly correlated with altitude. However, at global scale, the distributions of the small mammals and the fleas are reported to be worldwide and are not dependent on the elevation (Perry and Fetherston, 1997)

4.2.3. Influence of soil physical properties

Table 12 presents some soil physical properties which are considered to have influence on abundance of plague reservoirs and vectors. The soil physical properties considered are percent sand, silt, and clay and the soil effective depth. The results indicate significant positive correlation between plague reservoirs abundance and soil effective depth ($r = 0.67$) at $P = 0.05$. Previous studies have shown that shallow soils limit rodents to make deep burrows for nesting and security against on-surface predators and hostile weather conditions (Shenbrot *et al*., 2002). It is also evident that soil texture particularly sand ($r = 0.6$) and clay ($r = 0.59$) correlated well with the abundance of plague reservoirs. Soil texture has been related to the stability and easiness with which rodent burrows are made. Shenbrot *et al*. (2002) reported that most complex burrows occur in hard - clay and silt - soils, while the simplest burrows are found in sandy soils. Massawe *et al*. (2005) found that *Mastomys natalensis* prefers loam-textured soils with high percentage of sand than clay soils for burrowing and nesting. Other studies conducted in South Africa by Jackson *et al.* (2008), reported that the size and distribution of sand particles influenced the density and compactability of the soil, and both were positively correlated with the presence of golden moles. Other studies have indicated that too much sand will make it impossible to dig burrows as they will collapse easily, while heavy clay will make the soil too difficult to dig (Brady and Neil, 2002; Luna and Antinuchi, 2006).

Table 12: Correlations between soil physical properties and abundance of plague reservoirs and vectors

	Plague reservoirs abundance		Plague vectors abundance	
Parameter	**Pearson correlation**	**P - value**	**Pearson correlation**	**P - value**
% sand	-0.597	0.090 ^{NS}	-0.182	0.637 ^{NS}
% silt	-0.007	0.984 ^{NS}	0.305	0.424 ^{NS}
% clay	0.587	0.097 ^{NS}	0.071	0.852 ^{NS}
Soil effective depth (cm)	0.671	0.048*	0.401	0.284 ^{NS}

NS = not significant. * = significant

4.2.4. Influence of soil chemical properties

Table 13 presents some soil chemical properties which are considered to have influence on abundance of plague reservoirs and vectors. The soil chemical properties considered are pH, electrical conductivity (Ec), percent organic carbon (OC), percent total nitrogen (TN), available phosphorus (P), cation exchange capacity (CEC), exchangeable calcium (Ca), exchangeable magnesium (Mg), exchangeable Potassium (K), and exchangeable sodium (Na). These soil properties did not show any significant correlation with the abundance of both plague reservoirs and vectors. These results suggest that soil chemical properties in the study area have no significant effect on the abundance of plague reservoirs and vectors. However, further research in this is suggested as one would expect these properties to indirectly influence the presence of reservoirs through support of agricultural activities which affects reservoirs food availability (Parmenter *et al*., 1999).

Table 13: Correlations between soil chemical properties and abundance of plague reservoirs and vectors

	Plague reservoirs abundance		Plague vectors abundance	
Parameter	**Pearson correlation**	**P - value**	**Pearson correlation**	**P - value**
pH (in water)	-0.156	0.688 NS	0.155	0.691 NS
Ec (mS/cm)	-0.274	0.476 NS	0.096	0.806 NS
OC (%)	0.116	0.766 NS	0.264	0.493 NS
TN (%)	0.073	0.853 NS	0.364	0.335 NS
Available P (mg/kg)	-0.191	0.623 NS	0.112	0.774 NS
CEC (cmol(+)/kg)	0.26	0.500 NS	0.483	0.187 NS
Exch. Ca (cmol(+)/kg)	-0.065	0.868 NS	0.431	0.246 NS
Exch. Mg (cmol(+)/kg)	-0.230	0.551 NS	-0.174	0.655 NS
Exch. K (cmol(+)/kg)	-0.438	0.238 NS	-0.238	0.538 NS
Exch. Na (cmol(+)/kg)	-0.213	0.583 NS	0.125	0.748 NS

