A LANDSLIDE HAZARD ASSESSMENT APPROACH FOR TOWN PLANNING IN NTCHEU DISTRICT

MSc (ENVIRONMENTAL SCIENCE) THESIS

BY

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DECLARATION

I declare that this work is a result of my own effort and that wherever other people's work has been used, due reference has been made to such work. I further declare that this work has not been presented for any award at this or any other university.

Signed: …………………………………….. Date: ………………………………

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We declare that this thesis is a result of the candidate's own work and where assistance has been sought this has been acknowledged. This work is hereby submitted with our approval.

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DEDICATIONS

I dedicate this work to my wife Dorothy and our two lovely sons, Dalitso and Solomon. You had to put up with lonely days and nights without me around. Thanks for standing together with me. In your own unique way you have made this work a possibility.

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ABSTRACT

This study assessed the landslides hazard potential of the hill slopes of Ntcheu District Assembly. Landslides are known to cause lose of life and property, especially in settlements located in hilly areas. Since the Ntcheu District Assembly population is increasing at an annual growth rate of 3.1%, it became necessary that a study be conducted to aid the development of a sound physical plan for the Assembly.

The slope stability factors studied included geology, soil, topography, precipitation and land-use. Geology, topography and land-use were studied using aerial photographs (1:50 000); topographical maps (1:50 000) and through field traverses. Soil samples were also collected for the analysis of Liquid and Plastic Limits; Plasticity and Liquidity Indices and Bulk Density. Approximately 87% of the landslides identified occurred on the east facing slopes which had a gradient of 15° to 85°. This distribution was influenced by the bedding planes of the perthositic gneisses which dipped from 69° to 82°, sub-parallel to the general slope of the terrain. Soils are principally made up of sand particles, with very fine sand registering the highest figures of at least 65%. The Liquid and Plastic Limits ranged between 22.1-43% and 16.7-28.8%, respectively. The Liquidity and Plasticity Indices were generally low, an indication that these soils were sensitive to small water changes. These slopes have experienced high levels of deforestation between 1957 and 1991. This, together with a high rainfall of 636mm, contributed towards general slope instability.

It was concluded that landslides in Ntcheu District Assembly were caused by a combination of factors. Geology was identified as a major factor of slope instability, especially where the gneissic foliations were sub-parallel to the slope of the terrain. The east facing slopes were found to be more susceptible to landslides than the west facing ones. It was then recommended that town planning for dwelling quarters in Ntcheu District Assembly should avoid high risk areas in order to safeguard lives and property. A reforestation program for these hill slopes was also recommended in order to stabilize the area.

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ABBREVIATIONS AND ACRONYMS

EPOCH	- European Community Programme
FEMA	- Federal Emergency Management Agency
GIS	– Geographical Information system
GoM	– Government of Malawi
GPS	– Geographical Positioning System
GSD	– Geological Survey Department
GSI	– Geological Strength Index
ITCZ	– Inter Tropical Convergence Zone
LRF	- Landslide Risk Factor
LVI	- Landslide Vulnerability Index
MEET	- Malawi Environmental Endowment Trust
MPa	- Mega Pascal
NDA	– Ntcheu District Assembly
PI	- Plasticity Index
PP	- Physical Plan
RTC	- Rural Training Center
UNESCO	– United Nations Education and Scientific Organization
UNIMA	– University of Malawi
USA	– United States of America
USDA	- United States Department of Agriculture
USGS	– United States Geological Survey
ZAB	– Zaire Air Boundary

CHAPTER ONE

INTRODUCTION

1.1 Background

Ntcheu is located in the extreme south of the central region of Malawi. The main administrative center of the district is located along the Balaka – Lilongwe tarmac road (Figure 1) and a good network of earth roads access most of Ntcheu district.

In 2003, reports reached the office of the District Commissioner that the mountain slopes in the vicinity of Ntcheu District Assembly (NDA) experienced landslides which destroyed some maize fields and made one secondary road impassable. These are the first reported landslides in the area although landslides are not a new phenomenon in Malawi. The oldest recorded landslide in the country dates as far back as 1946 (Manda, 1999). Some of the major landslides include the Zomba and Phalombe events which took place in 1946 and 1991, respectively (Manda, 1999). This study will attempt to identify the causes of landslides in NDA and identify areas that are susceptible to landslides.

Since the study area does not have a Physical Plan to guide development activities in the Assembly, there is need to conduct this research whose results will assist in the development of one and will assist greatly in Town Planning.

1.2 The General Physiography of the Study Area

Ntcheu district shows the typical shelf and scarp topography which is akin to rifting. Walshaw (1965) identified four main physiographic units in the area (Figure 2):

- The Kirk Plateau which lies between the international border with Mozambique and the Kirk Range scarp. This forms the highest ground in the study area but only a small part of the plateau lies within Malawi. It locally rises to above 1829m as on Mvai (1887m) and Dzonze (1855m), which are ridges of horizons of the resistant Basement complex. Between the Kirk Plateau and Nsipe-Livelezi Shelf is the Ntcheu Step which is relatively flat.

- The Nsipe-Livelezi Shelf that extends from the foot of the Kirk Range scarp to the lower scarp overlooking the Bwanje Valley. This has been faulted to form the Kanzati step.

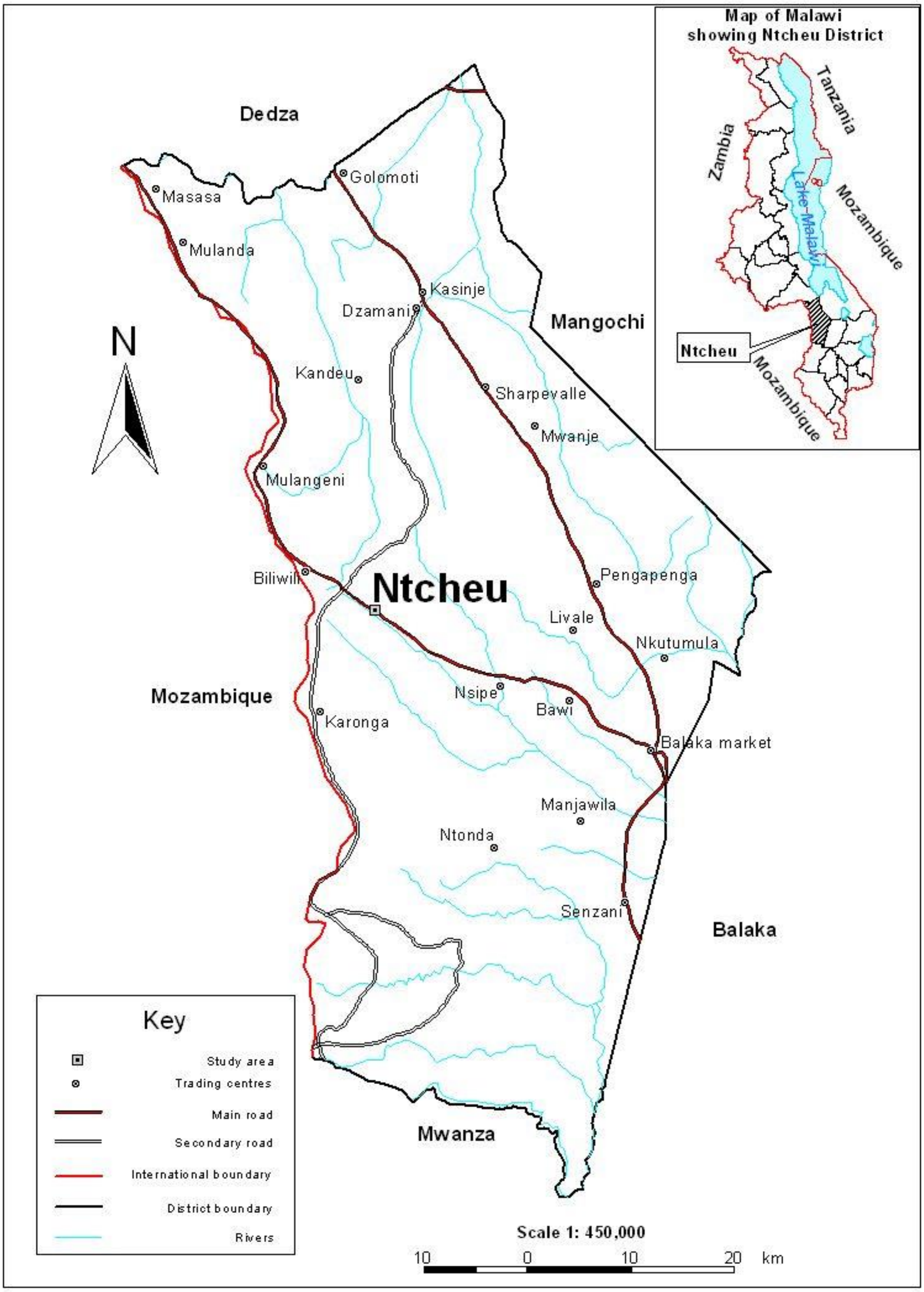


Figure 1. Map of Ntcheu District Showing the Location of the Study Area.

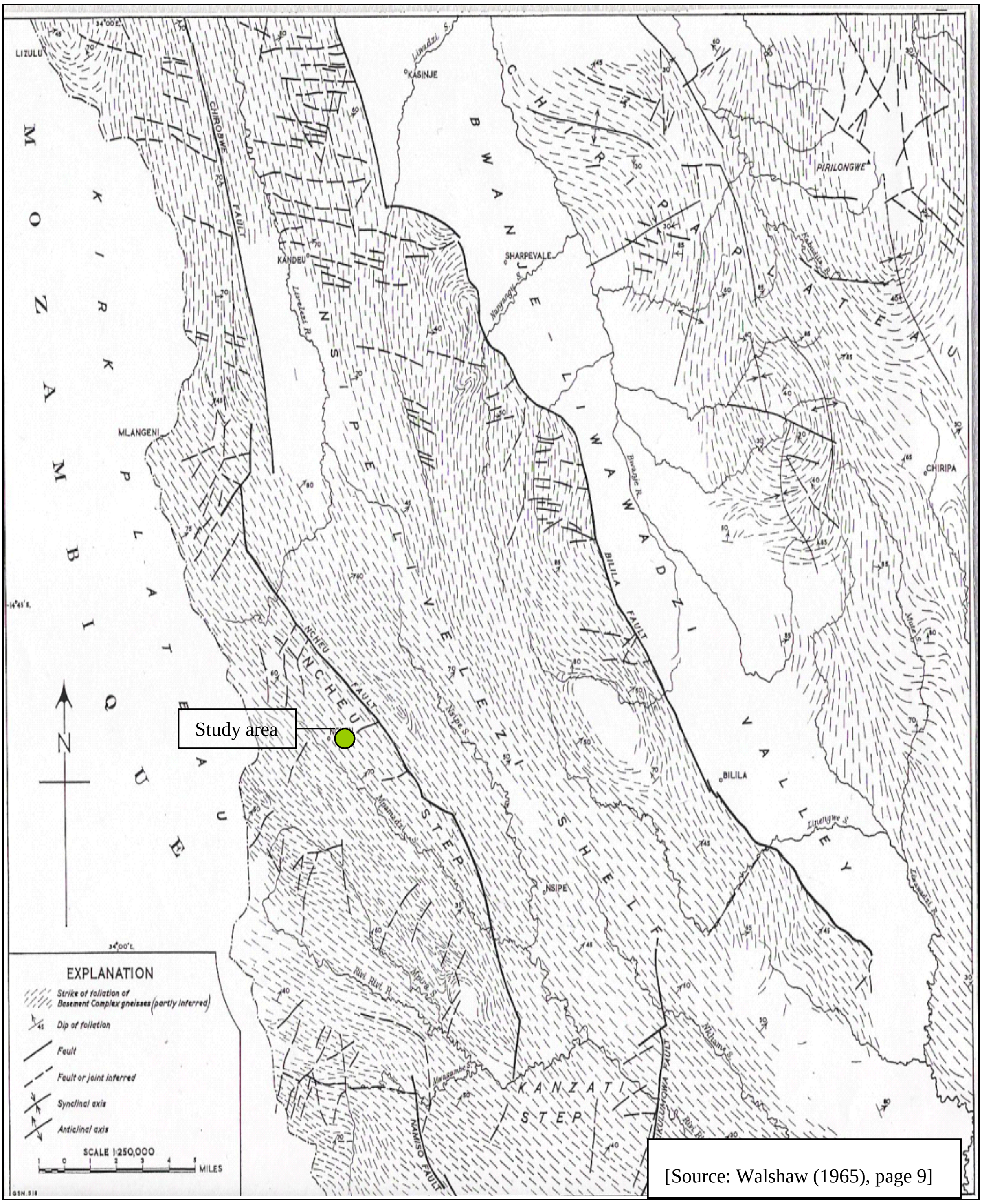


Figure 2. The Physiographical Map of the Ntcheu - Balaka Area.

- The Bwanje – Liwawadzi Valley which runs from Kasinje to Balaka and comprise of a flat featureless valley, is 6 km wide. The valley is drained by the Bwanje and Liwawadzi rivers.

- The Chiripa Plateau which continues to the scarp overlooking the Lake Malombe. This physiographic unit gently rises from about 762m at the border of Bwanje Valley to about 914m on the plain surrounding Phirilongwe.

1.3 The Local Climate in Relation to Physiography

Walshaw (1965) noted that variation in altitude causes major differences in climate between parts of the area. It was noted that there is generally an increase in temperature and decrease in rainfall eastwards from the Kirk Plateau to the Bwanje – Liwawadzi Valley which are at 1524m and 610m altitudes respectively (Figure 2). The higher ground has a warm temperate climate while the low lying areas experience a climate that is akin to the typical hot dry type, common in most parts of the Shire Valley. On the Kirk Plateau the mean annual temperature is low and in the cold season it drops to freezing point (Walshaw, 1965).

The rainfall varies from 787mm per annum near Balaka to between 1016mm and 1143mm on the Kirk Plateau and its flanks (Walshaw, 1965). Due to the high levels of precipitation, numerous rivers and streams dissect the area. From these observations it can be seen that the study area has a high altitude and generally receives high annual precipitation since it falls in the flanks of the Kirk Plateau.

1.4 Vegetation

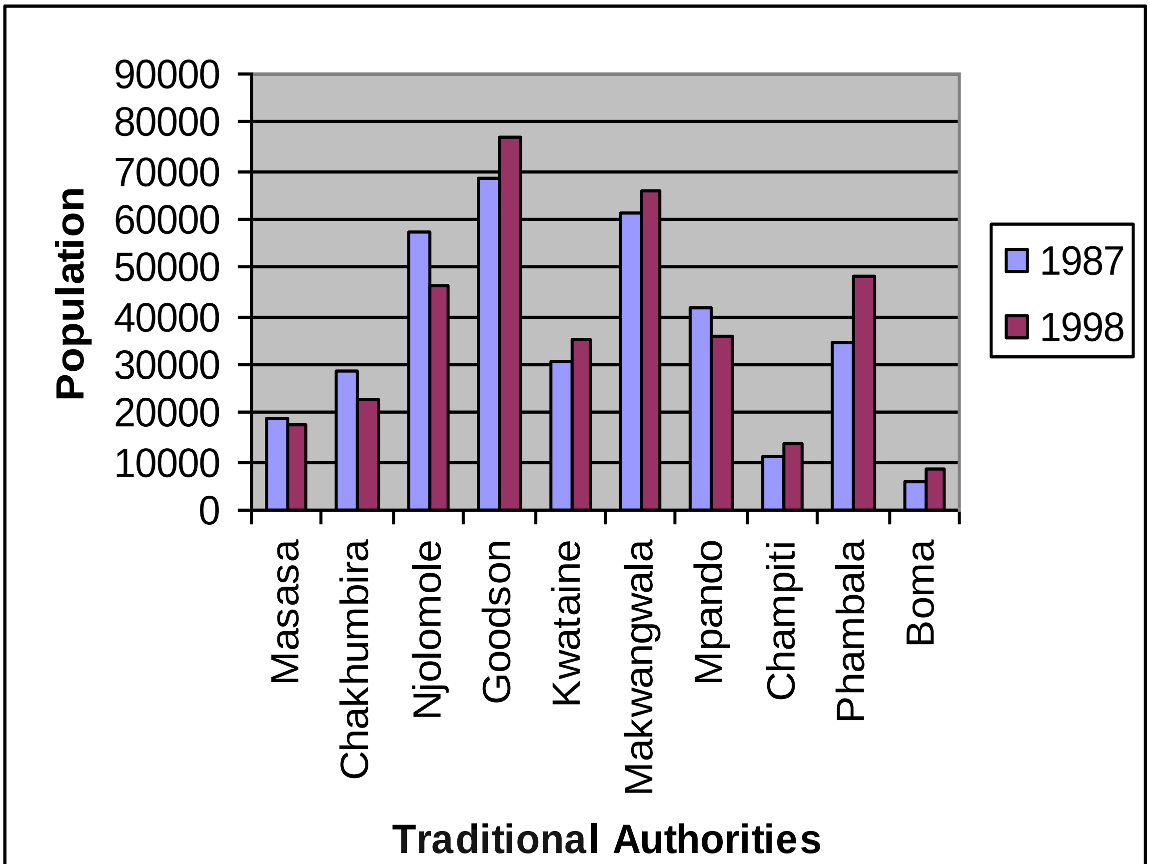
The local climate noted in section 1.3 above supports the growth of different types of vegetation. The Kirk Plateau vegetation comprises of rolling grassland with a few scattered short trees and bushes. Walshaw (1965) explained that the south-east moist winds rise up the Ntcheu and Chirobwe Scarp causing high relief rainfall which cause dense rain forest to develop on the crest and eastern slopes of the Kirk Plateau. However, the vegetation away from the scarps (in the Bwanje – Liwawadzi Valley) is typically of low–level thorn savannah which is interspersed with large timber trees e.g. *Acacia albida (Nsangu),Colophospermum mopane (Tsanya), Terminalia sericea (Napini), Hyphenae palm (Mgwalangwa), Tamarindus indica (Bwemba) and Adansonia digitata or baobab (Mlambe)* (Walshaw, 1965). This is probably in response to the lower rainfall.

1.5 Settlement

Ntcheu District Assembly is located on the Ntcheu Step which lies between the Kirk Plateau and Nsipe-Livelezi Shelf (Figure 2). The Ntcheu Step is relatively flat, hence it is densely populated compared to the areas overlooking the Bwanje Valley which are very rugged. Naturally, development in the area tends to favor the area lying between the Kirk Plateau scarp and the Balaka – Lilongwe M1 road.

The demographic studies carried out in Ntcheu district have shown that the population of NDA has been on the increase thereby exerting pressure on the natural resources (GoM, 2004). Between 1987 and 1998, the population increased from 5 815 to 8 188 representing an average annual growth rate of 3.1% (Figure 3). High population results in high demand for natural resources such as land for agriculture and construction raw materials. Today very little indigenous woodlands noted in sub-section 1.4 exist in the area as a result of increased demand of forest based resources for construction work and energy (GoM, 2004). The remnants of these woodlands exist mostly in the cemetery and government protected areas. The population density is generally high (512 persons per km^2) in the vicinity of [1]NDA and it falls in parts of the Kirk Range, Mvai and Dzodzi Forest reserves since settlement is prohibited in these areas.

[1] Ntcheu District Assembly (NDA) is used interchangeable with the word Boma.



