CHARACTERIZATION AND MAPPING THE DISTRIBUTION OF LANDSLIDES BY MAGNITUDE ON THE SLOPES OF MOUNT ELGON

BY

GUDOYI MAKOBA PAUL,

15/U/14393/GMAG/PE

BA. ED (KYU)

A DISSERTATION SUBMITTED TO THE DEPARTMENT OF GEOGRAPHY AND SOCIAL STUDIES IN PARTIAL FULLFILMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF ARTS (GEOGRAPHY) DEGREE OF KYAMBOGO UNIVERSITY

2018

DECLARATION

I hereby declare that this dissertation is my original work and has never been presented to any other university for any other degree award.

Signed.. Date...1st/Dec/2018...

GUDOYI MAKOBA PAUL

15/U/14393/GMAG/PE

APPROVAL

I hereby declare that this dissertation has been submitted with my approval.

Signature: .... Date 03/12/18............................

DR. JEROME SEBADDUKA LUGUMIRA

Signature: .... Date 3/12/2018............................

DR. LOY G. TURYABANAWE

DEDICATION

This research work is dedicated to my parents, Mr. & Mrs Lawrence and Oliver Mudega, my beloved wife, Edith, and children, Given, Luckie, and Victor.

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to all the people who contributed in different ways in making the accomplishment of this research project possible.

This work was funded off the budget line of NEMA and so special thanks to the institution for the support.

In a special way, I would like to thank my supervisors and mentors, Dr. Jerome Sebadduka Lugumira and Dr. Loy G. Turyabanawe for their rich mentorship and academic guidance. Am stunned, for you never grew weary of reading my write-ups and giving useful directions from time to time despite your busy schedules. I also owe a word of thanks to the rest of the members in the department of Geography for their finest input towards my academic life, right from undergraduate level.

Special thanks also go to my family members, who have always been a constant source of moral and spiritual support. I thank my loving father, whose encouragement and tenacity kept the urge in me to push to this end.

I would also like to thank my friends, Kyalaila Asuman, Chepskor Benard, Namuli Deborah, Akello Gertrude, Alonyo Sharon, Songha Ramadan, Namubiru Carol, Amonya David, and Mulabi Andrew for their supportive company during the study program.

I also acknowledge the support from the field research assistants in the districts of Sironko and Bulambuli who helped locate landslide scars and participated in field measurements and collection of soil samples. May the almighty God reward you all.

Finally, I am indebted to my supervisors at the work place for the psychological support that enabled me to pursue my dream up to the end.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABREVIATIONS/ACRYNOMS

ACCESS	African Collaborative Centre for Earth System Science
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographic Information Systems
GoU	Government of Uganda
IPCC	Intergovernmental Panel on Climate Change
MDA	Mean Decrease Accuracy
MLRM	Multinomial Logistic Regression Model
NARL	National Agricultural Research Laboratories
NEMA	National Environment Management Authority
NFA	National Forest Authority
SAGA	System for Automated Geoscientific Analyses
SRTM	Shuttle Radar Topographic Mission
UBOS	Uganda Bureau of Statistics
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
UWA	Uganda Wildlife Authority
WP/WLI	Working Party on World Landslide Inventory

ABSTRACT

Landslides are one of the most widespread natural hazards occurring every year all over the world. In Uganda, they are common in Mt. Elgon areas. To minimize fatalities, there is need to know where landslides are likely to occur. In this study therefore, attempts were made to; characterize landslides basing on magnitude, relate pedologic characteristics of the derived magnitude classes and, map the spatial distribution of the landslide magnitude classes in Sironko and Bulambuli districts. Towards such efforts, a cross sectional study design and a quantitative approach were employed. Using snowball sampling, 45 landslide scars were visited, geocoded and investigated for scar dimensions, from which data used in creating landslide magnitude classes using cluster analysis in R software version 3.4.4 was derived. At each landslide scar, a description of the soil morphological and physical properties was done. In addition, soil samples were picked for laboratory analysis of chemical properties of interest to this study. This data was compared with the derived landslide magnitude classes. To predict the spatial distribution of landslide magnitude classes, a response variable shape file for landslide classes and a predictor variables' raster file containing 18 layers of terrain, soil and geology data for the study area were prepared in SAGA GIS 2.3.1 and ArcGIS 10.5. Using this data, random forest modeling was implemented in R software and the output, further processed in ArcGIS to map distribution of the predicted landslide magnitude classes. The study shows that the area experiences three classes of landslide magnitude – low, moderate and high magnitude. These categories express themselves differently due to spatial and depth wise variation in soil physical and chemical properties. When the categories were predicted across the area, and using random forest modeling and terrain, geologic and pedologic covariates, it was found out that 507.15 km^2 land area is landslide-free whilst 2.5 km^2, 205.43 km^2 and 5.14 km^2 land area is susceptible to low, moderate and high magnitude landslides, respectively. In this modeling effort, it was found out that slope influences landslide magnitude to a large extent compared to soil and longitudinal curvature. From this study, it was concluded that: (i) it is possible to characterize landslides basing on volume, area and flow length, using an objective classifier; (ii) a large proportion of the land (29%) in Sironko and Bulambuli is susceptible to moderate magnitude landslides, but an equally large area is not at threat of landslides; and (iii) soil, topography and geology influence the category of landslide experienced in Mt Elgon areas. It is recommended that high and moderate magnitude landslide susceptible areas be used for activities that require minimal land interference, such as is the case with forestry and conservation.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Landslides are one of the most widespread natural hazards occurring every year all over the world (USGS, 2004). They are the 7^{th} largest killer among natural disasters, contributing an estimate of 17% of mortalities (Alimohammadlou, Najafi, & Yalcin, 2013). Globally, a land area of 3.7 million km^2 is prone to landslides (Dilley et al., 2005). In addition, landslides cause long-term economic disruptions, population displacement, negative environmental effects and billions of monetary losses every year (Dai & Ngai, 2002; Schuster & Highland, 2008).

In Uganda, landslides are a phenomenon of mountainous areas of Elgon, Kigezi, and Rwenzori. In addition to having steeply inclined slopes, these areas are densely populated, increasing land use pressure thus making them highly prone to these hazards (Knapen et al., 2006; Poesen & Deckers, 2009; Kitutu, 2010; & Muggaga, 2011). Landslides in these areas have been occurring since the 17^{th} Century and it is estimated that 542 people have been killed and about 10,000 others displaced (Kitutu, 2013). The biggest percentage of these cases have however been registered in Mount Elgon area districts (Langoya, 2012; Kitutu, 2013).

Although landsides are known to occur under all climatic and geological conditions (Cruden, 1990; and Schuster & Highland, 2008), their frequency is on the rise in the Mount Elgon areas (Knapen et al., 2006 & Kitutu, 2013); just like in any other mountainous area in the world where conditions for slope failure inherently exist. This trend has been blamed on climate change; causing migration to landslide prone slopes and increasing population and land use pressures (USGS, 2004; Muggaga, 2011; ACCESS, 2015). With climate change events predicted to increase yearly (IPCC, 2013) alongside increasing population and land-use pressures on inherently unstable Mount Elgon areas (Knapen et al., 2006, Muggaga, 2011, Kitutu, 2013, ACCESS, 2015), more disastrous landslides are eminent in the future.

To avoid fatalities from future landslide occurrences, there is need to develop the ability to predict with some level of certainty, future landslide locations such that land use planning, conservation, and restoration activities can be implemented in such areas. Such effort however requires exhaustive scientific understanding of the complex behaviour of some of the major landslide drivers in relation to landslide behaviour (Guzzetti, 2005; & USGS, 2008).

Previous attempts efforts developed to analyse landslide drivers in the Elgon areas have been largely generalised (Claessens, 2007; Kitutu, 2004, 2010; Knapen et al., 2006; Mugagga et al., 2011 & 2012) thus meagrely helping to predict specific future landslide areas and behaviour. Land use policies based upon such descriptive and generalized geo-hazard knowledge do not reflect the best planning for use of land vulnerable to landslides (Schuster & Highland, 2008).

Studies synthesized to landslide scar characteristics and their sites' terrain and pedologic properties (as major environmental landslide drivers) are therefore necessary to gain understanding of the individual and interactive effect of these slope failure predisposing factors. On the basis of such data, models can be developed to aid in predicting future landslide locations. For this reason this study was undertaken to derive landslide magnitude and landslide sites' terrain and pedologic characteristics and their after, examine the spatial prediction of these hazard over the landscape in Sironko and Bulambuli districts.

1.2 Problem Statement

Landslide investigations in the mountainous areas of Elgon in Uganda can be traced back to about two decades (Westerberg & Christiansson, 1999; Kitutu, 2004). These investigations have focused mainly on landslide cause-effect relationship in broad terms (Knapen et al., 2006: Kitutu, 2010; Leisbet et al., 2015), triggering mechanism (Knapen et al., 2006), peoples' perceptions of landslide disasters (Kitutu et al., 2004; Obua et al., 2004; Kitutu, 2010; Wanasolo, 2012; Turyabanawe, 2014), hazard assessment (Claessens et al., 2007), and vulnerability (Ekotu, 2012; Longoya, 2012; Wanasolo, 2012; Kitutu, 2013). A few investigations have attempted to establish the pedologic properties of landslide site soils in these areas (Breugelmans, 2003; Knapen, 2003; Kitutu et al., 2009; Mugagga et al., 2012; and Tamale, 2014) and here, assessments have mostly focused on soil texture and less on other pedologic properties like sodium content and rock fragments that also predispose material to failure (Guzzetti, 2005; Msilimba, 2007). These investigations have also ignored analysis of the interactive effect of various pedologic and terrain characteristics yet the complex nature of landslide phenomenon lend independent analysis of landslide drivers unrealistic (Tamale, 2014). Moreover, where landslides have been related to pedologic factors, the relationships have not been treated in relation to landslide magnitude. As a result, landslides continue to occur with disastrous effects in the Mount Elgon areas. In the current study therefore, efforts were made to characterise the magnitude of landslides experienced in Mt Elgon areas of Sironko and Bulambuli, and to predict their spatial distribution based on magnitude in these areas.

1.3 Objectives

1.3.1 General Objective

The overall objective of this study was to further understand the pedologic drivers and spatial distribution of landslide magnitude in Mount Elgon areas of Sironko and Bulambuli districts so as to guide policy on appropriate land-use, land management, and landslide mitigation to avoid losses from future occurrences of these disasters.

1.3.2 Specific Objectives

The specific objectives were:

i. To characterize landslides in Sironko and Bulambuli districts based upon magnitude.

ii. To relate landslide magnitude with pedologic characteristics of landslide sites in the study area.

iii. To model and map the spatial distribution of landsides in the study area based upon magnitude.

1.4 Research Questions

From the specific objectives of this research study, the following research questions were posed to guide the investigations.

i. How do landslides experienced in Sironko and Bulambuli vary in terms of area, volume and flow length?

ii. What is the relationship between landslide magnitude and pedologic characteristics of landslide sites in Sironko and Bulambuli districts?

iii. Discounting the contributing effect of other drivers of landslides, what is the influence of terrain and pedologic characteristics on the spatial distribution of landslide magnitude in Sironko and Bulambuli districts?

1.5 Conceptual framework

The conceptual framework in this study demonstrates links between terrain and pedologic characteristics, landslide scar characteristics and landslide magnitude classes (Figure 1.1).

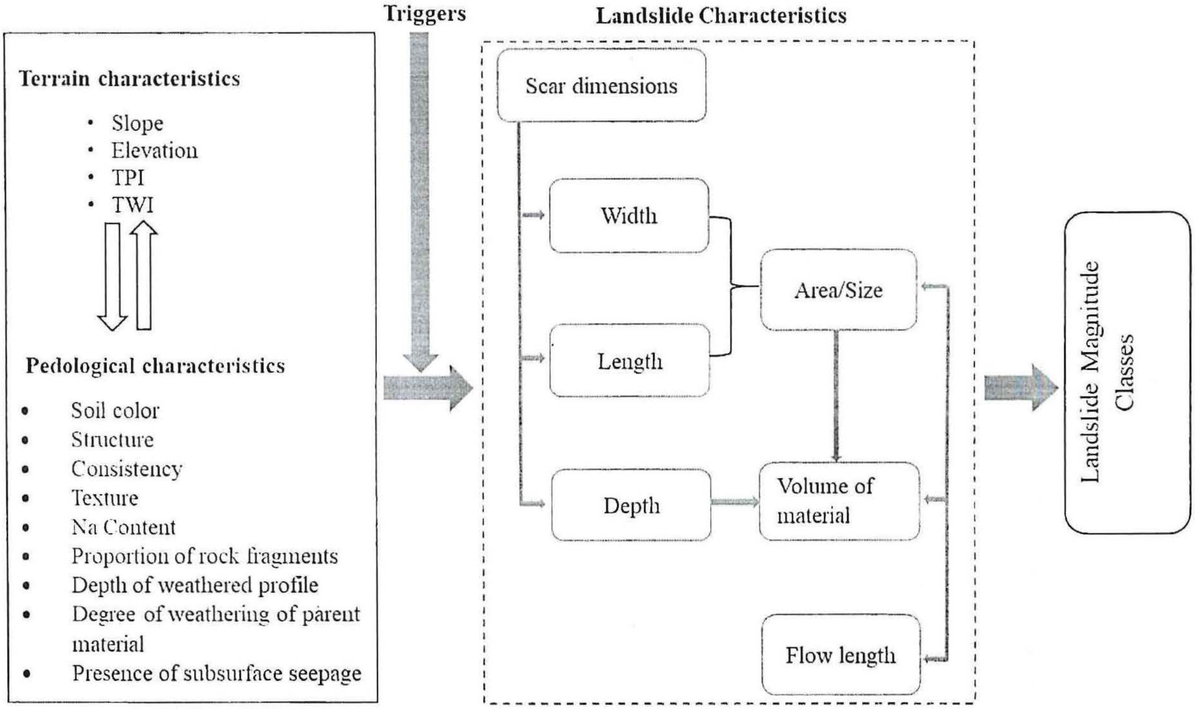


Figure 1.1: Conceptual framework

Source: Author's own conceptualization

In the conceptual framework above, terrain and pedologic characteristics are hypothesised as independent variables and landslide characteristics and landslides magnitude classes are the dependent variable whilst triggers like rain fall and earthquakes are intervening variables that disrupt the relationship between the dependent and independent variables. On the basis of spatial layers for the variables shown above, the spatial distribution of landslides in an area can be mapped with the help of Geographical Information Systems (GIS) and remote sensing spatial technologies.

1.6 Significance of the Study

Planning for use of land susceptible to landslides is necessary to manage these disasters and unless there is an exhaustive understanding of the relationship between different pedologic and topographic controls of landslide behavior, land-use planning agendas in these landslide prone mountainous areas can never be achieved to the satisfaction of the communities. This study therefore fits into a wider framework of planning where activities of a land-use nature can only be apportioned to land determined least susceptible to landslides while carrying out restoration programs in high magnitude landslide prone areas.

The findings of the study will provide a basis for delimiting land by land-use planners depending on its susceptibility to landslides. Environmental Conservation and Management Institutions like National Environment Management Authority (NEMA), National Forest Authority (NFA) and Uganda Wildlife Authority (UWA), ought to benefit from the findings through enabling planning for restoration and conservation activities. The study findings may also aid disaster management institutions in providing relief and rescue services in the wake of a landslide of a known magnitude and location. In addition, planning for resettlement may also be based upon the findings of the study. The random forest model of spatial landslide magnitude prediction, the first of its kind in the Elgon areas in Uganda will be a contribution to the already existing body of knowledge which may be applied in landslide studies elsewhere. The study will enable deeper understanding of the relationship between landslide magnitude and their areas' pedelogic and topographic characteristics in the tropical mountain lands. For a country without a clear landslide data base, this study may be an input in building one.

1.7 Scope

This study was conducted in Sironko and Bulambuli districts on the slopes of Mt Elgon in Eastern Ugand. The choice of this study area was motivated by the increased frequency of landslides over the last 2 decades as reported by Kitutu (2013). In addition, landslide literature for this area is fairy scanty as compared to Bududa and Manafwa districts lying to the south of the current study area. The study involved investigating field landslide characteristics and pedologic properties of landslide soils and modelling the spatial distribution of landslides magnitude basing on terrain and pedologic characteristics. The selection of terrain and soil spatial data sets was motivated by their relationship with landslide occurrence as reported elsewhere in the literature (Knapen, 2006; Kitutu et al., 2009; Zung et al., 2009; Lewis, 2009; Mugagga et al., 2011; Msilimba, 2012; Długosz, 2012; Wilson, 2012; Wahlstrand, 2015). Field data collection activities were conducted between November and December 2017, whilst laboratory analysis of soil samples was done between January and March 2018.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter contains a review of literature on landslide characteristics, classifications, magnitude characterization, and highlights some of the findings by other researchers on landslide sites' pedologic and topographic characteristics and models developed to predict the spatial distribution of landslides.

2.1.1 Landslide characteristics

According to Cruden (1990), the term landslide refers to the movement of a mass of rock or soil, or both, down a slope occurring on the surface of rupture-either curved (rotational slide) or planar (translational slide) rupture-in which much of the material often moves as a coherent or semi-coherent mass with little internal deformation. Landslides leave features and scars of varying dimensions on the landscape which form basis for detailed landslide investigations and mapping (Guzzetti, 2005; Wieczorek & Snyder, 2009). The main landslide features and scar dimensions are well illustrated and detailed by the Working Party on World Landslide Inventory (1993). Landslide features are important in determination of landslide type, amount of materials moved and associated risk (Jiao & Malone, 1999). In the current study, the key characteristics targeted for measurement were those at the depletion zone that is, scar length, width and depth and the flow length of materials.

2.1.2 Landslide classification

Different landslide classification schemes have been devised over the years on the basis of one or more aspects (van Westen, 2005; Wieczorek & Snyder, 2009). All classification schemes are however based on the assumption that they are just descriptive tools which reflect the requirement of the user (Singh, 2009). The most commonly used classification are the Varnes (1978) & Varnes & Cruden (1996) classifications (Guzzetti, 2005; Wieczorek & Snyder, 2009; Highland & Bobrowsky, 2008). Their bases are, type of material of the initial movement, and dominant type(s) of movement. The types of movement include falls, topples, slides, spreads, flows and complex movements involving more than one type whereas the materials are classified as rock, debris, and earth (Wieczorek & Snyder, 2009 & USGS, 2004). The Cruden & Varnes

(1996) classification however includes description of activity, water content, and rate of movement. The two classifications have also found favor among researchers in Mount Elgon areas (Kitutu et al., 2006; Kitutu et al., 2010; Knapen et al., 2006; Mugagga et al., 2011; Mugagga et al., 2012; Tamale, 2014; & Turyabanawe, 2014). However, these classifications do not communicate information regarding magnitude in a manner that can be used to guide land-use planning in affected areas. In the current study, the central focus was on understanding the degree of impact here defined as magnitude and not so much on the type of movement.

2.1.3 Landslide magnitude characterization

Magnitude is the measure of landslide size in terms of area and volume (Fell et al., 2008 & Corominas, 2008) whereas as severity is related to the damaging potential of a landslide which depends on material type and its potential flow length (van Westen, 2005; Guthrie & Evans, 2004; Wieczorek & Snyder, 2009). Therefore, magnitude of a landslide can be directly interpreted from the amount of displaced material and the area affected by the landslide activity. Van Schalkwyk and Thomas (1991) created five classes of landslide sizes basing of areal extent of the failure zone that is, very small (0.01-10.00 m^2), small (10.01-1000.00 m^2), medium (1000.01-10000.00 m^2), large (10000.01-1000000.00 m^2) and very large >1000000.00 m^2) but without indicating what magnitude they were. Fell (1994) derived seven landslides magnitude classes ranging from extremely small to extremely large with corresponding volume of <500 m^3 to >5,000,000 m^3, respectively. Guthrie & Evans (2004) characterized landslides magnitude basing on volume of material, calculated from air photographs. In another study, Guthrie & Evans (2004) derived an empirical formula after a detailed survey of 124 landslides basing on the total disturbed area of shallow debris slide or flow. The largest landslide displaced approximately 172000 m^3 of material while the smallest displaced about 280 m^3 in the areas studied by Guthrie & Evans (2004). Jaiswal et al. (2011) grouped landslides into three magnitude classes basing on volumes. The interest in the current study was placed on deriving landside magnitude basing on a combination of three parameters (i.e. area, volume and flow length) that would provide for all dimensions of magnitude as measured by the potential impact of a landslide.

2.2 Landslide magnitude drivers

Landslides occur due an interplay of conditioning and triggering factors (Wieczorek & Snyder, 2009). The conditioning factors are preparatory environmental conditions that predispose the landscape to slope failure and they include terrain characteristics, geology, soil geotechnical properties, land cover, and long term drainage patterns (Corominas et al., 2014). The triggering factors include intense rainfall, seismic activity, volcanic activity, water level change, storm waves or rapid stream erosion that cause rapid increase in shear stress or decrease in shear strength of materials forming the slope (Guzzetti, 2002; Feizizadeh et al., 2013; Van Westen et al., 2005). Both environmental and triggering factors determine the magnitude of a landslide activity although the later change from time to time making it very difficult to estimate (Guzzetti, 2002).

For tropical environments, most of the landslides are triggered by intense rains where rain water infiltrates through the soil mass and saturates the zone of interface between soil and semi permeable rock. The science that involves the study of movement and distribution of water in the soil and rocks of the earth crust to initiate geomorphic processes like landslides is termed as hydrogeology (Porges & Hammer, 2001). Therefore, slope, soil and rocks characteristics can collectively be referred to as hydrogeological controls (Schuster & Highland, 2008). Soil, rock and terrain characteristics direct movement and distribution of water in the soil and rocks of the earth's crust to initiate land sliding. Soil characteristics are best understood by studying soil individuals within the soil profile, which in turn infer information on the past pedologic processes (Buol et al., 2003).

Terrain characteristics relate to the slope geometry/morphometry that control geomorphologic processes on the landscape. In landslide occurrence, soil and rocks form the main mass that under goes down slope movement, whereas slope characteristics determine the rate of material movement downslope under the influence of gravity (Cruden, 1990; Selby, 1993). For rainfall triggered landslides, water plays an important role in reducing slope bearing strength and increasing slope shear stress through reduction in pore pressure; setting slope materials in motion downslope. Several attempts have been made to understand the influence of slope and slope material characteristics on landslide occurrence in different environments all over the world with variations and agreements in findings in some cases as shown in the following subsections.

2.2.1 Pedologic characteristics of landslide sites

Pedology is a science that studies soil and soil formation processes which is a function of environmental factors like soil parent rock material and climate (Buol et al., 2003). Soil relates to all naturally occurring loose material covering the earth's surface while rocks are aggregates of mineral grains and crystals tightly bound together by cements and interlocking crystals (IUSS Working Group WRB, 2014). Pedologic processes can be pried by looking through the profiles from the top surface down to the bed rock (Selby, 1993). The physical and chemical properties of soil and rocks determine the strength of slope material and its susceptibility to failure (Selby, 1991 & USGS, 2004). Some of the soil profile properties that control water and material movement include texture, structure, horizon cracks, consistency, mineralogy, rock fragments and depth of weathering (Buol et al., 2003).