NS = not significant

4.2.5. Influence of soil micronutrient levels

Table 14 presents some soil micronutrients that are considered to influence plague reservoirs and vectors abundance. The micronutrients considered included DTPA extractable iron (Fe), manganese (Mn), copper (Cu) and zinc (Zn). The micronutrient levels in the soils appear to vary widely on different landforms in the study area. It is observed that DTPA extractable copper has significant correlation with plague reservoirs abundance (r = 0.66) at P = 0.05. No significant correlation was observed between reservoirs abundance and iron, manganese and zinc. Similarly, no significant correlation was observed between plague vectors abundance and iron, manganese, copper and zinc. It is difficult to interprete these results because the knowledge of the individual and combined effects of these trace elements in rodents and fleas ecology is lacking (Neerinckx, 2010). However, it is worthy to note that the soil level of Cu in the map units which have high abundance of both plague reservoirs and vectors are rated very high as shown in Table 9 (E2 topsoil = 2.18 mg/kg, subsoil = 0.89 mg/kg; P14 topsoil = 5.82 mg/kg, subsoil = 4.06 mg/kg and P23 topsoil = 5.17 mg/kg, subsoil = 4.08 mg/kg). According to Sims and Johnson (1991), the critical level for copper by the DTPA-method (used in this study) ranges from 0.12 to 0.25 mg/kg.

Table 14: Correlations between soil micronutrients and abundance of plague reservoirs and vectors

	Plague reservoirs abundance		Plague vectors abundance	
Parameter	**Pearson correlation**	**P - value**	**Pearson correlation**	**P - value**
DTPA extr. Fe (%)	-0.226	0.56 NS	-0.131	0.737 NS
DTPA extr. Mn (%)	0.295	0.441 NS	0.478	0.193 NS
DTPA extr. Cu (%)	0.661	0.050*	0.226	0.558 NS
DTPA extr. Zn (%)	0.068	0.863 NS	0.321	0.400 NS

4.3. Spatial Relationship Between Landform and Soil Characteristics and Abundance of Plague Reservoirs and Vectors

4.3.1. Soil-landform model to quantify spatial distribution of plague reservoirs abundance

Soil-landform model for prediction of plague reservoirs abundance is presented in equation 2 and Table 15. According to the model, the abundance of plague reservoirs was significantly correlated (r = 99) with extractable copper, slope gradient, exchangeable potassium and available phosphorus at P = 0.05. The abundancy of plague reservoirs can be predicted as shown in equation (2):

***PR = 8.43Cu + 0.604SG + 0.82P - 27.1K - 27.331* ……………………………..(2)**

Where:

PR = Abundance of plague reservoirs

Cu = DTPA extractable copper

SG = Slope gradient

P = Available phosphorus

K = Exchangeable potassium

Accordingly, Plague reservoirs increases with increasing extractable copper, slope gradient, available phosphorus and decreasing exchangeable potassium. The model explained about 99% of the variations observed in the prediction of plague reservoirs abundance with DTPA extractable copper explaining about 53% and slope gradient about 32%.

Table 15: Prediction of plague reservoir abundance from landform and soil characteristics

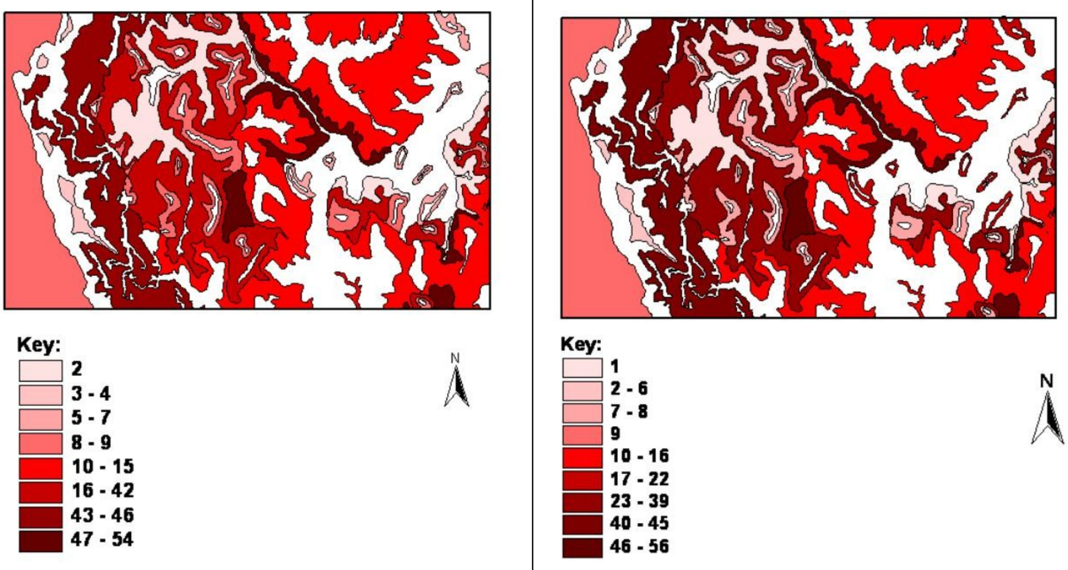
Variable	**Coefficient**	**R^2 (adjusted)**	**P- value**
DTPA extractable copper	8.43	53.3	0.001
Slope gradient	0.604	31.7	0.002
Available phosphorus	0.82	9.5	0.005
Exchangeable potassium	-27.1	4.3	0.029
Constant	-27.331		