[Data Source: Ntcheu Socio-Economic Profile (2001)]

Figure 3. Population Distribution by Traditional Authority; 1987 and 1998

1.6 Problem Statement and Justification

In 2003, the mountain slopes facing NDA experienced landslides that destroyed a maize garden and disrupted communication between Kachimanga area and NDA administrative centre. The causes and impacts of these landslides have not been studied in detail up to date. All along landslides have been reported to occur in districts such as Rumphi, Kasungu, Zomba and Phalombe. In all these areas, different researchers have noted that landslides were triggered by high levels of precipitation. However, the factors which caused the landslides in Ntcheu are not yet known.

As noted earlier, the *Ntcheu District Socio – Economic Profile (2001)* has demonstrated that the population of NDA increased considerably between 1987 and 1998 (Figure 3). Increase in population pressure and urbanization is known to force people in low lying areas and flood plains to habit the marginal areas for example hill slopes (Coates, 1981). These hill slope environments expose people to unstable soils and rock materials.

In order to avoid loss of property and lives of the Ntcheu District Assembly (NDA) inhabitants, there was need to carry out a Landslide Hazard assessment research work whose results could be useful for planning purposes. This study was therefore invaluable in contributing towards the understanding of the causes of landslides in the study area and in providing valuable information for land-use planning.

1.7 Aim

The aim of this study was to assess the landslides potential of the hill slopes of NDA.

1.7.1 Objectives

In order to achieve the aim outlined above, this project had the following objectives:-

1. To identify the types of landslides in NDA
2. To examine the causes of the landslides in NDA.
3. To map the distribution of both active and dormant landslides on the hill slopes of NDA.
4. To examine the impact of landslides on NDA.
5. To identify the landscape areas that are susceptible to landslides.
6. To generate information that could assist in town planning

1.8 Assumptions made in this study

A number of fundamental assumptions underlie the approach to Landslide Hazard studies. The approach adopted for this study is based on the primary assumptions made by the *Landslide Hazard Zonation Project protocol* (LHZ Project, 2005). The assumptions include:

- Existing landslide features can be used to predict the likelihood of future instability. Areas prone to these processes can be mapped based on physical characteristics, as interpreted from aerial photographs, topographic maps, geologic maps, soil analysis and field verification.

- Although some features are obscured by vegetation, a sufficient number of landslides can be identified on aerial photographs to allow identification of primary controls on landslides processes.

- Although most landslides are at least partly caused by natural processes or events, landslide features associated in time and space with forest practices will be assumed to be caused or expedited by those activities.

1.9 Organization of the Thesis

This thesis is divided into five chapters:

- Chapter one provides an introduction to the study area. The problem statement and justification for this study have been provided. The physiographical set up of the area, the aim, the objectives and the assumptions underlying the present study have also been outlined.

- In Chapter two, some important terms are defined and the classification system adopted for this study have been outlined. The existing knowledge on the problems of landslides, their causes and mitigation measures have been stated. Some relevant literature have been reviewed in order to capture the theories upon which landslide studies are based. These theories form the basis upon which this work has been argued out.

- Chapter three outlines the research tools and methodologies employed in the research work. The methodologies comprise those that were used for fieldwork and the approaches adopted for laboratory analysis. It also states the data analysis tools that were used in this study.

- All the research findings are presented and discussed in Chapter four. The results are interpreted and different types of maps are presented in this chapter.

- Finally, chapter five presents the summary of the results and provides some conclusions that can be drawn from the study. It goes further to recommend some possible land-uses and mitigation measures for the landslides.

CHAPTER TWO

LITERATURE REVIEW

2.1 Definition of a Landslide

Different authors have defined landslides in different ways. Cruden (1991) defined landslides as a movement of a mass of rock, earth or debris down a slope. In 1978, Varnes suggested that *slope movement* would be a better and comprehensive term because it does not infer process. He defined a landslide as a downward and outward movement of slope forming materials under the influence of gravity. Despite landslide being a popular term, Brunsden (1984) preferred the term *mass movement* because the movement of materials on a slope does not necessarily require a transport medium such as water, ice or air.

The term landslide is however used in this thesis as defined by Varnes (1984). He looked at a landslide as a geological phenomenon which he defined to mean almost all the types of mass movements on slopes such as rock falls, topples, and debris flows that involve little or true sliding.

2.2 Classification of Landslides

The numerous classifications of landslides depend on different landslide factors. Most of the classifications given in the literature tend to encompass both the processes as well as the material involved in the displacement (Varnes, 1978). Hutchinson (1988) came up with one of the most comprehensive classification schemes based on morphology, mechanism, type of material and rate of movement. In this thesis, the European classification developed by the EPOCH project (1991–1993) was adopted. In this classification the landslide types include a fall, topple, rotational and translational slides, lateral spreading, flow and complex.
(Table 1).

Table 1. Classification of Landslides (Mass Movements).

TYPE	ROCK	DEBRIS	SOIL
Fall	Rock fall	Debris fall	Soil fall
Topple	Rock topple	Debris topple	Soil topple
Slide (rotational)	Single (slump) Multiple Successive	Single Multiple Successive	Single Multiple Successive
Slide (translational) Non rotational	Block slides	Block slide	Slab slide
Planar	Rockslide	Debris slide	Mudslide
Lateral spreading	Rock spreading	Debris spreading	Soil (debris) spreading
Flow	Rock flow (Sackung)	Debris flow	Soil flow
Complex (with run-out or change of behavior down slope. Note: nearly all forms develop complex behavior)	e.g. Rock avalanche	e.g. Flow slide	e.g. Slump earth flow

Source: EPOCH (European Community Programme) Project (1993), page 3.

In this classification scheme, a fall denotes the free–fall movement of material from a steep slope or cliff. A topple, which is very similar to a fall, involves a pivoting action rather than a complete separation at the base of the failure. A slide was defined as movement occurring on a distinct slide or shear surface. These slides were further divided into rotational and translational according to the form of the failure surface (Table 1). The rotational slides are different from the translational slide in that the former involved a semicircular shear surface while the latter usually occur on planar slip surfaces. Low-angled slopes are characterized by lateral spreading movements and flows. The flows normally behave as fluidized mass in which water and air are involved. However, the complex failures are a combination of two or more of the previously described movements.

2.3 Causes of Landslides

The driving force behind landslides is the gravitational force. Factors that allow the force of gravity to overcome the resistance of the earth material to landslide movement include rainfall (water saturation), geology, topography (steepening of slopes by erosion or construction work), alternate freezing and thawing, earthquake shaking, and volcanic eruption.

2.3.1 Topography

The literature has demonstrated that landslides are strongly influenced by topography while vegetation cover was found to control landslide distribution (Fernandes *et al.,* 2004; Chen and Lee, 2004). Studies in Hong Kong have shown that 90 % of the landslides occurred in terrain that was steeper than 30°. A combination of heavy rainfall and man-made structures on steep slopes is known to lead to slope instabilities (Wong and Ho, 1995). Road cuttings and cut-and-fill structures on such slopes can lead to slope failures that can cause loss of properties and lives.

2.3.2 Geology

Different types of rocks on hill slopes show different resistance to weathering. Chen and Lee (2004) have shown that granites weather to a depth of greater than 30m thereby forming a residual silty sand mantle which offers low resistance to surface erosion. On the other hand volcanic rocks did not weather to the same depths and their residual silt soils were not as susceptible to erosion as the weathered granites. The presence of joints and fracture planes in the weathered granites, were found to cause localized failures in cut slopes (Brand, 1988). Where a brittle rock mass overlie a weak layer, slow deformation and fracturing was found to commonly precede catastrophic failures and rapid debris movements (Geertsema *et. al.*, 2006).

2.3.3 Rainfall

Shallow and deep seated landslides can be triggered by different types of rainfall. Shallow landslides, especially soil slips and debris flows, are known to be triggered by intense short-duration rainfall. However, landslides in clayey soils and deep-seated landslides are more sensitive to rainfall events of long and moderate intensity (Crosta, 2004). Pore pressure build-up in such soils depend not only on soil deformation, but also on soil permeability (Iverson *et al.*, 2000).

2.4 Effects of Landslides

When landslides occur, they usually cause great human suffering (Sassa, 2000). They frequently cause serious financial loss through infrastructural damage and they also cause loss of life. Landslides move at different speeds. Some landslides move slowly and cause damage gradually, whereas others move so rapid such that they destroy property and take lives suddenly and unexpectedly**.**

2.4.1 Landslides in Africa

Apart from Asia and Europe, landslides have also been reported on the African continent. However, literature on these is scanty probably because most of the landslides occurring on the continent have not been studied or it could be because where these have been studied, the findings have not been published.

Temple and Rapp (1972) did some work in Tanzania and they reported that 100 landslides occurred in the Mizugu Mgeta area after more than 100mm of rainfall fell over a period of 3 hours on February 23, 1970. These landslides were attributed to a combination of factors that included an earthquake shock measuring 4.7 on a Richter scale and a sudden rise in pore water pressure resulting from heavy rainfall.
Ogola (1998) observed that landslides in Kenya have been on the increase, causing both social and economic impacts. Landslides lead to loss of life, destruction of infrastructure and crops, and the degradation of agricultural land. These landslides were triggered by liquefaction of the slope forming soils due to 1200mm of rainfall, as a result of the El Niño (from October 1997 to February 1998).

2.4.2 Landslides in Malawi

In Malawi few landslides have been recorded, let alone studied. Those studied have been tabulated in Table 2. Manda (1999) noted that the [2]*Napolo* myth underlines the fact that landslides in Malawi have been a common phenomenon from time immemorial. The oldest slide on record is the Zomba landslide of 1946. Mtiya area in Zomba district received heavy rains amounting to 711mm within 33 hours. The resultant landslide claimed 21 lives, destroyed 24 bridges, electricity and the water supply lines were also disrupted (Poschinger, 1998; Cheyo, 1999). Recently, the Phalombe slides of 1991 occurred after high precipitation of 400mm – 700mm in the Michesi Mountains (Poschinger, 1998; Cheyo, 1999). The event claimed 500 lives, crops were washed away and infrastructure damage was estimated at MK59 million. Kaufulu and Dolozi (1992) also reported the occurrence of landslides on the slopes of Manyani hill, in northeast of Kasungu, in 1989. The event was preceded by heavy rainfall ranging from 800 to 1200mm and some earth tremors. It can be seen that all the studied landslides in Malawi are attributed to high precipitation, earth tremors, steep slopes and deforestation.

2.5 Mitigation of Landslides

Ahmad *et al.* (2002) divided landslides mitigation approaches into passive (non structural) and active (structural) as follows.

[2] Tradition looks at landslides as being caused by a giant snake, called Napolo that sleeps under the mountains and hills. When this is disturbed it escapes from its hiding place to the lake, causing damage in the process.

Table 2. Some of the Landslides in Malawi and their Causes and Impacts.

NAME	DATE	IMPACTS	CAUSES	REFERENCE	REMARK
Zomba Landslide	1946	▪ 21 people died and 24 bridges were destroyed ▪ Roads were damaged, electricity and water supply disrupted ▪ Gardens and buildings were destroyed ▪ Mtiya and Phuka villages were Washed away	High levels of precipitation	Poschinger, 1998 Cheyo, 1999	Studied
Lumbadzi	1975	• Bridges were destroyed and there were unspecified number of casualties • A UTM tanker was destroyed	High rainfall	………………….	Not studied
Banga	1984	• Some crop fields were destroyed	High rainfall	…………………	Not studied
Ntonya-Ulumba	1985	• There were no casualties and property Damage because the area was remote	High levels of rainfall	Chikusa, 1985	Studied
Dedza	1989	• No information	Unknown	………………….	Not studied
Manyani	1989	• There were no casualties and property Damage because the area was remote	High rainfall, steep slopes and earth tremors	Dolozi and Kaufulu, 1992 Manda, 1992	Studied
Nyambilo	1989	• As above	High rainfall	Chipili, 1989	Studied
Phalombe	1991	• 500 people were reported dead and crops were washed away • Infrastructure and property damage was evaluated to be MK59 million	High rainfall (400 – 700mm) and deforestation	Gondwe, et al. 1991 Mshali 1992 Poschinger et al. 1998 Cheyo, 1998 Mwafulirwa, 1999	Studied
Malosa	1991	• Property damage was very minimum	Unknown	…………………..	Not studied
Banga	1997	• Some crops were destroyed		………………….	Not studied
Zomba Mountain	1997	• Kuchawe road was blocked interrupting traffic	High precipitation	………………….	Not studied
Nyankhowa (Overton)	2000	• The road was blocked and water supply pipes were destroyed	High rainfall, steep slopes, deforestation and pore water pressure	Msilimba and Holmes, 2005 Msilimba (Thesis), 2002	Studied
Ntcheu	2003	Maize fields were destroyed and Mpira Dam experienced high levels of siltation	Unknown	………………… ….	The present study

Modified after Manda, (1999) pp. 13-17.

2.5.1 Passive (Non structural) Measures

These measures are cost effective in reducing hazards if the areas in question are subject to frequent debris flows. The measures include:

- Removing or converting the existing development
- Discouraging development
- Regulating development by limiting the type or amount of development
- Building houses with their length oriented perpendicular to the debris flow direction. The impacts of the debris become minimized with this orientation.
- Avoiding development projects in the problem areas.

2.5.2 Active (Structural) Measures

These aim at controlling the movement of the debris across the depositional fan by putting in place engineering measures. These measures are generally very costly in nature. Ahmad *et al.* (2002) divided them into the following two sub-measures:-

(a). Debris Source Areas

When dealing with the source area, the following measures are recommended:-

- Land-use practices must be revisited or an audit of the landslides source areas must be done. Debris can be reduced by stabilizing the debris source areas. This is a long term measure.
- A reforestation exercise can be conducted to stabilize the source areas.
- Road construction must be controlled by eliminating all unstable cuttings that could act as source of debris or initiation points.

(b). Transportation and Deposition Zones

These are the zones between the mountain front and the debris deposition area. Debris can be controlled by some of the following measures:

- Construction of open debris deposition basins to control the extent of depositional areas.
- Constructing retention barriers and basins in order to create a controlled deposition space fronted by a straining structure and a spill way.
- Raising the height of the bridges, channel dredging and widening culverts in order to allow safe passage of debris under the bridges and culverts.

CHAPTER THREE

METHODOLOGY

3.1 Determination of types and causes of landslides in NDA

In order to achieve specific objective 1 and 2 field studies were conducted and both active and passive landslides were studied. Geology, topography, soil, precipitation and human impacts on the environment were also studied in order to determine the causes of landslides in the study area. It was imperative that the geology of the area be studied because the rock types and the discontinuities therein have influence on rock weathering and slope stability. Geology was studied as outlined below:

3.1.1 Geology

To conduct the geological studies, the following equipment and methodology were used:-

Materials

- Aerial photographs at a scale of 1:50 000 for delineating the landslide scars
- Brunton Compass and Clinometer for determining slope orientation and angles
- Stereoscope for studying the aerial photographs
- Global Positioning System (GPS) for determining the position
- Camera for capturing field observations
- Hammer for getting fresh rock samples

3.1.1.1 Aerial Photograph Interpretation

Of the many systems available, usage of medium to large scale aerial photographs are said to be the most useful, accurate and cost effective. Aerial photographs give an overall perspective of a large area and boundaries of the existing landslides, outcrops and human–made structures can easily be outlined (Rib and Liang, 1978). Geology was studied using aerial photographs at a scale of 1:10 000 and 1:50 000 with the aid of a stereoscope. The structures and outcrops observed on the aerial photographs were outlined and later a ground truthing exercise carried out. According to Allum (1978), this has the following advantages:

(a) The aerial photos provide many more topographic details than maps. Hence, they allow the location of points to be plotted with much greater precision. The stereo model also allows a three dimensional study of the topography.

(b) At large scale, more detailed and accurate maps can be derived from the aerial photographs. The data generated from the photographs can be transferred with accuracy without the necessity of further work.

(c) Since the information on the photographic image corresponds to particular field observations, it means the observations can be extrapolated over a considerable distance.

The study of aerial photographs and topographical maps was followed by ground truthing. This was necessary because some important features of slope failure may be obscured by vegetation, hence they can be very difficult to identify from the aerial photographs. The central purpose of ground truthing was the identification and recognition of various lithologies and slope movements such as falls, topples, creep, slides, debris flow and translational block movements. Ground truthing was also essential because it assists in identifying areas with critical hydrologic conditions which can not easily show on aerial photographs.

3.1.1.2 Rock Strength Estimation for the Study Area

Weathering of rocks is known to cause general weakening of hill slopes (Chen and Lee, 2004). Hence, there was need to estimate the rock strengths in the study area in order to ascertain whether it had any influence in the occurrence of the landslides.

The rock strength for the hill slopes of Ntcheu District Assembly (NDA) was estimated using the RocLab program (Hoek *et al,* 2002). The RocLab program provides a convenient means of solving and plotting the rock strength equations (Hoek *et al,* 2002). In the RocLab program, the uniaxial (unconfined) compressive strength of a rock mass was defined using the Generalized Hoek-Brown criterion as:

$$\sigma_1^{'} = \sigma_3^{'} + \sigma_{ci}\left(m_b \frac{\sigma_3^{'}}{\sigma_{ci}} + s \right)^a \qquad \textbf{(1)}$$

Where:

- $\sigma_1^{'}$ and $\sigma_3^{'}$ are the major and minor principal stresses respectively
- σ_{ci} is the uniaxial compressive strength of the intact rock pieces
- m_b, s and a are material constants determined from the Geological Strength Index (GSI) rating

When σ_3^{i} = 0 is substituted in the equation, the uniaxial compressive strength of the rock mass become:

$$\sigma_c = \sigma_{ci}.s^a \qquad \textbf{(2)}$$

Hoek *et al.* (2002) defined the Mohr-Coulomb failure criterion by the equation:

$$\tau = c^{'} + \sigma_n^{'} \tan\phi \qquad \textbf{(3)}$$

Where:

- $c^{'}$ is the effective cohesive strength and ϕ is the friction angle

Then the uniaxial compressive strength of a rock mass which fails in accordance with the Mohr-Coulomb failure criterion is defined by:

$$\sigma_{cm}^{'} = \frac{2c^{'}Cos\phi^{'}}{1 - Sin\phi^{'}} \qquad \textbf{(4)}$$

Since the Mohr-Coulomb criterion is linear, its compressive strength is much less sensitive to confinement than the equivalent strength for the curvilinear Hoek-Brown criterion. The compressive strength defined by equation (4) is said to give a reasonable estimate of the average or ‘Global’ rock mass strength.

Hoek (2005) noted that a problem existed in fitting an equivalent Mohr-Coulomb failure envelope to the failure envelope defined by the Hoek-Brown criterion. The relationship between the global rock mass strength σ_{cm} and the Hoek-Brown parameters was then given by:

$$\sigma_{cm} = \sigma_{ci} \frac{m_b + 4s - a(m_b - 8s)(m_b / 4 + s)^{a-1}}{2(1+a)(2+a)} \qquad \textbf{(5)}$$

For the confining stress range $0 \langle \sigma_3 \langle \frac{\sigma_{ci}}{4}$ **(6)**

Using RocLab program, the Generalized Hoek-Brown criterion of σ_{cm} (Global strength of the rock mass) is calculated using equation (5) for the stress range defined by equation (6).

3.1.2 Topography

The literature reviewed has demonstrated that topography plays a pivotal role in the occurrence of landslides (Chang *et al.*, 2005; Wong and Ho, 1995). It was therefore necessary to assess whether topography was one of the factors contributing to landsliding in the study area. The topographical investigations were done using the following materials and methodology:-

Materials

- Topographic Map sheet at a scale of 1:50 000 for terrain determination
- Brunton Compass and Clinometer for determining structural orientation and dip angles
- 100m Tape for measuring distance
- Arc View Geographical Information System (GIS) for deriving thematic maps
- Geographical Positioning System (GPS) for determining position

The topographical map was used as a base map in this study because steep slopes can easily be recognized by the closeness of the contour lines. The contour lines were digitized from the topographical map (1:50 000), using Arc View GIS. Areas indicating the presence of steep slopes were later investigated using ground truthing exercise with the aim of identifying the presence of old landslide scars (Compton, 1985).