Soil texture is an estimate of sand, silt and clay particles present in the soil (Selby, 1993 & Buol et al., 2003). Soil structure on the other hand refers to the aggregation of individual soil particles, known as "peds" into larger units (Buol et al., 2003). Texture influences the physical and chemical behavior of the soil. For example the movement and availability of air, plasticity, friability, and shrink and swell potential of soil material (Lewis, 2008; Sahoo, 2009; Zung et al., 2009; Wieczorek & Snyder, 2009; Lanni, 2012). Mugagga et al. (2012a) report that soils at the landslide sites on the slopes of Mount Elgon are characterized by high clay content; well above 20% and high plasticity, with an average index of 33%, thus qualify to be Vertisols. They concluded that soils at landslide sites in Mount Elgon areas are inherently problem soils. Their analysis, however, was based on soil samples drawn from landslide debris and from only three landslide sites. Zung et al. (2009) in their study of landslides in Camp Davis quadrangle, Bridger-Teton National Forest, Wyoming- USA, compared landslide soil properties and landscape properties between stable and unstable sites using field and laboratory analysis. The soil properties in their study included texture, shrink-swell potential, clay mineralogy and horizonation some of were also selected in the current study.

Proportion of rock fragments in the soil also influence the stability situation of the slope by increasing pore spaces; enabling water infiltration and retention in the soil layers thus increasing pore pressure (Selby, 1993). Rock fragments are part of recently weathered lithologic materials. Presence of rock fragments at the boundary with the bed rock form low strength surface of rupture on which the landslide moves (Fell, 1985; Schelstraete, 2010). Apart from rock fragments in the soil profile, the rocks that form a slope and their depth of profile weathering also have a bearing on slope hydrology and stability of slope material (Lewis, 2008; Zung et al., 2009; Sahoo, 2009). Weathering is the main pedologic process related to slope material stability. The shearing strength of the rock material is influenced by the degree of cohesion of such material according to Selby (1993). The rate of weathering is high on volcanic rocks like pyro-crusts, tuff and saphrorites; increasing their permeability and porosity for rainfall triggered landslides (Wangari, 2007). Slopes underlain by impermeable rocks and overlain by shallow soils are highly susceptible to landslides as the interface between the impermeable rock layer and permeable soil body forms the slip surface when soil material gets saturated by rain water (Mugagga et al., 2012 & Lewis 2008). Pachri et al. (2015) reports that rainfall induced shallow landslides occur in soil mantle overlying a less permeable bedrock. Volcanic rocks and agglomerates, channel water from cliffs to the lower concave slopes; saturating the lower soil layers at the interface with the underlying impermeable layer initiating the sliding process (Mugagga et al., 2011; Kitutu, 2013). In addition to what had been studied, the current study considered additional properties that appear to have influence on soil water movement (i.e. Na content) and structure (i.e. proportion of rock fragments.

The stability of slope materials is also influenced by soil mineralogy (Tamale, 2014). Clay, calcium, silica, magnesium, and sodium minerals are some of such minerals that affect soil shrinkage and expansion thus slope instability (Selby, 1993). Clay minerals commonly reported at landslide sites are Illite and Montmorillonite, which are characteristically expansive and unstable clays (Brussel, 2014; Lewis, 2009; Vingiani et al., 2015). Sodium and calcium content on the other hand increase the dispensability of clay minerals in the soil, making such soils with clay fraction of 30-50 prone to sliding (Selby, 1993). Soils containing large proportions of Sodium minerals are referred to as sodic soils. These may result from influence of the sodic parent rock and or land-use activities such as irrigation (Soil, Resources, & Service, 2002). Tamale (2014) investigated the physio-chemical, micro morphological and mineralogical properties to determine the dominant soil forming processes, and their sensitivity to landslides; drawing focus on one landslide site in Bumwalukani-Bududa district. His findings relate more to the depth of profile weathering of soil and rock material and other soil forming processes which directly affect slope stability. Kitutu et al. (2009) and Wangari (2007) studied landslides soils in Bududa district, Uganda, and Elgon district, in Kenya, respectively, and found clay minerals of high plasticity like Kaolinite, and Illite in the soils at landslide sites. In the current study, soil mineralogy analysis involved mainly Na content whereas clay mineralogy was inferred from other soil properties.

2.2.2 Terrain characteristics of landslide sites

The hydrology, soil, and rock properties of an area are partly influenced by the terrain characteristics like slope angle, slope length, elevation, curvature, topographic position and wetness. These attributes act as landslide conditioning factors by reducing bearing strength and increasing shearing strength of slope material (Fernandes et al., 2004; USGS, 2004; Długosz, 2012; Wilson, 2012; Dragicevic et al., 2015 & Salvacion, 2016). Fernandes et al. (2004) investigated the role of slope attributes in controlling the spatial distribution of landslides and reported hill slope form and contributing area to have the strongest influence. Slope attributes affect other landslide characteristics. Larsen et al. (1998) while studying the frequency and distribution of landslides in three montane tropically regions of Puerto Rico reported that frequency of landslides increases with elevation above 300 meters that is, higher elevation slopes have a higher frequency than lower elevation slopes. In addition, the mean monthly moisture is also greater on higher slope elevation according to the study. Studies indicate that landslides in Mt Elgon areas are commonly experienced on steep and concave slopes with angles >25^{o} (Knapen et al., 2006; Claessens et al., 2007; Mugagga et al., 2012; and Kitutu, 2013). Mount Elgon is in the lower latitude location so slope aspect effect on slope hydrology is minimal however, the direction of the prevailing winds impacts of soil moisture. In the current study, terrain characteristics linked to slope hydrological and geomorphological processes that is, elevation, slope angle, slope length, profile curvature, horizontal curvature, surface area, topographic position index and topographic wetness index were selected and included in the analysis and spatial prediction of landslide magnitude due to their major role in directing surface and subsurface water flow thus triggering off landslides.

2.3 Mapping the spatial distribution of landslides

Accurate prediction of spatial distribution of landslides is a complex task to undertake, given the fact that selection and availability of key inputs' spatial data is constrained by costs and availability and as such, different models have been applied (van Western et al., 2003; Guzzetti, 2005; Mouchel, 2011; & Marjanović, 2013) with the help of spatial technologies including GIS and Remote sensing to produce landslide susceptibility maps. The map products show areas with their corresponding levels of susceptibility to landslides based on spatial data sets representing landslide drivers in the specific areas under study (Ayalew & Yamagishi, 2005; Guzzetti, 2005; Singh., 2009; Sahoo, 2009; Eeckhaut et al., 2010; Ray et al., 2011; Lanni et al., 2012;

Ramachandra, 2012; Iwahashi et al., 2014; Conoscenti et al., 2016; Deng et al., 2017). The methods used here are either qualitative like the direct and semi direct mapping or quantitative. Quantitative models employ statistical analyses to predict landslide occurrence on the basis of a number of continuous environmental factors (Corominas, 2001; Dai et al., 2001; Abolghasem et al., Guzzetti, 2005; Wieczorek & Snyder, 2009; Feizizadeh et al., 2013). Most commonly, the predictor input variables that have not missed out from modeling process are DEM derived products representing slope morphometry for example Claessens et al., (2007) used the LAPSUS-LS landslide model and digital terrain analysis to simulate shallow landslides in Manjiya County. However, Mt Elgon areas experience both shallow and deep-seated landslides which all need to be catered for in any landslide modelling and prediction effort.

Guzzetti (2005) demonstrates that the Logistic Regression Model as one of the quantitative approaches that has been widely applied in landslide susceptibility mapping, though with variations in input variables and spatial extent. The simple Logistic regression relies on measuring variables with dichotomous outcome such as yes and no. It is statistically built to predict the logit transformation of dependent variable (landslide) probability of occurrence (Biswajeet and Noordin, 2014). The factors considered important in landslide occurrence in this model are transformed into thematic map layers in a GIS environment (Guzzetti, 2005; Hong et al., 2016). Weights and ratings are attached to the thematic layers and a combination of thematic layers representing factors considered related to landslide occurrence make up a parameter map (Westen, 2008; Marrapu & Jakka, 2014). The parameter map is then overlaid on a landslide inventory map. The resulting map shows landslide areas with their corresponding susceptibility classes. Whereas such quantitative methods are superior in predicting landslides, absence of co-variants' spatial data in Uganda fails there application here. Moreover, susceptibility maps previous produced in some models didn't show magnitude of landslides predicted and the response variable has been measured on a binary scale (presence and absence of landslides). For such reasons landslide prediction models that would optimize both costs and large spatial data requirements are alternatives in areas like the Elgon region where information on future landslide locations is of paramount importance for urgent interventions.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

This chapter presents a description of background information about the study area and the methods employed in data collection and analysis. In addition, the sampling strategy, research design as well as limitations of the study are detailed here.

3.2. Description of the Study Area

3.2.1 Location

The study was conducted in Sironko and Bulambuli districts. However, analysis was restricted to the area stretching from 34^0 12′ 52.013″ to 34^0 3′ 7.655″ East and 1^0 5′ 55.301″ and 1^0 18′ 8.788″ North; covering a land area of approximately 720 square kilometers (Figure 3.1) from where much of the field sampling was done. Sironko and Bulambuli districts are boarded by Nakapiripirit district to the North, Kapchorwa and Kween districts to the Northeast, Republic of Kenya to the East, Bududa district to the South East, Mbale district to the Southwest, Bukedea district to the west and Kumi district to the Northwest. Sironko is approximately 265 kilometers by road from the capital-Kampala and 22 kilometers North of Mbale town. Some part of the study area lies within the Mount Elgon National Park (ACCESS, 2015).

3.2.2 Geology and Soil

The geology of the study area is part of that characterizing Mt. Elgon. It is composed of rocks of Cainozoic formations that include volcanics, granites, and sediments (Lehto et al., 2014; Geological Survey of Finland, 2014; ACCESS, 2015). Mbogga (2013) reports that, "Cainozoic formations consist of Pleistocene to recent sediment, alluvium, black soils and moraines". The impermeable rocks of the areas adjucent to the National Park make these areas highly prone to landslides especially during periods of heavy rain (Mbogga, 2013). The soils of the study area are classified as; Acric ferralsols, Gleysols, Luvisols, Nitsols, Patric Plathosols, and vertisols (FAO soil classification system). These soils have resulted from past volcanic activities and other geomorphological processes (ACCESS, 2015). Deeply weathered Nitisols are characteristically prone to landslides (Christiansen & Westerberg, 1999). On the steep slopes in the high-altitude moorlands, very shallow soils are found to exist, while red brown, clay loams have formed on the gentle slopes. These soils support tropical forest vegetation if no human interference takes place and once the forest is cleared, they are highly productive for crop growth (MCEP, 1997; Mugagga et al., 2011). This accounts for their overuse in terms of farming, triggering off landslides.

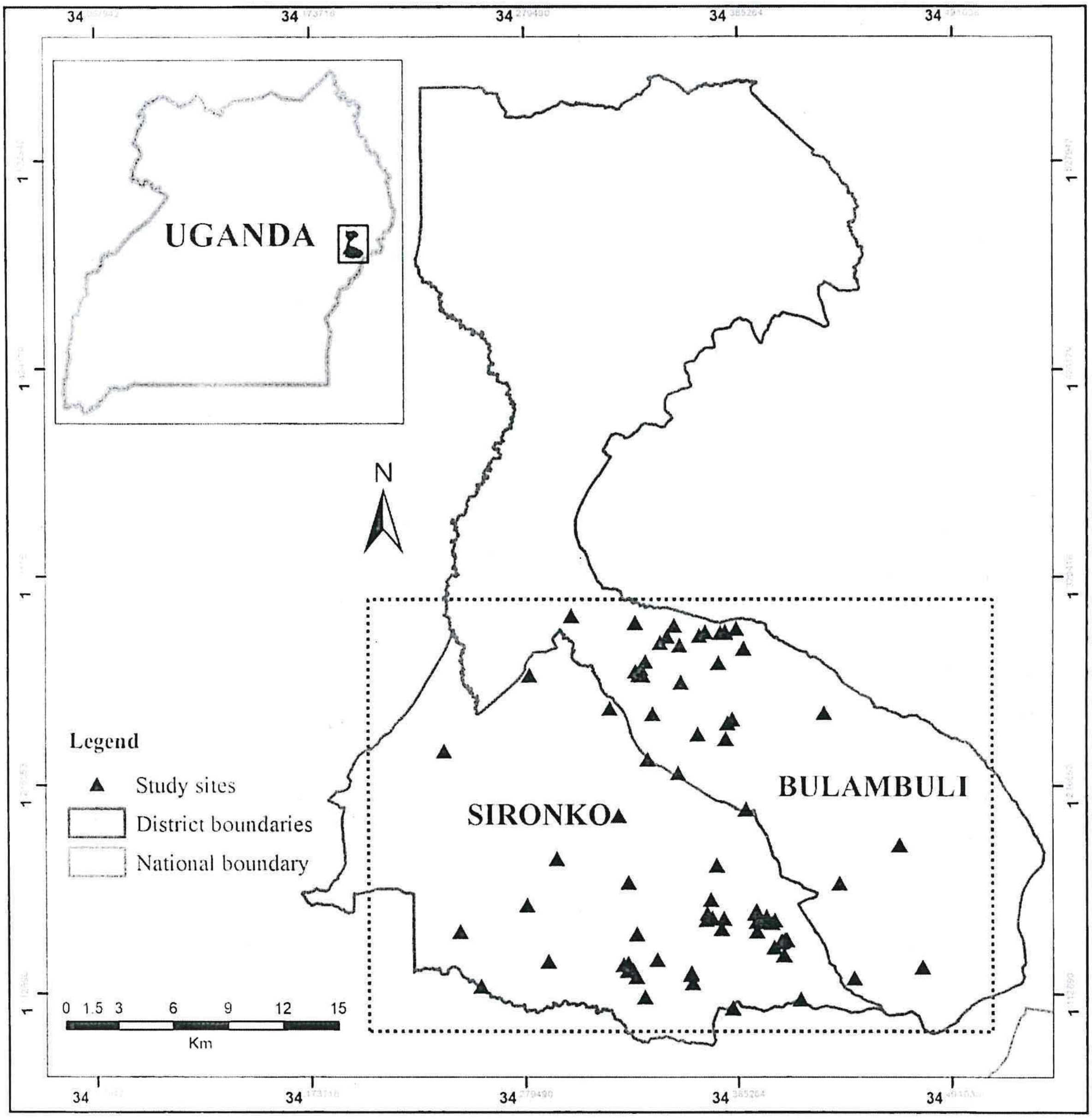


Figure 3.1: Location of the study area (The dotted line indicates the area where the landslide magnitude distribution model was applied)

3.2.3 Geomorphology

The study area lies on the slopes of Mt. Elgon which is one of the oldest extinct shield volcanoes associated with the Great East African Rift Valley System (ACCESS, 2015). The elevation of the study area ranges from 1076 and 3961 meters above sea level with 1922 meters as average elevation (Shuttle Rader Topographic (SRTM) Mission Digital Elevation Model (DEM)). The area is characterized by numerous relief consisting of cliffs, ridges, and V-shaped river valleys, on rivers Sironko, Simu and Sisyi. Some parts are however characterized by low-lying and flat relief. The steep nature of the landscape overlain by loose soil materials increases the risk of land sliding according to Mugagga et al. (2011).

3.2.4 Climate

The study area experience rains mainly between March and September but with a sharp dry spell in June and a dry period from December to February (NEMA, 2009; Mbogga, 2013). Orographic influence of the Mountain and proximity to Lake Victoria impacts on the rainfall patterns of this area by increasing rainfall totals and increasing dry period's severity (Knapen et al., 2005 and NEMA, 2009). The southern parts lying within the mountainous belt receive heavy rainfall, with mean annual ranges between 1500mm and 2000mm and mean maximum and minimum temperature of 23°C and 15° C respectively (Mugagga et al., 2012), while the northern parts close to Nakapiripiriti district are dry with rainfall amounts dropping to 1,000 mm and below and temperatures exceeding 27 ° C (NEMA, 2009). Relative humidity is also high in most parts of the zone due to its equatorial location, montane vegetation, and high rainfall (NEMA, 2009). High rainfall amounts received in the upper slopes play a role in triggering off landslides through increasing shearing stress (Acces, 2015).

3.2.5 Drainage

The drainage in Sironko and Bulambuli districts is part of the large Mount Elgon water catchment that feeds into the Lake Kyoga water basin (Directorate of Water Report on Kyoga Basin, 2011). The Lake Kyoga basin is divided into 11 sub-basins which cover a land area of 57,080 square km and Mt. Elgon catchment falls under the Awoja and Impologoma sub-basins (Rannveig et al., 2012; Makenzi, 2016). The Crater Lake on top of the volcano supplies water to a vast array of rivers some flowing into Kenya. The major rivers flowing through the study area, and contributing to the Awoja sub-basin include Simu, Sisiyi, and Sironko. The major ground water recharge source for this catchment is the Mt. Elgon National park forest (Olago et al., 2015). River undercutting and subsurface flow triggers off landslides (Selby, 1993 & Lewis, 2008).

3.2.6 Vegetation

The vegetation of the study area is representative of that around much of Mt. Elgon which reflects the altitudinal influence like on any other mountain range. On Mt. Elgon, four vegetation zones are distinct that is, the now cultivated lower slopes formally woodlands below 2000m above sea level, the afro-montane moist forest on the mid slopes between 2000-2500 meters above sea level, the bamboo forest between 2500-3000 meters above sea level and the Afro-alpine vegetation zone (Mbogga, 2013; Abwoli et al., 2014). The Afro-montane moist forest zone is now designated as a national park, which stretches between 0° 52′ and 1° 25′ N and 34° 14′ and 34° 44′ E covering a land area of 1145 km^2 (Abwoli et., al 2014). Clearance of forest vegetation to create land for agriculture is reported to have been responsible for some of the landslides experienced in Mt. Elgon areas (Kitutu, 2010 and Mugagga et al., 2011).

3.2.7 Population and Ethnicity

UBOS (2014) puts the population of Sironko at 242,422 people, with a population density of 601 persons per square kilometer and average household size of 4.4 and Bulambuli at 174,508 people, with a density of 251 persons per square kilometer and average household size of 5.1. In 2002, the population of Sironko was 185,819 people and that of Bulambuli was 97,273 people, implying that the growth rate between 2002 and 2014 was 2.2 for Sironko and 4.9 for Bulambuli (UBOS, 2014). This points towards increased pressure on land and its resources leading to land use induced landslides (Kitutu, 2013). The Bagisu ethnic group are the majority of the people in the Mount Elgon areas of Sironko. They are also known as the 'BaMasaba' who consider Mountain Elgon to be the 'embodiment' of their father Masaba which name is used to refer to the mountain (UBOS, 2014; Mugagga et al., 2011).

3.2.8 Land-use activities

The major land use activities on the slopes of Mount Elgon are crop and livestock production. Maize, millet, potatoes, cassava, yams, beans, and bananas form major food crops while Arabica coffee is the main cash crop grown in the area. In addition to these, vegetables such as tomatoes, onions, and cabbage and fruits like passion fruits are also grown. The topography of this area impacts on the land-use that is, the steep slopes between 36^0 and 58^0 are cleared for crop farming and settlement while rearing of cattle, goats, pigs and others takes place on the arid low laying plains (Mugagga et al., 2011, & NARO, 2016). A combination of unsustainable land-use practices, high population densities, high rainfall, slope steepness, and soil properties has accelerated the occurrence of landslides in these areas (Mugagga et al., 2012).

3.3 Research Design

This study adopted a cross-sectional study design where data was picked from the field during a single field survey. A cross-sectional study design was preferred due to the fact that the variables of interest to the study (pedologic and terrain characteristics) don't vary some much within the year thus could be studied during a one-moment field visit, consequently a one-time field survey was meant to give a picture of the landslide sites' pedologic and terrain characteristics. Beside, time constraints couldn't allow the use of other study designs like a longitudinal study design. The study also followed a quantitative approach. A quantitative approach was preferred because more statistical data requiring robust quantitative techniques of analysis were involved as compared to qualitative data. The approach was also meant to communicate study findings precisely rather than provide theoretical information that has already been provided by most previous researches.

3.4 Sample Design

The main locations for field investigations and sample collection were in the hilly areas of Sironko and Bulambuli districts. However, analysis was restricted to Sironko and southern parts of Bulambuli district in the sub-counties of Bulago, Buluganya, Bumasifwa, Busulani, Lusha, Luzzi, Masaba, Namisuni, Sisiyi and Zesui. The expectation was that landslide data would be picked to cover the two districts but this was not possible, owing to time and financial constraints. Therefore in Bulambuli district, data was picked in the southern parts neigbouring Sironko district. The study areas were purposely selected because studies conducted in Sironko district between 2001 and 2013 indicated the sub-counties mentioned above to have experienced more landslides than others (Kitutu, 2004; NEMA, 2011; Mugagga et al., 2011; Langoya, 2012; and Kitutu, 2013) and thus deemed representative of the areas affected by landslides. The study targeted at least 60 landslide sites to comprise the sample size. This sample size would to enable prediction of landslides based on probability using regression analysis; at data-hungry approach which would need over 60 samples (Carmen et al., 2007). However, 45 sites were realized during the field study which called for change of the modeling approach to random forests. The sample size was arrived at through snow ball sampling, involving inquiries with local council leaders in each of the sub counties shown above and later confirmation from the researcher's judgment and interpretation of landslide in the field. Random sampling techniques like systematic sampling could not be implemented due to the fact that the sample population was not known due to cases of recurrence on an annual basis and lack of a landslides data base for the country (Kitutu, 2013).

3.5 Data Collection

3.5.1 Landslide data

While in the landslide scars were identified and geo-coded using a Global Positioning System (Germin *eTrek* 30, ± 5m) in UTM N36. In addition to the GPS coordinate, a site identity (ID) number was generated for each site visited. The site IDs contained a number corresponding to the order in which a given site was visited and three letters representing village, parish and sub-county in which a given landslide site is located. For each scar, length, width, depth and maximum flow length were determined using a tape measure (100 meter survey tape) (see Appendix I for field data collection sheets). Three different positions were used to determine each of these dimensions and finally, averages were generated for each dimension for use. This was meant to minimize under and/or over estimation associated with reliance on single point measurements. From these measurements, the spatial extent (area) and the volume of each landslides studied were computed. Area was computed from scar length and width whereas volume was computed from scar length, width and depth (Working Party on World Landslide Inventory, 1993). Using this information, ordinal categories of landslide magnitude were derived using cluster analysis package in R computing software version 3.4.4. The results were then tabulated and imported in a GIS software (ArcGIS 10.5) for display. In addition to the GPS coordinates of the investigated landslide scars, 34 landslide-free sites were geocoded using a GPS in the field and Google earth Map tools (15:19). Google earth map tools enable viewing and collection of spatial data from referenced historical imagery (Landsat, Copenicus, Spot and Orbimage) of different areas at varying scales. These tools formed a variable source of data on landslide free sites, especially from areas that were not reached during the field survey. The data collected were required to create an additional class of landslide magnitude (i.e. unaffected areas) against which the other classes would be compared in the landslide magnitude spatial distribution modal training shape file data.