S = 2.30; R^2 = 99.49; R^2 (adjusted) = 98.81

The model equation shows the importance of copper in the occurrence of plague reservoirs. Neerinckx (2010), remarks that the knowledge of the individual and combined effects of the trace elements including Cu in rodents ecology, particularly in West Usambaras is important. However, from Table 9 and Fig. 12, it is shown that the levels of Cu in the soils are very high corresponding to landform units with high abundance of both plague reservoirs and vectors. For example in landform unit E2, the levels of Cu in the topsoil are 2.18 mg/kg and subsoil 0.89 mg/kg; while in P14 topsoil have 5.82 mg/kg and subsoil 4.06 mg/kg and those of P23 topsoils are 5.17 mg/kg while the subsoil have 4.08 mg/kg. Sims and Johnson (1991) established the critical level for copper by the DTPA-method to be ranging from 0.12 to 0.25 mg/kg. In this study, steep slope gradients were found in the escarpment (map unit E2) (Figure 12) which was also dominated by rock outcrops, boulders, fissures and cliffs. According to studies conducted by Bateman *et al*. (2010) the occurrence of boulders could also be one of the basic factors of small mammals' distribution and abundance. These observations are supported by a study conducted in the Blue Mountains of Oregon, where cliff faces and associated talus slopes were reported to be associated with small mammals' habitats (Maser *et al.,* 1979). The contribution of available phosphorus and exchangeable potassium to the ecology of plague reservoirs could not be directly explained in this study. During this study, no literature was found to link directly the levels of available phosphorus and exchangeable potassium in the soil with plague vectors and reservoirs abundance except through the influence of these elements in food production. Phosphorus and potassium are among the three most limiting nutrients in the soil (Landon, 1991) and their high levels will favour vegetation growth which provides not only cover and habitat to the rodents (Mulungu *et al.,* 2008) but also seeds and herbage (Krebs, 2001).

The general pattern of the predicted plague reservoirs abundance is presented in Fig. 13. The results showed that the spatial distribution of the predicted abundance of plague reservoirs in different landforms is good. Spatial comparison of the model output with the field observed plague reservoir abundance showed a similar pattern.

A slight overprediction occurred on the upper slopes of low altitude plateau ridges. This discrepancy could not be explained.



Spatial distribution of field observed plague reservoirs abundance

Spatial distribution of model predicted plague reservoirs abundance

Figure 13: Spatial comparison between model predicted and field observed plague reservoir abundance

The scatter plot of the model predicted versus field observed plague reservoirs abundance indicated a good fit with an R^2 value of 0.93 (Fig. 14).