A clinometer was used to measure the slope angles of the terrain. This exercise generated quantitative data on the critical landslide slope angles for the area. The slope morphology characteristics were then studied through traverses in the affected area. Where necessary, the measurements were done using a 100m tape.

3.1.2.1 Delineation of the Landslides

Delineation of the landslide areas was done using aerial photographs with the aid of a stereoscope (Rib and Liang, 1978). In some instances, the field observations were located on the base map using GPS coordinates and the orientation of the slopes was determined using a Brunton Compass.

3.1.3 Soil Analysis

In order to characterize the soils making up the slopes in the study area, soil sampling was done using the methodology and materials outlined below:

Materials

- Aerial photographs at a scale of 1:50 000 for determining one’s location
- Topographic map sheet at a scale of 1:50 000 for determining one’s location
- Hoe for collecting samples
- Sieves for grain size analysis
- Global Positioning System (GPS) for determining the location of sampling points
- Sample bags for packaging the soil samples

The areas that experienced landslides were targeted for soil sampling using a hoe. Since the material of the landslide is lost, this study was essentially a *post mortem* analysis. As such, soil sampling was done on the materials immediately surrounding the 'head' and sides of the landslide scars. Rogers and Selby (1980) noted that samples collected in the immediate vicinity of landslides characterize the materials that failed. It was therefore necessary to carry out the soil analysis because it would provide vital information on the engineering properties of the materials forming the mountain slopes. This information is important in determining whether the soil was one of the causative factors for the slope failures or not.

The sample locations were determined using the Global Positioning System (GPS) and these were plotted and recorded on a base map and field notebook, respectively. Analysis of the soil samples was done using the following methodologies:

3.1.3.1 Particle Size Distribution

Weil (1993) defined soil texture as the relative proportion of sand, silt and clay separates in a particular soil. There are two approaches to separating and determining the proportions of sand, silt and clay. The initial stage is the mechanical sieving of the sample. However, separates of less than 50 microns in diameter cannot be determined using this method because a mesh of smaller diameter than this cannot be made. This then calls for the usage of pipette and hydrometer methods which utilize the sedimentation concept. However, this second stage, in the analysis, was not done because the equipment was not available. This will affect the results in that they will not be complete. The sand content of the samples was determined following the steps below.

(a). Determination of the Sand Content

The samples were prepared as follows:

- Initially, the organic matter was removed from the samples by hand picking and using tweezers.
- After that a representative sample was prepared using quartering and ratio method (riffling).

- Then a 500g sample was weighed and oven dried at 105 -110°C for four hours.
- The sample was weighed again and then it was wet sieved to remove all the clays and silt, in order to retain the sand.
- Upon drying, the sample was re-weighed and the weight subtracted from the original 500g in order to determine the total silt and clay mass.

Then a stake of sieves of different mesh sizes was used to separate the soil particles into fine sand (0.5-0.05mm), coarse sand (1.0-0.5mm) and very coarse sand (2.0-1.0mm) (Appendix 1A). The sieves were arranged in the decreasing mesh sizes and the amount retained by each mesh was then weighed and then converted to a percentage.

3.1.3.2 Liquid Limit

The Liquid Limit (LL) is defined as the moisture content at which a soil changes from a liquid state to a plastic state (http://www.civl.port.ac.uk/projects/geotech/geo2.html). At the LL, the water content of the soil is said to be at maximum and the soil resistance to shearing is said to approach zero. The LL, therefore, gives a measure of the water content of a soil beyond which it can move. The LL together with the Plastic Limit (PL) provide a means of soil classification and they also assist in determining other soil properties such as the Plastic Limit.

(a). Determination of the Liquid Limit

The Liquid Limit was determined using the Casagrande method (http://www.civl.port.ac.uk/projects/geotech/geo2.html). The soil to be tested was sampled and prepared as follows:

- The coarse particles present in the sample were removed by hand (coarse particles are those retained on a 425 micron sieve).
- A representative sample weighing 200g was then collected.
- The sample was then cut into small pieces using a knife or shredder and any coarse particles were removed with tweezers.
- Then the sample was transferred to a flat glass plate and distilled water was added. The soil and water was mixed thoroughly with two palette knives until the mass

became a thick homogenous paste.

- The paste was then transferred to an air-tight container for 24 hours to allow water to penetrate the soil fully.

After 24 hours, the samples were tested using the following procedure as suggested by the reference:-

- The apparatus to be used were inspected to ensure they were in good working order, clean and dry. The height to which the cup rises was adjusted so that the 10mm gauge just passes beneath it.
- With the cup of the apparatus resting on its base (Appendix 1B), a portion of the sample was placed in the cup making sure no air is entrapped. The cup was then filled and leveled.
- The sample (in the cup) was then divided into two sections using the grooving tool. This was done by running the grooving tool along the base of the cup from the hinge to front edge of the cup in a continuous circular movement.
- The crank handle was turned at a rate of approximately 2 rotations per second such that the cup was lifted and dropped. The number of bumps was counted until the two parts of the sample came into contact at the bottom of the groove along a distance of 13mm (this was measured using the end of the grooving tool or with a rule).
- The number of bumps required for the two parts of the sample to come into contact was recorded.
- Then more soil was added and the process repeated until the number of bumps for the contact to occur was the same for two consecutive runs.
- This was repeated at least three more times with varying amounts of distilled water added, proceeding from the dryer to the wetter condition of the soil. The amount of water added was such that when four or more moisture contents were plotted they were distributed evenly over the range 10-50 bumps.

(b). Calculating the Liquid Limit

- Moisture content of each test sample was calculated and the relationship between the moisture content and the corresponding number of bumps was plotted on a semi-logarithmic chart. The percentage moisture contents were plotted as ordinates on the linear scale and the number of bumps was on the logarithmic scale.

- Then the line of best fit was drawn (this is the flow curve)
- From the flow curve, the moisture content corresponding to 25 blows was read off to the first decimal place.
- This moisture content was expressed to the nearest whole number and was reported as the **LIQUID LIMIT**.

3.1.3.3 The Plastic Limit and Plasticity Index

The Plastic Limit (PL) is defined as that moisture content of a soil at which it becomes too dry to be plastic (http://www.civl.port.ac.uk/projects/geotech/geo5.html**)**. The PL was used together with the LL results, from section 3.1.3.2, to determine the Plasticity Index (PI) which when plotted against the Liquid Limit on the plasticity chart enables the classification of cohesive soils. Calculation of the PI was necessary because it gives a measure of the range of water content over which the soil displays plastic behavior (Flawn, 1970). If the range is narrow, it means a small increase in the soil water content may be sufficient to cause a slope failure.

(a). Determination of the Plastic Limit

To determine the PL the following apparatus were used;

- Sample of Cohesive Soil
- Glass mixing plate
- Standard Hand

Then the following testing procedures were used in the determination of the Plastic Limit (http://www.civl.port.ac.uk/projects/geotech/geo5.html**)**.

- A sample of about 20g from the prepared soil paste was placed on a glass mixing plate.
- The soil was then allowed to partially dry by spreading it out until it became plastic enough to be shaped into a ball.
- The ball of soil was molded between the fingers and rolled between the palms of the hands until the heat of the hands dried the soil sufficiently for slight cracks to

appear in the surface.

- This sample was divided into two sub-samples of about 10g each and a separate determination on each portion was carried out. Each sub-sample was further divided into four more or less equal parts.
- Soil in the fingers was molded to equalize the distribution of moisture and then a thread of about 6mm in diameter was formed between the first finger and thumb of each hand.
- The thread was then rolled between the fingers (from the fingertip to the second joint) of one hand and the surface of the glass rolling plate.
- Enough constant pressure was used to reduce the diameter of the thread to about 3mm in five to ten complete forward and backward movements of the hand.
- The soil was picked up again and molded between the fingers to dry it further. It was formed into a thread and then rolled out again.
- This was repeated until the thread sheared both longitudinally and transversely when it was rolled to about 3mm in diameter, as gauged by a rod. The pieces of soil were not gathered together for the purpose of reforming a thread and continue with rolling after they had crumbled because the first crumbling point is the Plastic Limit.
- The portions of crumbled soil thread were gathered together, transferred to a suitable container and then the lid was replaced instantly. This procedure was repeated on the other three portions of soil, placing the crumbled soil into the same container. The procedure also applied when testing the duplicate samples.

(b). Calculation of the Plastic Limit and Plasticity Index

The moisture content of both samples tested was calculated and recorded on a data form. The average of the four moisture content values was calculated and the result expressed to the nearest whole number. This was recorded as the **Plastic Limit (PL)**.

After getting the Liquid Limit (LL) and the Plastic Limit (PL), the Plasticity Index (PI) was calculated using the following equation (http://pasture.ecn.purdue.edu/~eql/labmanual2.htm):-

$$\boxed{\mathbf{P\,I = (L\,L) - (P\,L)}}$$

3.1.3.4 Bulk Density

After determining the PI of the soil, there was also need to know its Bulk density. This was necessary because it assists in characterizing a soil being studied. Since Bulk density is inversely related to soil porosity, it therefore gives an insight about the texture of the soil in question. The bulk density of clayey soil ranges from 1.1 – 1.6 g/cm^3 and that of sandy soils can be as high as 1.8 g/cm^3. Bulk density of soil is a function of the degree of compaction, the shrinkage and swelling characteristics of clay (Black, 1965).

Bulk density is defined as the ratio between the mass of oven dried soil to the total volume of soil. In other words, it is the ratio between mass of oven dried soil to the volume of the soil particles and the volume of pores (http://pasture.ecn.purdue.edu/~eql/labmanual2.htm). This is expressed as

$$P_b = \frac{M_S}{V_T}$$

Where:

P_b is the soil Bulk density

M_s is the mass of the [3]'oven dried soil'

V_T is the total volume of soil

[3] Soil that has been dried at 105°C until it reaches a constant mass.

(a). Clod Method

The soil Bulk Density was calculated using the Clod Method. The materials required for the clod method included:-

- Paraffin wax kept in a container at a temperature between 60 - 70°C
- Oven with 100 - 110°C temperature control
- A balance of ± 0.01g precision
- Desiccator that contains active desiccant such as magnesium perchlorate or calcium sulfate
- Coarse mesh wire pan
- 100 or 200 ml beaker

These were utilized in the following way:-

1. A soil clod was obtained and then air-dried.
2. The air-dried clod was weighed and the weight was recorded as M_{sa}.
3. The clod was then placed in the wire pan and then dipped (the clod and the wire pan) in melted paraffin. The pan was taken out, excess paraffin drained and the remaining paraffin was allowed to dry on the clod surface.
4. The paraffin-coated clod was weighed and this weight was recorded as M_{pa}.
5. A beaker was partly filled with water and then its weight was determined.
6. The paraffin-coated clod was then placed in the beaker and the weight of the filled beaker plus the coated clod was determined. The difference in weight between step 6 and 5 is the weight of the paraffin coated soil sample in water. The difference was recorded as M_{spw}.
7. To obtain the correction for the soil water content, the soil clod was broken open and a soil sample was taken for drying in the oven at 105ºC. The soil moisture content was determined on weight basis and recorded as θ_d.

(b). Determination of Bulk Density and Soil Porosity

The calculations were carried out with the aid of the following formulas:

1. The oven dry mass of the soil sample (M_{ods}) was calculated using the formula

$$M_{ods} = \frac{M_{sa}}{1+\theta_d}$$

2. The soil sample bulk density (P_b) was calculated using the formula

$$P_b = \frac{P_{wM_{ods}}}{M_{sa} - M_{spw} + M_{pa} - \left(P_w + \frac{M_{pa}}{P_{pf}}\right)}$$

Where:

P_w is the water density which is approximately equal to 1

P_{pf} is the paraffin density which is approximately equal to 0.9

3. The soil sample porosity was determined using the calculated bulk density as follows:

   Total volume of the soil sample is equal to the volume of solid space plus the volume of pore space, expressed in an equation as follows:-

$$V_T = V_P + V_S$$

   This equation can be rewritten as

$$\eta = 1 - \frac{V_S}{V_T}$$ Where η is porosity

- The particle density (P_p) is defined as the mass of oven dried soil particle relative to the volume space. The bulk density (P_b) is utilized for the determination of the solid space fraction of a soil sample.

- Since soil porosity is inversely related to bulk density, the formula for calculating Porosity becomes:-

$$\eta = 1 - \frac{P_b}{P_p}$$

The particle density (P_p) of soils is approximately equal to 2.65 g/cm^3.

3.1.4 Human Impact Studies

Apart from the natural phenomena, human activities increase the natural tendency for landslides to occur in an area. Forest management activities that tend to convert a forested area to grassland or one where crops are cultivated can increase the soil moisture enough to cause landslide problems (DeGraff, 1979). In agreement to this, Jakob (2000) concluded that logging increases the prevalence of landslides in hilly areas.

Research has shown that building roads which cut off the toes of steep slopes can also increase landslide susceptibility of an area (Kockelman, 1985). However, it is possible to reduce the potential impact of natural landslide activities and limit development-initiated landslides occurrences by early consideration of these facts.

In order to study the human factor in the occurrence of these landslides, the following materials and methodologies were used:-

- Aerial photographs at a scale of 1:10 000 and 1: 50 000 for determining land-use
- Topographic map at a scale of 1:50 000 for location
- Ground Truthing for verifying what was observed on the aerial photographs
- GIS used for producing thematic maps

3.1.4.1 Data Capturing Tools and Methodology

Land use in the area was studied using aerial photographs at the scale of 1:10 000 and 1:50 000. Extra information was obtained from fieldwork and the topographical map sheet for Ntcheu.

The 1957 and 1991 aerial photographs were used for the time series study of the area. This study was necessary because it allowed changes in land-use to be appreciated and links between these changes and the occurrence of landslides to be established. Upon studying the land-use changes, there was also need to look at the rainfall patterns of the affected area and establish a relationship between rainfall and the slides that occurred in study area.

3.1.5 Precipitation

Merritts (1997) noted that apart from the force of gravity, water is another factor that influences the strength of materials on a steep slope. When water enters the pore spaces of the weathered soil material, it reduces the resistance forces of the slope material to movement. When water is in excess, as it is during a storm, water pressure pushes the particles apart causing them to move more freely. This eventually makes the soil more susceptible to sliding. To study the rainfall characteristics of the area, the following materials and methodologies were employed:-

- Secondary rainfall data from Nkhande RTC weather station
- Microsoft Excel package for producing bar graphs

The precipitation characteristics of the study area were analyzed using secondary rainfall data sourced from Nkhande Rural Training Center weather station. The precipitation data from 1990 to 2005 rain seasons was analyzed using a Microsoft Excel package to produce tables and graphs. This assisted in identifying rainfall patterns for the area. Of particular interest were the rainfall patterns preceding the landslides. These assisted in establishing the rainfall patterns that are associated with the occurrence of landslides in the study area.

3.2 Determination of the Impact and Distribution of Landslides

In order to achieve objective 2 and 3, field studies and GIS were used. The GIS tool was used as described below:-

3.2.1 Geographical Information System (GIS)

Arc View GIS software was used for data capturing and the development of thematic maps. The topographical map, village points, land use, geology and old landslides were directly digitized to GIS as input. The methodology by Brabb *et al.* (1972) was used to develop a Landslide Hazard thematic map as follows:-

i. The initial step was to develop a *Landslide Inventory Thematic Map*. The locations of the landslide scars were determined using a GPS.
ii. This was then superimposed on the *Geologic Thematic Map* in order to identify the units in which failures had occurred.
iii. The *Slope Thematic Map* was also superimposed on the combined *Geologic* and *Landslide Inventory Thematic Map.* The slopes were then studied to determine the slopes interval that displayed maximum landslide frequency for each lithological unit. Then the assessment of slope stability was extended to the adjacent areas using aerial photographic interpretation with field checks (Nilsen *et al.* 1979).

GIS assisted in the overlaying of the various thematic maps in order to map the interaction of the various themes. This assisted in coming up with factors that contributed to the occurrence of landslides and in the development of a *Landslide Hazard Susceptibility Map*.

3.3 Determination of Areas that are Susceptible to Landslides

In order to facilitate the development of an urban Physical Plan, the Landslide Risk Factors (LRF) were determined for each sampled area. Stevenson (1977)'s numerical rating system was used to assess the role of factors that contributed to slope instability. He came up with a simple but effective empirical approach for evaluating and mapping relative landslide hazard and risk in the clay slopes. The rating system was based on the variables in Table 3. The choice of these variables was based on fieldwork observations. The variables contributing to a landslide were graded on a scoring scale of 1, 2 and 3; representing low, intermediate and high risk respectively (Holmes and Msilimba, 2005).

3.3.1 Interpretation

Landslide Vulnerability Indices (LVI) were determined by calculating the mean of the total score for each sample site. The mean is said to give a crude index of vulnerability. Holmes and Msilimba (2005) noted that the mid points of the vulnerability scores gave logical divisions in terms of classifying an area as stable, potentially unstable or unstable. They recommended that the critical values, for determining whether a slope is stable or not, be lowered to ensure that a researcher errors on the side of conservation. Therefore, a Vulnerability Index of 1.5 or less meant the area was stable, a value that falls between 1.5 and 2.0 meant the area was potentially unstable and if the value was above 2.0 it was an indication of instability. Using this information, a *Landslide Hazard Susceptibility Map* was produced to assist decision makers in land–use planning.

These methodologies were found to be convenient and to produce rapid results at a minimum cost. This is essential, especially in a developing country like Malawi where high technology is not readily accessible yet technical information is required for decision making.

Table 3. Variables used in the Determination of the Landslides Vulnerability Scores.

Value	Slope (◦)	Geology	Land Disturb.	Land Cover	Slope Complex	Total Sand (%)	Porosity Index	Plasticity Index	Bulk Density (d_b) Gm/ cm^3.
1	≤ 10	Structures dip into slope	Low	Woodland	Simple Slope	< 60	< 0.45	> 15	> 1.25
2	10 – 17	Structures dip into slope but old scars are present or structures dip sub-parallel to slope but no old slides present	Medium	Grass/ shrub or built on with special precaution	Old slide, now partly obliterated by erosion	60–70	0.45–0.50	15 – 10	1.25–1.20
3	> 17	Structures dip sub-parallel to slope and old slides are present	High	Cultivation or built on without special precaution	New failure, now stable but not eroded	> 70	> 0.50	< 10	< 1.20

Modified after Msilimba and Holmes (2005), pp. 208.

3.4 Limitations of the Study

The limitations of this study included the following:

- The financial allocation for this work was very limited and this meant some of the proposed field activities were not done. Since drilling is an expensive undertaking, the hydraulic conductivity and the piezometric response of the weathered perthositic gneisses were not tested.

- The aerial photographs for 2003 were not available for this study. This means the field observations of landslides were supposed to be physically transferred to the base map, using GIS. This process generated errors in terms of landslides dimensions. Therefore, the user of these map outputs is advised to use them with caution.

- Since this is an academic work, it was supposed to be completed within a set time frame. This means the areas studied were only those that were accessible. Some landslides occurred in areas of the scarp that were too steep to be accessed hence these were not studied.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Landslides in Ntcheu

A total of 15 landslides were identified and studied in the vicinity of NDA. The local people estimate over 60 landslides to have occurred in Mvai Forest Reserve alone. However, this study concentrated only on those landslides that were accessible and in proximity to areas with potential for the district assembly expansion. Out of the 15 landslides that were studied, 9 were located in the Mvai Forest Reserve and the other 6 occurred in Ntcheu Forest Reserve area (Figure 4).