3.5.2 Field and laboratory soil data

After collecting landslides data, extensive field profiling of landslide sites' soil properties was conducted. Profile pits were excavated at each landslide site (at the scarp and flank's positions). Care was taken to avoid sampling in landslide debris by excavating more than one profile and ascertaining the profiles' structure before further tests. In each pit, soil was sampled to between 0.5 and 3 meters deep, but at varying depth intervals (10-40cm) depending on profile development at specific sites and following USDA soil sampling procedures (Soil Survey Staff, 2014). Various field measurements were then applied on the samples to determine soil color, structure, plasticity and proportion of rock fragments. The general profile was also probed for soil profile cracks, excavation difficulty, and depth of weathered profile, degree of bedrock weathering and presence of seepages surfaces in the subsurface soil layers. Soil color was determined by observation with the help of Munsell Soil Color Charts (2002); soil structure by scooping out volumes of soil and carefully observing how the material crumbled into peds; soil plasticity by "feel" technique; profile depth (in meters) using a measuring tape; rock fragments using "eye ball technique"; and degree of bedrock weathering by scraping using a pocket knife. The field tests were conducted following the guidelines in the Field Book for describing and sampling soil (2012). These were supplemented by observations of the surrounding slope-cuttings which revealed soil profiles to the depth of the bed rock (Appendix I).

Within each profile observation depth range (up to a maximum of four zones) 500 grams of soil samples were scooped and packed in properly labeled paper bags for particle size and Sodium content in the laboratory. The 500 grams weight sample was meant to allow for preparation of several subsamples incase such a need arose. These were stored in boxes until the end of field activities in December 2017 and thereafter taken to National Agricultural Research Laboratories (NARL) at Kawanda in Wakiso District in January 2018. The specific depth at which the soil samples were picked were also recorded in addition to depth of weathered profile. Pre-processing of the soil samples involved air-drying and crashing of material into individual particles. Soil particle size analysis was then performed on air-dried samples using hydrometer method according to Bouyoucos (1936) and reported as percentages of clay, silt and clay contents.

Table 3.1: Derived terrain attributes used in landslides magnitude spatial prediction model

Predictor variable	Units	Source	Scale	Category	Minimum	Maximum	Mean
1. Slope	Degrees	DEM	Continuous	Topographic	0	84.965	12.487
2. Profile curvature	-	DEM	Continuous	Topographic	-0.0656	0.0921	-4.1352
3. Slope length	Meters	DEM	Continuous	Hydrologic	0	2266.69	92.70
4. Elevation	Meters	DEM	Continuous	Topographic	1076	3961	1922
5. Surface area	-	DEM	Continuous	Topographic	900	10256.48	940.90
6. Longitudinal curvature	-	DEM	Continuous	Topographic	-1.0278	0.9671	6.0263
7. SAGA TWI	Radians	DEM	Continuous	Hydrologic	0.0954	10.7218	4.5842
8. TPI at processing window; 100	-	DEM	Continuous	Topographic	-41.4320	41.7049	-1.6445
9. TPI at 300	-	DEM	Continuous	Topographic	-16.7087	19.4143	-4.0907
10. TPI at 500	-	DEM	Continuous	Topographic	-9.7590	12.1666	6.3703
11. TPI at 700	-	DEM	Continuous	Topographic	-7.1912	9.5133	3.0705
12. TPI at 900	-	DEM	Continuous	Topographic	-6.0125	8.0960	-4.4064
13. TPI at 1100	-	DEM	Continuous	Topographic	-5.1063	6.9827	4.4194
14. TPI at 1300	-	DEM	Continuous	Topographic	-4.3306	6.0800	2.3468
15. TPI at 1500	-	DEM	Continuous	Topographic	-4.1458	5.7007	-1.9039

Slope is given by change in elevation divided by horizontal distance. It shows how steep a slope is in terms of angle of inclination and influences overland and subsurface flow, precipitation, vegetation, soil water content and general land geomorphology (Grozavu & Patriche, 2010). Profile curvature is a measure of convexity and concavity of the slope indicated by positive and negative values respectively, and is expressed in a one hundredth of a z-unit, where the z-unit is the adjustment factor (Seif, 2014). Profile curvature represents landscape control on flow accumulation and deceleration, thus determines the erosion potential of an area. Slope length is given by the distance from the point of origin of overland flow to the point where slope decreases significantly for deposition to take place or to a point where runoff enters a defined channel. Elevation represents height of land above sea level. It infers special characteristics on climate, vegetation and energy potential (Schillaci & Braun, 2015). Surface area represents area size for possible saturation. Longitudinal curvature indicates divergence and convergence of flow thus determines soil water or the deposition of particles. TWI is a steady state Wetness Index used to quantify topographic control on hydrological processes (Schillaci & Braun, 2015). For rainfall triggered landslides like the case of the current study area, TWI is important because of its strong relationship with other landslide predisposing processes and factors (Gorsevski, 2006). TWI indicated zones of saturation and runoff generation (Oh & Lee, 2017). TPI on the other hand represents the difference between elevation of each cell in DEM and the mean elevation of a specified neighborhood around that cell (Jones et al., 2000; Weiss, 2000; Jenness, 2006; Schillaci & Braun, 2015). Features on the lower surrounding are indicated by negative TPI values whereas those on a higher surrounding are indicated by positive TPI values (Jenness, 2006; D£ugosz, 2012; Wilson, 2012). TPI is scale dependent meaning that in relating it to landscape processes, it can be significant at one scale but not any another (Seif, 2014). For this reason TPI in the current study was processed at varying scales ranging from 100 to 1500 meters at intervals of 200 meters.

3.5.3.2 Soil data spatial layers

FAO compiles soil data for different parts of the world through digital geologic mapping and GIS. This is the only data currently available for Uganda on a country wide scale. The shape files for soil type, class and parent material were sourced from NEMA GIS archives. Only a portion covering the current study area was clipped out. From this shape file, twelve (12) soil types are identified for the study area; including black humose sandy clay loam, dark brown clays and clay loams, humose red sandy clay loams, red clay loams and sandy clay loams, red sandy clay loams, red clay loams occasionally laterised, red sandy clay loams occasionally underlain by laterites, reddish-brown clay loams over laterite, shallow grey brown sandy loams over laterite, yellowish brown sandy clay loams, black calcareous clays and clay loams, and black and grey clays often calcareous. Soil type data was considered important in this study because it communicates broad characteristics of a soil mass in a given area. In terms of FAO class, six (6) levels are represented in the study area to include; Acric ferralsols, Gleysols, Luvisols, Nitsols, Patric Plathosols, and Vertisols. FAO soil classes provide information about the soil characteristics mainly in the control section of the profile which is believed to be a result of interacting processes relating more to landscape disturbances (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009).

3.5.3.2 Geology data spatial layer

Data on the soil parent material was used to represent the geology of the landslide sites as it determines soil pedology and water movement to initiate landslides (Lewis, 2008). According to the FAO parent materials shape file, the study area is underlain by nine (9) classes of parent material which include, Ancient Alluvium and Colluvium, Basement Complex Granites, Basement Complex Mica Schist and Amphibolites, Basement Complex Gneisses, Colluvium from Elgon Volcanics, Elgon Volcanics, Elgon Volcanics and Basement Complex Granites, Lake Deposits from Basement Complex Granites and Gneisses and River Alluvium.

3.6 Data Analysis

Landslide scars data, field and laboratory pedolgic characteristics data were analyzed using parametric statistical techniques whereas spatial data was analyzed using mainly non parametric statistical techniques. The first the first phase involved use of descriptive statistical methods whilst the subsequent stages involved vigorous clustering techniques and non-parametric Random forest modeling. These analyses were conducted using Microsoft excel, SAGA GIS, ArcGIS and R computer programs.

3.6.1 Derivation of landslide magnitude classes

Data on landslide scar dimensions that is, scar length, width and depth, was used to compute area and volume of landslides. To gain insight into the distribution of data on all landslide characteristics including scar length, width, depth, area, volume, and flow distance, descriptive statistical analyses were conducted involving determination of means, minimum, maximum, and standard deviations.

To characterize landslides in the study area based upon a measure that describes magnitude, three parameters that is, area, volume and flow length were selected. Previous landslide magnitude classifications depended on either area affected by the landslide (Van Schalkwyk & Thomas (1991; Guthurie & Evans 2004) or volume (Fell, 1991; Jaiswal et al., 2011). This study introduced flow length of failed material as the third parameter of magnitude and used all the three parameters (area, volume & flow length). Data on these was imported into R. statistical computing software version 3.4.4 and using cluster analysis, ordinal categories of landslide magnitude were derived. Cluster analysis uses an algorithm that divides a dataset into groups of observations that are similar to each other using the Cluster package in R (Maechler et al., 2017). Specifically, hierarchical and partitioning techniques were used. Hierarchical methods construct a hierarchy of clustering with the number of clusters ranging from one to the number of observations. On the other hand, partitioning methods like partitioning around modoids (PAM) require user-defined number of clusters (Maechler et al., 2017). The results from these analyses were presented in tables and graphs backed by descriptive statistics.

3.6.2 Relating pedologic characteristics and landslide magnitude

To establish the relationship between pedologic characteristics and landslide magnitude, descriptive and exploratory statistical analyses were conducted on data on landslide sites' soil characteristics in relation to the landslide magnitude classes. Categorical variables (.i.e. soil color, consistency, structure, and depth of profile weathering and subsurface seepage) were analyzed by cross tabulation and consequent interpretation. The resulting findings are presented in tables. For continuous variables that is, rock fragments, profile depth, texture proportions and Na content, means, standard deviations, minimum, and maximum were preferred for analysis of the patterns of distribution between the landslide magnitude classes and the final results are presented in tables and graphs. Statistical analyses were conducted in Excel and R. statistical computing software.

3.6.3 Mapping the spatial distribution of landslide magnitude

To model and map the spatial distribution of landslides in Sironko and Bulambuli districts, Random forest (RF) modeling and prediction was implemented in R and ArcGIS respectively.

Random forest modeling is an approach for building a predictor assemble with decision trees that grow in randomly selected subspaces of data (Biau, 2010). RF is based on Breiman's random forest algorithm that uses bootstrap aggregation (bagging) and classification or regression trees (Ehrlinger, 2014). Bootstrap aggregation takes uniform samples from an original dataset of predictor and response variables to create a subset of data that is allowed to have duplicated samples. Then, each sample is used to create a tree. Tree breaks datasets up into subsets based on measures of variance. The breaks are applied on the grounds of creating two subsets up into subsets with the minimum possible total intra-subset (Ehrlinger, 2014). The model was deemed suitable in this study because of the categorical nature of the response variable (landslide magnitude classes) against continuous predictor variables (terrain attributes).

To implement the RF model, a shape file containing geolocation data of the derived landslide magnitude classes was prepared for model training and a stacked raster file containing 18 layers representing predictor variables was also prepared in SAGA GIS 2.3.1 and ArcGIS 10.5. Raster data layers' stacking (of predictors) was done using raster processing tools in ArcGIS and later exported as an image file (in img format) for further handling in R. All the terrain derived variables were measured on a continuous scale. The categorical soil and geology layers were also converted to continuous variables during the stacking of all the co-variates. Due to a limited number of observations, the model training data set could not be split to allow for both model training and validation, save for out of bag (OOB) accuracy estimation. Using R packages that is, randomForest, sp, rgdal, maptools, raster, and MASS (Bivand et al., 2008; Hjimans, 2017; & R core team 2018), the two data sets were called into the software, preceded by model permutations. The permutations were applied across varying number of trees (.i.e. 100, 300, 600 & 900) and the model with the smallest out of bag error was used to predict landslides magnitude in the study area. The model results were then exported as a single raster file which was further processed in ArcGIS to map areas according to their predisposition to each of the landslides magnitude classes.

To establish the contribution of each of the predictor variables towards landslides magnitude spatial prediction, Variable Importance (VI) statistics were computed using the same RF package in R. VI ascertains the contribution of each predictor variable through the split rule optimization (Breiman, 2002; Ehrlinger, 2014; and Loupe et al., 2014). VI values close to Zero indicate that the variable contributes nothing towards predictive accuracy and negative values indicate that predictive accuracy improves when the variable is miss-specified (Ehrlinger, 2014). Variables with negative and near zero values are therefore ignored whilst those with large positive values are considered to be improving the predictive power of the forest (Ehrlinger, 2014; R. core Team 2018). For this study, VI was used to establish the influence of terrain and soil characteristics on the distribution of landslide magnitude in Sironko and Bulambuli districts. Variables with higher and positive VI values were considered to be having more influence on landslide magnitude than those with negative VI values.

3.7 Limitations of the Study

The rugged terrain in Mount Elgon areas coupled with torrential rains made some places inaccessible which hindered access to some landslide sites and yet landslides sites' identification was done mainly through field surveys. This was however overcome by use of Google earth Pro, historical imagery.

Most of the landslides in the Elgon areas occurred between 1990 and 2013 thus most of the scars had been modified by revegetation, erosion, and reactivation. To overcome this, an inquiry into historical landslides whose scars which were not still visible on the landscape was carried out involving key opinion leaders from the communities visited.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter entails data presentation, analysis, interpretation and discussion. The data is presented according to the study objectives. A total of 45 landslide sites were investigated for scar dimensions and key landslide drivers in the districts of Sironko and Bulambuli. The full list of site IDs and their geo-locations are given in Appendix II. The site IDs contained a number corresponding to the order in which a site was visited and three letters representing village, parish and sub-county in which a given landslide site is located. In addition, the GPS coordinates (in UTM N36) of the specific sites were appended.

In the analysis of terrain and pedologic characteristics as drivers of landslide magnitude, descriptive and/or exploratory statistical analyses and Random forest modeling and prediction using spatial technologies were performed in R and GIS computing environments as shown in chapter three to arrive at the findings presented, analyzed and discussed herein. Some of the findings from these analyses have provided new insights into the matter of investigation whilst other aspects relate more or less to what has been already reported in previous studies, both within the current study area and elsewhere.

4.2 Magnitude of landslides in Sironko and Bulambuli Districts

The summary statistics of the 45 landslide scar dimensions investigated during the study are presented in Table 4.1.

Table 4.1: Descriptive statistics of the landslide scar characteristics

Parameter	N	Minimum	Maximum	Mean	Std. Deviation
Length (m)	45	14	175.00	47.1	32.16
Width (m)	45	15	112.00	38.5	21.4
Depth (m)	45	0.6	14.60	3.5	3.1
Area (m^2)	45	266	17850.00	2317.5	3355.1
Volume (m^3)	45	265.2	110517.09	10625.3	20956.6
Flow length (m)	45	26.6	435.22	128.0	89.2

Table 4.1 reveals that the minimum scar length of the investigated slides was 14 meters recorded at Makuyu-Bugitimwa sub-county whereas maximum scar length was 175 meters recorded at Nalufudu in Namisuni sub-county. The average scar length was 47.1 meters and standard deviation was 32.16 meters of all the investigated scars. The minimum scar width was 15 meters recorded at Busanjja in Masaba sub-county whereas maximum scar width was 112 meters recorded at Bulusabe in Masaba sub-county. The mean width of all the landslides was 38.5 meters with a standard deviation of 21.4 meters. The minimum scar depth was 0.7 meters, recorded at Kisakye in Namisuni whereas maximum scar depth extended to 14.6 meters at Bugibulungu in Bumasifwa (Plate 4.1). The mean depth of all the slides was 3.5 meters with a standard deviation of 3.1 meters.

Plate 4.1: Scar depth at selected sites (A-Kirwali, B-Bugibulungu, C-Jibaru)

The implication of findings on landslide dimensions is that the investigated landslides depicted great variations in terms of scar dimensions Plate 4.2). This also means that landslides experienced in Sironko and Bulambuli districts had extremely deep, wide and long scars as well as having cases of extremes in the lower limits. The findings are related to the findings by Mugagga et al. (2012), in a study involving determination of scar dimensions of Nametsi and Kitati landslides in Mt. Elgon areas. The average scar depth recorded in their study was 4.5 meters, contrasting from current study average. The main difference in scar depth between these two studies is could be accounted for by the varying number of study sites (i.e. three sites in Mugagga et al., 2012a)'s study against 45 sites in the current study. Similarly, studies by

Kimono (2010) and Knapen et al. (2006) involving determination of landslide scar dimensions on the southern slopes of Mount Elgon yielded not quite different results.

Plate 4.2: Measuring landslide scar dimensions at selected sites (A-Kamwanyi-Sisiyi, B-Bumwadyeki-Sisiyi, C-Chilumbi-Zesui and D-Nasanga-Bulago)

From landslides scar dimensions, area and volume of each landslide was computed and the summary statistics of these are also shown in Table 4.1. This table indicates that minimum landslide scar area was 266 square meters at Makuyu in Bugitimwa sub-county whereas the maximum scar area was 17,850 square meters recorded at Nalufudu- Namisuni Sub-county. The mean scar area of all the investigated scars was 2317.54 square meters and the standard deviation was 3,355.12 square meters. The total area affected by all the landslides was 104,289 square meters. The minimum volume of displaced material was 265.20 cubic meters whereas the maximum volume of displaced material was 110,517.09 cubic meters. The mean volume was 10,625.35 and standard deviation was 20956.6 cubic meters. The sum of material displaced by all the 45 slides was approximately 478,140.76 cubic meters. From these scar characteristics findings, it can be argued that the investigated landslides in the study area varied in size from very small to very large slides.

The minimum flow length of displaced material was 26.6 meters, recorded at Makuyu in Bugitimwa sub-county whereas the maximum flow length covered by displaced materials was 435.22 meters, recorded at Nalufudu in Namisuni sub-county (Plate 4.3). The mean flow length was 128 meters and the standard deviation was 89.2 meters.

Plate 4.3: Flow length of landslide material at selected landslide sites (A&B-Nalufudu-and C&D-Bulusabe)

Results from computation of area and volume in addition to flow length (as measures of landslide magnitude) were used as inputs in the landslide magnitude characterization process (The data on the three parameters is shown Appendix III). This was aimed at distinguishing the damaging potential of the landslides experienced in the study area. Landslide area, volume and flow lengths were considered to measure magnitude because these can best illustrate the differences in landslide occurrence across any landscape. Using the data on the three parameters ordinal categories of landslide magnitude were derived using both hierarchical and partitioning around medoids (PAM) clustering techniques (Maechler et al., 2017), in R computing software. The result from these procedures can be observed in Figures; 4.1 & 4.2.

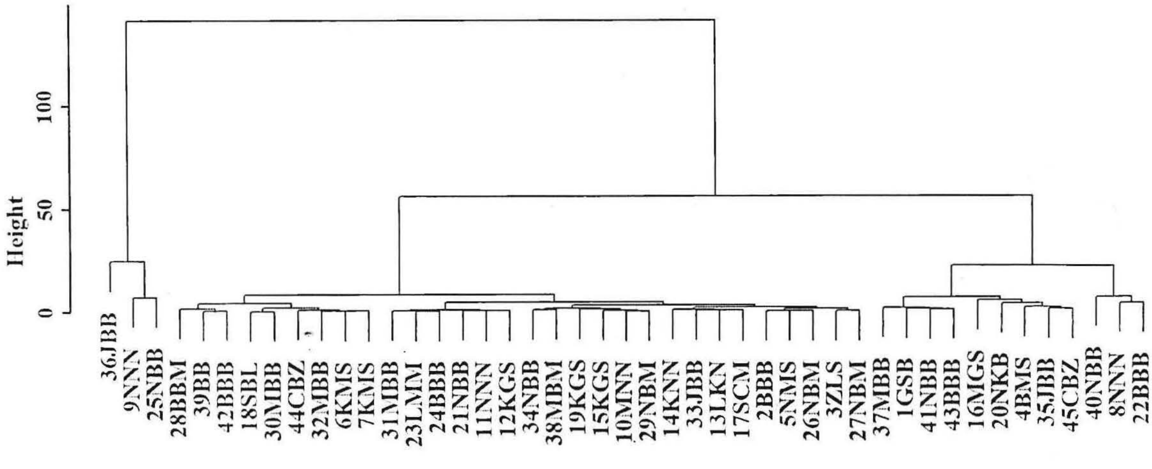


Figure 4.1: Hierarchical clustering, where three clusters are conceivable at height 50

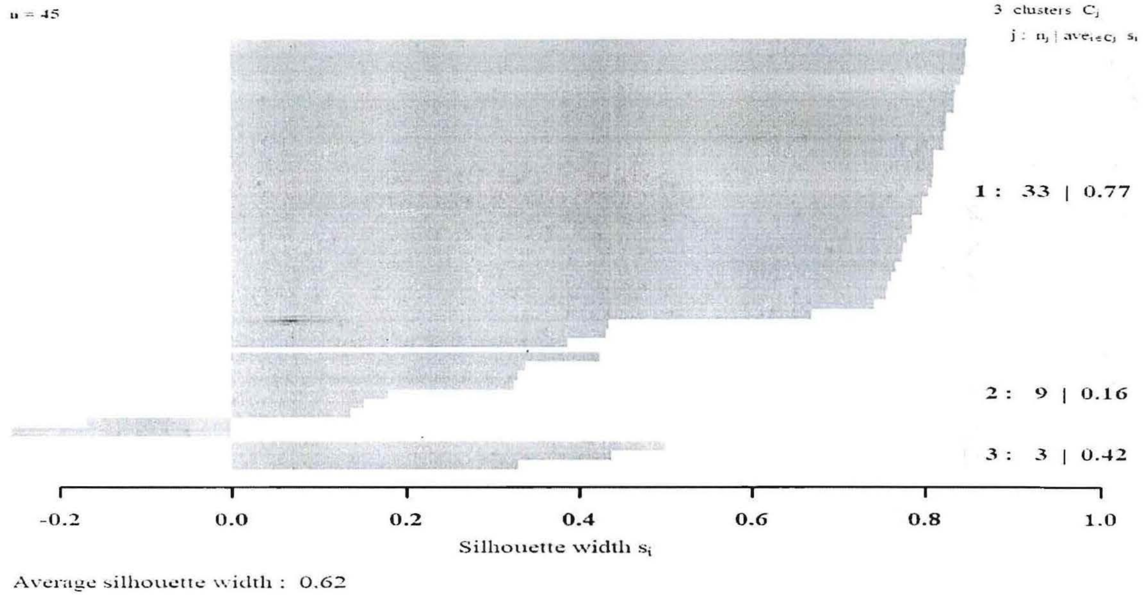


Figure 4.2: Silhouette plot for a three-cluster solution with a reasonable structure (average silhouette width = 0.62). The three samples with negative values were found to belong to cluster 1, and hence moved as necessary

Cluster 1 in Figure 4.1 is defined as low magnitude landslides, cluster 2 is of moderate magnitude, and cluster 3 is the high magnitude landslides, on the account of the effect of the event in and around the area. A close scrutiny of the results shows consistency in so far as agglomerating samples to the right clusters is concerned (Figures 4.1 and 4.2). The descriptive statistics of the three parameters used in landslide magnitude classification are shown in Table 4.2.