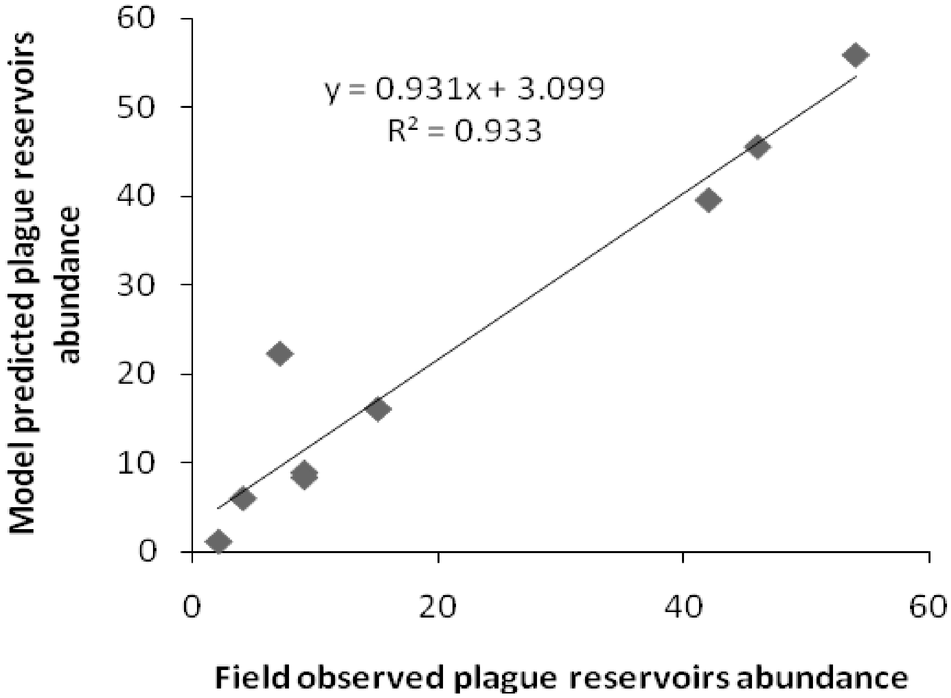


Figure 14: Scatter plot of predicted against observed abundance of plague reservoir

4.3.2. Soil-landform model to quantify spatial distribution of plague vectors abundance

Soil-landform model for quantification of plague vectors abundance in the study area is presented in Equation 3 and Table 16. The model showed that the abundance of plague vectors was highly correlated with silt content, exchangeable sodium percentage, total nitrogen, ammonium-acid-oxalate extractable iron, exchangeable sodium and exchangeable calcium at $P = 0.05$. The abundancy of plague vectors can be predicted as shown in equation (3):

$$PV = 146.54 - 8.89261Si - 20.9735ESP - 450.580N + 34.1779Fe - 4.143Na + 0.00455Ca \quad \text{....(3)}$$

Where:

PV = Abundance of plague vectors

Si = Percent silt

ESP = Exchangeable sodium percentage

N = Percent total nitrogen

Fe = Ammonium-acid-oxalate extractable iron

Na = Exchangeable sodium

Ca = Exchangeable calcium

Accordingly, plague vectors increased with increasing ammonium-acid-oxalate extractable iron, exchangeable sodium, exchangeable calcium and decreasing percent silt, exchangeable sodium percentage, and percent total nitrogen. The model explained about 100% of the variations observed in the prediction of plague vectors abundance with percent silt explaining 63%.

Table 16: Prediction of plague vectors abundance from landform and soil characteristics

Variable	Coefficient	R^2 (adjusted)	P- value
Percent silt	-8.89261	62.8	0.000
Exchangeable sodium percentage	-20.9735	29.7	0.000
Percent total nitrogen	-450.58	4.4	0.000
Ammonium-acid-oxalate extractable iron	34.1779	3.0	0.000
Exchangeable sodium	-4.143	0.0	0.004
Exchangeable calcium	0.00455	0.0	0.037
Constant	146.54		