4.2 Types of Landslides Identified in the Study Area.

The identified landslides were classified into three groups which included rock slides (Rock creep and slumps), topples and lateral spreading (soil spreading) as described below.

4.2.1 Rock Slides

Rotational slides 1, 2, 3, 4, 7 and 10 occurred on the east facing Kirk Plateau scarps which slope at an angle of 30°. The slope morphology was generally stepped and the scars were located mid slope to near crest at altitudes ranging from 1198m to 1275m above sea-level. These landslides generated debris flows that contained a chaotic mixture of grain sizes and vegetation matter. Most of the slides in the area were [4]shallow (1, 2, 3, 4, 7 and 8) measuring 1 to 2m in depth and the debris materials moved down slope over a short distance of 5 to 10m (Plate 1). Landslide 8 had a head depth of 1.5m and the debris materials could be traced over a distance of 9m. Today, 2m down the landslide scar is a dewatering point. Landslides i, ii, iii, 8, 11 and 12 were identified as translational and only slide (iii) out of these occurred on the westward facing slopes (Figure 4).

[4] Shallow landslides are landslides with a 'head' depth of ≤ 3m.

Boulders were found to be a common feature on these slopes and they measured 1 to 3m in diameter.

Erosion in the weathered perthositic gneisses has left behind gullies measuring 4m deep in some instances (Plate2). These gullies gave an opportunity for the soil profile to be studied in the area. Generally, it was found that the slopes were made up of 50cm of top soil that overlay approximately 90cm of saprolite.

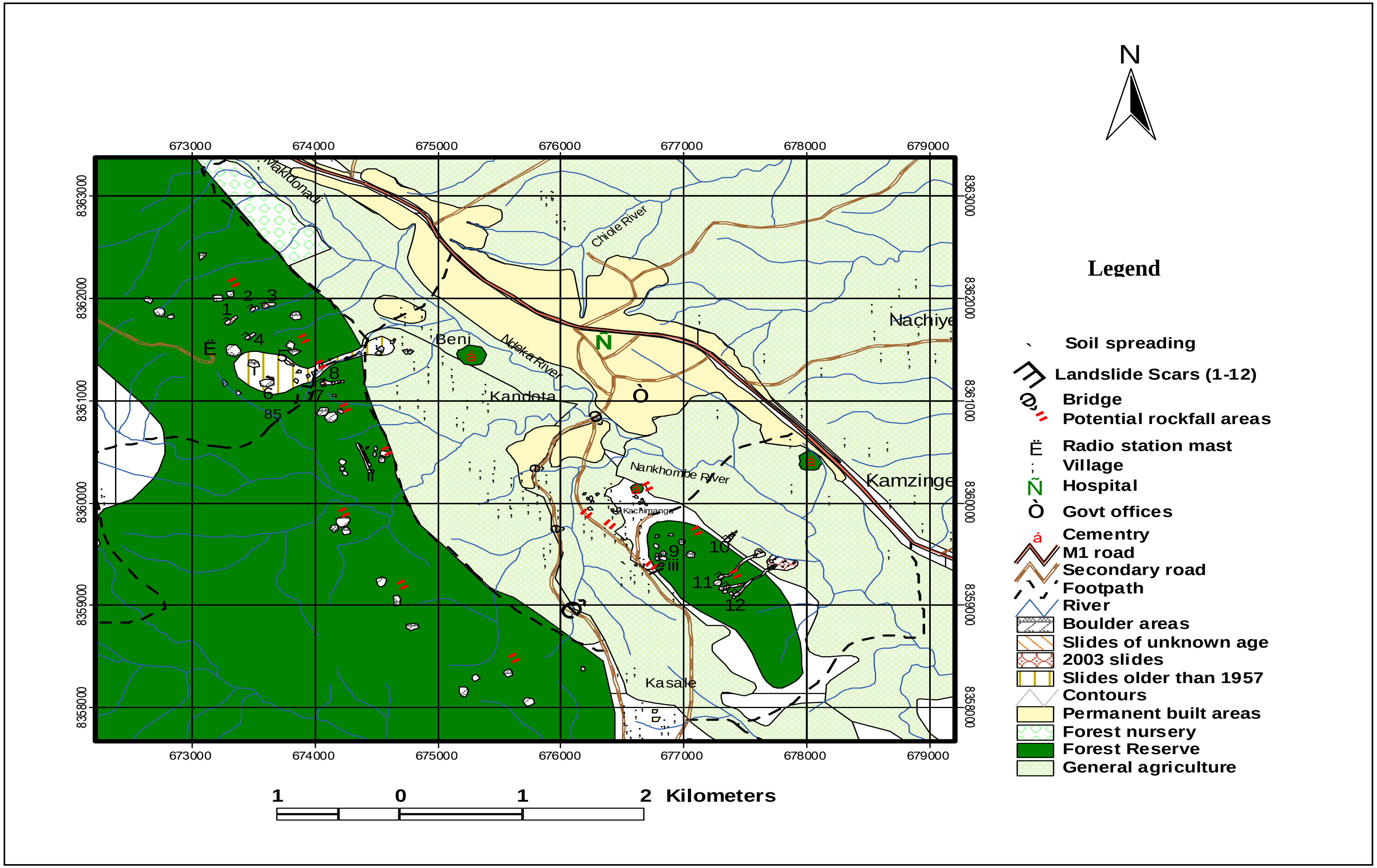


Figure 4. Landslide Inventory Map for Ntcheu District Assembly

Plate 1. Shallow Landslide on the Slope of Mvai Forest Reserve.

Plate 2. Gully Erosion in the Perthositic Gneisses Showing the Soil Profile.

4.2.1.1 Successive Rotational Sliding (Slumping)

This is defined as the occurrence of a series of individual rotational slides one above the other on a slope (Haefeli, 1948). These slides (slides 1 to 3) were shallow, at most 1.5m deep, and their ‘heads’ were between 5; 3 and 2m wide respectively. The landslides produced debris materials which got transported over a distance of 6 to 12m on slopes measuring 20° to 30°. The slopes were devoid of trees apart from a few which were widely scattered (Plate 3).

These observations closely fit those made by Dikau *et al.* (1997). Dikau and others noted that terracettes or successive slides, on slopes with such morphological characteristics, were a result of successive shallow sliding which utilize the soil horizons (as shear surfaces), soil tensions and through-flow water to generate suitable hydrological failure conditions. Most of the debris materials did not reach the bottom of the slope. Therefore, in the event of high precipitation these slides might be rejuvenated.

Plate 3. The Successive Rotational Slides on the Eastwards Facing Scarp.

4.2.1.2 Rock Creep

Rock creeps (or Block slides) are generated by deep-seated gravitational deformation affecting densely jointed or stratified hard rock masses (Dramis and Sorriso-Valvo, 1994).

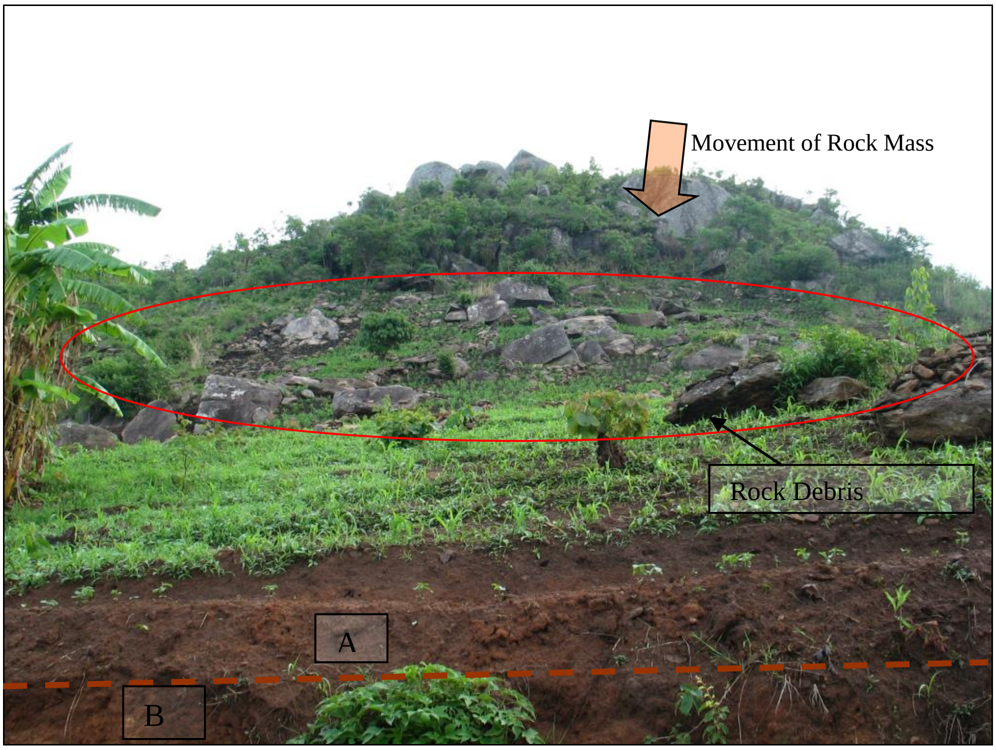
The structural element associated with rock creeping (slide ii) in NDA was probably the high angle extensional shear plane in the upper part of the deforming slope. The rocks dip at an angle of 67 degrees, sub-parallel to the general slope of the landscape, and the rock mass moved down along the shear plane to a depth of 5m thereby producing a depression or trough at the base (Plate 4). This trough traps and allows large quantities of water to infiltrate the slopes during the wet seasons. Since most of the water infiltrating the slope is not lost, except through evapo-transpiration, this can eventually lead to further instabilities due to high soil pore water pressure build up. These observations tend to suggest that the area is still unstable. The lateral extent of the trough was 40m along the slope contours. The age of this event is not known.

4.2.2 Topple

This consists of a forward rotational movement of a mass of rock, debris or soil on a hill slope. Dikau *et al.* (1996) explained that the rocks involved in a topple usually lean forward in bulk and when they fail at the base, they rapidly rotate onto the slopes below and break up, bounce or simply slide forward.

The blocks that fell had irregular cleavage planes, joints and tension cracks. These rocks were partially weathered and underlain by softer soil material. Due to the processes of erosion, the resistant rocks were left protruding out above the west facing slopes. The motion of these boulders was probably initiated by rainwater eroding this soft material thereby causing rapid toppling of the boulders. Swelling and shrinkage of the underlying soils was thought to have contributed towards the progressive failure of the boulders. Dikau *et al.* (1996) similarly noted that erosion unloading (decompression) of the slopes is often an essential prerequisite to toppling. Erosion might have been aggravated by the agricultural activities taking place on these slopes as depicted by Plate 5.

Plate 4. The Section of the Eastwards Facing Slope that Experienced Rock Creeping



(A) Saprolite is about 42cm and supports agriculture. Agricultural activities might have contributed towards the destabilization of the rocks. (B) is the saprock and its gneissic foliations dip into the slope.

Plate 5. Fragmented Rock Mass as a Result of Toppling.

4.2.3 Soil Spreading

Buma and Van Asch (1997) defined soil spreading as 'the collapse of a sensitive soil layer at a certain depth, followed by either settlement of the overlying more resistant soil layer(s) or the progressive failure throughout the whole sliding mass'.

In Kachimanga area, soil spreading occurred over an area measuring 5m across. The competent layer of soil settled to a depth of approximately 1m and this has suffered from strong fracturing and subsequent flowing over the gentle slopes of 10º. The affected soils are generally light grey in color and contrast very well with the surrounding reddish soils. The sunken soil has exposed angular rock boulders, one of which measured 1m in diameter (Plate 6). The difference in soil color and the presence of buried boulders tends to suggest that this area might be an old debris flow fan area.

Plate 6. A Crater Created by Soil Spreading in Kachimanga Area.

The deposited boulders were probably buried over the years by '[5]hill wash' materials from the perthositic and quartzo-feldspathic gneisses forming the surrounding ridges. The light grey soils probably owe their color to the local geology.

4.3 The Causes of landslides

This study has identified the following factors to have contributed towards the occurrence of landslides:-

4.3.1 Geology

The geology of the study area is generally made up of perthositic gneisses which grade into perthosites (Xsy). These and the banded gneisses (Xs) form the high relief in the area. The gneissic foliations of these rocks generally strike 346° and their dip angles ranged from 69° to 82°, sub-parallel to the eastwards facing slopes. This probably explains why 87% of the landslides in the study area are associated with the eastwards facing slopes. The biotite-hornblende gneisses are intruded by the meta-pyroxene dykes and one of these cut the secondary road to Mpira dam, near Kasale Village (Figure 5).

When the landslides inventory layer was superimposed on the geology, it became evident that these events were confined to the perthositic gneisses (Figure 6). This tends to suggest that these slides were to a greater extent controlled by the local geology. For instance, the field study of these rocks has shown that they consist of a network of joints and tension cracks which frequently produce wedged loose blocks of rocks. These joints and cracks facilitate easy percolation of water into the rocks. This has resulted into chemical weathering extending outwards from the joints and the schistosity planes, leading to the formation of thick saprock[6] and saprolite[7] in some instances. Perthites, unlike the country gneisses, have a large feldspar component which weathers to kaolinitic clays. Delano and Wilshusen (2001) noted that a rock slope subjected to considerably weathering can have a large volume of loose rock built on it and this material can eventually slide. Similarly, weathering of the perthositic rocks has led to the formation of clayey soils in the rock joints, cracks and schistosity planes; thereby creating

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[5] Hill wash is used here to mean the removal of top soils from the slopes by the action of rainfall.
[6] Saprock is weathered bedrock material in which the primary rock structures are still evident.
[7] Saprolite is the in-situ weathered bedrock material in which the primary structures are not evident

an accumulation of loosely bound rock materials on the slopes (Plate 7A). Erosion of these clays, together with the orientation of the dip angles in the perthite gneisses, contributed to the occurrence of the 2003 landslides (Plate 7B-C).