Table 4.2: Descriptive statistics of three parameters used to characterize landslide magnitude

Parameters	Low magnitude		Moderate magnitude		High magnitude	
	Mean	S.dev	Mean	S.dev	Mean	S.dev
Area (m^2)	1,125.61	760.24	3,624.56	1,222.26	13,173.63	5,071.43
Volume (m^3)	2,887.00	2,441.43	19,804.28	10,575.51	79,488.63	27,731.87
Flow length (m)	100.29	53.68	176.69	100.98	338.37	85.79

Results in Table 4.2 prove that differences in landslide magnitude classification were wholly based on differences in area affected by the slide, volume of materials moved and flow length of landslide material as shown by the means and standard deviations. The differences in landslide characteristics (area, volume and flow length) across the three landslide magnitude classes are further shown by the exploratory statistical data boxplots in Figure 4.3.

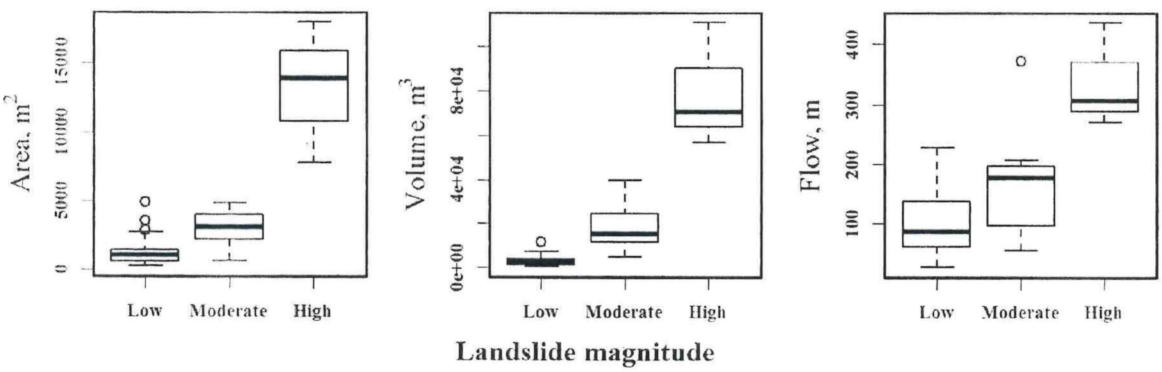


Figure 4.3: Differences in area, volume and flow length between the three landslide magnitude classes

In this study, combining areal extent of disturbed area, volume and flow length of displaced material clearly demonstrates that landslide magnitude can be best described from a combination of the three descriptors. In other words, it is not practical to use any one of them in isolation of the other because magnitude of landslides is best understood if a combination of all the three parameters is known (Guzzetti, 2005). The area might be small but experience large land loss on account of depth at the affected area.

Following the classification criteria, the sites falling under each of the magnitude classes are shown in Table 4.3

Table 4.3: Landslide sites under each of the three landslide magnitude classes

Class	Site ID
Low	1GSB, 2BBB, 3ZLS, 5NMS, 6KMS, 7KMS, 10MNN, 11NNN, 12KGS, 13LKN, 14KNN, 15KGS, 17SCM, 18SBL, 19KGS, 21NBB, 23LMM, 24BBB, 26NBM, 27NBM, 28BBM, 29NBM, 30MBB, 31MBB, 32MBB, 33JBB, 34NBB, 35JBB, 37MBB, 38MBM, 39BBB, 41NBB, 42BBB, 43BBB, 44CBZ
Moderate	4BMS, 8NNN, 16MGS, 20NKB, 22BBB, 40NBB, 45CBZ
High	9NNN, 25NBB, 36JBB

NB. The details of every site ids are given in Appendix II

Table 4.3 indicates that, out of the 45 slides investigated, 3 were classified as high magnitude, 7 were moderate whereas 35 of the slides were classified as low magnitude landslides. This data implies that whereas Sironko and Bulambuli were heavily devastated by landslides, the biggest number of those investigated during the study were low magnitude slides. The findings generally reveal that landslides experienced in Sironko and Bulambuli districts vary in magnitude basing on differences in the area, volume and flow length as used in the current study. The spatial distribution of the landslide scars in relation to the derived landslide magnitude classes in the study area is shown in Figure 4.4.

If landslides in the current study were classified basing on either volume or area as applied in previous studies, landslides falling under a one magnitude class in a given classification would shift to another class in a different classification. For instance if landslides were classified basing on area as used by Van Schalkwyk & Thomas (1991) and Guthrie & Evans (2004), the current study 3 landslides falling under "Large" in the former would be classified as medium magnitude landslides in the later. Similarly if landslides were classified basing on volume as used by Jaiswal et al. (2011) and Fell (1991), 10 landslides in the current study falling under magnitude three (high magnitude) under Jaiswal et al. (2011) would be classified as slightly large under Fell (1991) classification whilst the 29 slides falling under magnitude 2 (moderate magnitude) in the former would be classified as small/low magnitude landslides in the later classification. The approach adopted in this study therefore harmonizes the inconsistences in magnitude classification that come as a result of reliance on a single landslide magnitude descriptor.

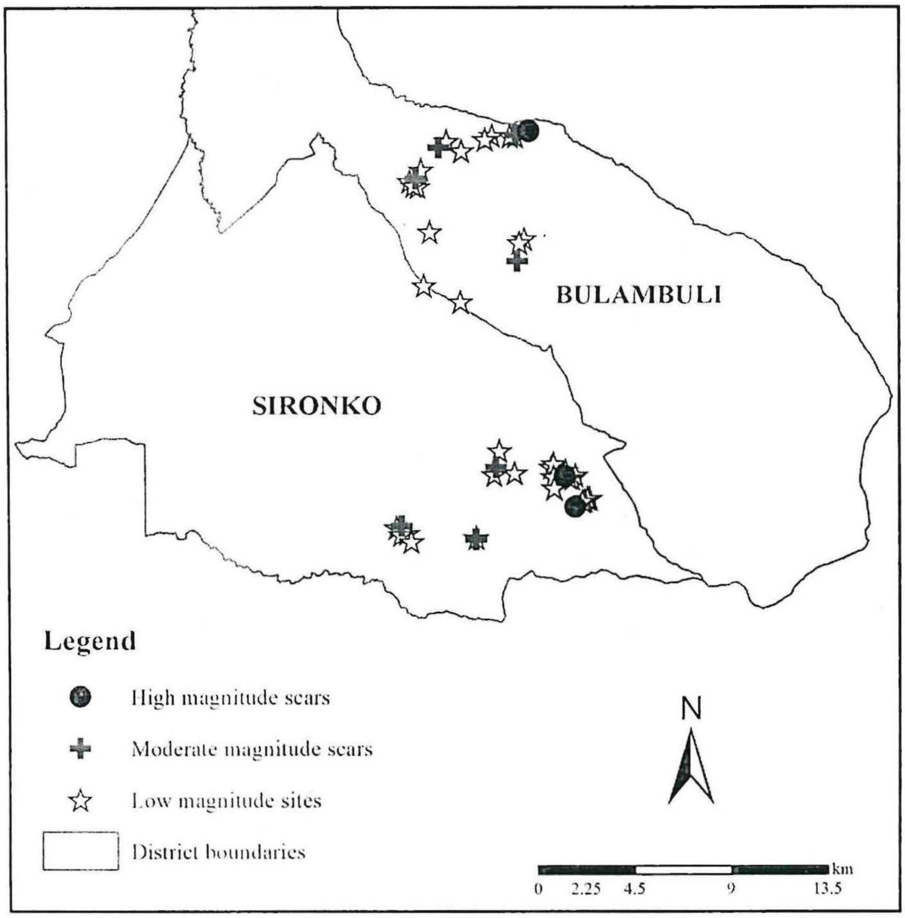


Figure 4.4: Distribution of landslide scars under the magnitude classes in the study area

4.3 Relationship between pedologic characteristics and landslide magnitude

The variables measured in soil profiles at landslide sites using field methods included soil morphology (soil color, structure, evidence of cracking, excavation difficulty and plasticity), depth of weathered material, rock fragments, degree of bed rock weathering and evidence of seepage surfaces. Results of soil texture and Na content determined by laboratory methods are also presented under this section. These results were presented by way of tables and graphs accompanied by photographs taken during the field activities in some cases and interpreted accordingly.

4.3.1 Soil morphologic characteristics (soil color, structure, evidence of cracking, excavation difficulty and plasticity) across landslide sites

The data collected from the field on landslide sites' soil profile color are shown in Appendix IV. The findings here reveal that soil colors at low magnitude sites varied in color within hues of 2.5Y, 5YR, 7.5YR and 10YR, and with Values and Chroma ranging between 2-5 and 1-6 respectively. The variations where mainly vertical that is with increase in depth down the soil profile. This means that low magnitude sites were characterized by grayish, yellowish, and reddish brown soils with varying dark and bright shades from the A to B horizons.

At moderate magnitude sites, soil colors varied within hues of 2.5Y, 5YR, 7YR, 7.5YR and 10YR, and with differing values and Chroma between 2.5-5 and 1-4 respectively with increase in depth towards the BC soil layers. These represented dark brighter shades of yellowish and reddish brown soils especially in the B soil layers. There were cases of completely yellowish soils in the layers >60cm at some sites under the moderate magnitude class.

At high magnitude landslides sites, soil colors varied within hues of 5YR and 10YR and varying Values and Chroma ranging between 3-5 and 1-4 respectively with respect to depth down the profile. These were mainly yellowish and reddish brown soils (profile H in Figure 4.7).

From the soil color findings, it can be observed that whereas soil colors ranged within hues 2.5Y, 5YR, 7YR, 7.5YR and 10YR, across all the three magnitude sites, differences existed mainly in their saturation and contrast as depicted by varying Values and Chroma. Notably, high magnitude sites had higher values and Chroma within hues of 10 YR (i.e. between 3 & 5) implying brighter reddish brown and yellowish brown soils.

In general landslide soils varied in color from black, very dark brown, dark gray, dark reddish brown, dark yellowish brown and dark grayish brown in the first 60cm profile layers whereas the dominant colors of the profile layers > 60cm depicted higher values and higher Chroma at all landslide sites (Plate 4.4).

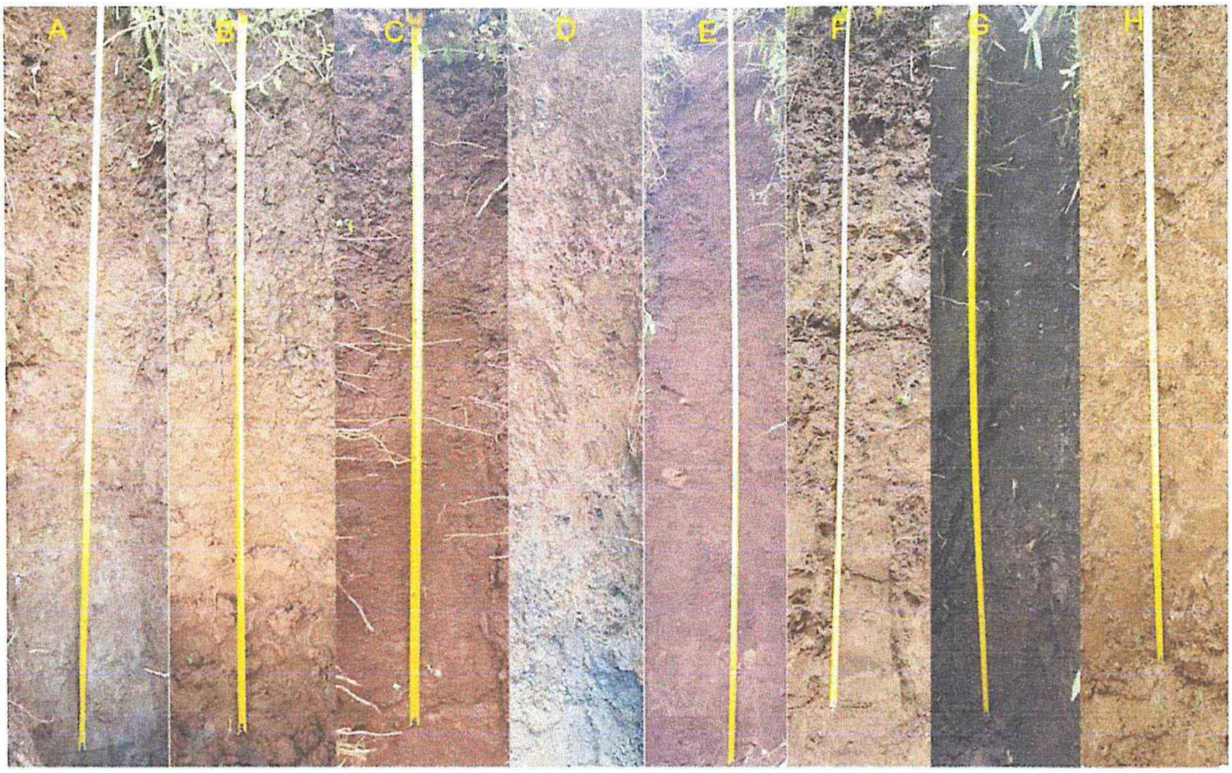


Plate 4.4: Soil profile colors at selected landslide sites (A= 38MBM, B = site 37MBB, C=40NBB, D = site 13LKN, E= site 18SBL, F= 6KMS, G = site 15KGS, and H = site 9NNN).

Yellow Red colors in the soil imply presence of moisture and thus high dynamism in terms of soil processes like weathering that act upon slope materials to weaken them further. The B-horizon reddish brown colors also imply heavy concentration of iron, aluminum and other soil minerals. Some sites (e.g. Lunyodo in Namisuni sub-county-site 13LKN-D in Plate 4.4) had gleyed C-horizons with high Values and low Chroma which implies continuous presence of water that attacked the volcanic bedrock material. In FAO soil classification, soils with grayish, yellowish, blackish, and reddish colors of varying dark and bright shades are associated with soils such as Nitsols, Luvisols, Vertisol and Andosols; which have been shown to be problematic in related studies on the Mount Elgon Slopes (Kitutu et al., 2009; Mugagga et al., 2011; ACCESS 2015).

Classes used for describing structure were, granular (gr), angular blocky (bk), sub-angular blocky (sbk), wedge (wr), Prismatic (pl), and columnar for structured soils and; single grain (sgr), and massive (ma) for non-structured soils. However only classes represented in field on which data was collected are summarized and presented here (Appendix IV).

A scrutiny of the results reveals that soils in the first 60cm profile depth at low magnitude landslides sites were dominated by prism structured soils but less of sub-angular soils and single-grain non-structured soils. In the profile depths; 60-100cm, prism structured soils still dominated as compared to single-grain, sub-angular and massive non structure soils. In the profile layers, >100cm, single-grain and massive non-structured soils accounted for the biggest proportions.

At moderate magnitude landslides sites, prism structured soils dominated in the profile depth range ~100cm whereas single grain structure-less soils dominated in the lower profile layers with depths above 100cm. Sub-angular and Single grain structures accounted for small proportions in the first 100cm profile layers whereas massive and single grain structures dominated in the soil layers above 100cm.

At high magnitude landslide sites, the first 60cm soil profile depth were dominated by prism structured soils followed by sub-angular, whilst these same structure classes, in addition to single grain structure-less category, were distributed in equal proportions in the profile soil layers ranging between 60-100cm. Profile layers at depths >100cm on the other hand were characterized by mostly single grain and massive structure-less soils.

The results signify that all landslide sites in the study area, irrespective of magnitude class were characterized by prism and single grain structured soils in the first 100cm profile layers and single grain and massive non-structured soils in the profile layers >100cm. However, high magnitude sites were characterized by massive structure-less soils in their profile layers >100cm as compared to single grain non-structured soils at low and moderate magnitude landslide sites (Plate 4.5).

Plate 4.5: Soil structure classes at selected landslide sites (Kirwali in Lusha=A, B= Gombe in Buluganya & Nalufudu in Namisuni=C)

Source: Field survey data 2017

Under single grain class, individual particles were easily pried from the profile face and under massive where material pried from the profile face failed to show any planes of weakness (especially at depths >100cm). Single grained soil material at the BC soil layers implies heavily weathered and weak bed rock material such as saprolite and if such material gets into contact with subsurface water, overlying coherent mass easily slides down the slope (Husin et al., 2014). Soil structure is related to hydrologic conductivity in the subsurface soil layers according to Boul (2003). Saprolite materials have been reported in BC soil layers at landslide sites in Mount Elgon areas (Knapen et al., 2006; Poesen & Deckers, 2009; Kimono, 2010; Kitutu, 2013). Massive grained non structured soils are clayey soils according to Lanni et al. (2012) which are high expansive and unstable.

Evidence of cracking and type of cracks in landslide sites' soil horizon/surface was assessed using 4 level class descriptors including, reversible crust related (RCR), irreversible crust related (ICR), reversible trans-horizon (RTH), and irreversible trans-horizon cracks (ITH). Analysis of the results revealed that low magnitude landslide sites were characterized by a balanced distribution of the four types of soil cracks. At moderate magnitude landslide sites, RTH and ITH type of classes dominated as compared to RCR and ICR. On the other hand, at high magnitude sites, RCR (site 25NBB), RTH (site 9NNN) and ITH (site 36JBB) cracks were equally balanced between the three sites under this magnitude cluster. Generally, there was a balanced distribution of the four classes of cracks across the 45 study sites (Plate 4.6).

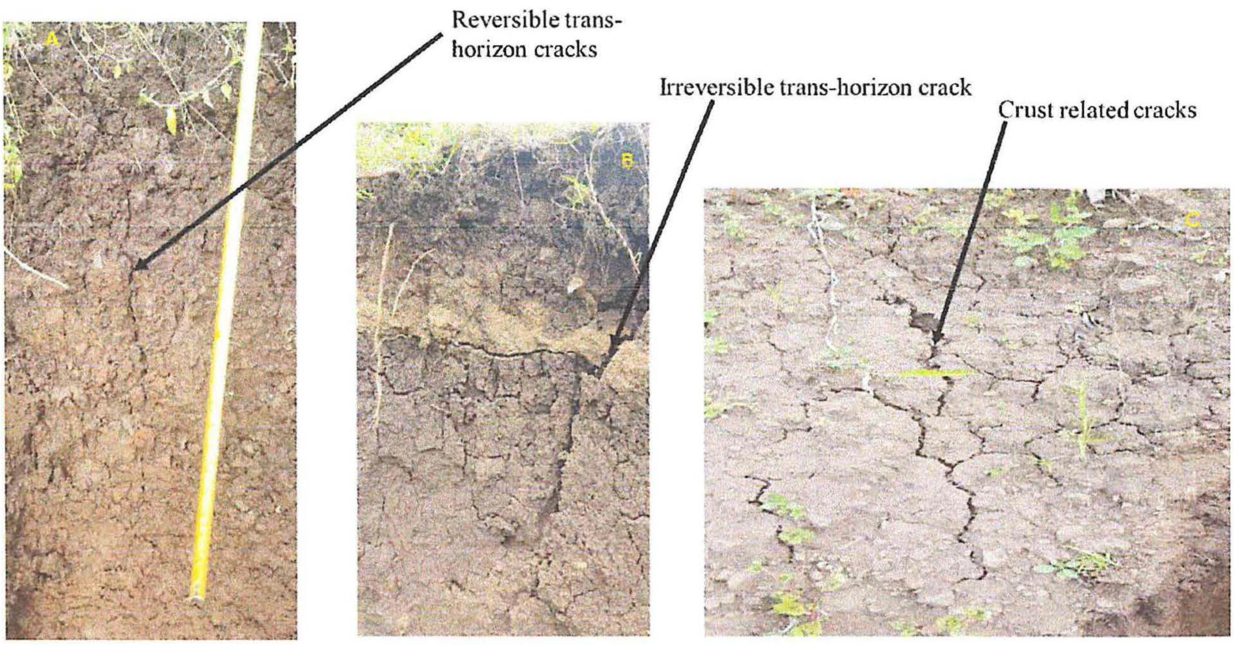


Plate 4.6: Horizon cracks on selected sites (A=Mayumba lower-Bugitimwa, B=Nasanga-Bulago, & C= Mayumba upper-Bugitimwa)

Source: Field survey data 2017

Irreversible and reversible trans-horizon cracks in the surface soil layers play a vital role in channeling water to the shear zone for translational slides along planner slopes and flows on lower slopes. Crust-related and trans-horizon cracks are also related to problem soils such as Vertisols and Nitsols that are characterized by large proportions of clay and therefore highly unstable when exposed to alternating wet and dry conditions. Mugagga et al. (2012) while investigating the problem nature of landslide soils in the Elgon areas reported Vertic soils of high clay content of above 20% at landslides sites studied. In the current study, mean clay proportions at the different magnitude landslide sites were above 20% which confirms previous study findings. Kitutu et al. (2009) reported landslide soils in Manjiya to be associated with high infiltration rates in the upper layers which facilitated down profile movement of water that gets concentrated at the zone of interface between soil lower layers and saprolite bedrock material. Infiltration is influenced by soil pores including cracks thus, the current study findings point towards previous discoveries.

Excavation difficulty which is one of the measures of soil consistency was measured by five level class descriptors that is, Light (L) Moderate (M) Hard (H) Very Hard (VH) and extremely hard (EH). Results in line with these classes revealed that, both moderate and high magnitude landslides sites were characterized by soils with light excavation difficulty whereas low magnitude sites were characterized by both light and moderately hard soils. These findings imply that high and moderate magnitude slides occur mostly in soils of light excavation difficulty thus reduced resistance to the forces of gravity related to land sliding. Low excavation difficulty soils have a high infiltration capacity associated with subsurface soil saturation leading to sliding. According to Selby (1993), volcanic soils such as Andisols are very fertile because of the chemistry associated with volcanic ejecta. They are also easy to cultivate because of low bulk density. This could provide some explanation as to why most the landslide sites in the current study area have been historically farmed and therefore escalating the magnitude of landslides. In a study by Kitutu et al. (2009), the soils at landslide sites in Manjiya were discovered to be of very low bulky density as compared to those at landslide-free sites thus confirming the current study findings.

Soil plasticity was measured by 4-level class descriptors that is, non-plastic (po), slightly (sp) plastic (p), and very plastic (vp). The data collected on soil plasticity as shown in (Plate 4.7) is presented in the Appendix IV. Analysis of the data reveals that, at low magnitude landslides sites, soils in the first 60cm of the profiles were slightly plastic. In the profile layers between 60-100cm, soils were plastic. In the profile layers >100cm, the soils were mostly non-plastic with a few exceptions having slightly plastic and plastic soils.

At moderate magnitude landslides sites, soils were mostly slightly plastic but with some cases of plastic soils in the profile depth ~60cm. In the depth range 60-100cm, plastic class soils dominated as compared to other plasticity classes. Both very plastic and slightly plastic soil classes dominated the soil layers above 100cm deep.

At high magnitude landslide sites, slightly plastic soil were recorded at two sites whereas the third site registered plastic soil class in the first 60cm profile depth. In the profile depth range of 60-100cm, mostly plastic and less of very plastic soils were recorded but the soil layers beyond 100cm were dominated by very plastic soils as compared to the plastic soils class.