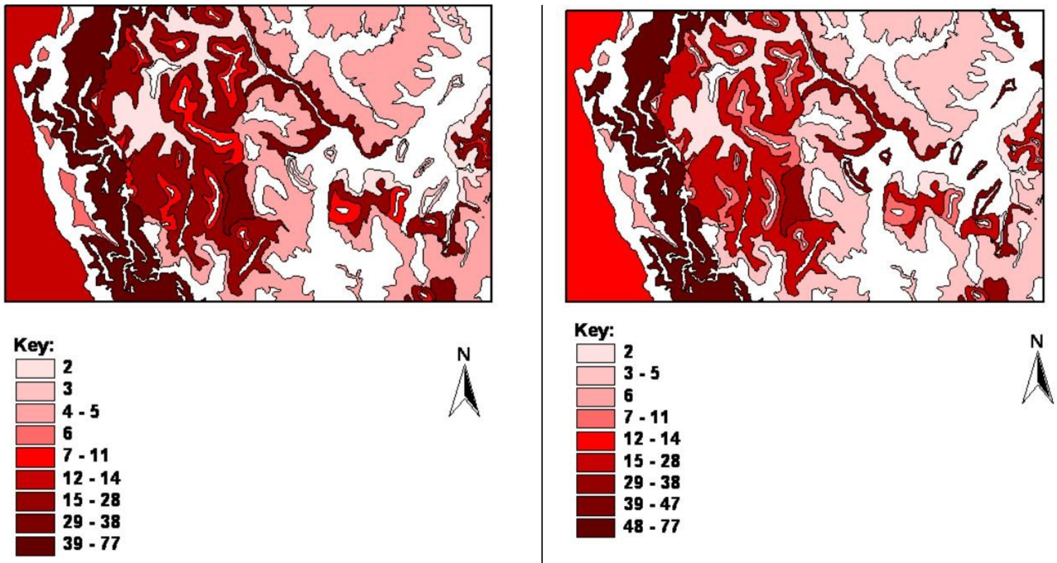
S = 0.00102; R^2 = 100.00; R^2 (adjusted) = 100.00

The results show that percent silt and exchangeable sodium percentage are the major contributors in prediction of vectors abundance in the study area. These factors explained about 92% of the observed variations. Other parameters included in the model but with very small contribution are percent total nitrogen, iron, exchangeable sodium and exchangeable calcium. In this study (Fig. 12) the distributions of fleas in different landform units appear to follow similar pattern to that of rodents (plague reservoirs). Kennedy and Bush (1994), Caro *et al*. (1997) and Krasnov *et al*. (1997) reported that the parasites encountered in a given area are related to their specific location and the host. In this study the observed distribution of fleas mirrored distribution of the trapped rodents.

The high contribution of percent silt in this model could be attributed to the importance of soil texture to energy spent in burrow digging and the stability and structure of the burrows (Laundré and Reynolds, 1993; Shenbrot *et al.,* 2002; Massawe *et al*., 2005). The above authors reported that soils which are dominanated by clay are difficult to dig especially when they are compacted, while those dominanated by sand are unstable and hence unsuitable for rodent burrowing and nesting. The contribution of iron in the ecology of fleas could also be related to the ecology of rodents. It is worth to note that according to Sim and Johnson (1991), the soil trace elements (iron, zinc, copper and manganese) levels were generally high throughout the study area (Table 9). Rotshild (2001) wrote a comprehensive sum up of several field studies that revealed close associations with patches of repetitively plague infected rodent colonies and medium or high concentration of iron, cobalt and titanium and low concentrations of copper, nickel and vanadium. According to Neerinckx (2010), the trace elements are essential in mammals for multiple cellular biochemical functions, including immunity. According to the model developed in this study; exchangeable sodium percentage, total nitrogen and calcium are important elements to fleas' ecology. The levels of these parameters are generally low in landforms which have high abundance of rodents and fleas i.e. landforms E2, P14 and P23 (Fig. 12), coupled with low pH in the last two landforms (pH 5.0 and 6.0) respectively (Table 8). However, care should be taken when considering the effects of these elements individually on ecology of plague reservoirs and vectors because the effects of different elements in tandem are not the same as the sum of their individual effects (Neerinckx, 2010). For example, calcium concentration and pH interaction affected uptake of zinc and copper in the crustacean *Daphnia magma* (Park *et al*., 2009).

Additionally, the three landform units (E2, P14 and P23) (Fig. 12) which have relative high abundance of plague vectors (fleas) are located in humid environments which have been shown to be advantageous to fleas survival and reproduction (Cavanaugh, 1971). Humidity is critical to flea survival. Eggs need relative humidity of at least 70–75% to hatch, and larvae need at least 50% humidity to survive (University of California, 2000). However, relative humidity >95% can promote the growth of destructive fungi that diminish larval survival and potentially kill flea eggs and larvae in the rodents' nests (Parmenter *et al.*, 1999).

The mean annual relative humidity of the study area is 70% (Annaert, 2010). Fig. 15 presents the general pattern of the predicted plague vectors abundance. The results showed that the spatial distribution of predicted abundance of plague vectors in different landforms is good. A slight overprediction occurred on the upper slopes of low altitude plateau ridges and on the piedmont-plain. The discrepancies could not be explained in this study.