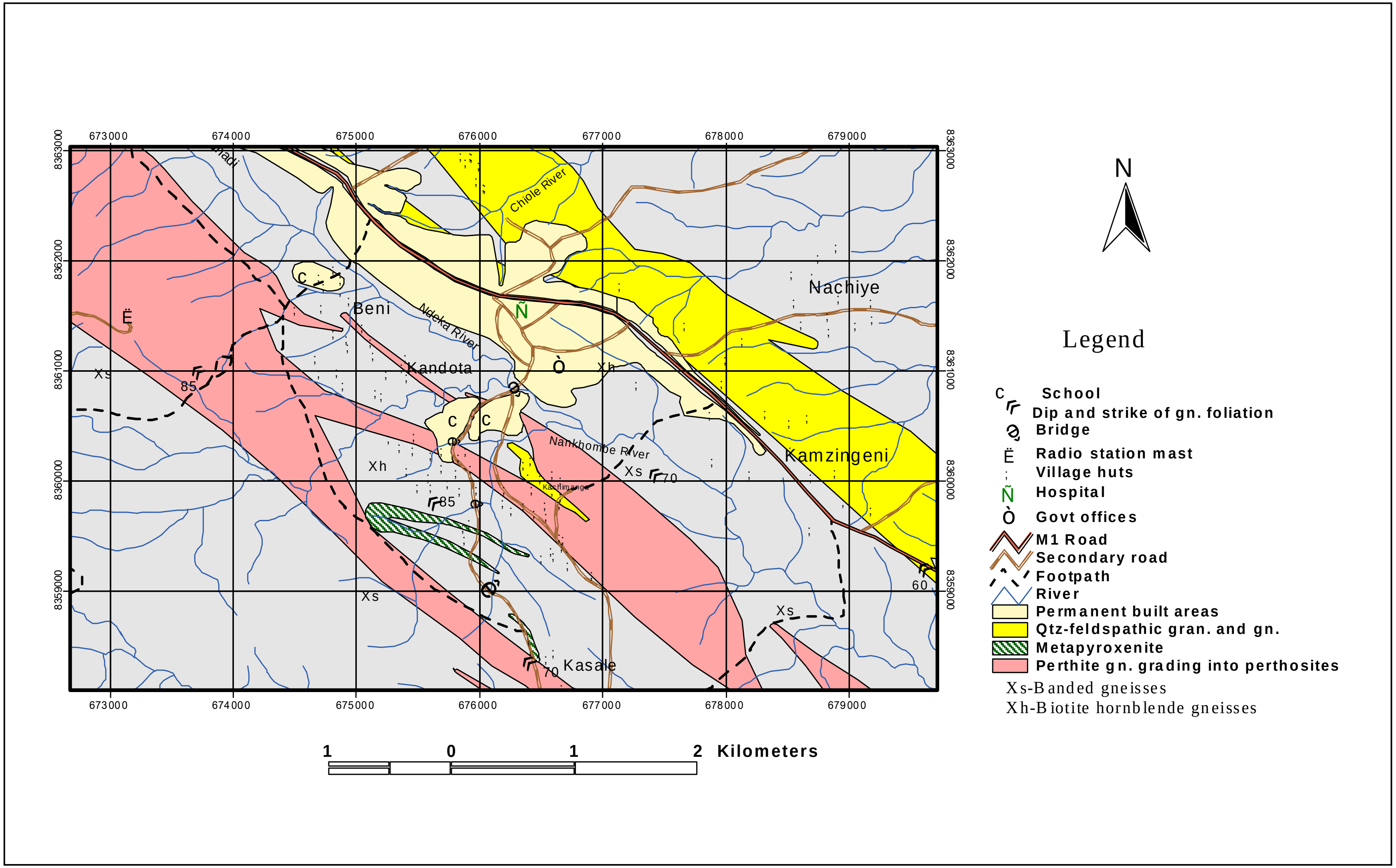


Figure 5. The Local Geology of the Study Area

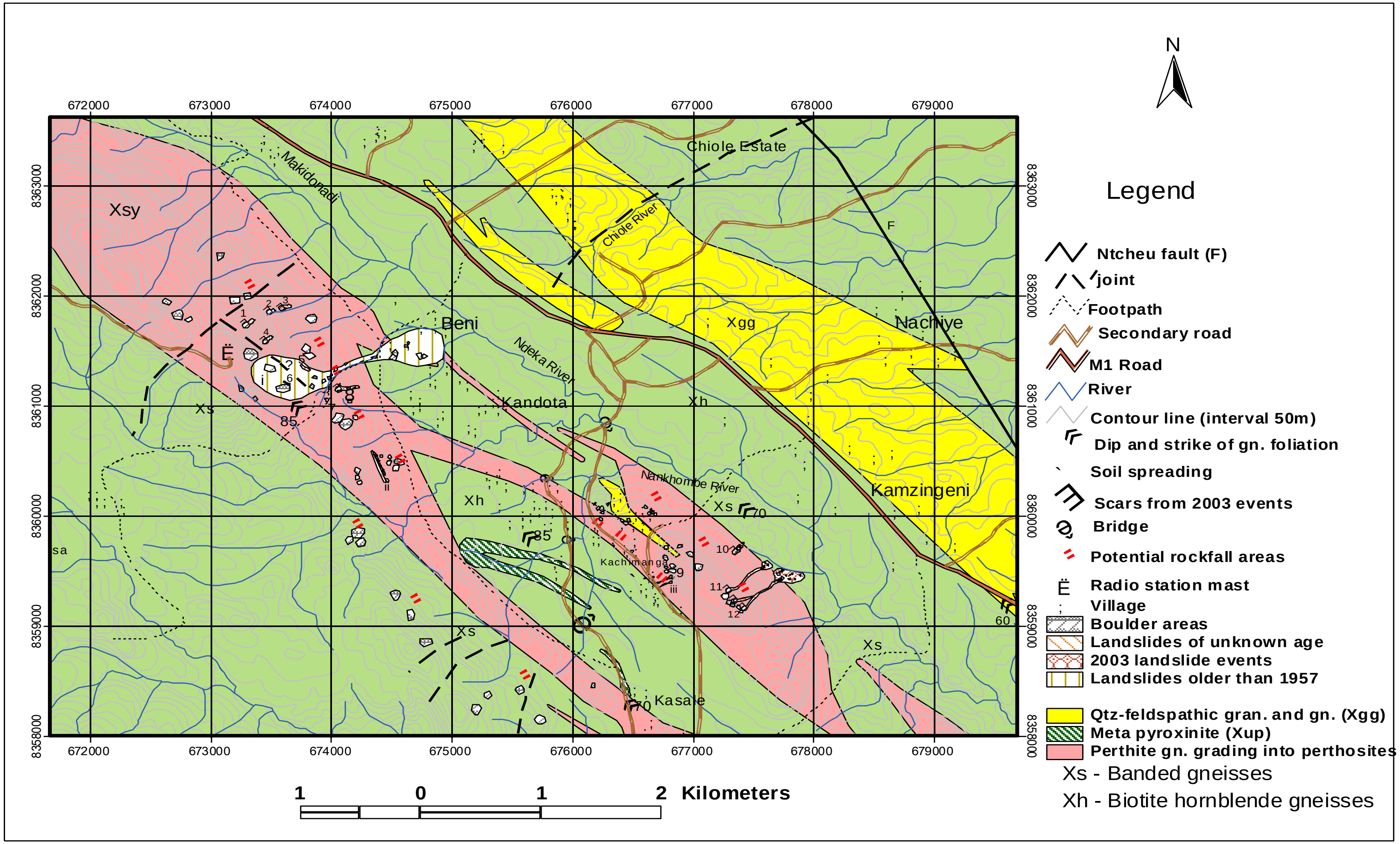
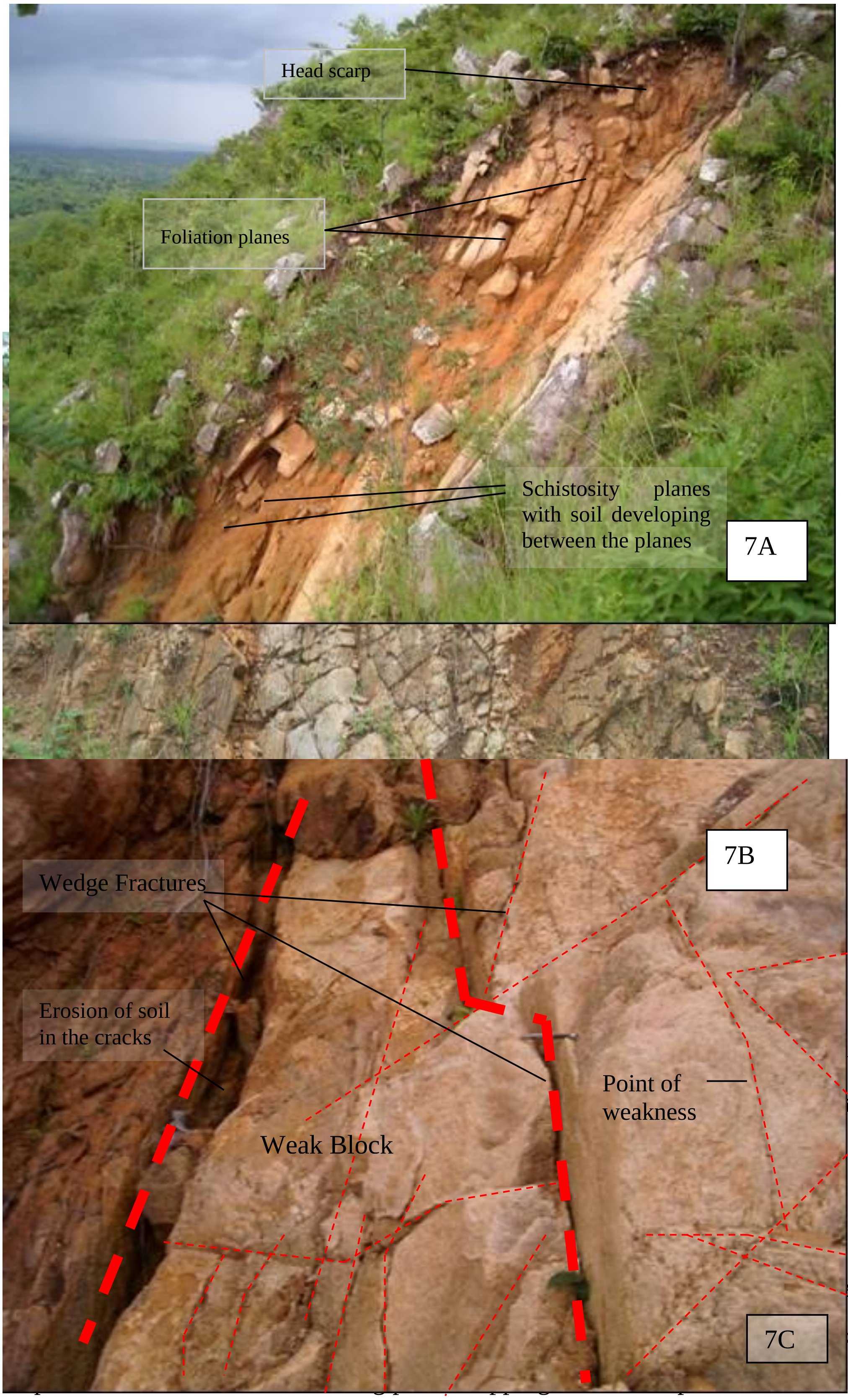


Figure 6. The Relationship Between Landslides Occurrences and the Local Geology



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a stabilizing effect on these slopes. Consequently, the resultant slides had small scars which were shallow. For example, landslide 9 (Figure 6) was measured to be 2m wide and its depth was approximately 50cm. The sliding materials comprised of pebbles of fragmented quartzo-feldspathic gneisses and some vegetation. These went down the slope until they were diverted by a house and ended up blocking a secondary road.

Apart from lithology, the landslides were also influenced by the geological structures. When the *Structural Geology Map* was superimposed on the *Landslides Inventory Map*, it became evident that landslide (i) (the largest in the area) was associated with the NE trending joints. It was then concluded, though prematurely, that a combination of perthositic gneisses, high angle dipping and joints led to a deep-seated large landslide occurring in the area.

4.3.1.1 Estimation of Rock Strength

The fieldwork has shown that the slopes under study had highly weathered perthositic gneisses which were very fractured and at the time of this fieldwork no excavation work was seen on the slopes. Using the RocLab program (Hoek, 2005), the rock mass in the area was defined by the following ratings:-

- Intact uniaxial compressive strength *(for highly weathered rocks*) = 3 MPa
- Geological Strength Index (GSI) *(for partially disturbed rock mass with multi-faceted angular blocks formed by 4 or more joint sets)* = 46
- Rock type (Mi) *(gneissic rocks)* = 28
- Disturbance Factor *(where there is no disturbance e.g. excavation)* = 0

The uniaxial compressive strength was then estimated to be 0.143 MPa. This defines the stress at which failure initiates on the slope (Hoek, 2005). The failure envelope for this rock mass is given in Figure 7. By fitting the Mohr-Coulomb failure criterion (in red color) to the Generalized Hoek-Brown failure criterion or tangent (in blue), the critical slope angle was estimated to be 36.73° and the apparent cohesion of the slope material was 0.218 MPa. Since the Mohr diagram cuts the tangent or failure criterion (in blue color), this suggests that the critical stresses in the rock mass were exceeded and the slopes were unstable (Peters, 1987).

It can be seen that the estimated critical angle was higher than those measured in the field. This difference was probably due to the fact that the calculated critical angle did not take into account failures that might take place along discontinuities.

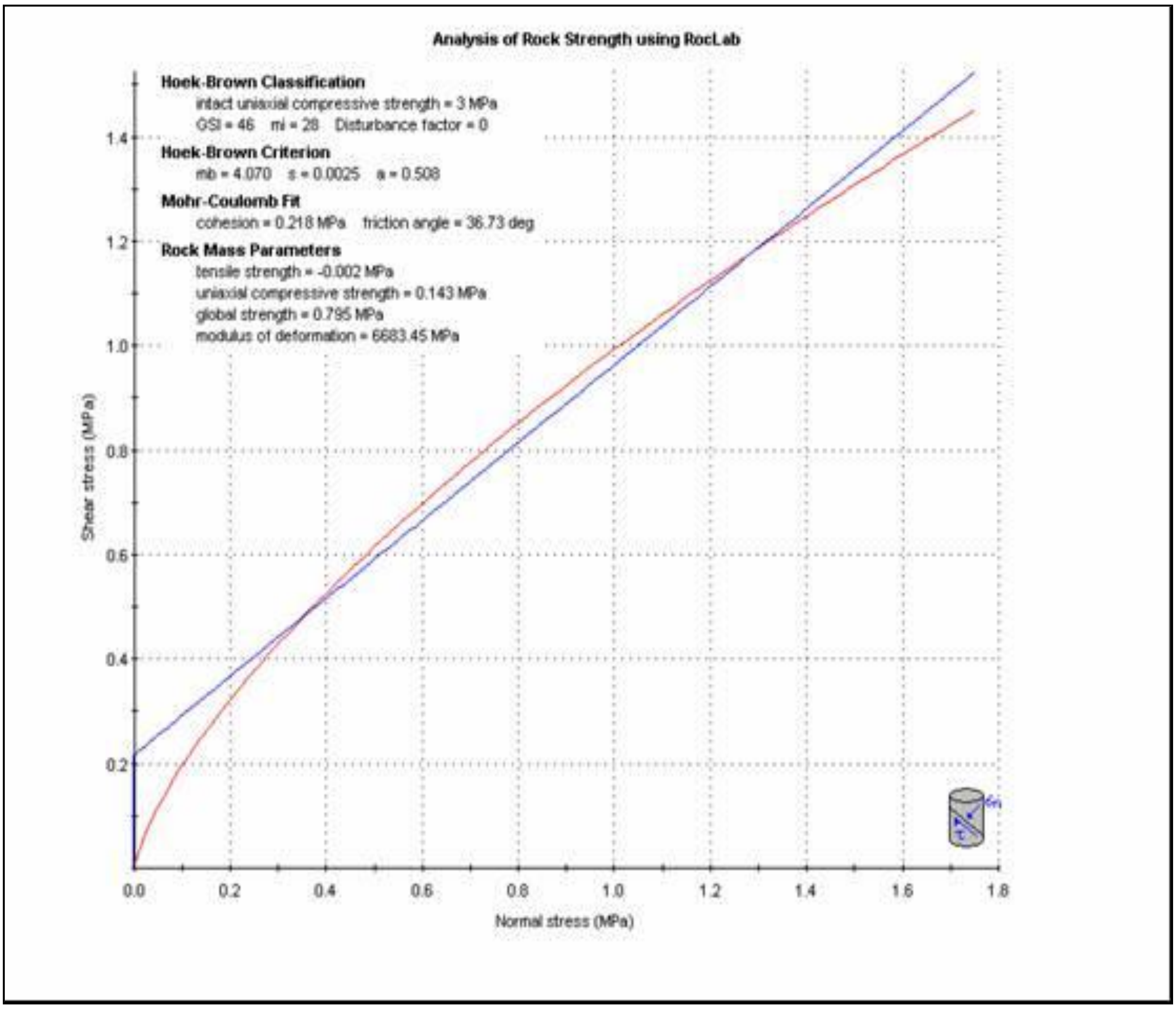


Figure 7. Failure Envelopes for the Generalized Hoek-Brown and Mohr-Coulomb Criterions

4.3.2 Slope Morphology and Landslides Occurrence

The landslides in the area seem to show strong association with the slope orientation. Out of 15 landslides studied, 12 events (representing approximately 87 %) occurred on slopes facing east, northeast and southeast (Table 4). These slides were either located near the summit or mid way of the slopes of Mvai and Ntcheu Forest reserves. This was so because these slopes were generally steeper mid to near summit (Day, 1980). Only one landslide (slide10) occurred on the lower end of the spur.

The slopes experiencing these landslides were characterized by short grass, spaced shrubs and trees, except for landslide 5 and 6 which occurred on the bare scar of an old slide [landslide (i)]. The affected slopes had a general slope angle of 15° to 85° and their orientations were as presented in Table 4.

Table 4. The Slope Angle, Orientation, Location of Scars and Vegetation Cover.

SLIDE NUMBER	SLOPE ANGLE (°)	APPROX. SLOPE ORIENTATION	GENERAL LOCATION OF LANDSLIDES ON SLOPE	VEGETATION
1	33	E	Near the crest	Grass and spaced shrubs
2	32	E	Mid way of the slope	Grass and spaced shrubs
3	31	E	Mid way of the slope	Grass and spaced shrubs
4	31	E	Near the crest	Grass and spaced shrubs
5	35	SE	Mid way of the slope	No vegetation/ old scar
6	34	SE	Mid way of the slope	No vegetation/ old scar
7	27	NW	Near the crest	Grass and spaced shrubs
8	30	E	Near the crest	Grass and spaced shrubs
9	27	SW	Mid way of the slope	Grass and shrubs
10	15	NE	Lower side of the slope	Grass and spaced shrubs
11	28	NE	Near the crest	Grass and spaced shrubs
12	29	NE	Near the crest	Grass and spaced shrubs
I	35	SE	Near the crest	Grass and spaced trees
Ii	85	E	Mid way of the slope	Grass and spaced shrubs
Iii	27	SW	Mid way of the slope	Grass and spaced shrubs

4.3.3 Soil Analysis Results

Apart from geology, the engineering properties of [8]soils can also contribute to slope instability. In order to determine the soil characteristics, a total of 36 samples were collected from the study area for laboratory testing for Liquid (LL) and Plastic Limits (PL), and Plasticity (PI) and Liquidity Indices (LI). The results were as presented below:

4.3.3.1 Liquid and Plastic Limits, and Liquidity and Plasticity Indices Results

The Liquid Limits of samples tested were found to range between 22.0% and 43.0% with sample 14 showing the lowest value (Table 5). When these samples were analyzed for the PL, they gave lower values. For instance, all the samples gave results that ranged from 16.7% to 28.2%. This means a small increase in water content of these soils can lead to slope instability.

When the PI was calculated using these results, it was found that most of the samples gave results that were below 10 except for samples 1A, 1, 2, 3, 13 and 34. The highest PI (20%), in the study area, was obtained from sample 3. Since the PI is an indirect measure of the relative abundance of clay in a soil, the lower PI indirectly suggests that clay was relatively lower than the sand fraction (Table 5). The abundance in very fine sand therefore means these soils have relatively poor permeability (Msilimba, 2002).

The difference between the LL and PL is also a measure of the range of water content over which a soil behaves plastically (Flawn, 1970). The results in Table 5 show that there was a small range over which the soil could show the plasticity behavior. As such, a small increase in soil water content was enough to cause high enough soil pore water pressure for movement to occur (Poschinger, 1998).

[8] A relatively loose agglomerate of minerals, organic materials and sediments found above the bedrock (Holtz and Kovacs, 1981)

Table 5. Liuid and Plastic Limits, and Plasticity and Liquidity Indices.

Sample Number	Liquid Limit (*LL*) %	Plastic Limit (*PL*) %	Plasticity Index (*PI*) %	Natural Water content (%) *(Wn)*	Liquidity Index *LI=PL-Wn /PI*	Stability (*Refer to LI)*
1A	39.4	24.9	14.5	8.0	1	Unstable
1	34.0	22.5	11.5	1.3	2	Unstable
2	42.0	26.3	15.7	9.6	1	Unstable
3	43.0	23.0	20.0	0.7	1	Unstable
4	33.1	28.2	4.9	0.9	6	Unstable
5	25.1	19.4	5.7	2.7	3	Unstable
6	28.0	21.0	7.0	0.5	3	Unstable
7	30.4	22.6	7.8	0.8	3	Unstable
8	26.1	18.0	8.1	10.5	2	Unstable
9	29.5	21.1	8.4	0.7	1	Unstable
10	30.9	23.1	7.8	0.7	3	Unstable
11	26.9	17.4	9.5	0.5	2	Unstable
12	24.5	20.8	3.7	0.5	6	Unstable
13	39.0	26.7	12.3	1.5	2	Unstable
14	22.1	17.9	4.2	1.1	4	Unstable
15	34.1	25.9	8.2	1.2	3	Unstable
16	24.5	16.7	7.8	1.3	2	Unstable
17	32.9	27.1	5.8	1.7	5	Unstable
18	35.5	21.8	13.7	1.3	2	Unstable
19	29.4	20.3	9.1	1.1	2	Unstable
20	27.5	22.5	5.0	0.9	4	Unstable
21	30.6	21.3	9.3	0.8	2	Unstable
22	32.5	25.7	6.8	1.0	4	Unstable
23	*	*	*	*	*	*
24	*	*	*	*	*	*
25	27.0	19.97	7.03	0.7	2	Unstable
26	*	*	*	*	*	*
27	*	*	*	*	*	*
28	27.5	22.1	5.4	0.7	4	Unstable
29	29.9	23.9	6.0	0.9	4	Unstable
30	32.1	25.0	7.1	0.8	3	Unstable
31	34.4	26.6	7.8	1.0	3	Unstable
32	22.9	17.9	5.0	0.6	4	Unstable
33	27.0	20.3	6.7	0.7	3	Unstable
34	42.9	28.8	14.1	1.7	2	Unstable
35	28.5	26.8	1.7	0.7	15	Unstable

Note: * Data not available due to spoiled samples

In an attempt to express the soil consistency or stiffness quantitatively, the Liquidity Index (LI) was calculated. This was determined by *dividing the difference between the water content at the Plastic Limit (PL) and the natural water content (Wn) by the Plasticity Index (PI)* (Table 5). The moisture content analysis results are presented in Appendix2. Flawn (1970) noted that a LI of at least 1 meant the soil was at the LL (very soft with no strength) while the LI of 0 meant the soil was at the PL (stiff). The LI results are all ≥ 1, which suggest that the water content of the soils studied were at maximum and their shear strength was approaching zero. It can be said, therefore, that the slopes studied were sensitive to slight water changes.

4.3.3.2 Grain Size Analysis Results

The United States Department of Agriculture (USDA) recognizes three groups of soil separates namely Sand (2.0mm to 0.05mm diameter), Silt (0.05mm to 0.002mm diameter) and Clay (below 0.002mm). The full range of the separates and their surface areas is given in Table 6. From this table it can be seen that soil grain size is inversely related to grain surface area; as soil grain size decreases, its surface area increases. The maximum surface area is obtained in clay separates.

Table 6. The USDA Classification for Soil Separates.

Separates	Diameter (mm)	Surface Area (in 1g/ cm^2)
Very coarse sand	2.00 – 1.00	11
Coarse sand	1.00 – 0.50	23
Medium sand	0.50 – 0.25	45
Fine sand	0.25 – 0.10	91
Very fine sand	0.10 – 0.05	227
Silt	0.05 – 0.002	454
Clay	> 0.002	8 000 000

Source: United States Department of Agriculture (2003).