Plate 4.7: Testing for soil consistency at Zamalini (A) and Nakidibo (B) in Sisiyi sub-county

From the findings on soil plasticity shown above, it can be noted that although all landslide sites had soils of some level of plasticity, high magnitude sites never registered soils that were non-plastic in their overall profile depths as compared to the low and moderate landslide magnitude sites. In addition, the soils at depths >100cm at high magnitude sites, ranged from being plastic to very plastic whereas under low and moderate magnitude sites, slightly plastic and non-plastic soils were represented. In general, soils at landslides sites depicted high levels of plasticity which graduated down the profile and faded into the underlying semi permeable profile layers. The soils in the B horizons formed ribbons beyond 4cm without rapturing. Plastic soils in the B layer of the soil profile implies presence of soil minerals like clay, whose origin could be traced from the upper soil layers (Claessens et al., 2007). Soils of high plasticity are also highly unstable when exposed to different moisture levels (Husin et al., 2014). Highly plastic material overlying a deeply weathered/semi permeable rock layer imply reduced resistance to the gravitational effect, making the materials susceptible to downslope displacement. The materials also showed evidence of being highly sticky when moist which means they easily get detached as a coherent mass. The findings on soil plasticity levels in the current study are consistent with those from previous landslide soil studies conducted in Mount Elgon areas (Knapen et al., 2006; Claessens et al., 2007; Kitutu, 2009; and Mugagga et al., 2012). Mugagga et al. (2012) reported 59% and 53% liquid limits at two of the landslide sites studied in Bududa.

4.3.2 Soil texture and landslide magnitude

The weight percentage of sand, silt, and clay separates in landslide site soils determined by laboratory procedures and further analyzed using descriptive and exploratory statistical methods are presented in tables, bar plots, and scatter plots.

Sand is a representation of fine earth material with grain size ranging between 0.6mm to 2mm. represents soil particles ranging in size between 0.074-2 millimeters. The data on percent sand obtained by laboratory methods is shown in Appendix V. The summary statistics from the analysis of this data in relation to the three landslide magnitude classes are shown Table 4.4.

Table 4.4: Descriptive statistics for percent sand in landslide sites' soil profiles

Depth of observation in the profile depth

	0-40 cm			41-90 cm			91-140 cm		
Magnitude	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**
Low	35.76	13.06	15.68-59.68	38.59	16.21	13.68-78	39.34	14.85	17.68-75
Moderate	34.64	12.23	13.68-55	30.25	12.64	13.68-50.96	31.03	13.34	15.68-55.68
High	38.59	16.21	13.68-50.96	35.02	8.08	27.68-43.68	31.68	5.29	27.68-37.68

Table 4.4 indicates that at low magnitude sites, average sand percentages increased with increase in profile depth i.e. from 35.37% to 38.59% & 39.34%. At moderate magnitude sites mean sand percentage decreased in the profile depth between 41-90cm before slightly increasing in the soil layers lower above 91 cm, that is, from 34.64% to 30.25% and to 31.03%. At high magnitude sites mean sand percentages decreased with increase in profile depth at high from 38.59% to 35.02% and to 31.68%. The distribution of mean percentages of sand in the soil profiles in relation to the three landslides magnitude classes is further visualized in Figure 4.5.

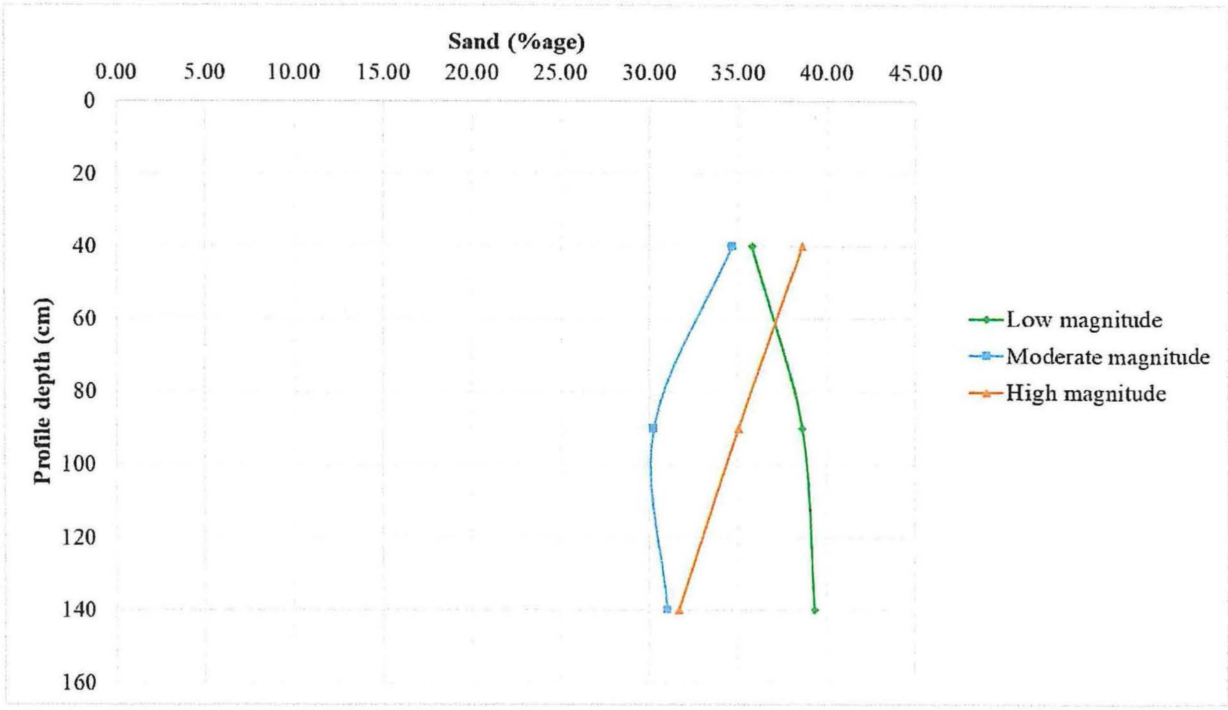


Figure 4.5. Mean percent sand distribution in soil profiles at landslide sites

Figure 4.5 indicates that percentage of sand on average increased with profile depth for low magnitude landslides but decreased with profile depth for moderate and high magnitude landslides. These results imply that magnitude of landslides increases where sand content decreases down the soil profiles and decrease where composition of sand increases down the soil profiles.

Silt content includes a fraction of fine earth material with grain size ranging between 0.005mm to 0.074 mm. The data on percent silt obtained by laboratory methods is shown in Appendix V. Results from the statistical analysis of silt proportions in soil profiles under the three landslide magnitude classes are summarized in Table 4.5.

Table 4.5: Descriptive statistics for percent silt in landslide sites' soil profiles

	Depth of observation in the profile depth								
	0-40 cm			41-90 cm			91-140 cm		
Magnitude	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**
Low	37.85	7.8	23.48-50.2	35.72	10.06	14-53.2	35.09	8.86	17-47.2
Moderate	40.31	9.06	26-53.2	41.7	8.76	26-51.48	39.62	7.43	26.2-48.2
High	45.29	1.86	43.48-47.2	40.29	5.6	34.2-45.2	40.96	4.12	36.2-43.48

Table 4.5 indicates that at low magnitudes, average percentage of silt decreased with increase in profile depth that is, from 37.85% to 35.72%, & finally to 35.09%. At moderate magnitude sites, silt increased from 40.31% to 41.7% in the profile depth range 0-90 but decreased to 39.62% in the profile layer >91 cm deep. Average percentage of silt at high magnitude sites decreased from 45.29%, to 40.29% in the profile depth ranges 0-90 but increased slightly to 40.96% in the profile depth above 91cm. Generally, mean percentage of silt decreased with increase in profile depth for high and low magnitude landslides' whereas that for the moderate magnitude landslides increased in the depth range between 41-90 before dropping in the profile layers above 91cm deep. The distribution of mean silt content in soil profiles under the three landslide magnitude sites is further visualized in the bar plots in Figure 4.6.

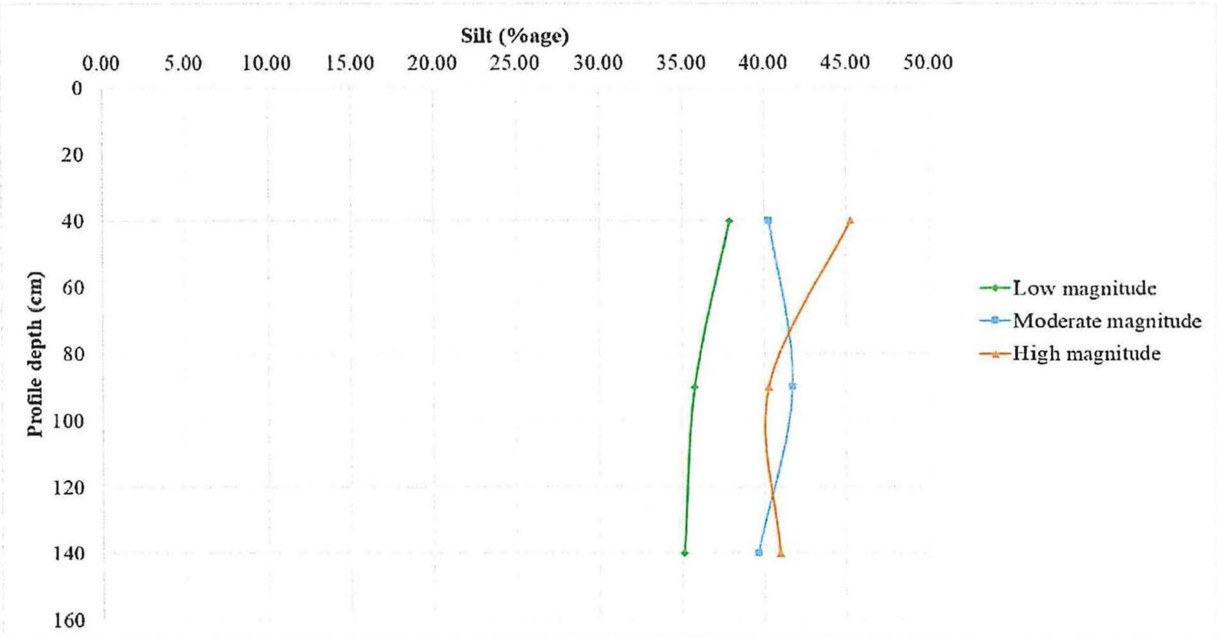


Figure 4.6: Mean silt percentage distribution in soil profiles at landslide sites

The results shown in Figure 4.6 reveal that although average silt percentage decreased with increase in profile depth under low and high magnitude sites and increased under moderate magnitude sites, the quantities were high across the general profiles at high and moderate magnitude landslides which suggest that magnitude of landslides increases where soils are characterized by high silt content.

Clay forms the smallest particle size in fine earth fraction (≤ 2mm). Its grain size ranges between 0.001 mm to 0.005 mm. The data on percentage of clay obtained by laboratory methods is shown in Appendix V. Results from the statistical analysis of this data are summarized in Table 4.6.

Table 4.6: Descriptive statistics for percent clay in land sites' soil profiles

	Depth of observation in the profile depth								
	0-40 cm			41-90 cm			91-140 cm		
Magnitude	Mean	Stdv	Min-Max	Mean	Stdv	Min-Max	Mean	Stdv	Min-Max
Low	20.39	6.89	15.84-38.84	25.7	7.62	8-38	25.57	8.68	8-44
Moderate	25.06	4.71	17.84-33.12	28.04	4.82	19.56-34	29.35	6.68	18.12-38.84
High	29.27	2.22	27.12-31.56	24.69	2.5	22.12-27.12	27.36	1.57	26.12-29.12

Table 4.6 indicates that average clay percentages at low magnitude landslides sites increased with increase in profile depth in the upper soil layers that is, from 20.39% to 25.7% but dropped to 25.57% in the third observation depth. At moderate magnitude sites, clay content increased with increase in profile depth (at the three observational zones) from 25.06% to 28.04% and finally to 29.12%. The mean clay content at high magnitude landslides decreased from 29.29% to 24.69% in the first and second observation depth (upper soil layers) before increasing to 27.35% in the lower profile layers. Mean clay content was highest at high magnitude sites followed by moderate magnitude sites in the upper soil layers, highest at moderate magnitude sites in the second and third observation zone in the soil profiles as shown in Figure 4.7. It is noted that whereas clay content increased under low magnitude landslide sites, it was higher than that of high magnitude sites only in the second observation depth in the profile. This points towards the direction that high clay content in the B3 soil layers increased magnitude of landslides.

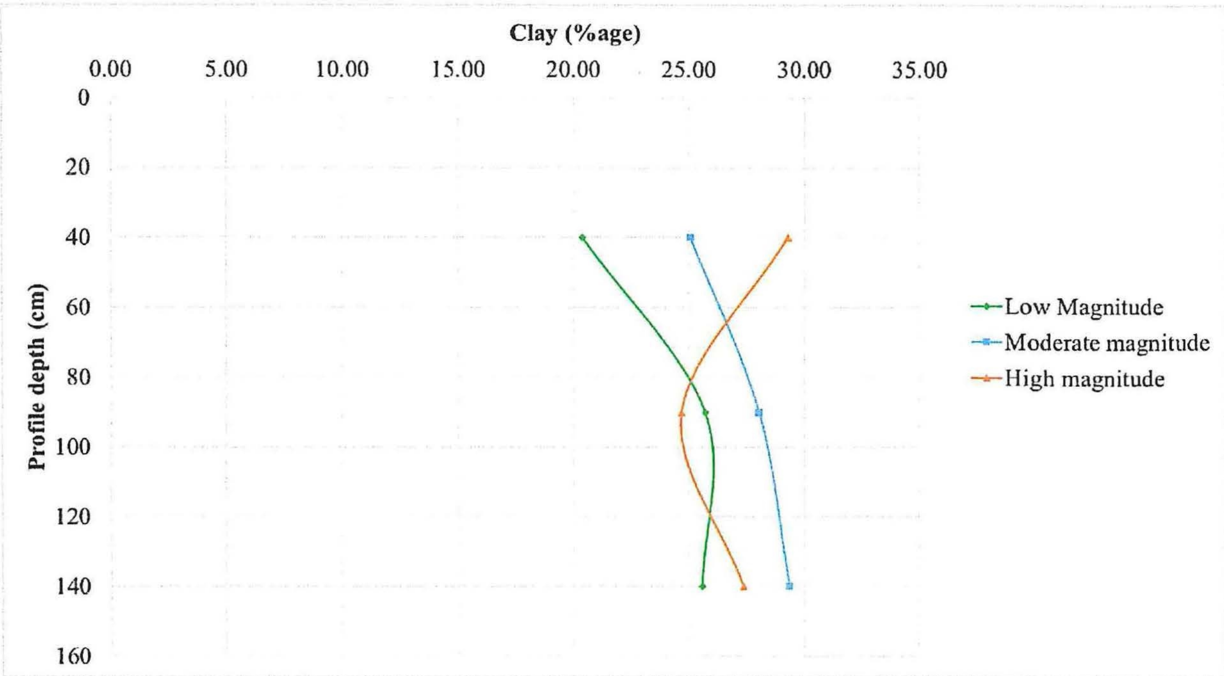


Figure 4.7: Average clay percentage distribution in soil profiles at landslide sites

The results on soil texture proportions as presented in the above show that there exists variations in percent sand, silt, and clay in the soil profiles of the different landslide magnitude sites which could have accounted for the occurrence of landslides of varying magnitude. Analysis of soil textural class results revealed that soils at the landslide sites where majorly of loam and clay loam texture classes at the three observational mean profile depth. The least dominant texture classes were loamy sand, silty loam, and sandy clay loam. This cuts across the different landslide magnitude sites' soil profiles. In general, soil profiles depicted higher quantities of silt and sand as compared to clay. Clay and sand content increased with increase in profile depth whereas percentages of silt decreased with increase in profile depth. The soil texture results imply that landslide magnitude and severity increases where clay and silt proportions increase down the soil profile at the expense of sand proportion. In earlier studies by Poesen & Deckers (2009) and Mugagga et al. (2012) in the same area, landslide soils were reported to be characterized by quantities of clay above 20% which is comparable to the current average of 26% although variations existed at different sites with reference to landslide magnitude classes. The high magnitude landslide sites had the highest mean and maximum clay percentages that is 29.29% and 49% respectively which are well above 32 % clay proportions reported at Nametsi killer landslide site (Mugagga et al., 2012). Kitutu et al. (2009) showed much higher clay percentages at one of landslide sites soil profiles studied, that is, 49.6% and 63.6% for the A and B layers. Even though there are variations in clay content reported in different studies, it is evident enough from the current study that landslide sites are characterized by high clay content (above 25%). In addition, most landslide soil in the current study were of loam and clay loam texture classes although there were sites with clay texture class which results are similar to what was reported by Kitutu et al. (2009).

4.3.3 Depth of weathered profile

Apart from depth at which soil samples were picked for both field and laboratory analysis and mean observation profile depth (referred to here for reporting of findings), general soil profile depth was another pedologic characteristic measured in the field. Results obtained here indicated that the deepest profile extended 320 cm, at Bumwadyeki-Mabono-Sisiyi landslide site 4 BMS whereas the lowest profile extended to 70 cm at Kisakye A-Namudongo-Namisuni debris slide site 13KNN. The overall mean profile depth was 198 cm whereas the deviation away from the mean was by 50.7 cm. The difference in profile depth across landslides magnitude is shown in the exploratory data analysis statistics are shown by boxplots in Figure 4.8 of depth of weathered profile.

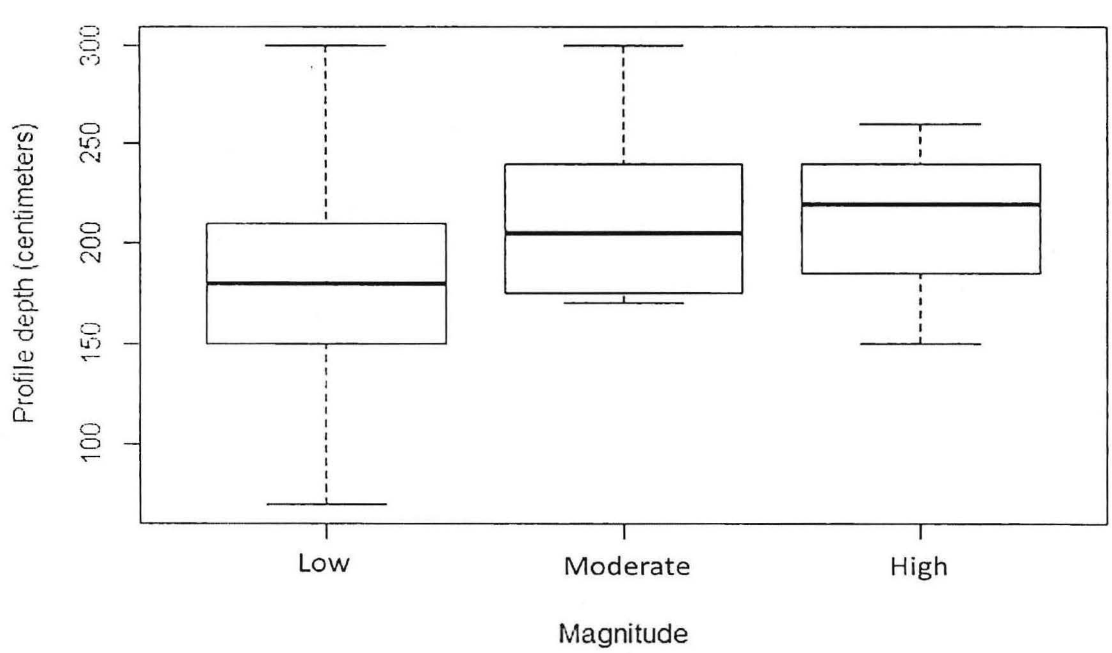


Figure 4.8: Variations in weathered profile depth across landslide magnitude classes

Figure 4.8 indicates that the lowest profile depth was recorded at low magnitude landslide site although low magnitude sites also registered cases of high maximum profile depth. Moderate landslide sites registered both high minimum and maximum profile depth. At high magnitude sites, the minimum depth was still high but the maximum depth was lower than that of the other two classes. However the upper quantile was still higher than that of the low and moderate magnitude sites. These results signify that there were variations in soil weathered profile depths across the different landslide sites and thus magnitude classes mainly in terms of median, minimum, lower and upper quantiles. The implication is that whereas low magnitude landslides can occur in both deeply weathered and shallow profiles, high and moderate magnitude slides are only restricted to profiles with minimum depth of 150 cm and deeper profiles on average.

4.3.4 Degree of bed rock weathering

Bed rock weathering was measured using 3-level-class descriptors that is, slightly weathered (SL), moderately weathered (MO) and strongly weathered (ST) from the soil profiles and/ or surrounding areas such as roadside cuttings. Analysis of the results indicates that landslides sites under the different magnitude classes had bed rock materials that ranged from being moderately weathered to being strongly weathered. However bed rock material under moderate and high magnitude slides were more strongly weathered than those at low magnitude sites. In general, bed rocks 88.8% out of the 45 investigated sites could be scrapped or peeled off from the main bed rock surface with ease. Some moderate and high magnitude landslide sites had strongly weathered bedrock material as deep as 15 meters (Plate 4.8). The material could also be crashed in the hand with minimum force. Only 11.1% of the sites had moderately weathered rocks which required extra force to scrap off with a pocket knife.

Plate 4.8: Strongly weathered bedrock material at selected landslide sites (A=site 45BZ, B= site 4BMS & C= site 35JBB)

These results on bed rock weathering imply that the magnitude of landslides increases where bed rock materials are strongly weathered. The findings indicate further that soil forming processes continue to operate beyond the BC layers (bed rock) of the landslide soils which is also implied in the soil colors' findings (Plate 4.4). An inquiry into the chemical and physical properties of soils at Bumwalukani landslide site in Bududa district by Tamale (2014) and that by Turyabanawe (2014) involving an investigation of the effects of geomorphic processes on slope stability on the slopes of Mount Elgon, unraveled results on soil and rock weathering not far different from those in the current study. The revelation is also in line with the findings by Pachri et al. (2015) who reported that rainfall induced shallow landslides occur in the soil mantle overlying a less permeable bedrock. Wangari (2011) also reported that landslides in the Mt Elgon district in Kenya are commonly experienced on slopes underline by volcanic rocks like pyro-crusts that have been easily weathered thus increasing their permeability and porosity for rainfall triggered landslides. During periods of heavy rain, high pore pressure is responsible for a reduction in slope stability (Jiao, 2000). Jiao (2000) states that deeply weathered igneous rocks like saprolite and gneiss are characterized by high hydraulic conductivity. The geological conditions associated with high sliding potential include weathered basalt, granite and volcanic rocks and weathered interbedded rocks like clay and limestone (Robinson, 1985).

4.3.5 Proportion of rock fragments

Related to the degree of bed rock weathering is proportion of rock fragments in the soil profile layers at landslide sites which was also measured during the field study. Six descriptors were used that is, very few, few, common, many, and very many and latter converted to corresponding percentages; 1-10, 11-20, 21-30, 31-50, 51 and 90. Rock fragments in profiles of some of the sites are shown in Plate 4.9.