Spatial distribution of field observed plague vectors abundance

Spatial distribution model prdicted plague vectors abundance

Figure 15: Spatial comparison between model predicted and field observed plague vectors abundance

The scatter plot of the model predicted versus field observed plague vectors abundance indicated a good fit with an R^2 value of 0.68 (Fig. 16).

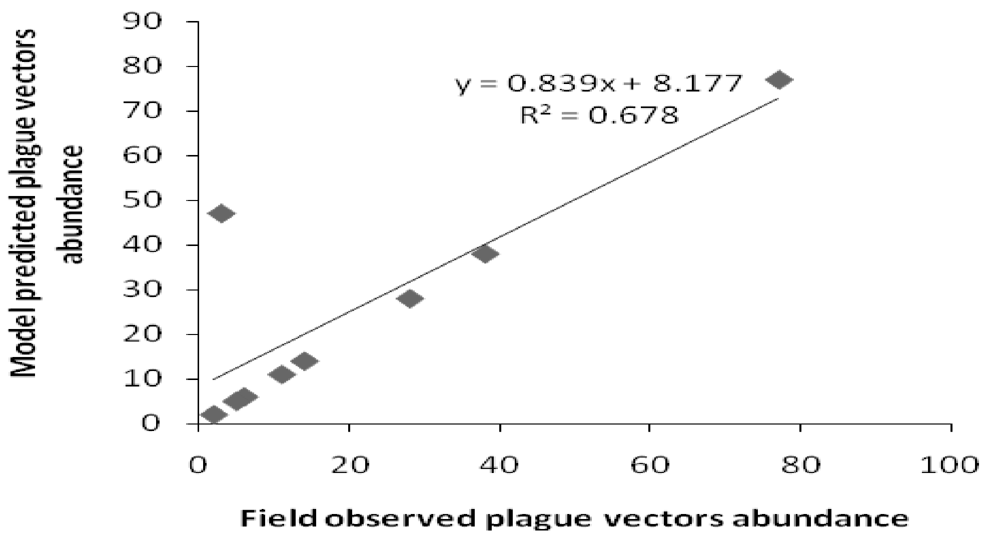


Figure 16: Scatter plot of predicted against observed plague reservoir abundance

CHAPTER FIVE

5.0. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

From this study it is clear that landscapes and their associated landform features and soils have an impact on the distribution of plague reservoirs (rodents) and vectors (fleas). The study has identified 20 landforms and 13 soil types from three major landscapes in which some of them showed correlation with plague reservoirs and vectors.

The results have indicated relatively high abundance of reservoirs and vectors in the lower slopes of high altitude plateau bordering the valley bottoms which are commonly continuously cropped. These segments of the landform have access to water and food for rodents.

The abundance of the plague reservoirs (rodents) is also relatively high in the escarpment which is characterized by many rock caves, canyon, and fissures which provide favourable micro-environment for plague reservoirs' survival.

Slope gradient correlates well with abundance of both plague reservoirs and vectors, implying that their abundance increases with slope gradient.

Abundance of plague reservoirs was observed to increase as the effective soil depth increases. Deep soils would normally allow deep burrows to be made by rodents.

Soil texture particularly sand and clay correlated well with the abundance of plague reservoirs. A relatively stable and balanced texture would be ideal for rodent burrowing and nesting. Of the microelements studied, only DTPA extractable copper had significant correlation with abundance of plague reservoirs.

About 99% of the observed variations in rodents (plague reservoirs) and fleas (plague vectors) occurrence could be explained by their predictive models respectively. The study has demonstrated that plague reservoirs (rodents) and fleas occurrence vary spatially in terms of landform features (slope characteristics), soil physical and chemical characteristics and levels of soil micronutrients.

5.2. Recommendations

The following recommendations are made in the light of gaps revealed from the results of this study so as to provide further insights into the plague disease:

- In this study, the soils were mapped at 1:50 000 scale. A finer map scale is recommended in order to come up with more detailed and accurate spatial information.
- Most of the villages located in the study area are frequently affected by plague outbreak. The piedmont-plain landscape in which no plague cases have been documented as almost non-inhabited by people. Therefore, it is recommended that the same research be conducted within different locations of low or no plague prevalence but inhabited by people in order to validate these findings.

- Trapping was done in few selected map units. More intensive trapping is recommended in order to take into account the spatial variabilities of soil properties.
- It is also recommended that trapping should cut across all seasons of the year in order to be able to take into account the dynamics of rodents in different seasons.