The grain size analysis results have shown that grain size range of 4.00mm – 0.05mm make the bulk of the soil separates, with very fine sand (0.10mm – 0.05mm) constituting the highest percentage. Therefore, this soil was predominantly made up of sand particles with the total sand ranging from 65.0 % – 91.3 % (Table 7). Since very fine sand has a surface area of 227 g/ cm^2 (Table 6), it means these soils were coarse enough to allow rapid water infiltration and fine enough to have a higher surface area for water retention (Bryant, 1991). The higher percentage of sand particles therefore suggests that these slopes are generally made up of weak bodies.

Table 7. The Grain Size Analysis Results.

Sampling Site	Total Sand (4.00 – 0.05mm) %	Silt+ Clay (Below 0.05mm) %	*Very coarse sand (4.00 – 1.00mm) %	*Coarse sand (1.00 – 0.50mm) %	*Medium sand (0.50 – 0.25mm) %	*Fine sand (0.25 – 0.10mm) %	*Very fine sand (0.10 – 0.05mm) %
1A	91.3	8.7	11.0	12.7	12.0	12.1	43.5
1	88.5	11.5	16.7	17.4	13.8	11.8	28.8
2	65.5	34.5	4.9	10.4	15.4	17.7	17.1
3	88.1	11.9	3.9	9.4	14.0	17.9	42.9
4	81.9	18.1	2.9	2.7	8.4	23.2	44.7
5	76.9	23.1	3.6	1.6	6.6	26.4	38.7
6	88.5	11.5	7.3	4.0	7.2	23.0	47.0
7	88.1	11.9	3.8	6.2	9.1	20.8	48.2
8	82.9	17.1	4.6	5.1	8.0	18.7	46.5
9	71.1	28.9	3.7	4.0	5.4	10.6	47.4
10	86.7	13.3	2.5	4.2	8.6	25.6	45.8
11	79.8	20.2	10.6	5.9	7.6	17.7	38.0
12	82.3	17.7	5.2	4.1	6.1	14.8	52.1
13	79.1	20.9	4.4	3.0	5.3	13.4	53.0
14	79.9	20.1	4.6	3.9	6.3	14.3	50.8
15	81.5	18.5	3.8	4.5	7.6	13.5	52.1
16	88.2	11.8	3.8	4.8	8.8	16.7	54.1
17	81.1	18.9	2.2	4.1	10.1	15.5	49.2
18	83.6	16.4	1.7	4.7	9.0	13.7	54.5
19	84.5	15.5	2.2	3.3	6.3	15.7	57.0
20	84.3	15.7	5.1	4.1	6.8	12.5	55.8
21	49.2	50.8	2.3	2.7	5.5	17.0	21.7
22	84.0	16.0	9.8	5.3	10.2	17.5	41.2
23	75.9	24.1	3.2	2.4	5.5	21.6	43.2
24	80.1	19.9	9.4	7.3	10.3	13.9	39.2
25	81.5	18.5	11.9	6.6	9.7	16.0	37.3
26	82.8	17.2	8.0	7.5	10.5	18.9	37.9
27	84.0	16.0	9.2	10.9	13.9	19.2	30.8
28	72.6	27.4	3.8	3.2	4.4	6.2	55.0

* Sand proportions are given as % of total sample.

4.3.3.3 Soil Bulk Density, Porosity and Porosity Index Results

Bulk density analysis has yielded the highest value of 1.98g/ cm^3 in sample 25 while sample 20 gave the least value of 1.10g/ cm^3 (Table 8). Since Bulk density is a measure of soil compaction, the results (Table 8 and Appendix 3) mean that these soils were less compacted. The soil porosity results obtained from the area also suggest that the studied slopes were less compacted.

Table 8. The Soil Bulk Density, Porosity and Porosity Index Results.

Sample Number	Bulk Density (g/ cm^3)	Porosity Index	Porosity (%) (η)

	(P_b)		
1	1.60	0.40	40
1A	1.48	0.44	44
2	1.39	0.48	48
3	1.47	0.45	45
4	1.74	0.34	34
5	*	*	*
6	1.49	0.44	44
7	1.34	0.49	49
8	1.68	0.37	37
9	1.82	0.31	31
10	1.97	0.26	26
11	1.57	0.41	41
12	1.44	0.46	46
13	*	*	*
14	*	*	*
15	*	*	*
16	1.58	0.40	40
17	1.87	0.29	29
18	1.38	0.48	48
19	1.71	0.36	36
20	1.10	0.59	59
21	1.58	0.40	40
22	1.41	0.47	47
23	1.77	0.36	36
24	*	*	*
25	1.98	0.25	25
26	1.90	0.28	28
27	1.64	0.38	38
28	1.47	0.45	45

Note: * Data not available due to spoiled samples.

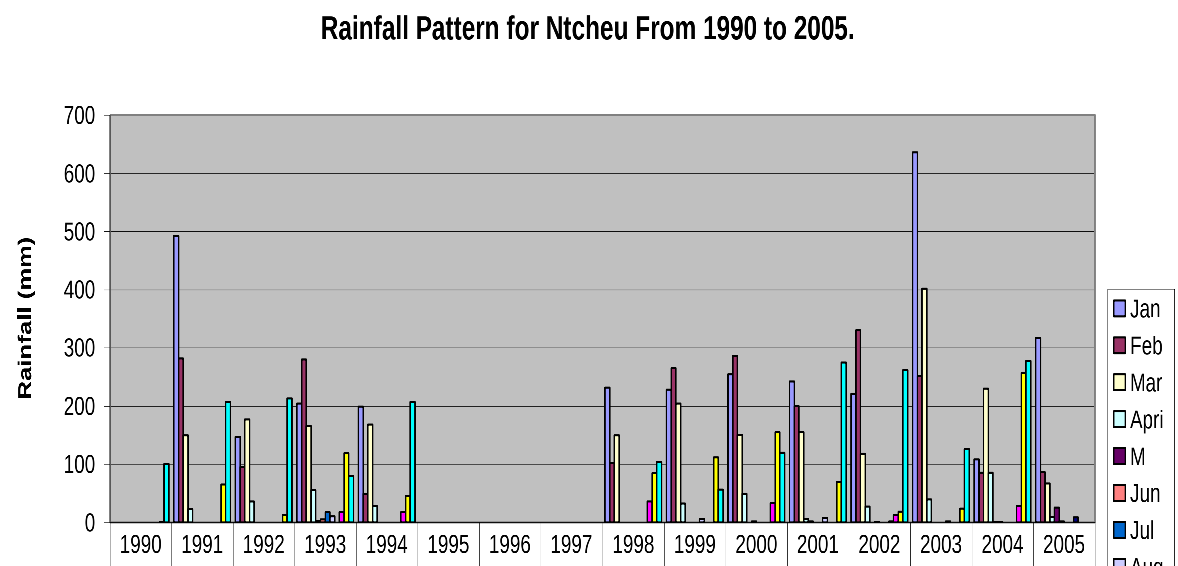
4.3.4 Precipitation and Slope Stability

Wieczorek (1996) emphasized that apart from the over-steepened slopes by erosion or construction work, earthquake shaking and volcanic eruption; the effects of meteoric events are of primary importance, both as predisposing elements and above all as triggering factors of landslides.

Landslides in Ntcheu were notably preceded by a period of heavy rainfall. The rainfall data for NDA show that the month of January 2003 received a record high precipitation of at least 636mm; the highest in 10 years (Figure 8). On 18th February 2003, eighteen days prior to the landslides, the area also received 241mm of rainfall. These two rainfall events are thought to have caused the general weakening of the slopes due to gradual pore pressure build up. The verbal reports of Ntcheu residents all point to the fact that landslides occurred on the night of the 24th of February 2003. On this day Ntcheu received low intensity rainfall amounting to 8.2mm over 15 hours.

The high intensity rainfall events the area experienced caused a gradual increase of the soil pore pressure. The critical levels might have been reached due to the low intensity rains of the 24th of February 2003. Similarly, Montgomery (1997) noted that rainfall-induced landslides are caused by pore pressure and seepage forces during periods of intense rainfall. The rainfall events of Ntcheu led to increased soil pore water pressure which caused the gravitational force acting on the slopes to exceed the existing strength of the slope materials.

Hengxing (2003) also pointed out that slopes respond differently to rainfall depending on their permeability. The grain size analysis results have shown that soils in the study area can best be described as having low to medium permeability due to the high percentage of very fine sand. Slopes with lower permeability are known to be prone to shallow slides owing to their remarkable pore pressure response to rainfall (Hengxing, 2003). Since the landslides in the study area are shallow, it can be said therefore that these landslides were triggered by precipitation.



	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Jan		492.4	146.7	203.9	198.7				232	227.9	254.9	242.2	221	636.1	108.7	317.4
Feb		282.1	95.2	280.4	48.9				101.9	264.9	286.5	200.1	330	252.2	85.1	86.4
Mar		149.7	177.3	165.7	168.5				149.4	204.1	150.2	154.8	117.8	401.2	229.4	67.1
Apri		22.5	36.4	55.4	28.6				0	33	49.4	6	27.4	39.3	85.2	9.9
M		0		2.3	0				0	0	0	2.1	0	0	1	25.4
Jun		0		5.4	0				0	0	1.9	0	0.8	0	0.6	1.5
Jul		0		17.3	0				0	0	0	0	0	0	0	0.4
Aug		0		10.3	0				0	6.5	0	8	0	1.4	0	0

Year

Note: Blanks mean data not available.

Figure 8. Rainfall Pattern for NDA Over a Period of 15 Years

4.3.5 Human Impact Studies

As the human population increases, there is always need for humans to make decisions that ensure that resources are used sustainably. Decisions must be made as to whether land should be reserved for forestry, agriculture or should be converted to other uses e.g. urbanization. However, with increased urbanization more land tends to be converted from other land-uses to settlement purposes.

4.3.5.1 Land-use

In the study area most of the land is generally being utilized for agricultural purpose. The local population grows food crops that include maize and sweet potatoes for subsistence use. Irish potatoes are generally cultivated as a cash crop. Apart from agricultural use, land is also used for forestry and infrastructure development (Figure 9).

All the mountainous areas have been reserved for forestry purposes while the river valleys are being used for vegetable farming. However, despite restricting entry into the Mvai and Ntcheu Forest reserves, these areas have suffered considerably from human impacts. Annually, the areas suffer from bushfires which are deliberately set to chase away wild animals (hyenas) and to encourage the regeneration of grass for livestock grazing.

The relationship between the removal of natural vegetation cover and the occurrence of landslides is well established in literature (Blong and Dunkerley, 1976). The study of the 1957 and 1991 aerial photographs has revealed that within a span of 34 years the area has experienced serious deforestation (Figure 10). The forested area has shrunk from 43.07 km^2 to 18.92 km^2. The association of the 2003 landslide events and the deforested areas suggests that deforestation had a role to play in the occurrence of these events (Figure 10).

Deforestation in the area can probably be attributed to the economic characteristics of the population in question. Since the population of NDA is characteristically rural, it tends to over depend on forestry based resources which include timber for construction and firewood for fuel. Selling of charcoal and firewood is a very common business in the area. With increasing urbanization, there is also demand for additional dwelling quarters which is thought to have increased the demand of timber for brick baking.

Deforestation increases the likelihood of landslides by altering the groundwater condition and the stability of the slopes (Blong *et al.,* 1976; Jakob, 2000). Lumbering leaves slopes vulnerable to direct rain drop impact which leads to increased erosion and this eventually leads to over steepening of the slopes. The steepening of slopes, removal of deep rooted vegetation and the annual bushfires worked together to increase the susceptibility of the slopes to sliding. Since tree roots have a binding effect on the saprolite and sap-rock making up the

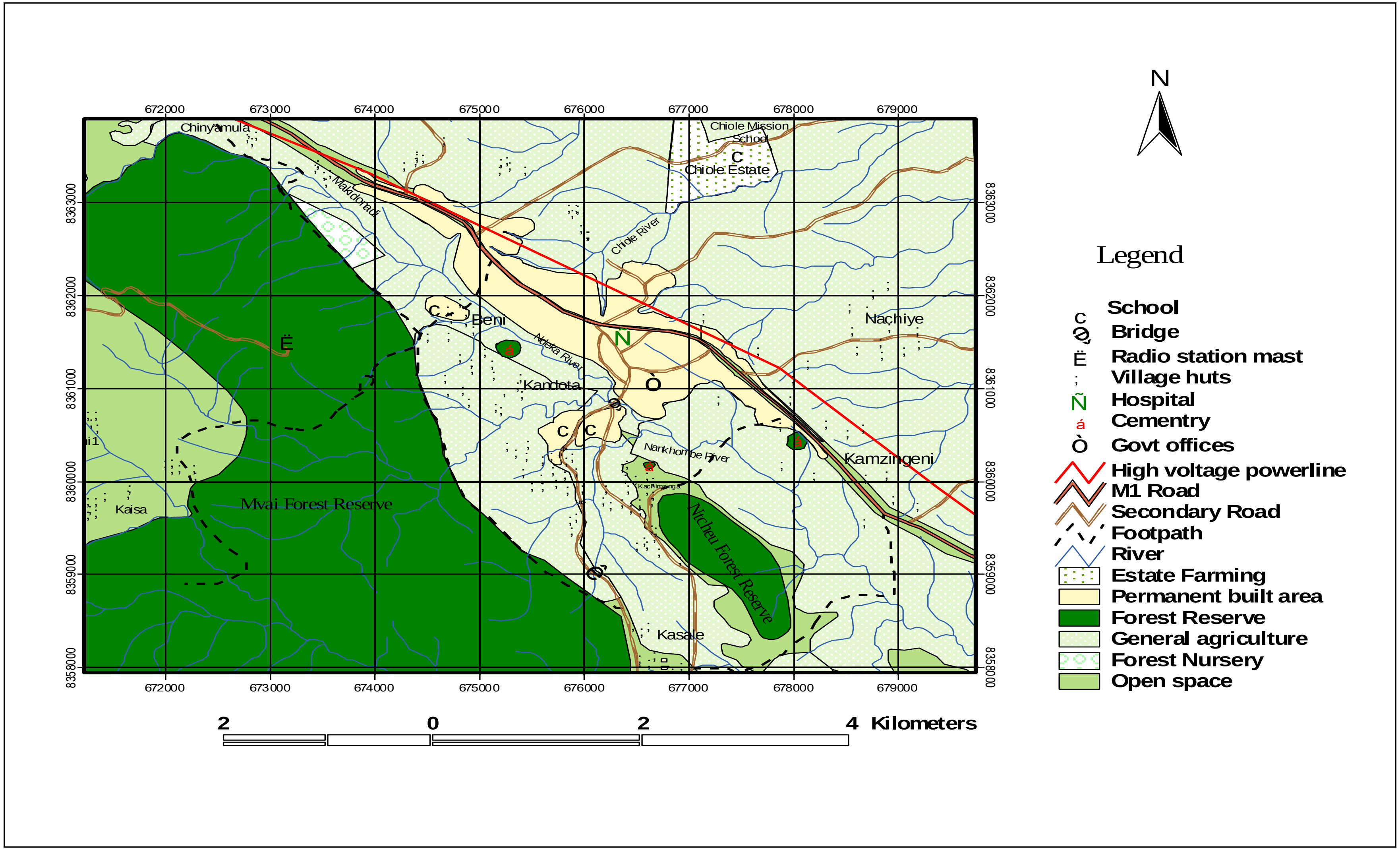


Figure 9. Land-use Map for Ntcheu District Assembly

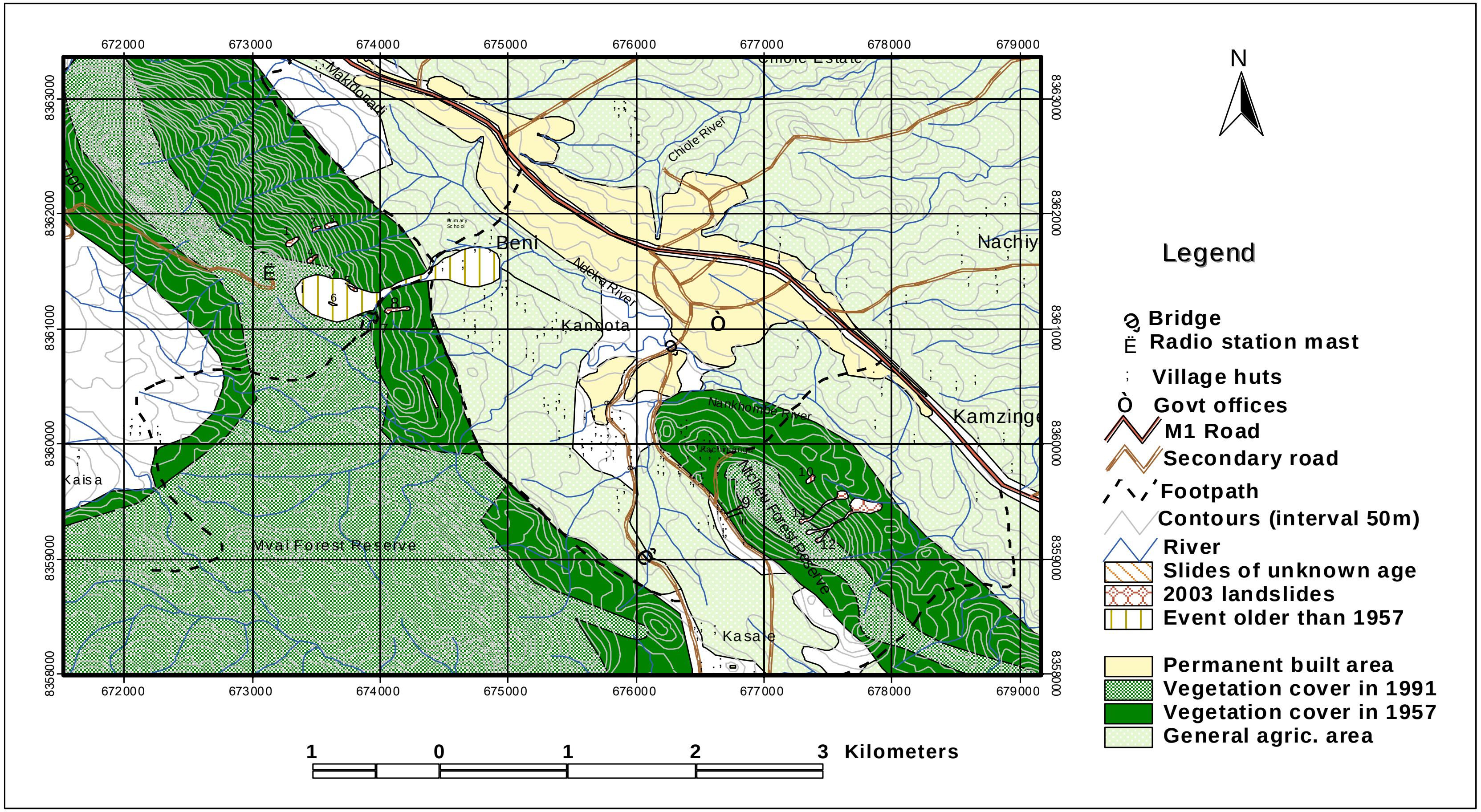


Figure 10. Deforestation of Mvai and Ntcheu Forest Reserves and the Associated Landslides

slopes, it therefore means any human activities that lead to replacement of deep rooted natural vegetation with shallow rooted vegetation will likely lead to slope instability. Although deforestation is a well known contributor towards landsliding, the event that took place before 1957 tend to suggest that deforestation might not have played a major role in causing the 2003 events. This is so because the event took place when the area was well vegetated (Figure 9).