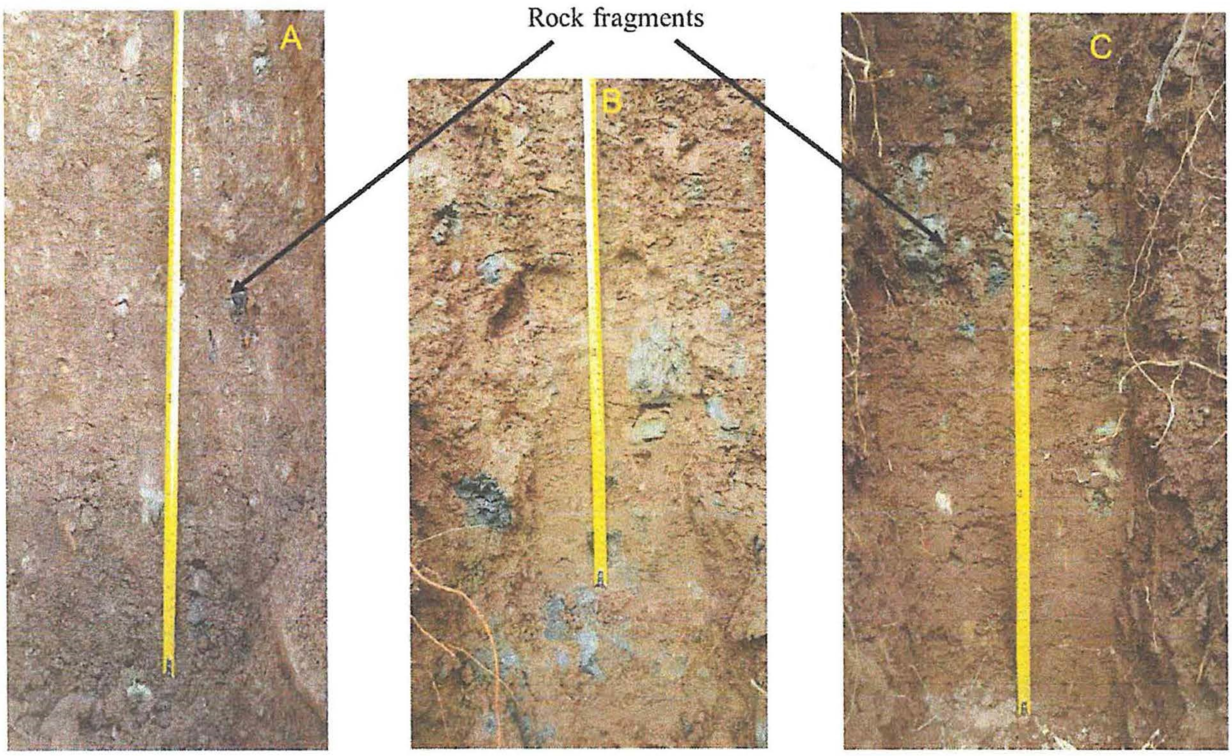


Plate 4.9: Residual rocks in the weathered profiles at selected sites (Nalufudu-Namisuni (A) Jibaru-Bugitimwa (B) and Naloli-Buteza (C)

The descriptive summary statistics from the analysis of rock fragments' data shown in Appendix VI is presented in the Table 4.7.

Table 4.7: Descriptive summary statistics for percentage of rock fragments in landslide sites' soil profiles

	Depth of observation in the profile depth								
	0-40 cm			41-90 cm			91-140 cm		
Magnitude	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**	**Mean**	**Stdv**	**Min-Max**
Low	4.6	6.39	1-25	13.23	26.53	1-90	29.33	18.13	5-100
Moderate	6.5	13.98	1-50	13	24.4	1-90	22.08	12.15	5-50
High	3.67	2.31	1-5	13.33	10.41	5-25	20	8.66	10-25

Table 4.7 reveals that at low magnitude sites, mean percentage of rock fragments increased in soil profile layers towards the bed rock that is, from to 4.6% to 13.23% and 29.33%. At moderate magnitude sites, rock fragments increased from 6.5% to 13% and to 22.08% down the profile. At high magnitude sites, mean percentage of rock fragments increased from 3.67% to 13.33% and to 20%. However, there were slight variations in the mean percentages of rock fragments especially in the first 40cm and the soil profile layers >90 cm in the different magnitude slides. The main differences in rock fragments concentration at the different landslide magnitude sites were emergent in maximum (upper limits) and surprisingly the low and moderate magnitude classes all had higher maximum rock fragments' proportions (90%) in their profiles than landslides under the high magnitude. The distribution of rock fragments in the soil profiles of different landside magnitude classes is visualized in Figure 4.9.

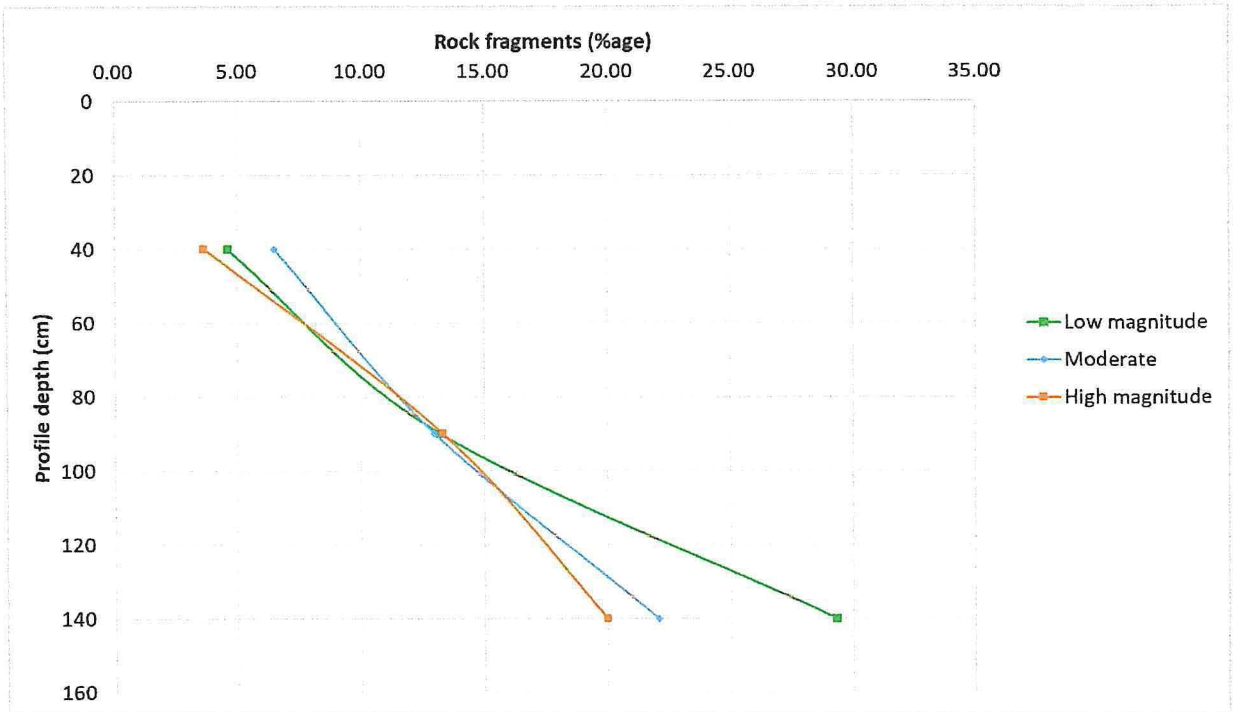


Figure 4.9: Distribution of rock fragments under the three landslide magnitude classes

The results on distribution of rock fragments in respect to landslide magnitude as shown above imply that landslide sites' soils are characterized by rock fragments in percentages ranging from as low as 5% to as high as 90%. The concentration of rock fragments increases with increase in depth down the profile. The first 40cm profile layers have less than 10 % rock fragments. The B2-B3 layers have between 10 and 20 % whereas the lower BC layers have more than 30 % rock fragments. These vary in size between 7mm to 200mm. The rock fragments' sizes also increase with depth down the profiles. In a study by Turyabanawe (2014), soil profiles at landslide sites at Maboona in Buduada were reported to have had varying proportions of rock fragments. The differences in rock fragments' composition bring about differences in landslide expressions thus differences in landslide magnitude. Where large rock fragments are involved just like at sites 9NNN and 25 BNN in the current study landslide magnitude also increases as these increases the stress conditions of the slope material especially when saturated.

4.3.6 Presence of seepage surfaces

Another aspect related to landslide initiation and measured during the study is evidence of seepage surfaces measured by evidence of discharge points at the landslide sites. This landslide site characteristic was evaluated on a binary scale that is, presence or absence of subsurface water flow in form of springs within the landslide scar and/or areas within the vicinity. The results obtained revealed that indicate that 60% of the low magnitude sites had evidence of seepage water surfaces as compared to 40% of the sites without. 75 % of the sites under moderate magnitude landslide site had evidence of seepage surfaces whereas only 25% did not have. At high magnitude slides sites, 66.7% had evidence of seepage surfaces compared to 33.3% without. Generally, out of the 45 sites investigated, 56% sites had evidence of subsurface discharge within their scars in form of springs (Plate 4.10) whereas the remaining 20 (44%) sites had no evidence of sub-surface flow. Most of the sites also had rivers flowing within their vicinity moreover some sites had river cutting at their toe slopes.

Plate 4.10: Seepage surfaces at selected landslide sites (A=Site 13LKN, B=Site 16MGS & C=Site 44CBZ)

The findings above point to the fact seepage surfaces in the subsurface soil layers could have played a major role not only in initiating the previous slides but also increasing their magnitude in the Mt Elgon areas. For rainfall triggered landslides like those in the Elgon areas, subsurface water flow implies increased pore pressure and reduced slope material bearing strength. While studying the impact of confined groundwater zone in weathered igneous rocks on slope stability in (Jiao, 2000) reported deep seated landslides to be associated with complex hydrogeological conditions; a situation related to the Elgon high magnitude landslides.

4.3.7 Soil chemical properties and landside magnitude

Na content of landslide sites' soils was the main soil mineral element investigated in this study using laboratory analysis methods. The other mineral elements like clay were inferred from other pedologic properties like profile weathering, particle size distribution and soil color. Na content was measured in terms of proportions of concentration in the soil volume of 100 grams (ppm) and thus can be reported as percentages (Appendix VII). The summary statistics of the results obtained on extractable Na content are shown in Table 4.10.

Table 4.8: Descriptive summary statistics for Na content in landslide sites' soil profiles

	Depth of observation in the profile depth								
	0-40 cm			41-90 cm			91-140 cm		
Magnitude	Mean	Stdv	Min-Max	Mean	Stdv	Min-Max	Mean	Stdv	Min-Max
Low	28.44	3.94	20.7-36.8	27.84	3.33	20.7-39.1	27.17	3.13	20.7-32.2
Moderate	27.6	3.4	20.7-32.2	26.7	2.83	20.7-29.9	25.88	3.69	20.7-32.2
High	26.07	4.79	20.7-29.9	27.6	2.3	25.3-29.9	28.37	4.79	23-32

Table 4.8 reveals that at low magnitude landslide sites, mean Na content decreased with increase in profile depth from 28.44 to 27.84 and to 27.17. At moderate magnitude landslides sites, sodium content decreased from 27.6 to 26.7 and to 25.88 down the profile. At high magnitude sites, Na proportions increased with increase in profile depth that is from 26.07 to 27.6 and to 28.37. Deviations away from the mean for all the landslide magnitude classes ranged between 2 and 4 at the three observational ranges (0-40cm, 41-90cm & 91-140cm) in the profiles. The distribution of Na content in soil profiles with reference to the three landslide magnitude classes are further visualized in the line plots in Figure 4.10.

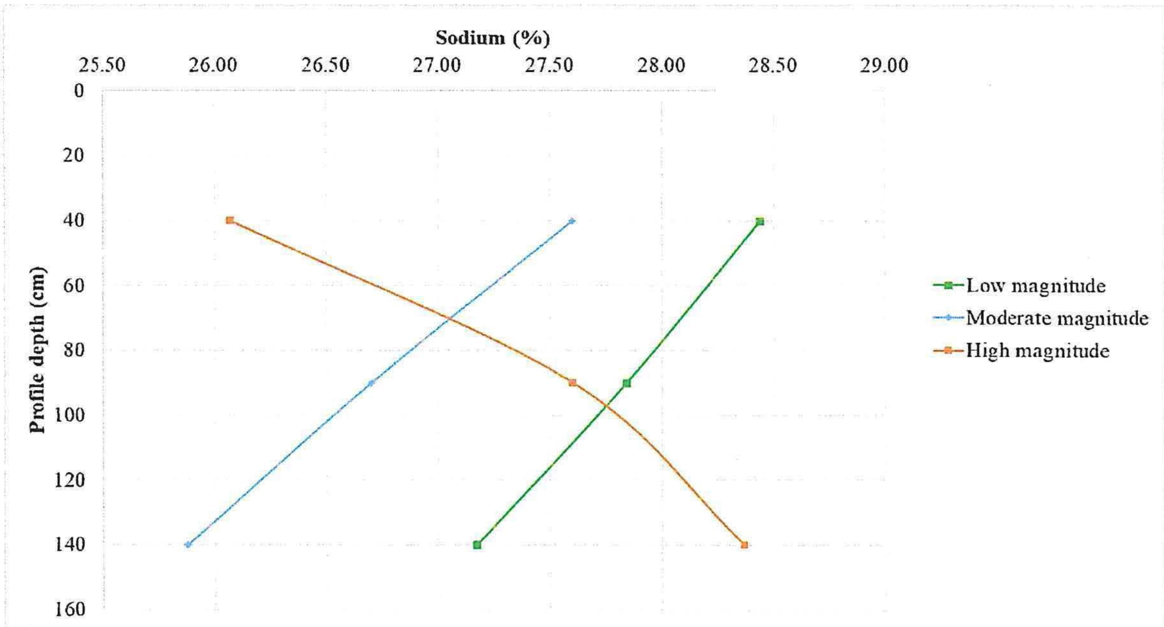


Figure 4.10: Mean Na content versus depth of soil at landslide sites

Figure 4.9 indicates that average Na content decreased with increase in profile depth for low and moderate magnitude landslide soils. However, Na content increased with increase in profile depth for high magnitude landslide soils. The line plots above reveal that there is an inverse relationship between profile depth and sodium content at low and moderate magnitude landslide sites and a direct relationship at high magnitude landslides. However, because low and moderate magnitude slides were established in this study to occur under relatively poorly weathered soil profiles, it would be expected that sodium content in their soil profiles occur in the lower layers close to the bed rock. Their appearance close to the surface is a phenomena that demands further inquiry.

Generally, all landslides sites were characterized by large quantities of exchangeable Na content. Presence of large quantities of sodium content in the soil hardens soil particles, causing them to repel thus destroying soil structure (Marchuk & Rengasamy, 2013; Boul, 2003). According to ACCESS (2015) sodic rocks exist at higher altitudes on Mount Elgon slopes, beyond where samples for the current study were picked. However higher quantities in the lower profile layers of high magnitude sites soils signal that there could be cases of sodicity in rocks underlying some landslide sites and thus play a role facilitating slope failure. To Vingiani et al. (2015) sodicity can be caused by land-use related activities, which explanation could account for some of the Na in the upper soil layers recorded at low and moderate landslides sites in the present study. Sodium content is of paramount importance in dispersion of various clay minerals like Montmorillonite (Rolfe & Miller, 1960) which are associated with volcanic soils such as those in the Elgon areas and prone to land sliding. Vingiani et al. (2015) while establishing the relationship between volcanic soils and landslides reported high Na content between 40-65% in the soil profiles at the three landslide slide sites studied which confirms that fact that sodium participates in landslide occurrence if present in the soil profiles.

4.4 Spatial distribution of landslides magnitude in Sironko and Bulamabuli districts

From the random forest modeling efforts aimed at ascertaining the spatial distribution of landslide magnitude classes in the study area, four zones representing low magnitude, moderate magnitude, high magnitude and unaffected areas were delineated and the results are shown by the map in Figure 4.11.

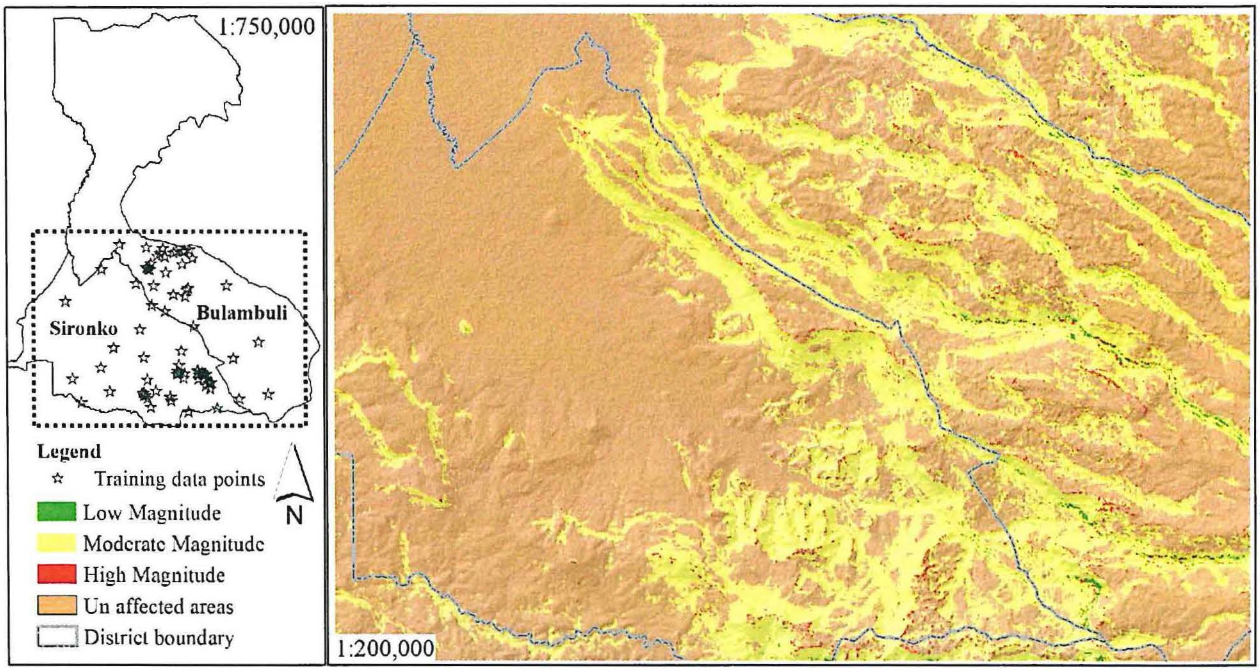


Figure 4.11: Landslide magnitude distribution in Sironko and Bulambuli

Due to the limited model training data, it was not possible to validate the random forest model results shown here (Figure 4.10). However the model with 900 trees was used in landslide magnitude prediction because it had the lowest out of bag error (27.85%) signifying best accuracy consideration. A close scrutiny of the results shows that some classes of landslide magnitude were misclassified for example some of the landslides under low and high magnitude were misclassified either under moderate magnitude class or unaffected areas. The misclassification could be explained by the fact that the data set used in model development was unbalanced between the four classes. The model prediction accuracy plot of the magnitude classes at 900 trees is shown in Figure 4.12.

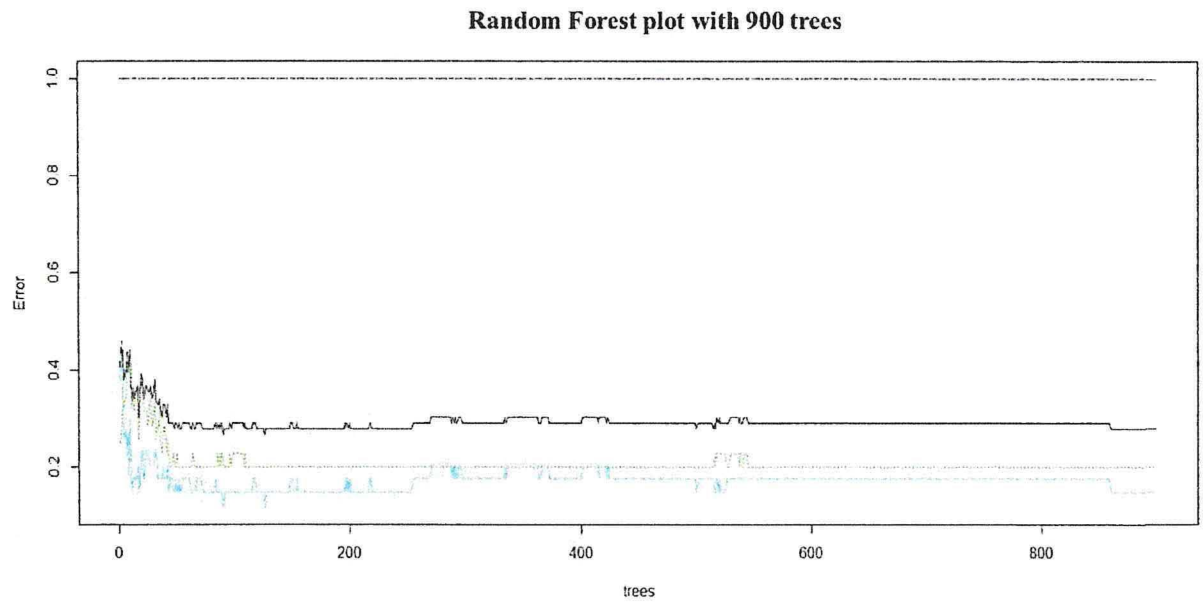


Figure 4.12: Random forest model performance with 900 trees

From the landslide magnitude classes' spatial prediction output (Figure 4.11), a land area of 507.15 km^2 is landslide free, 2.5 km^2 area is under low magnitude, and 205.43 km^2 is under moderate magnitude whilst 5.14 km^2 is under high magnitude. The implication of these findings is that, the major (low moderate and high) landslide magnitude classes are unevenly distributed over landscape in Sironko and Bulambuli districts. However, the landscape in the two districts is more susceptible to moderate magnitude landslides (29%) and least likely to be affected by high (0.7%) and low magnitude landslides (0.3%).

Basing on expert judgement of the location of landslide sites during the field study, sites now under low magnitude landslides were common on lower slopes whereas moderate and high magnitude landslides were common on back slope positions of cliffs and ridges (Plate 4.11) which is consistent with the areas delineated on the spatial distribution map. A quick look at Mean Decrease Accuracy (MDA) shows that slope was the second highest contributor to mean decrease accuracy. This makes it one most important variable in landslide magnitude spatial prediction.