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APPENDICES

Appendix 1: Diagnostic horizons, other diagnostic features and FAO-WRB soil names for Mavumo area studied soils

Soil profile	Diagnostic horizons	Other diagnostic features/materials	Reference Soil Group (RSG)	Prefix Qualifiers	Suffix Qualifiers	WRB soil name
MIG-P1	Cambic	Fluvic materials	Fluvisols	Mollic	Hypereutric	Fluvic Cambisols (Hypereutric)
MIG-P2	Mollic	Fluvic materials	Fluvisols	Mollic	Hypereutric	Mollic Fluvisols (Hypereutric)
KIT-P1	Ochric, Argic	High CEC, high BS argic horizon, Colluvic materials	Luvisols	Cutanic	Hypereutric, Chromic	Cutanic Luvisols (Chromic, Hypereutric)
KIT-P2	Umbric	Colluvic materials	Umbrisols	Haplic	Endoeutric, Arenic, Chromic	Haplic Umbrisols (Chromic, Arenic, Endoeutric)
KIT-P3	Mollic	-	Leptosols	Mollic	Humic, Epieutric	Mollic Leptosols (Epieutric, Humic)
KIT-P4	Mollic	-	Leptosols	Mollic	Humic, Epieutric	Mollic Leptosols (Epieutric, Humic)
SHU-P1	Ochric, Cambic	-	Cambisols	Haplic	Humic, Hypereutric	Haplic Cambisols (Hypereutric, Humic)
SHU-P2	Umbric, Cambic	Ferralic properties	Cambisols	Ferralic	Humic, Hyperdystric, Chromic	Ferralic Cambisols (Chromic, Hyperdystric, Humic)
GOL-P1	Mollic, Argic	Low CEC, low BS argic horizon	Acrisols	Cutanic	Humic, Hyperdystric, Epiclayic	Cutanic Acrisols (Epiclayic, Hyperdystric, Humic)
GOL-P2	Mollic	Fluvic materials, gleyic colour pattern, abrupt textural change	Fluvisols	Gleyis, Mollic	Humic, Orthoeutric, Epiclayic	Mollic Gleyic Fluvisols (Epiclayic, Orthoeutric, Humic)
VIT-P1	Ochric, Argic	Ferralic properties, low CEC, low BS argic horizon	Acrisols	Vetic, Cutanic	Humic, Hyperdystric, Profondic	Cutanic Vetic Acrisols (Profondic, Hyperdystric, Humic)
VIT-P2	Ochric, Argic	Ferralic properties, low CEC, low BS argic horizon	Acrisols	Cutanic	Humic, Profondic, Epiclayic	Cutanic Acrisols (Epiclayic, Profondic, Humic)

Appendix 1: (continued). Diagnostic horizons, other diagnostic features and FAO-WRB soil names for Mavumo area soils

Soil profile	Diagnostic horizons	Other diagnostic features/materials	Reference Soil Group (RSG)	Prefix Qualifiers	Suffix Qualifiers	WRB soil name
KWE-P1	Ochric, Argic	High CEC, low BS argic horizon, abrupt textural change	Alisols	Cutanic	Abruptic, Humic, Hyperdystric	Cutanic Alisols (Hyperdystric, Humic, Abruptic)
KWE-P2	Mollic, Argic	High CEC, low BS argic horizon, abrupt textural change	Alisols	Cutanic	Abruptic, Humic, Chromic	Cutanic Alisols (Chromic, Humic, Abruptic)
KWE-P3	Ochric	-	Regosols	Haplic	-	Haplic Regosols
KWE-P4	Mollic, Argic	Ferralic properties, high CEC, high BS argic horizon, abrupt textural change	Phaeozems	Ferralic, Luvic	Abruptic, Epiclayic, Chromic	Luvic Ferralic Phaeozems (Chromic, Epiclayic, Abruptic)
LUK-P1	Ochric, Argic	High CEC, low BS argic horizon	Alisols	Cutanic	Humic, Hyperdystric, Profondic	Cutanic Alisols (Profondic, Hyperdystric, Humic)
KWEM-P1	Ochric, Argic	Ferralic properties, high CEC, low BS argic horizon	Alisols	Cutanic	Humic, Profondic, Chromic	Cutanic Alisols (Chromic, Profondic, Humic)
KWEM-P2	Ochric, Argic	High CEC, low BS argic horizon	Alisols	Cutanic	Humic, Hyperdystric, Profondic	Cutanic Alisols (Profondic, Hyperdystric, Humic)