4.4 The Landslides Characteristics

The characteristics of the 15 landslides studied in NDA are described below:-

4.4.1 The Landslides Dimensions

Most of the landslides studied were characterized by a well defined head scarp and flanks. These scars had little or no debris materials accumulated in them while their transportation channels were normally accumulated by a mass of debris materials. The spreading and deposition of the debris materials was controlled by the inclination of the topography. As the slope angle decreased, the velocity of debris materials also dropped considerably thereby causing the debris load to be deposited in the landslides' transportation channels. This probably caused the subsequent debris materials to spread out into the fan area (Plate 8).

Most of the fifteen landslide scars studied were linear in shape with their longest axis running parallel to the line of maximum slope. However, landslide (ii) gave the lowest ratio because its maximum length was oriented along the slope contours while its maximum width was parallel to the line of maximum slope (Table 9). This is so because the cohesive rock block moved down to a depth of 5m along its plane of weakness as described to some detail in sub-section 4.2.1.2. Only three of the slides examined had an approximately fan-shape.

Plate 8. Debris Deposited in the Transportation Channel.

Landslide (12): Drop in the debris velocity led to the deposition of these materials in the transportation channels. However, these materials have high potential of being triggered into motion in the event of a heavy rain storm.

Table 9. The Dimensions of the Landslide Scars and their Impacts.

Slide Number	Shape	Max. Length (L) (in meters)	Max. Width (W) (in meters)	Ratio (L/W)	Impact
1	Linear	7	3	2.3	Vegetation & soil removed
2	Linear	6	4	1.5	Vegetation & soil removed
3	Linear	12	5	2.4	Vegetation & soil removed
4	Linear	11	4	2.8	Vegetation & soil removed
5	Linear	7	3	2.3	Top soil removed
6	Linear	5	2	2.5	Top soil removed
7	Linear	4	3	1.3	Vegetation & soil removed
8	Linear	9	5	1.8	Vegetation & soil removed
9	Linear	18	2	9.0	Vegetation, soil eroded, house partially destroyed & road damaged
10	Linear	7	4	1.8	Vegetation & top soil removed
11	Fan – shaped	12	2	6.0	Vegetation, topsoil and some crops removed.
12	Fan – shaped	17	4	4.3	Vegetation, topsoil and crops removed.
(i)	Fan – shaped	115	45	2.6	Old slide
(ii)	Linear	5	40	0.13	Old slide
(iii)	Linear	13	2	6.5	Old slide

From the list of landslides (Table 5), slides (i) to (iii) were historic (it is not known for sure when they occurred). However, the study of aerial photographs has indicated that slide (i) pre-dates 1957. Today, its transportation channel is partially obscured by shrubs and widely spaced trees which grow on the moved materials. Landslides 9 and (iii) had the highest ratios while landslide (ii) had the lowest. The 2003 landslides were generally shallow with their depth ranging between 1m and 2.5m. This can be attributed to the shallow soils on these slopes.

4.4.2 Groundwater Conditions

Swampy conditions exist 7m and 3m from the edge of the scars of landslides (i) and 8, respectively. The stream that developed in the transportation channel of landslide (i) disappears into the debris 5m down slope. This and a combination of deforestation and bushfires are bound to destabilize these otherwise stabilized debris flows. There is high probability that these materials can be reactivated into motion in the event of rain storms and earth tremors.

4.5 Impacts of Landslides

Sassa (2000) re-iterated that rainfall induced slope failures, especially those in which slides are transferred into flows, cause increasing losses of lives and properties especially where development occurs in the deposition fan. However, Ntcheu landslides caused minimum property damage. This was so because they mostly occurred in the protected areas where habitation was limited and most of these slides were shallow with limited down slope extent. Lastly, these slides occurred in areas where the saprolite depth was within the range of 1m to 3m hence the volume of the debris flow generated was minimal.

The slides have mostly eroded the protective layer of shrubs and grass, thereby leaving behind transportation channels of at least 1.5m in depth e.g. landslide 11 and 12 (Plate 9). These landslides generated rock debris which destroyed a maize garden of approximately 1 acre. The gullies created by the erosive water and the deposited debris materials have seriously reduced the quality of land. Today, only a small portion of this land is still being utilized for agricultural purposes.

Landslide 9 generated debris materials which partially destroyed a house and a secondary road located down slope. At the time of this study, it was noted that some trees had already been planted in order to stabilize the debris transportation channel.

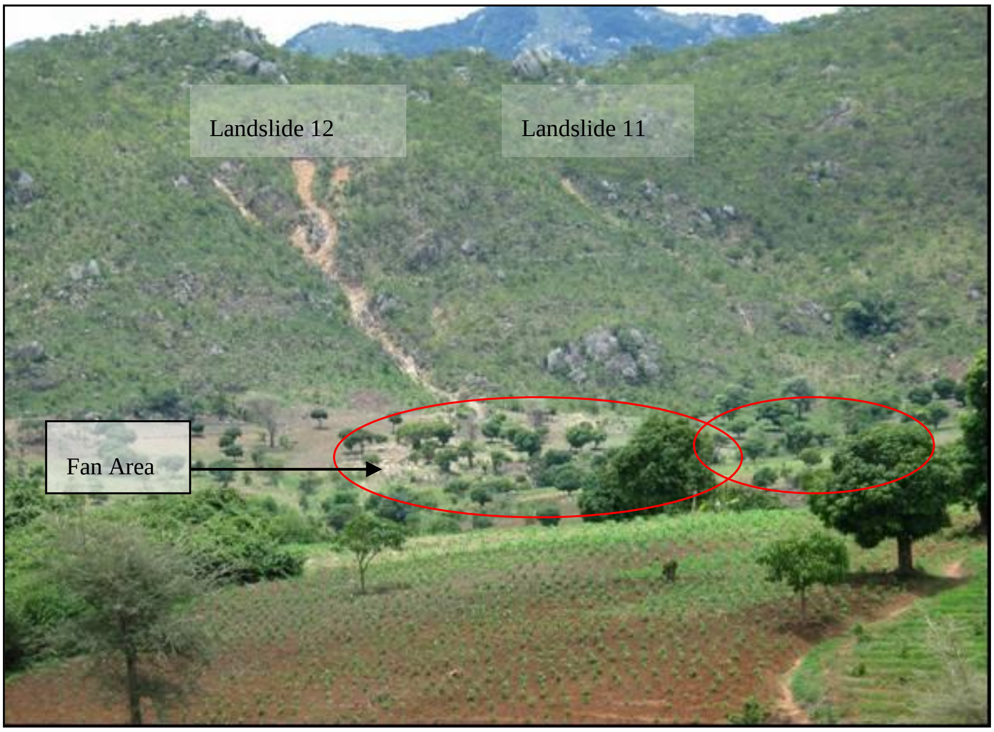


Plate 9. Location of Landslides 11 and 12 that Destroyed a Maize Garden.

The fan areas were once maize fields that were destroyed by Landslides (10) and (11) in 2003.

4.6 Landslide Vulnerability Assessment Results

The Landslide Vulnerability Index (LVI) was determined using the following Landslide Risk Factors (LRF); slope, land disturbance, land cover, slope complexity, geology, total sand in soil, porosity and plasticity indices, and bulk density. All the areas with LVI of less than 1.4 were zoned as stable, those that were 1.4 to 2.0 as potentially unstable (medium risk) areas and those which were above 2.0 as unstable (high risk) areas.

The results (Table 10) from NDA have shown that almost all the areas studied fall in the high risk zones (LVI is > 2.0) except for sample points 2, 3, 8, 9, 10, 11, 26 and 27 which are in the medium risk areas (LVI is 1.4 to 2.0). These results were then used to come up with the *Landslide Hazard Susceptibility Map* (Figure 11). In this map, the high hazard area are represented by the red color while the potentially hazard areas are denoted by the yellow color. All the areas that gave the lowest LVI are represented by the green color and these are areas with the lowest hazard.

Table 10. Landslide Vulnerability Factor Scoring Results.

Sampling Number	Slope	Land disturb.	Land cover	Slope complex.	Geology	Total sand	Porosity index	Plasticity index	Bulk density	Total score	LVI
1A	3	2	2	3	3	3	1	2	1	20	2.2
1	3	2	2	3	3	3	1	2	1	20	2.2
2	3	2	2	2	3	2	2	1	1	18	2.0
3	3	2	2	1	3	3	2	1	1	18	2.0
4	3	2	2	1	3	3	1	3	1	19	2.1
5	3	2	2	1	3	3	-	3	-	17	2.4
6	3	2	2	1	3	3	1	3	1	19	2.1
7	3	2	2	1	3	3	2	3	1	20	2.2
8	2	2	2	1	3	3	1	3	1	18	2.0
9	2	2	2	1	3	3	1	3	1	18	2.0
10	2	2	2	1	3	3	1	3	1	18	2.0
11	2	2	2	1	3	3	1	3	1	18	2.0
12	3	2	2	1	3	3	2	3	1	20	2.2
13	3	2	2	1	3	3	-	2	-	16	2.3
14	3	2	2	1	3	3	-	3	-	17	2.4
15	3	2	2	1	3	3	-	3	-	17	2.4
16	3	2	2	1	3	3	1	3	1	19	2.1
17	3	2	2	1	3	3	1	3	1	19	2.1
18	3	2	2	1	3	3	2	3	1	19	2.1
19	3	2	2	1	3	3	1	3	1	19	2.1
20	3	2	2	1	3	3	3	3	1	21	2.3
21	3	2	2	1	2	3	1	3	1	20	2.2
22	3	2	2	3	2	3	2	3	1	21	2.3
23	3	2	2	3	3	3	1	-	1	18	2.3
24	2	2	2	3	3	3	-	-	-	13	2.2
25	3	2	2	1	3	3	1	3	1	19	2.1
26	3	2	2	1	3	3	1	-	1	16	2.0
27	3	2	2	1	3	3	1	-	1	16	2.0
28	2	2	2	1	3	3	2	3	1	19	2.1
29	3	2	2	1	3	-	-	3	-	14	2.3
30	3	2	2	1	3	-	-	3	-	14	2.3
31	3	2	2	1	3	-	-	3	-	14	2.3
32	3	2	2	1	3	-	-	3	-	14	2.3
33	2	2	2	1	3	-	-	3	-	13	2.2
34	2	2	2	1	3	-	-	2	-	12	2.0
35	2	2	2	1	3	-	-	3	-	13	2.2

Note: LVI – Landslides Vulnerability Index (**LVI = total score/ No. of factors**)

- No data due to spoiled samples

***** Landslides factors were rated 1, 2 and 3. Those with 1 are the least rated while those with 3 are the highest rated.

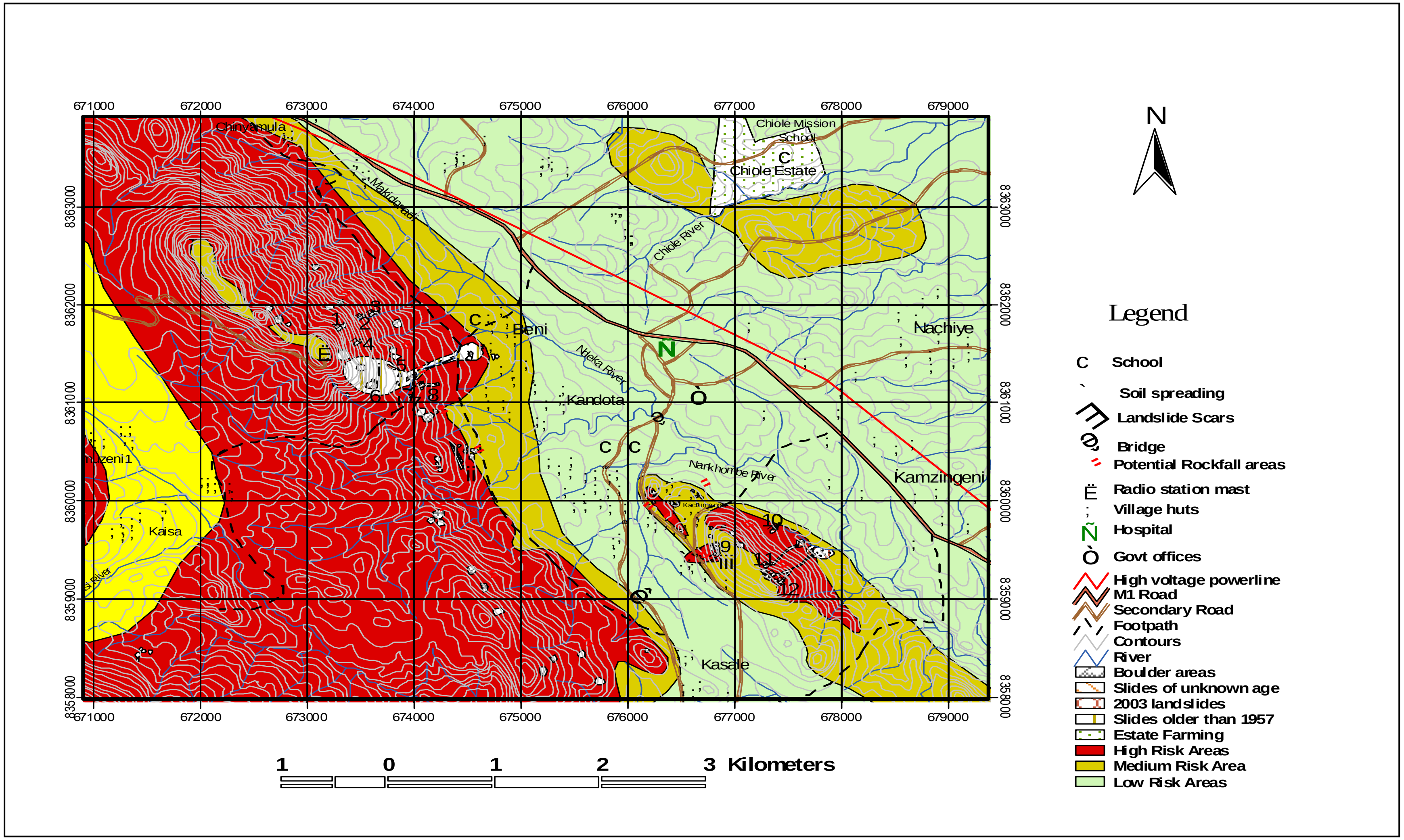


Figure 11. Landslide Hazard Susceptibility Map for NDA

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The landslides determining factors studied included geology, soil, topography, land-use and precipitation. Since Ntcheu District Assembly does not have a physical plan to guide its developmental activities, the results of this assessment will be vital in the development of one.

5.1 Conclusions

Basing on the findings of this study, the following conclusions can be made;

- Ntcheu District Assembly was affected by landslides which can be classified into three groups as Rock slides, topples and lateral spreads. However, rock slides were by far the commonest in the area. It can be concluded that NDA landslides were caused by a combination of factors which included soil, geology, slope, precipitation and land-use. However, geology and the associated structures can be singled out as the major factors of landslides occurrences in NDA. The internal and external changes occurring on the slopes acted in combination to destabilize these slopes without actual inducing the movement. The actual slope movement was induced by precipitation.

- One of the important geomorphological characteristics considered in landslide zonation is the presence or absence of former landslide events. Since the evidences of past instabilities were mostly distributed over the east facing slopes of Mvai and Ntcheu Forest reserves, and that most of these areas have shown Landslides Vulnerability Index of at least 2.0, it can be concluded that these slopes are unstable. Therefore, settlements such as Beni and Kandota Villages are at risk of landslides debris flows.

- This study has shown that the landslides had minimal impacts to the study area. This was so because these landslides were mainly shallow and their debris flowed over a short distance except for landslides 11 and 12. Secondly, these areas were sparsely inhabited and infrastructural development was minimal. Lastly, most of the areas bordering the toes of the hill slopes were being used for agriculture. Hence, it is not surprising that the landslides had limited impact on the area and no loss of life was reported. The debris materials blocked a secondary road that runs from Kachimanga village to the District Assembly administrative center and they also destroyed approximately 1 acre of a maize field. The resultant debris materials and gullies have seriously reduced the quality of land in the affected areas. However, future landslide events may well cause serious damage and loss of life since NDA appears to be fast expanding towards the high hazard zones e.g. Education institutions, Beni and Kandota villages (Figure 9).

- The east facing slopes of Mvai and Ntcheu Forest reserves were identified to have high susceptibility to landslides than the opposite slopes. Although the landslides studied were mostly shallow, the possibility of deep-seated landslides occurring can not be completely ruled out. Most of the rocks forming the slopes are densely fractured, frequently showing evidence of weathering along the fracture planes and gneissic foliations. In the event of strong earthquake tremors and high precipitation, it is possible to have catastrophic events occurring in the area. The presence of talus at the toes of the hill slopes suggests that these slopes are generally unstable. Therefore, the presence of loose boulders on these slopes makes the immediate low lying areas to also be susceptible to rock falls.

- This study has shown that the landslides under study were preceded by a period of heavy rainfall and then a low intensity rainfall event. Since the landslides did not occur immediately after the high intensity rains, it can be concluded that the heavy rains were important only in causing gradually weakening of the slopes due to pore pressure buildup. It can be said, therefore, that low intensity rains were important as the immediate trigger of the landslides.

5.2 Recommendations

Most of the areas studied can be put to infrastructural development use if some precautionary measures are put in place. Since NDA does not yet have a Physical Plan (PP) to guide the development activities in the area, there is need to come up with one and the Landslide Susceptibility Map (Figure 11) is vital for this. In order to develop a sound plan, the process should bring aboard all professionals from other relevant disciplines so that all issues of concern are incorporated.

As noted earlier on, installation of engineering structures is a very expensive mitigation measure for landslides. Otherwise, it is recommended that these should be taken as the last option because it is more economical to leave high risk areas undisturbed. The following are some of the land-use implications that could be derived from the findings of this work

a) Low Risk areas (slope ≤ 10°)

- These are good locations for infrastructure development or agriculture. In these areas, surface erosion is of primary concern.
- River banks must be left undisturbed and where necessary these areas should be vegetated to encourage ground cover.

b) Medium Risk areas (slope 10° – 17°)

- Infrastructures should be limited in these areas.
- The east facing slopes should be reinforced by planting deep rooted trees together with shrubs and grass. This will assist in keeping pore water pressure low enough to keep the slopes stable.
- Road cuttings in the hill slope toes should be avoided. Where they exist, like in Kasale village, these should be reinforced with vegetation, gabions and returning walls.
- Culverts or bridges must be designed high enough to allow free passage of debris flows.

c) High Risk areas (slope ≥ 17°)

- These areas must be protected by all means. Slope cutting for roads or terracing must be avoided.
- Infrastructure development, either on or below these areas, is not recommended.
- Deep rooted tree varieties can be planted on these slopes. This is a relatively cheap mitigation measure of slope instability as compared to rock bolting and other engineering structures.
- Water drainage pipes can be installed to drain the slopes facing Beni village.

It is recommended that future land-use planning for Ntcheu District Assembly should be done with reference to the Landslide Susceptibility Map (Figure 11). This map is essential to a Town Planner because it demarcates land according to its level of susceptibility to landslides.

5.3 Suggested Further Research

The following are some of the possible further research areas:

- To assess the hydraulic conductivity and the piezometric response of the weathered perthositic gneisses.
- There is a need to carry out a detailed soil survey in order to delineate the areas vulnerable to soil spreading and also to have an in-depth understanding of the causes of soil spreading in Kachimanga area.
- There is need to understand why landslides in southern Malawi are commonly associated with perthositic or syenitic rocks and not other rock types.