Figure 4.13 indicates that 14 out of the 18 predictors used in the model had positive Mean Decrease Accuracy whereas only four predictors, that is slope length, soil type, FAO soil class, and longitudinal curvature had negative MDA. With reference to the model, these results imply that exclusion of the 14 predictors with positive MDA from the model would reduce the prediction whereas exclusion of those predictors with zero or negative MDA would have no impact on the prediction accuracy of the model. With reference to the spatial distribution of landslides, the results here imply that topography as measured by surface area, slope, TPI 100-1500, elevation, profile curvature, TWI and geology as measured by parent material significantly influence the magnitude and distribution of landslides experienced in the Mount Elgon areas of Sironko and Bulambuli. The influence becomes stronger when these drivers interact thus increasing the magnitude of landslides. However, where spatial terrain characteristics are involved in the prediction, influence of soil characteristics is shielded under slope since the later influences general land geomorphology from which soils develop (Grozavu & Patriche, 2010). For this reason, soil type and FAO soil class were shown as having no contribution towards model accuracy. This means that, in the landslide prediction modeling, inclusion or exclusion of soil spatial data won't improve on model performance. The only terrain related attributes that were shown as poor predictors in the model were slope length and longitudinal curvature.

Surface area was the strongest predictor of landslide magnitude distribution in the study area. It is part of the local relief conditions that predispose slope material to sliding as it represents area size for possible saturation. Elevation was among the top five predictors of landslide magnitude distribution which means that it has a strong influence on landslide prediction. Represented by height of land above sea level, elevation infers special characteristics on climate, vegetation and energy potential on the slope (Schillaci & Braun, 2015). Vingiani et al. (2015) while assessing landslides in spatial scale for each event reports that highest landslide contribution belonged to the slope elevation between 1500-2000 meters.

TPI was shown to contribute positively towards landslide spatial distribution at scales ranging from 100-1500 meters which imply that its role in landslide occurrence in paramount as it represents the impact of slope on landscape processes. However, when used in landscape processes modeling, care should be taken to have several processing windows since it is scale dependent. For example in the present study, TPI at scale of 700 meters contributed strongly towards model prediction as compared to that at 100 meters. TWI was also shown to improve model performance which signifies that landslides are initiated in zones of saturation and runoff generation. This justifies why landslides in the Elgon areas occur during or after rain, when slope material gets saturated in specific slope positions triggering off slope material movements (Kitutu, 2013). Besides, TWI is strongly related to other landslide predisposing processes and factors (Gorsevski, 2006; Oh & Lee, 2017).

Slope as one of the terrain attributes used in this study has been shown elsewhere to have strong influence on landslide occurrence (Guzzetti, 2002, 2005; Knapen et al., 2006; Claessens et al., 2007; Kimono, 2010; Muggaga, 2011; Mugagga et al., 2012; Kitutu, 2013). In a study by Mugagga (2010) conducted on the southern slopes of Mount Elgon where landslide scar locations were overlaid onto a slope map of the study area, a positive correlation was established between landslide occurrence and slope. Dragicevic et al. (2015) conducted a review of the influence of terrain attributes like elevation, aspect, and other topographic indices' on occurrence of landslides and for most attributes, positive relationships with landslide occurrence were reported to exist.

Soil type and FAO class in this study were shown to be poor predictors of landslide magnitude, given their negative VI values. A study by Kitutu et al. (2009) involving determination of the of soil types and their influence on landslide occurrence on the southern slopes of Mt. Elgon showed the influence of soil type on landslide occurrence as not being significant. It was further noted that soil texture was significant in some landslides. This is in conformity with the findings in the current study where during the mapping of soil profile characteristics of landslide sites, it was established that variations in texture and depth of weathered profile are linked to various landslide magnitude classes. Mugagga et al. (2012)'s study also returned soil properties' results at landslide sites not so different from what was established in the current study.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This chapter presents summary of the study findings, conclusions and recommendations. The recommendations cover areas related to policy and future research needs.

5.2 Summary

This study involved categorizing landslides into magnitude classes, mapping the relationship between derived landslide magnitude classes and pedologic properties at landslide sites and predicting the spatial distribution of landslides based upon magnitude in Mount Elgon areas of Sironko and Bulambuli districts. Basing on the fact that landslide magnitude is best measured by volume, area/size, and flow length, landslides have been categorized into low, moderate and high magnitude and these fit perfectly in the approach adopted because if applied as used previously in other studies, the results would be misleading as far as interpretation of landslide magnitude is concerned. These landslides express themselves differently due to variations in soil structure, soil seepage surfaces, degree of bedrock weathering, soil consistency, percentage of clay in the soil, sodium content and depth of weathered profile. The three classes of landslide magnitude have also been spatially predicted over the study area using DEM derived terrain attributes and soil spatial layers as key landslide drivers using RF modeling in R. The RF model output map is a clear and definite representation of the potential future landslide areas and their corresponding magnitude (low magnitude-0.3%, moderate magnitude-29% and high magnitude landslides-0.7%, whilst 70% of the area is landslide-free. The contribution of each of the predictor variables towards the prediction as indicated by variable importance by means of MDA shows that surface area, slope, and elevation contribute highly towards landslide spatial prediction whereas soil class, soil type and longitudinal curvature are poor predictors. The influence of soil is shielded when slope is used as a predictor. The predictors shown to have contributed positively towards landslide magnitude spatial prediction here represent landslide drivers that can be further used to delineate landslide prone areas.

5.3 Conclusions

A number of conclusions are construed basing on the study findings shown in previous chapters of this report which include the following.

It is possible to characterize landslides basing on three parameters reflective of magnitude that is, volume, area and flow length, using an objective statistical classification.

A large proportion of the land (29%) in Sironko and Bulambuli is susceptible to moderate magnitude landslides but also an equally large area (70%) is not at threat of landslides. High magnitude landslides are limited in the area (accounting for only 0.7% land area). Moreover, these are mostly restricted to areas not currently being used for agriculture.

Soil, topography and geology impact on the classes of landslides experienced in Mt. Elgon areas of Sironko and Sironko. Evidence shown by this study (RF VI) suggests that the magnitude of landslides relates strongly to the difference in soil, topography and geology of the area.

5.3 Recommendations

Basing on the findings in this study, a number of recommendations are made to address issues of methodology and policy.

a) An extensive survey of all landslide scars in the current study areas is necessary for comparison against the approach which has been used here to see whether it is satisfactory after all it's noted that the approach is somehow consistent with the literature only if volume or area is used independently.
b) While this study has attempted to further the understanding of the linkage between landslide magnitude and pedological properties, it is important that analysis be done to understand the interplay between clay mineralogy and landslide magnitude including any differences there are between clay minerology and the classes of landslides.
c) In this study, it was noted that about 70% of the land in the study area is landslide-free. Unfortunately this land is mostly in the lowlands or tops of hills. The challenge is how to make use of 30% of land predisposed to landslides mostly of moderate magnitude. Since this land area is in low proportions, it can be used for activities that require minimal land interference such as is the case with forestry and conservation. This is especially possible

given the need for wood fuel. Where this area is to be used, it is important that structural measures to stabilize the slopes are applied but also that crops grown are in the category of annuals.

REFERENCES

ACCESS (2015) Atlas of Mt. Elgon. Prepared by African Collaborative Centre for Earth System Science (ACCESS). Authors: Thomas J. Ballatore and Lydia Olaka. Edited by Eric Odada and Daniel Olago. Published by USAID/IUCN. 54p.

Alimohammadlou, Y., Najafi, A., & Yalcin, A. (2013). Landslide process and impacts: A proposed classification method. *Catena, 104*, 219–232. https://doi.org/10.1016/j.catena.2012.11.013

Ayalew, L., & Yamagishi, H. (2005). The application of GIS-based logistic regression for landslide susceptibility mapping in the Kakuda-Yahiko Mountains , Central Japan, *65*, 15–31. https://doi.org/10.1016/j.geomorph.2004.06.010

Brussel, V. U. (2014). Soil characterization in the landslide-prone area, 2013–2014.

C. P. B. (1977). Soil Taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. 1975. 754 pp., 12 coloured plates. Agriculture Handbook No. 436. Soil Conservation Service, U.S. Department of Agriculture. From Superintendent of Documents, U. *Geological Magazine*, *114*(06), 492. https://doi.org/10.1017/S0016756800045489

Claessens, L., Knapen, A., Kitutu, M. G., Poesen, J., & Deckers, J. A. (2007). Modelling landslide hazard, soil redistribution and sediment yield of landslides on the Ugandan footslopes of Mount Elgon. *Geomorphology*, *90*(1–2), 23–35. https://doi.org/10.1016/j.geomorph.2007.01.007

Conoscenti, C., Rotigliano, E., Cama, M., Caraballo-arias, N. A., Lombardo, L., & Agnesi, V. (2016). Geomorphology Exploring the effect of absence selection on landslide susceptibility models : A case study in Sicily , Italy. *Geomorphology*, *261*, 222–235. https://doi.org/10.1016/j.geomorph.2016.03.006

Corominas, J, van Westen, C, Frattini, P, Cascini, L, Malet, J. P, Fotopoulou, S, Smith, J. T. (2014). Recommendations for the quantitative analysis of landslide risk. *Bulletin of Engineering Geology and the Environment*, *73*(2). https://doi.org/10.1007/s10064-013-0538-8

Cruden, D. M. (1990). The Working Classification of Landslides : material matters.

D£ugosz, M. (2012). Digital Terrain Model (DTM) As a Tool for Landslide Investigation, *Xlvi*(62), 5–23. https://doi.org/10.2478/v10302-012-000

Dai, F. C., Lee, C. F., & Ngai, Y. Y. (2002). Landslide risk assessment and management : an overview, *64*, 65–87.

Deng, X., Li, L., & Tan, Y. (2017). Validation of Spatial Prediction Models for Landslide Susceptibility Mapping by Considering Structural Similarity. https://doi.org/10.3390/ijgi6040103

Eeckhaut, M. Van Den, Hervás, J., Jaedicke, C., & Malet, J. (2010). Calibration of logistic regression coefficients from limited landslide inventory data for European-wide landslide susceptibility modelling, 515–521.

Ehrlinger, J. (2014). ggRandomForests : Random Forests for Regression, (Breiman 2001).

Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., & Savage, W. Z. (2008). Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning. *Engineering Geology*, *102*(3–4), 99–111. https://doi.org/10.1016/j.enggeo.2008.03.014

Gorsevski, P. V, Gessler, P. E., & Elliot, W. J. (2006). Spatial Prediction of Landslide Hazard Using Logistic Regression and ROC Analysis, *10*(3), 395–415.

Grozavu, A., M, M. C., & Patriche, C. V. (2010.). GIS applications for landslide susceptibility assessment : a case study in Ia ş i County (Moldavian Plateau , Romania), *43*, 393–404. https://doi.org/10.2495/Risk100341

Guzzetti, F. (2002). Landslide Hazard Assessment and Risk Evaluation: Limits and Prospectives, (October 2002).

Guzzetti, F. (2005). Landslide hazard and risk assessment. *Tesis Doctoral*, 373. Retrieved from http://geomorphology.irpi.cnr.it/Members/fausto/PhD-dissertation

Husin, M. A. Y. M., Wulandary, H. F., & Musta, B. (2014). Effect of moisture on the strength of soil from Crocker formation in Tamparuli, Sabah, Malaysia. *Electronic Journal of Geotechnical Engineering*, *19*(Z1), 9643–9652.

IUSS Working Group WRB. (2014). *World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106*. https://doi.org/10.1017/S0014479706394902

Iwahashi, J., Okatani, T., Nakano, T., & Koarai, M. (2014). Landslide Susceptibility Analysis by Terrain and Vegetation Attributes Derived from Pre-event LiDAR data : a case study of granitic mountain slopes in Hofu ,.

Jiao, J. J. (2000). A confined groundwater zone in weathered igneous rocks and its impact on slope stability 1 Introduction 2 Hydrogeology and failure features of some deep-seated landslides in Hong Kong.

Jiao, J., Nandy, S., & Malone, A. (1999). Hydrogeological studies of the slope failure at Tuen Mun highway chainage 550, Hong Kong. *Proc., 2nd Int. Conf. on Landslides, Slope ...*, 27–28. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.157.3603&rep=rep1&type=pdf

Kimono, K., & Goretti, M. (2010). *Landslide Occurrences in the Hilly Areas of Bududa District in Eastern Uganda and Their Causes a Thesis Submitted To the Graduate School for the Award of the Degree of Doctor of Philosophy*.

Kitutu. (2013). Uganda National Commission for Unesco Study on The Natural-Hazards Vulnerability and Risk Profiles In Hot- By Dr . Kitutu Kimono Mary Goretti.

Knapen, A., Kitutu, M. G., Poesen, J., Breugelmans, W., Deckers, J., & Muwanga, A. (2006). Landslides in a densely populated county at the footslopes of Mount Elgon (Uganda): Characteristics and causal factors. *Geomorphology*, *73*(1–2), 149–165. https://doi.org/10.1016/j.geomorph.2005.07.004

Lanni, C. (2012). Hydrological controls on the triggering of shallow landslides: from local to landscape scale, 155.

Lanni, C., Borga, M., Rigon, R., & Tarolli, P. (2012). Modelling shallow landslide susceptibility by means of a subsurface flow path connectivity index and estimates of soil depth spatial distribution, 3959–3971. https://doi.org/10.5194/hess-16-3959-2012

Lewis, Y. W. (2008). Geologic Controls for Landslides in the Central American Highlands, 1–52.

Longoya D. (2012). Feasibility Study Report. Mt Elgon Landslide Information Needs Landslides: *Cause and Effect*, (October).

Longoya D. (2012). Capacity assessment to undertake Vulnerability and Impact Assessment (VIA) for the Ecosystem Based Adaptation (EBA) in Mt Elgon Ecosystem-Uganda.

Marchuk, A., Rengasamy, P., & Mcneill, A. (2013). Influence of organic matter , clay mineralogy , and pH on the effects of CROSS on soil structure is related to the zeta potential of the dispersed clay, (January). https://doi.org/10.1071/SR13012

Msilimba, G. G. A. C. (2007). A Comparative Study of Landslides and Geohazard Mitigation in Northern and Central Malawi. A *thesis Submitted for the Degree Doctor of Philosophy, Faculty of Agricultural and Natural Sciences, Department of Geography, University of the Free State*

Muggaga, F. (2011). Land use change, landslide occurance & livelihood strategies on Mt. Elgon Slopes, Eastern Uganda, (January).

Mugagga, F., Kakembo, V., & Buyinza, M. (2012a). A characterisation of the physical properties of soil and the implications for landslide occurrence on the slopes of Mount Elgon, Eastern Uganda. *Natural Hazard*, *60*(3), 1113–1131. https://doi.org/10.1007/s11069-011-9896-3

Mugagga, F., Kakembo, V., & Buyinza, M. (2012b). Land use changes on the slopes of Mount Elgon and the implications for the occurrence of landslides. *Catena*, *90*, 39–46. https://doi.org/10.1016/j.catena.2011.11.004

Nchez, J. (1998). The frequency and distribution of Larsen, M.C., Torres Sa recent landslides in three montane tropical regions of Puerto Rico. *Geomorphology*, *24309e331*, 309–331.

National Environment Management Authority (NEMA). (2008). State of the Environment Report for Uganda, 265 pg.

NEMA (2009), "Uganda: Atlas of Our Changing Environment." National Environment Management Authority (NEMA) P. O Box 22255 Kampala Uganda

NEMA Uganda (2010). State of the Environment Report for Uganda 2010, 205. Retrieved from http://www.nemaug.org/national_s_o_reports.php

NEMA (2011). Bulambuli District Landslides Report, (August), 1–10.

Oh, H., & Lee, S. (2017). applied sciences Shallow Landslide Susceptibility Modeling Using the Data Mining Models Artificial Neural Network and Boosted Tree, 1–14. https://doi.org/10.3390/app7101000

Pachri, H., Mitani, Y., Ikemi, H., & Jiang, W. (2015). Spatial Variation of Soil Depth and Shallow Slope Failures in Sangun Mountains , Fukuoka Prefecture , Japan, *2015*(August), 813–820.

Poesen, M. G. K. M. J., & Deckers, J. (2009). Influence of soil properties on landslide occurrences in Bududa district , Eastern Uganda. *African Journal of Agricultural Research*, *4*(July), 611–620. https://doi.org/10.5897/AJAR09.158

Ramachandra, T. V. (2012). Landslide Susceptible Zone Mapping in Uttara Kannada , Central Western Ghats.

Ray, R. L., Jacobs, J. M., & Ballestero, T. P. (2011). Regional landslide susceptibility : spatiotemporal variations under dynamic soil moisture conditions. https://doi.org/10.1007/s11069-011-9834-4

Robinson, K. J. (1985). Australian Geomechanics News, *42*(1).

Sahoo, S. (2009). A Semi Quantitative Landslide Susceptibility Assessment using Logistic

Regression Model and Rock Mass Classification System : Study in a Part of Uttarakhand Himalaya , India Semi Q uantitat tive Lan ptibility Assess sment.

Salvacion, A. R. (2016). Terrain characterization of Small Island using publicly available data and open- source software : a case study of Marinduque, Philippines. *Modeling Earth Systems and Environment*, *2*(1), 1–9. https://doi.org/10.1007/s40808-016-0085-y

Schillaci, C., & Braun, A. (2015). Terrain analysis and landform recognition, *2*, 1–18.

Schlögel, R., Marchesini, I., Alvioli, M., Reichenbach, P., Rossi, M., & Malet, J. (2017). Abstract NU SC regression models. *Geomorphology*. https://doi.org/10.1016/j.geomorph.2017.10.018

Schuster, R. L., & Highland, L. M. (2008). Impact of Landslides and Innovative Landslide-Mitigation Measures on the Natural Environment, (1978).

Singh, R. G. (2009). Landslide Classification , Characterization and Susceptibility Modeling in Kwazulu-Nata, 170.

Soil, N., Resources, N., & Service, C. (2002). Field Book for Describing and Sampling Soils. *Agriculture*, *33*(September), 1–228. https://doi.org/10.1111/j.1600-0587.2009.05973.x

Soil Survey Staff. (2014). Soil survey field and laboratory methods manual. *Soil survey investigations report no. 51*, Version 2.0, (51), 487.

Turyabanawe, L.G (2014). Effects of Geomorphic Processes and Land Use Activities on Slope Stability in Mount Elgon Region, Eastern Uganda. *A thesis submitted in fulfilment of the Degree of Doctor of Philosophy in the School of Humanity and Social Sciences of Kenyatta University*

USGS (2004). Landslide Types and Processes. *Highway Research Board Special Report*, (July), 1–4. https://doi.org/Fact Sheet 2004-3072

Verlag, C., & Jentzsch-cuvillier, I. A. (n.d.). Gerd Robert Rücker (Autor) Spatial variability of soils on national and hillslope scale in Uganda, *49*(0), 0–5.

Vingiani, S., Mele, G., Mascellis, R. De, Terribile, F., & Basile, A. (2015). Volcanic soils and landslides : a case study of the island of Ischia (southern Italy) and its relationship with other Campania events, (May 1998), 783–797. https://doi.org/10.5194/se-6-783-2015

Wangari, K. E. (2011). Comparative Factors that Influence Landslide Occurrence : Application of Gis and Rainfall Thresholds in Landslide Assessment in Kenya.

Weiss, A. D., & Conservancy, T. N. (2000). Topographic Position and Landforms Analysis, 200.

Westerberg, L.-O., & Christiansson, C. (1999). Highlands in East Africa: unstable slopes, unstable environments? *AMBIO - A Journal of the Human Environment*, *28*(5), 419. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=8gh&AN=8375419&site=ehost-live

Wieczorek, G. F., & Snyder, J. B. (2009). Monitoring slope movements, (11), 245–271. https://doi.org/10.1130/2009.monitoring(11).

Wilson, J. P. (2012). Geomorphology Digital terrain modeling. *Geomorphology*, *137*(1), 107–121. https://doi.org/10.1016/j.geomorph.2011.03.012

APPENDICES

Appendix I: Field Data Collection Sheets

Landslide Scar Characteristics Date: ____/____/_______.

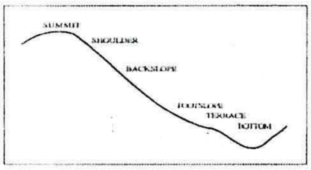
1. Location

Site ID: ____________________. Village: _________________. Parish: ___________________.

Sub-County: _________________________.

Latitude: ________________. N. Longitude: _______________. E. Altitude: __________. (masl)

Slope position:



2. Scar Dimensions & Materials

Approximate depth: ____________________. (m). Approximate Length: _________________. (m)

Width: __________. (m). Length of material movement: ___________. (m). Area: ________.$(m^2$

Type of movements

Rotational Slide (Slump)		Translational Slide	
Topple		Rock Slide	
Rock Fall		Debris Slide	
Flow		Complex movement	

Material Composition (e.g. fine earth and or rock) _______________________________________

3. Land-use and Additional Site Notes

____

____

____

____

____

Soil profile description

Profile No._________________________. Map Reference: ________________________________

Weather Conditions:

Sunny	
Partly cloudy	
Overcast	
Rain	

Profile (axis)								
Surface		General profile characteristics	Specific profile characteristics					
Evidence of cracking[1]	Excavation difficulty[2]	Depth of profie weathering[3]	Depth of observation (cm)	Characteristics				
				Color[4]	Rock Fragments[5]	Plasticity[6]	Structure	
							No[7]	Yes[8]

[1]Use the following descriptors as applicable: RCR, ICR, RTH, ITH.
[2]Use the following descriptors as applicable: L, M, H, VH, EH.
[3]Use the following descriptors as applicable: SL, MO, ST.
[4]Report color: Hue Value & Chroma and state of the sample (**Wet** or **Dry**).
[5]Use the following descriptors as applicable: vf, f, c, m, vn.
[6]Use the following descriptors as applicable: po, sp, p, vp
[7]Use the following descriptors as applicable: sgr, Ma.
[8]Use the following descriptors as applicable: gr, abk, sbk, pl, wed, pr.