Appendix 2: Diagnostic epipedons, diagnostic sub surface horizons, diagnostic features and USDA Soil Taxonomy names for Mavumo area soils

Profile	**Diagnostic epipedons**	**Diagnostic subsurface horizons**	**Other diagnostic features**	**Order**	**Sub order**	**Great group**	**Sub group**
MIG-P1	Mollic	Cambic	Ustic SMR, isohyperthermic STR, stratification	Mollisols	Ustolls	Haplustolls	Fluventic Haplustolls
MIG-P2	Mollic	-	Ustic SMR, isohyperthermic STR, stratification	Mollisols	Ustolls	Haplustolls	Fluventic Haplustolls
KIT-P1	Ochric	Argillic	Ustic SMR, isohyperthermic STR, high CEC, high BS illuvial horizon	Alfisols	Ustalfs	Haplustalfs	Inceptic Haplustalfs
KIT-P2	Umbric	-	Ustic SMR, isohyperthermic STR	Entisols	Psamments	Ustipsamments	Typic Ustipsamments
KIT-P3	Mollic	-	Ustic SMR, isohyperthermic STR	Entisols	Orthents	Ustorthents	Lithic Ustorthents
KIT-P4	Mollic	-	Ustic SMR, isohyperthermic STR	Entisols	Orthents	Ustorthents	Lithic Ustorthents
SHU-P1	Ochric	Cambic	Udic SMR, isothermic STR	Inceptisols	Udepts	Eutrudepts	Typic Eutrudepts
SHU-P2	Umbric	Cambic	Udic SMR, isothermic STR	Inceptisols	Udepts	Dystrudepts	Humic Dystrudepts
GOL-P1	Mollic	Argillic	Udic SMR, isothermic STR, low CEC, low BS illuvial horizon	Ultisols	Udults	Rhodudults	Typic Rhodudults
GOL-P2	Mollic	-	Aquic SMR, isothermic STR, stratification, abrupt textural change	Mollisols	Aquolls	Endoaquolls	Fluvaquentic Endoaquolls
VIT-P1	Ochric	Argillic	Udic SMR, isothermic STR, low CEC, low BS illuvial horizon	Ultisols	Udults	Paleudults	Rhodic Paleudults
VIT-P2	Ochric	Argillic	Udic SMR, isothermic STR, low CEC, low BS illuvial horizon	Ultisols	Udults	Paleudults	Rhodic Paleudults

Appendix 2: (continued). Diagnostic epipedons, diagnostic sub surface horizons, diagnostic features and USDA Soil Taxonomy names for Mavumo area soils

Profile	Diagnostic epipedons	Diagnostic subsurface horizons	Other diagnostic features	Order	Sub order	Great group	Sub group
KWE-P1	Ochric	Argillic	Udic SMR, isothermic STR, high CEC, low BS illuvial horizon, abrupt textural change	Ultisols	Udults	Paleudults	Rhodic Paleudults
KWE-P2	Mollic	Argillic	Udic SMR, isothermic STR, high CEC, low BS illuvial horizon, abrupt textural change	Ultisols	Udults	Hapludults	Inceptic Hapludults
KWE-P3	Ochric	-	Udic SMR, isothermic STR	Entisols	Orthents	udorthents	Typic Udorthents
KWE-P4	Mollic	Argillic	Udic SMR, isothermic STR, high CEC, high BS illuvial horizon, abrupt textural change	Mollisols	Udolls	Argiudolls	Oxic Argiudolls
LUK-P1	Ochric	Argillic	Udic SMR, isothermic STR, high CEC, low BS illuvial horizon	Ultisols	Udults	Paleudults	Typic Paleudults
KWEMP1	Ochric	Argillic	Udic SMR, isothermic STR, high CEC, low BS illuvial horizon	Ultisols	Udults	Hapludults	Typic Hapludults
KWEMP2	Ochric	Argillic	Udic SMR, isothermic STR, high CEC, low BS illuvial horizon	Ultisols	Udults	Paleudults	Tyipic Paleudults