REFERENCES

Ahmad, R., Miller, D. J. and Row, D. C. (2002). Landslides Related to Precipitation in Eastern Jamaica.

Allum, J. A. E. (1978). Photo - Geology and Regional Mapping. Pergamon Press Ltd, UK.

Black, C. A. (1965). ‘Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties’. In: *2003 Environmental Quality Laboratory Manual (Draft).* Agriculture and Biological Engineering Department, Purdue University, pp. 1-46.

Blong, R. J. and Dunkerley, D.L. (1976). Landslides in the Razorback Area, New South Wales, Australia. In: *Case studies of Rapid Mass Movements in Different Climates, Geografiska Annaler. Series A, Physical Geography*, *Vol. 58, No. 3.*

Brabb, E. E., Pampeyan, E. H. and Bonilla, M. G. (1972). Landslide Susceptibility in San Mateo County, California. U.S. Geol. Surv. Misc. Field Studies Map, MF-360. (Reprinted 1978).

Brand, E. W. (1988). Special Lecture: Landslide Risk Assessment in Hong Kong. In: *Proceedings of 5th International Symposium of landslides,* Lausanne vol. 3.

Brunsden, D. (1984). Mudslides. In: *Slope Stability* **(**Eds: D. Brunsden and D. B Prior). Wiley, Chichester.

Bryant, E.A. (1991). Natural Hazards. Cambridge University Press. Cambridge.

Buma, J. and Van Asch, T. (1997). Soil (Debris) Spreading. In: *Landslides Recognition, Identification, Movement and Causes.* Report No.1 of the European Commission Environment Programme Contract No. EV5V-CT94-0454. John Wiley & Sons, New York, pp. 137-148.

Chang, M., Chiu, Y. and Ke, T. (2005). Preliminary Study on the 2003 Slope Failure in Woo-wan-chai Area, Mount Ali Road, Taiwan. Engineering Geology vol. 80, Issue 1-2.

Casagrande Method. Retrieved October 6, 2005,from http://www.civl.port.ac.uk/projects/geotech/geo4.html

Chen, H. and Lee, C. F. (2004). Geohazards of Slope Mass Movement and its Prevention in Hong Kong. *Engineering Geology vol*. 76, Issue 1-2. pp. 3-25

Cheyo, D. R. (1999). Geo-hazards Around the Michesi and Zomba Areas. In: *The Proc. Of The Symposium On Natural Geological Hazards In Southern Malawi; 27th – 28th July*.

Coates, D. R. (1981). *Environmental Geology*. John Wiley and Sons, New York.

Compton, R. R. (1985). *Geology in the Field*. John Wiley and Sons, New York.

Crosta, G. B. (2004). Introduction to the Special Issue on Rainfall-triggered Landslides and Debris Flows. *Engineering Geology vol*. 73, Issue 3-4. pp. 191-192

Cruden, D. M. (1991). A Simple Definition of a Landslide. *International Association for Engineering Geology Bulletin, vol*. 43.

Day, M. J. (1980). Landslides in the Gunung Mulu National Park. *The Geog. Journal, Vol*. 146, No. 1.

DeGratt, J. V. (1978). Regional Landslide Evolution: Two Utah Examples. *Environmental Geology, Vol*. 2.

Delano, H. L., and Wilshusen, J. P. (2001). Landslides in Pennsylvania. (4th ed.). *Pennsylvania Geological Survey*, Education Series 9.

Determination of the Plastic Limit and Plasticity Index. Retrieved October 5, 2005, from http://www.civl.port.ac.uk/projects/geotech/geo5.html

Dikau, R., Brunsden, D., Schrott, L. and Ibsen, M. (1997). *Landslides Recognition, Identification, Movement and Causes*. Report No. 1 of the European Commission on Environment Programme Contract No. EV5V-CT94-0454. John Wiley & Sons, New York.

Dikau, R., Schrott, L. and Dehn, M. (1996). Topple**.** In: *Landslides Recognition, Identification, Movement and Causes*. Report No. 1 of the European Commission on Environment Programme Contract No. EV5V-CT94-0454. John Wiley & Sons, New York, pp. 29-41.

Dramis, F. and Sorriso-Valvo, M. (1994). *Deep-seated Gravitational Slope Deformations Related Landslides and Tectonics*. Engineering Geology.

Flageollet, J. C. (Ed.). (1993). *Temporal Occurrence and Forecasting of Landslides in the European Community.* European Community Programme Contract No. 900025, Volume 3

FEMA (2004). *Landslides and Debris Flows*. Retrieved May 21, 2005, from http://www.fema.gov/hazards/landslides/

Fernandes, N., Guimarães, R., Gomes, R.A.T., Vieira, B. C., Montgomery, D. R. and Greenberg, H. (2004). *Topographic Controls of Landslides in Rio De Janeiro: Field Evidence and Modeling*. Science Direct (CATENA) vol. 55, Issue 2. pp. 163-181

Flawn, P. T. (1970). *Environmental Geology: Conservation, Land-use Planning and Resource Management*. Harper & Row, New York.

Geertsema, M., Claque, J. J., Shwab, J. W. and Evans, S. G. (2006). An Overview of Recent Large Catastrophic Landslides in Northern British Columbia, Canada. *Engineering Geology vol.* 83, Issue 1-3, pp. 120-143.

Government of Malawi (1998). Malawi Population and Housing Census, 1998; Report of Preliminary Results. In: *2001 Ntcheu District Socio – Economic Profile*. NSO, Zomba.

Government of Malawi (2001). *Ntcheu District Socio – Economic Profile*. NSO, Zomba.

Government of Malawi (2004). *State of the Environment Reports Part A: Ntcheu, (2004); Part B: Balaka (2004).* NSO, Zomba.

Government of Malawi (1998). *National Environmental Action Plan (NEAP): Environment and Development in Malawi*. Retrieved September 4, 2006, from http://gideonmbanga.mw/enviro/action_plan/chap_3.html

Haefeli, R. (1948). *The Stability of Slopes Acted on by Parallel Seepage*. Proc. 2nd Inst. Conf. on Soil Mechanics and Foundation Eng. Rotterdam.

Hengxing, L., Chenghu, Z., Lee, C.F., Sijing, W. and Faquan, W. (2003). *Rainfall-Induced Landslide Stability Analysis in Response to Transient Pore Pressure: A Case Study of Natural Terrain Landslide in Hong Kong*. Science in China Ser. E. Technological Science. Vol. 46.

Hoek, E., Caranza-Torres, C. T. and Corcum, B. (2002). '*Hoek-Brown Failure Criterion – 2002 Edition'*. Toronto, Canada.

Hoek, E. (2005). *Uniaxial Compressive Strength Versus Global Strength in the Hoek-Brown Criterion.* Retrieved August 28, 2006, from http://www.rocscience.com

Holmes, P. J. and Msilimba, G. G. (2005). A Landslide Hazard Assessment and Vulnerability Appraisal Procedure: Vunguvungu/ Banga Catchment, Northern Malawi. *Natural Hazards vol.* 34, pp.199 – 216.

Holtz, R. D. and Kovacs, W. D. (1981). *An Introduction to Geotechnical Engineering*. Englewood Cliffs, New Jersey, Prentice-Hall.

Hutchinson, J. N. (1988). Morphological and Geotechnical Parameters of Landslides in Relation to Geology and Hydrology. *General report in: Landslides, Proc. 5th. Int. Symposium on Landslides (Ed. C. Bonnard)*, vol. 1.

Iverson, R. M., Reid, M. E., Iverson, N. R., La Husen, R. G., Logan, M., Mann, J. E. and Brien, D. L. (2000). Acute Sensitivity of Landslide Rates to Initial Soil Porosity. *Science,* 290, pp. 513-516.

Jakob, M. (2000). The Impacts of Logging on Landslide Activity at Clayoquot Sound, British Columbia. *Science Direct (CATENA), vol*. 38, Issue 4. pp. 279 – 300.

Kaufulu, Z. and Dolozi, M. B. (1992). The Manyani Hill Landslide in Northeastern Kasungu, Malawi. *National Paper of Malawi Department of Antiquities*, Vol.1.

Kockelman, W. J. (1985). *Some Techniques for Reducing Landslide Hazards*. In: *Bulletin of the Association of Engineering Geologists.*

LHZ Project Protocol (2005.) *Assessment Methods*. Retrieved September 3, 2006, from www.dnr.wa.gov/forestpractices/lhzproject

Manda, B. W. C. (1999). Geological Hazards in Malawi (A Historical Overview): Paper presented at a Symposium on Natural Geol. Hazards, Ku Chawe Inn, Zomba.

McCall, G. J. H. (1992). *Geo-Hazards, Natural and Man-Made*. Chapman and Hall, London.

Merritts, D., De Wet, A. and Menking, K. (1997). *Environmental Geology: An Earth System Science Approach.* W.H. Freeman and Company, New York.

Montgomery, D. R., Dietrich, W.E., Torres, R., Anderson, S. P., Heffner, J. T. and Loague, K. (1997). Hydrologic Response of a Steep, Unchanneled Valley to Natural and Applied Rainfall. *Water Resources Research,* 331, pp. 91 – 109.

Msilimba, G. G. A. C. (2002). *Landslides Geohazard Assessment of the Vunguvungu/ Banga Catchment Area in Rumphi District***.** MSc Thesis, University of Malawi.

Mwenelupembe, J. (1999). *Debris Flow in Zomba and Michesi Mountain Slope: Their Causes, Mitigation and Return Period***.** Geological Survey Department of Malawi.

Nilsen, T. H.; Wright, R. H.; Vlasic, T. C.; Spangle, W. (1979). *Relative Slope Stability and Land-use Planning in the San Francisco Bay Region, California*.

Ogola, J. (1998). *Landslides in Kenya: The Need to Set Up Early Warning Systems*. Retrieved February 19, 2006, from http://www.gfz-potsdam.de/ewc98/abstract/ogola.html

Peters, W. C. (1987). *Exploration and Mining Geology* (2nd Ed.). Wiley, New York.

Poschinger, A., Cheyo, D.R. and Mwenelupembe, J. (1998). *Geohazards in the Michesi and Zomba Mountain Areas in Malawi.* Technical Cooperation Report No. 96.20915.5.

Rib, H. T., Liang, T. and Varnes D.J. (Ed.). (1978) '*Recognition and Identification of Landslides'*. In: *Landslide hazard Zonation: A review of Principles and Practices.* Vol. 3, UNESCO.

Rogers, N. V. and Selby, M. J. (1980). Mechanism of Shallow Translational Landsliding During Summer Rainstorms. North Island, New Zealand. *Geog. Ann*. 62A (1-2), pp.11-21.

Sassa, K. (2000). Mechanism of Flows in Granular Soils. Invited paper In: *Proceedings of Geo Eng 2000, Melbourne, 19 – 24 November vol. 1,* Technomic Publishing Company, USA, pp. 1671 – 1702.

Stevenson, P. C. (1977). An Empirical Method for the Evaluation of Relative Landslide Risk. *Int. Ass. Engineering Geology Bulletin, Vol*.16.

Temple, P. H. and Rapp, A. (1972). Landslides in the Mgeta Area, Western Uluguru Mountains, Tanzania. *Physical Geog. Vol*.54, No. 3/4, Studies of Soil Erosion and Sedimentation in Tanzania, pp.157 – 193.

USGS (2005). *Cascades Volcano Observatory*. Retrieved August 26, 2005, from http://vulcan.wr.usgs.gov/home.html

Varnes, D. J. (1978). Slope Movements: Type and Processes. In: *Landslides analysis and control*. Eckel, E.B. (Ed). Transp. Res. Board, Spec. Rep. 176, pp. 11-33.

Varnes, D. J. (1984). *Landslide Hazard Zonation: A Review of Principles and Practice*. UNESCO.

Walshaw, R. D. (1965). *The Geology of the Ntcheu – Balaka Area*. Geological Survey Department, Government of Malawi.

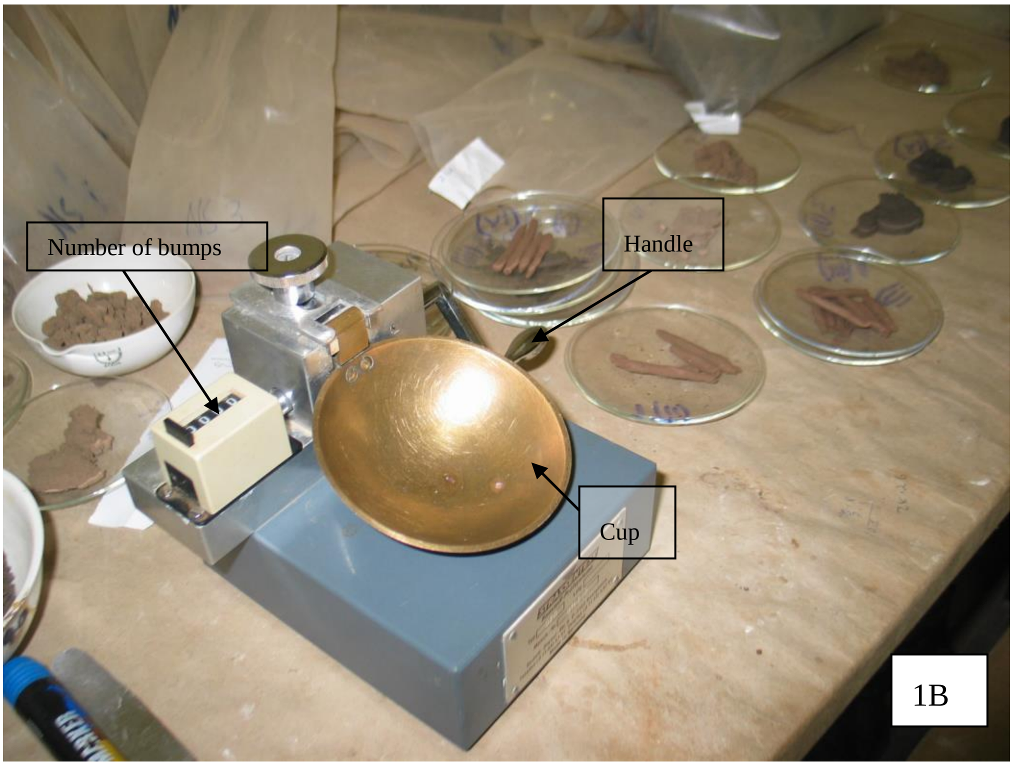
Weil, R. R. (1993). *Laboratory Manual for Introductory Soils*, (6^{th} ed.). Kendall/Hunt Publishing Company.

Wieczorek, G. F. (1996). Landslide Triggering Mechanism. In:, *Landslides: Investigation and Mitigation*, Turner and Shuster (Eds). Transportation Research Board-National Research Council, Special Report vol. 247.

Wong, H. N. and Ho, K. K. S. (1995). General Report on Landslips of 5^{th} November 1993 at Man-Made Features in Lantau. *Report No. SPR7/ 94, Geotechnical Engineering Office*, Hong Kong Government, Hong Kong.

Appendix 1. Soil Analysis and Liquid Limit Determination Equipment

Sieve analysis for grain size distribution.



The Casagrande method

Appendix 2. Moisture Content Analysis Results.

Sample Number	Wt of Beaker (gm) (a)	Wt of Beaker + Wt of sample (b)	Wt of wet sample (gm) (c) = b-a	Wt of Beaker + sample dried at 110°C (gm) (d)	Wt of dry sample (gm) (e) = d-a	Wt of moisture (gm) (f)= c - e	Moisture content in a wet sample (%) (g) = (f/c)*100
1A	36.7	86.7	50	78.7	42.0	8.0	16
1	37.5	87.5	50	86.2	48.7	1.3	2.6
2	35.3	76.4	50	75.7	40.4	9.6	19.2
3	37.9	87.9	50	87.2	49.3	0.7	1.4
4	38.1	88.1	50	87.2	49.1	0.9	1.8
5	38.1	88.1	50	85.4	47.3	2.7	5.4
6	35.1	85.1	50	84.6	49.5	0.5	1.0
7	37.2	87.2	50	86.4	49.2	0.8	1.6
8	38.3	78.4	50	77.8	39.5	10.5	21.0
9	33.7	83.7	50	83.0	49.3	0.7	1.4
10	38.1	88.1	50	87.4	49.3	0.7	1.4
11	38.1	88.1	50	87.6	49.5	0.5	1.0
12	33.6	83.6	50	83.1	49.5	0.5	1.0
13	38.6	88.6	50	87.1	48.5	1.5	3.0
14	37.4	87.4	50	86.3	48.9	1.1	2.2
15	37.5	87.5	50	86.3	48.8	1.2	2.4
16	34.5	84.5	50	83.2	48.7	1.3	2.6
17	37.0	87.0	50	85.3	48.3	1.7	3.4
18	34.0	84.0	50	82.7	48.7	1.3	2.6
19	37.0	87.0	50	85.9	48.9	1.1	2.2
20	38.2	88.2	50	87.3	49.1	0.9	1.8
21	38.7	88.7	50	87.9	49.2	0.8	1.6
22	33.8	83.8	50	82.8	49.0	1.0	2.0
23	33.8	83.8	50	83.1	49.3	0.7	1.4
24	38.2	84.2	50	83.1	44.9	5.1	10.2
25	38.4	88.4	50	87.7	49.3	0.7	1.4
26	36.5	86.5	50	85.4	48.9	1.1	2.2
27	37.9	87.9	50	87.0	49.1	0.9	1.8
28	37.1	87.1	50	86.4	49.3	0.7	1.4
29	38.2	88.2	50	87.3	49.1	0.9	1.8
30	65.9	115.9	50	115.1	49.2	0.8	1.6
31	38.3	88.3	50	87.3	49.0	1.0	2.0
32	74.9	124.9	50	124.3	49.4	0.6	1.2
33	75.6	125.6	50	124.9	49.3	0.7	1.4
34	148.2	198.2	50	196.5	48.3	1.7	3.4
35	154.7	204.7	50	204.0	49.3	0.7	1.4

Laboratory: Geological Survey Industrial Minerals and Applied Research Laboratory.
Note: Wt – weight.

Appendix 3. Soil Bulk Density and Porosity Results.

Sample Number	Mass of Clod (g)- (M_{sa})	Initial Volume of Water (cm^3)	Volume of water (cm^3) + Clod (g)	Total Volume of Clod (cm^3)	Bulk Density (g/ cm^3)- (P_b)	Porosity (%) (η)
1	30.3	100	119	19	1.60	40
1A	7.4	100	105	5	1.48	44
2	13.9	100	110	10	1.39	48
3	8.8	100	106	6	1.47	45
4	17.4	100	110	10	1.74	34
5	*	*	*	*	*	*
6	22.3	100	115	15	1.49	44
7	13.4	100	110	10	1.34	49
8	20.2	100	112	12	1.68	37
9	36.3	100	120	20	1.82	31
10	19.7	100	110	10	1.97	26
11	25.1	100	116	16	1.57	41
12	27.4	100	119	19	1.44	46
13	*	*	*	*	*	*
14	*	*	*	*	*	*
15	*	*	*	*	*	*
16	17.4	100	111	11	1.58	40
17	24.3	100	113	13	1.87	29
18	13.8	100	110	10	1.38	48
19	20.5	100	112	12	1.71	36
20	20.9	100	119	19	1.10	59
21	23.7	100	115	15	1.58	40
22	40.8	100	119	29	1.41	47
23	30.1	100	117	17	1.77	36
24	*	100	*	*	*	*
25	9.9	100	105	5	1.98	25
26	17.1	100	109	9	1.90	28
27	16.4	100	110	10	1.64	38
28	4.4	100	103	3	1.47	45

Note: * Data not available due to spoiled samples.