Appendix II: Study sites' IDs and their geographic location

SiteID	Easting	Nothing	Altitude	Village	Parish	SCounty
1GSB	649180	135977	1901	Gombe	Sotti	Buluganya
2BBB	650866	135221	1731	Bundesi	Buluganya	Buluganya
3ZLS	649459	138478	1642	Zamalini	Luzzi	Sisiyi
4BMS	648790	140950	1610	Bumwadyeki	Mabono	Sisiyi
5NMS	648509	140838	1552	Nakidibo	Mabono	Sisiyi
6KMS	648896	140592	1614	Kimuli	Mabono	Sisiyi
7KMS	648685	140624	1574	Kamwanyi	Mabono	Sisiyi
8NNN	653442	142995	1725	Nalufudu	Namudongo	Namisuni
9NNN	654055	143149	1765	Nalufudu	Namudongo	Namisuni
10MNN	653441	142926	1762	Mabono	Namudongo	Namisuni
11NNN	653182	142935	1694	Nalufudu	Namudongo	Namisuni
12KGS	650234	142711	1554	Kitondwani	Gibuzale	Sisiyi
13LKN	652354	142967	1670	Lunyodo	Kisakye	Namisuni
14KNN	652013	142772	1775	Kisakye A	Namudongo	Namisuni
15KGS	650924	142251	1660	Kisotonni	Gibuzale	Sisiyi
16MGS	649864	142394	1627	Majjikiri	Gibuzale	Sisiyi
17SCM	649054	141358	1640	Chiluku	Mabono	Sisiyi
18SBL	653863	138171	2173	Suguta	Bunabude	Lusha
19KGS	653614	137977	2165	Kirwali	Gombe	Lusha
20NKB	653510	137122	2177	Nasanga	Kimuli	Bulago
21NBB	652662	128252	1403	Nakulu	Bufaka	Bumasifwa
22BBB	652473	127487	1319	Bugibulungu	Bundagala	Bumasifwa
23LMM	653381	127219	1360	Lugongo	Muluwe	Masaba
24BBB	652411	127136	1344	Budeda	Bugube	Busulani
25NBB	656184	125619	1890	Bulusabe	Bufupa	Masaba
26NBM	656851	126042	1789	Busanjja	Bufupa	Masaba
27NBM	656759	126034	1797	Busanjja	Bufupa	Masaba
28BBM	656620	125944	1860	Busanjja	Bufupa	Masaba
29NBM	656530	125912	1813	Namagoye	Bufupa	Masaba
30MBB	655079	127489	1558	Makuyu	Bugitimwa	Bugitimwa
31MBB	655180	127641	1609	Makuyu	Bugitimwa	Bugitimwa
32MBB	655744	127323	1633	Mayumber Upper	Bugiboni	Bugitimwa
33JBB	656040	126975	1615	Jibaru	Bugiboni	Bugitimwa
34NBB	656192	127128	1645	Namusiru	Bugiboni	Bugitimwa
35JBB	655883	127005	1601	Jibaru	Bugiboni	Bugitimwa
36JBB	655697	127063	1587	Jibaru	Bugiboni	Bugitimwa
37MBB	655188	127041	1501	Mayumber Lower	Bugiboni	Bugitimwa
38MBM	655212	126502	1502	Mabaya	Buboolo	Masaba
39BBB	647852	124657	1972	Bunambozo	Bumukone	Buteza
40NBB	648085	124743	1854	Nankungu	Bukahengere	Buteza
41NBB	648340	124383	1821	Nalooli	Bukahengere	Buteza
42BBB	648066	124344	1798	Bunamoli	Bumukone	Buteza
43BBB	648543	124018	1819	Bunamoli	Bumukone	Buteza
44CBZ	651574	124199	1759	Chebugunga	Bunumulo	Zesui
45CBZ	651551	124122	1755	Chilumbi	Bumumulo	Zesui

Appendix III: Landslide data used in magnitude characterization

Site Id	Area	Volume	Flow Length
2BBB	691.2	1866.24	85
3ZLS	329.4	955.26	72
5NMS	720	1656	86
6KMS	1440	3888	112
7KMS	1394	4460.8	121
10MNN	1080	2268	46
11MNN	498.48	1545.288	32.6
12KGS	520	1248	47.3
13LKN	1447.61	1013.327	77
14KNN	899.84	2789.504	68.8
15KGS	1022.4	1963.008	83.8
17SCM	1064	2447.2	144
18SBL	694.07	4927.897	64
19KGS	850	1105	30
21NBB	388.96	427.856	40.8
22BBB	375.9	270.648	52.9
23LMM	780.1	1638.21	83
24BBB	454.5	1227.15	74.8
26NBM	631.8	1029.834	227.85
27NBM	922.5	2490.75	46.9
28BBM	1056	2428.8	152.75
29NBM	266	505.4	26.6
30MBB	1393.14	3761.478	128.6
31MBB	1232.496	2341.7424	88
32MBB	1610	3381	43
33JBB	1659.6	4480.92	84.15
34NBB	442	265.2	149.57
38MBM	858	4461.6	127
42BBB	1046.52	1590.7104	98.4
44CBZ	458.25	870.675	136
1GSB	1835.2	26793.92	56
4BMS	2257	7222.4	195
8NNN	3337	15416.94	187
16MGS	4864	21888	129
20NKB	4724.98	9922.458	372.8
35JBB	4896	11750.4	107
37MBB	1846.8	11634.84	151
39BBB	3541.835	6729.4865	217.91
40NBB	3120.15	39625.905	207.01
41NBB	2694.3512	5927.57264	178.53
43BBB	2829.6	6225.12	138
45CBZ	2594.575	13232.3325	178
9NNN	17850	57120	308
25NBB	13888	70828.8	435.22
36JBB	7782.8933	110517.0853	271.9

Appendix IV: Soil Textural class, color, structure and plasticity data

Low magnitude (n=30)						
SiteID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Textural cass	Color	Structure	Plasticity
2BBB	30	1	Sandy loam	7YR 2.5/1	pl	sp
3ZLS	60	1	Clay loam	7YR 3/2	sbk	sp
5NMS	30	1	Clay loam	5YR 3/1	sbk	sp
6KMS	30	1	Clay loam	5YR 3/2	sbk	p
7KMS	40	1	Loam	5YR 3/1	sgr	sp
10MNN	50	1	Sandy clay l	5YR 3/2	sbk	sp
11NNN	60	1	Silty clay lo	5YR 3/1	pl	p
12KGS	20	1	Silty clay lo	5YR 3/3	pl	p
13LKN	90	1	Loam	5YR 3/1	ma	p
14KNN	20	1	Clay loam	5YR 3/2	pl	sp
15KGS	30	1	Loam	7YR 2.5/1	sbk	sp
17SCM	30	1	Clay loam	5YR 3/3	pl	p
18SBL	30	1	Clay loam	5YR 3/2	sgr	sp
19KGL	50	1	Loam	5YR 3/2	pl	sp
21NBB	30	1	Sandy loam	7YR 3/1	sgr	po
22BBB	50	1	Clay loam	5YR 3/3	pl	p
23LMM	50	1	Loam	10YR 5/6	ma	sp
24BBB	30	1	Loam	7YR 3/1	sgr	sp
26 NBM	60	1	Clay loam	10YR 2/2	pl	sp
27NBM	40	1	Loam	10YR 3/2	sgr	sp
28BBM	30	1	Loam	2.5YR 3/1	sgr	sp
29NBM	30	1	Loam	10 YR 3/2	pl	sp
30MBB	30	1	Silt Clay Lo	10YR 3/3	pl	sp
31MBB	30	1	Silt loam	10YR 3/6	pl	sp
32MBB	30	1	Loam	10YR 2/1	pl	sp
33JBB	20	1	Loam	10YR 3/2	sbk	sp
34NBB	30	1	Loam	10YR 3/3	pl	p
38MBM	30	1	Silt loam	10YR 3/3	pl	sp
42BBB	70	1	Sandy loam	2.5Y 2.5/1	sgr	sp
44CBZ	20	1	Silt Clay Lo	10YR 4/6	pl	p
2BBB	50	2	Sandy clay l	7YR 3/1	pl	sp
3ZLS	90	2	Clay loam	7YR 3/4	sbk	p
5NMS	90	2	Sandy loam	5YR 3/2	sbk	sp
6KMS	80	2	Sandy loam	5YR 3/3	sbk	vp
7KMS	100	2	Loamy sand	5YR 3/2	sgr	p
10MNN	90	2	Loam	5YR 3/3	sbk	sp
11NNN	100	2	Clay loam	5YR 4/1	pl	vp
12KGS	50	2	Silty clay lo	5YR 4/4	pl	vp
13LKN	90	2	Clay loam	5YR 3/2	ma	po
15KGS	70	2	Loam	7YR 3/1	sbk	p
17SCM	80	2	Clay loam	5YR 4/1	pl	p
18SBL	100	2	Clay loam	5YR 3/3	sgr	sp
19KGL	110	2	Clay loam	5YR 3/3	pl	p
21NBB	90	2	Silty clay lo	7YR 4/4	sgr	po
22BBB	110	2	Sandy loam	5YR 3/4	pl	p
23LMM	100	2	Loam	10YR 3/2	ma	po
24BBB	70	2	Sandy loam	7YR 3/3	sgr	sp
26NBM	100	2	Clay loam	10YR 3/3	pl	vp
27NBM	80	2	Loam	10YR 4/2	sgr	p
28BBM	60	2	Sandy loam	2.5YR 3/2	sgr	p
29NBM	60	2	Sandy clay l	10YR 3/3	pl	p
30MBB	80	2	Loam	10YR 4/4	pl	p
31MBB	90	2	Silt loam	10YR 4/6	pl	p
32MBB	70	2	Loam	10YR 3/1	pl	p
33JBB	60	2	Silt loam	10YR 4/3	sbk	p
34NBB	70	2	Silty clay lo	10YR 3/4	pl	vp
38MBM	80	2	Silt loam	10YR 4/3	pl	p
42BBB	100	2	Sandy loam	2.5Y 3/1	sgr	po
44CBZ	100	2	Clay loam	10YR 5/6	pl	vp
2BBB	80	3	Sandy clay l	7YR 5/3	ma	po
3ZLS	120	3	Clay	7YR 4/4	sgr	sp
5NMS	180	3	Loam	5YR 5/3	sgr	po
6KMS	120	3	Loamy sand	5YR 4/4	sgr	sp
7KMS	160	3	Sandy loam	5YR 2.5/2	sgr	po
10MNN	140	3	Loam	5YR 4/4	sgr	po
11NNN	150	3	Loamy sand	5YR 4/2	sgr	po
12KGS	100	3	Silty clay lo	5YR 4/3	ma	p
13LKN	150	3	Clay loam	5YR 4/1	sgr	sp
15KGS	120	3	Loam	7YR 4/1	sgr	vp
17SCM	130	3	Loam	5YR 5/6	sgr	po
18SBL	100	3	Clay loam	5YR 3/4	sgr	po
19KGL	190	3	Clay loam	5YR 3/4	ma	sp
21NBB	150	3	Loam	7YR 4/6	sgr	sp
22BBB	150	3	Clay loam	5YR 4/3	sgr	po
23LMM	170	3	Loam	10YR 4/2	sgr	sp
24BBB	120	3	Sandy clay l	7YR 3/4	sgr	sp
26NBM	160	3	Loam	10YR 3/4	pl	p
27NBN	130	3	Loam	10YR 5/1	ma	po
29NBM	90	3	Loam	10YR 4/1	ma	sp
30MBB	150	3	Clay loam	10YR 4/3	ma	po
31MBB	150	3	Loam	10YR 5/4	sgr	p
32MBB	130	3	Loam	10YR 4/1	ma	po
33JBB	120	3	Sandy loam	10YR 4/3	sgr	vp
34NBB	140	3	Silt loam	10YR 3/6	ma	p
38MBM	140	3	Clay loam	10YR 4/6	sgr	p
44CBZ	160	3	Clay loam	2.5Y 4/2	ma	po

Moderate magnitude (n=12)						
SiteID	Observation depth in profile (cm)	1st/2nd/3rd observation zone	Textural cass	Color	Structure	Plasticity
1GSB	30	1	Clay loam	7YR 2.5/1	sbk	sp
4BMS	30	1	Sandy loam	5YR 3/1	pl	p
8NNN	30	1	Loam	7YR 2.5/1	sgr	sp
16MGS	50	1	Silty loam	5YR 2.5/1	pl	sp
20NKB	30	1	Loam	5YR 3/1	ma	po
35JBB	40	1	Loam	10YR 2/1	pl	sp
37MBB	20	1	Silty clay lo	7.5YR 3/2	pl	p
39BBB	30	1	Loam	10YR 3/3	pl	sp
40NBB	30	1	Clay loam	7YR 2.5/3	pl	sp
41NBB	30	1	Sandy loam	2.5Y 3/1	pl	po
43BBB	30	1	Clay loam	10YR 3/2	pl	p
45CBZ	40	1	Loam	10YR 4/6	pl	p
1GSB	90	2	Silt loam	7YR 2.5/2	sbk	p
4BMS	70	2	Sandy clay l	5YR 3/2	pl	vp
8NNN	80	2	Loam	7YR 3/1	sgr	sp
16MGS	110	2	Silty clay lo	5YR 3/1	pl	p
20NKB	120	2	Clay loam	5YR 4/1	ma	po
35JBB	90	2	Loam	10YR 5/1	pl	P
37MBB	50	2	Silty clay lo	7.5YR 4/3	pl	vp
39BBB	60	2	Loam	10YR 3/2	pl	p
40NBB	70	2	Clay loam	7YR 3/4	pl	p
41NBB	90	2	Loam	2.5Y 3/2	pl	sp
43BBB	100	2	Silt Clay Lo	10YR 4/6	pl	vp
45CBZ	100	2	Clay loam	10YR 5/6	pl	vp
1GSB	180	3	Silt loam	10YR 5/8	sgr	vp
4BMS	130	3	Sandy clay l	7YR 3/1	sgr	po
8NNN	170	3	Loam	5YR 3/3	pl	p
16MGS	180	3	Silty clay lo	7YR 4/1	sgr	po
35JBB	170	3	Sandy loam	5YR 3/2	pl	vp
20NKB	210	3	Clay loam	5YR 3/2	sgr	sp
37MBB	100	3	Silty clay lo	10YR 4/1	sgr	P
39BBB	130	3	Loam	7YR 5/4	pl	vp
40NBB	140	3	Clay loam	10YR 4/4	sgr	p
41NBB	170	3	Loam	7YR 4/6	sgr	p
43BBB	160	3	Silt Clay Lo	2.5Y 4/2	sgr	sp
45CBZ	190	3	Clay loam	10YR 5/6	pl	vp

High magnitude (n=3)						
SiteID	Observation depth in profile (cm)	1st/2nd/3rd observation zone	Textural cass	Color	Structure	Plasticity
9NNN	70	1	Loam	5YR 3/2	sbk	p
25NBB	30	1	Clay loam	10YR 3/1	pl	sp
36JBB	60	1	Silt loam	10YR 3/1	sgr	sp
9NNN	140	2	Loam	5YR 3/3	sbk	vp
25NBB	90	2	Loam	10YR 3/2	pl	p
36JBB	160	2	Loam	10YR 4/1	sgr	p
9NNN	170	3	Loam	5YR 4/4	sgr	p
25NBB	150	3	Clay loam	10YR 3/3	ma	sp
36JBB	210	3	Loam	10YR 5/2	ma	sp

Appendix V: Landslide soils particle size distribution (Laboratory data)

Low magnitude (n=30)

Site ID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Sand (%)	Clay (%)	Silt (%)
2BBB	30	1	56	18	27
3ZLS	60	1	43	31	26
5NMS	30	1	48	26	26
6KMS	30	1	45	28	27
7KMS	40	1	46	15	39
10MNN	50	1	52	21	27
11NNN	60	1	20	38	42
12KGS	20	1	16	34	50
13LKN	90	1	49	22	29
14KNN	20	1	28	31	41
15KGS	30	1	38	22	40
17SCM	30	1	24	34	43
18SBL	30	1	20	34	47
19KGL	50	1	30	27	44
21NBB	30	1	54	16	30
22BBB	50	1	37	30	33
23LMM	50	1	46	17	38
24BBB	30	1	39	23	38
26 NBM	60	1	26	29	45
27NBM	40	1	35	25	40
28BBM	30	1	46	20	34
29NBM	30	1	34	26	40
30MBB	30	1	16	36	48
31MBB	30	1	22	34	44
32MBB	30	1	38	25	37
33JBB	20	1	44	19	37
34NBB	30	1	32	29	39
38MBM	30	1	20	30	50
42BBB	70	1	60	17	23
44CBZ	20	1	16	39	45
2BBB	50	2	54	21	25
3ZLS	90	2	41	38	21
5NMS	90	2	51	19	30
6KMS	80	2	63	16	21
7KMS	100	2	78	8	14
10MNN	90	2	34	27	39
11NNN	100	2	34	30	36
12KGS	50	2	14	33	53
13LKN	90	2	30	31	39
15KGS	70	2	38	21	41
17SCM	80	2	30	30	41
18SBL	100	2	24	30	47
19KGL	110	2	24	31	45
21NBB	90	2	15	38	47
22BBB	110	2	63	16	21
23LMM	100	2	50	15	36
24BBB	70	2	54	18	29
26NBM	100	2	26	30	44
27NBM	80	2	37	27	36
28BBM	60	2	60	17	23
29NBM	60	2	51	23	26
30MBB	80	2	38	27	35
31MBB	90	2	28	33	39
32MBB	70	2	42	24	34
33JBB	60	2	26	28	46
34NBB	70	2	18	31	51
38MBM	80	2	22	33	45
42BBB	100	2	51	19	30
44CBZ	100	2	29	35	36
2BBB	80	3	51	31	18
3ZLS	120	3	36	44	20
5NMS	180	3	46	21	33
6KMS	120	3	75	8	17
7KMS	160	3	55	13	32
10MNN	140	3	44	25	31
11NNN	150	3	74	8	18
12KGS	100	3	18	37	45
13LKN	150	3	30	31	39
15KGS	120	3	36	26	38
17SCM	130	3	38	26	37
18SBL	100	3	24	32	45
19KGL	190	3	20	34	47
21NBB	150	3	48	18	35
22BBB	150	3	20	36	45
23LMM	170	3	43	21	36
24BBB	120	3	53	18	29
26NBM	160	3	40	18	43
27NBN	130	3	40	26	34
29NBM	90	3	42	25	33
30MBB	150	3	34	29	37
31MBB	150	3	32	31	37
32MBB	130	3	34	28	38
33JBB	120	3	56	17	27
34NBB	140	3	26	27	47
38MBM	140	3	30	29	41
44CBZ	160	3	23	35	42

Moderate magnitude (n=12)

SiteID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Sand (%)	Clay (%)	Silt (%)
1GSB	30	1	44	30	26
4BMS	30	1	55	18	27
8NNN	30	1	36	25	39
16MGS	50	1	24	28	48
20NKB	30	1	35	25	40
35JBB	40	1	32	25	43
37MBB	20	1	14	33	53
39BBB	30	1	40	21	39
40NBB	30	1	25	25	50
41NBB	30	1	54	18	28
43BBB	30	1	24	30	46
45CBZ	40	1	35	24	41
1GSB	90	2	28	29	43
4BMS	70	2	48	26	26
8NNN	80	2	40	23	37
16MGS	110	2	18	32	51
20NKB	120	2	28	28	44
35JBB	90	2	44	25	31
37MBB	50	2	16	33	51
39BBB	60	2	31	23	46
40NBB	70	2	24	31	45
41NBB	90	2	51	20	29
43BBB	100	2	14	35	51
45CBZ	100	2	24	33	43
1GSB	180	3	26	33	41
4BMS	130	3	48	25	27
8NNN	170	3	40	26	34
16MGS	180	3	16	37	48
35JBB	170	3	56	18	26
20NKB	210	3	30	28	42
37MBB	100	3	16	36	48
39BBB	130	3	44	22	34
40NBB	140	3	23	34	43
41NBB	170	3	35	23	42
43BBB	160	3	18	39	43
45CBZ	190	3	23	33	44

High magnitude (n=3)

SiteID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Sand (%)	Clay (%)	Silt (%)
9NNN	70	1	28	27	45
25NBB	30	1	25	32	43
36JBB	60	1	24	29	47
9NNN	140	2	28	27	45
25NBB	90	2	34	25	41
36JBB	160	2	44	22	34
9NNN	170	3	28	29	43
25NBB	150	3	30	27	43
36JBB	210	3	38	26	36

Appendix VI: Percentage of rock fragments in landslide sites soils

Low magnitude (n=30)				Moderate magnitude (n=12)				High magnitude (n=3)			
Site ID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Rock Fragments (%)	Site ID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Rock Fragments (%)	Site ID	Sampling depth in profile (cm)	1st/2nd/3rd zone	Rock Fragments (%)
2BBB	30	1	1	1GSB	30	1	1	9NNN	70	1	1
3ZLS	60	1	5	4BMS	30	1	1	25NBB	30	1	5
5NMS	30	1	1	8NNN	30	1	5	36JBB	60	1	5
6KMS	30	1	1	16MGS	50	1	1	9NNN	140	2	5
7KMS	40	1	1	20NKB	30	1	50	25NBB	90	2	25
10MNN	50	1	1	35JBB	40	1	1	36JBB	160	2	10
11NNN	60	1	1	37MBB	20	1	1	9NNN	170	3	10
12KGS	20	1	1	39BBB	30	1	10	25NBB	150	3	25
13LKN	90	1	1	40NBB	30	1	1	36JBB	210	3	25
14KNN	20	1	1	41NBB	30	1	5				
15KGS	30	1	1	43BBB	30	1	1				
17SCM	30	1	10	45CBZ	40	1	1				
18SBL	30	1	10	1GSB	90	2	5				
19KGL	50	1	1	4BMS	70	2	5				
21NBB	30	1	10	8NNN	80	2	10				
22BBB	50	1	1	16MGS	110	2	5				
23LMM	50	1	10	20NKB	120	2	90				
24BBB	30	1	25	35JBB	90	2	25				
26 NBM	60	1	1	37MBB	50	2	5				
27NBM	40	1	5	39BBB	60	2	10				
28BBM	30	1	1	40NBB	70	2	5				
29NBM	30	1	5	41NBB	90	2	10				
30MBB	30	1	5	43BBB	100	2	1				
31MBB	30	1	1	45CBZ	100	2	5				
32MBB	30	1	1	1GSB	180	3	50				
33JBB	20	1	5	4BMS	130	3	25				
34NBB	30	1	5	8NNN	170	3	25				
38MBM	30	1	1	16MGS	180	3	10				
42BBB	70	1	25	35JBB	170	3	25				
44CBZ	20	1	1	20NKB	210	3	10				
2BBB	50	2	5	37MBB	100	3	50				
3ZLS	90	2	10	39BBB	130	3	10				
5NMS	90	2	5	40NBB	140	3	25				
6KMS	80	2	5	41NBB	170	3	25				
7KMS	100	2	5	43BBB	160	3	25				
10MNN	90	2	5	45CBZ	190	3	5				
11NNN	100	2	5								
12KGS	50	2	1								
13LKN	90	2	90								
15KGS	70	2	5								
17SCM	80	2	10								
18SBL	100	2	15								
19KGL	110	2	1								
21NBB	90	2	10								
22BBB	110	2	10								
23LMM	100	2	25								
24BBB	70	2	25								
26NBM	100	2	5								
27NBM	80	2	25								
28BBM	60	2	5								
29NBM	60	2	25								
30MBB	80	2	10								
31MBB	90	2	5								
32MBB	70	2	5								
33JBB	60	2	10								
34NBB	70	2	25								
38MBM	80	2	10								
42BBB	100	2	25								
44CBZ	100	2	5								
2BBB	80	3	25								
3ZLS	120	3	25								
5NMS	180	3	25								
6KMS	120	3	25								
7KMS	160	3	25								
10MNN	140	3	25								
11NNN	150	3	10								
12KGS	100	3	10								
13LKN	150	3	50								
15KGS	120	3	25								
17SCM	130	3	25								
18SBL	100	3	30								
19KGL	190	3	10								
21NBB	150	3	5								
22BBB	150	3	50								
23LMM	170	3	30								
24BBB	120	3	25								
26NBM	160	3	10								
27NBN	130	3	50								
29NBM	90	3	25								
30MBB	150	3	25								
31MBB	150	3	25								
32MBB	130	3	25								
33JBB	120	3	25								
34NBB	140	3	25								
38MBM	140	3	50								
44CBZ	160	3	25								