MAJOR FACTORS INFLUENCING THE OCCURRENCE OF LANDSLIDES IN THE NORTHERN SLOPES OF THE ULUGURU MOUNTAINS, TANZANIA[1]

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ABSTRACT

Landslide mitigation largely depends on the understanding of the nature of the factors that have direct bearing on the occurrence of landslides. Identification of these factors is of paramount importance in setting out appropriate and strategic landslides control measures. The present study focused on the identification of the major factors influencing the occurrence of landslides in the Northern slopes of the Uluguru Mountains, Tanzania. The main objective was to establish relationship between spatial distribution of landslides and their causative factors. Such information would enable the planning of appropriate and strategic control measures. Aerial photographs, field survey and Geographic Information System (GIS) techniques were employed to identify the landslides features which occurred during *EL NIÑO* rains, spatial distribution and their corresponding factors. The results show that landslides dominate the geomorphic units with slope gradient ranging from 25% to over 80%. The most affected geomorphic units are in the order: debris slopes > incisions and V-shaped valleys > amphitheatres. Factors which cause the occurrence of landslides are both soil and terrain related. The most important soil characteristics are presence of shallow soil solum with low bulk density and high macro porosity overlying a relatively less porous saprolite or hard bed rock. The terrain related factors include: undercutting of slopes by roads and pathways and presence of very steep concave side slopes. Water flow from roads and pathways and seepage from irrigation channels are precursors for the triggering of landslides in the study area.

Key words: Major factors, landslides, Uluguru Mountains, Tanzania

INTRODUCTION

Landslides are a result of geomorphic processes affecting the stability and evolution of ridge slopes in the Uluguru Mountains (Westerberg, 1999; Kimaro, 2003). The triggering of landslides depends on several complex but interrelated factors such as soil characteristics (Westerberg, 1999; Mburu, 2001) slope characteristics (Lopez and Zinck, 1991) and geomorphology (Ahmad and McCalpin, 1999, Westerberg and Christiansson, 1999), vegetation, land use and infrastructure (Larsen and Torres-Sanchez, 196; 1998).

Of the soil characteristics, the soil physical properties largely determine the occurrence of landslides. A study conducted in Columbia on the factors conditioning the occurrence of landslides by Lopez and Zinck (1991) shows that soil physical properties such as soil texture, bulk density, water retention and soil consistence limits were key factors influencing the occurrence of landslides. Working in a tropical mountainous area in Ecuador, Vanacker (2002) reported that landslides were more related to increased soil moisture and soil pore water pressure. The occurrences of the shallow landslides in Nyandarua range in Kenya were mainly attributed to the shallow soil solum overlying the bedrock (Larsson, 1989; Mburu, 2001). The authors observed that the larger and deeper landslides were found in Andosols and Nitisols, characterised by very deep soil profiles with increasing clay content down the profile.

The degree, length and shape of slope are the main slope characteristics reported to have potential influence in the development and occurrence of landslides (Larsson, 1989). Lands with steep slopes are more vulnerable to landslides than gentle ones (Lopez and Zinck, 1991). In Kingston Metropolitan area in Jamaica, Ahmad and McCalpin (1999) observed that shallow landslides were more common on slopes between 20° and 35°.

Lithology, faults, and downslope curvature are among the important factors which control the occurrence of landslides (Ahmad and McCalpin 1999). According to Westerberg (1999), the highlands of East Africa characterised by complex of concave slopes are prone to slope instability. According to Fernandes *et al.* (1994) and Westerberg and Christiansson (1999) troughs which exist between rock outcrops and soil-filled concavities and hillslope hollows act as water reservoirs that influence the occurrence of landslides. Westerberg and Christiansson (1999) attribute landslides to the presence of geological structures that control the development of weak layers serving as potential sliding planes. Rapid weathering produces regolith prone to high pore water pressure (Westerberg, 1999) which according to Temple and Rapp (1972) cause water blowouts which are a precursor for occurrence of landslides.

This paper provides knowledge on the cause-effect relationships between landslide-conditioning factors and landslide spatial distribution in the northern slopes of the Uluguru Mountains in Tanzania.

MATERIALS AND METHODS

Setting of the study area

The study area is located on the northern slopes of the Uluguru Mountains between longitude 37°39″ and 37°41″E and latitude 06°54″ and 06°51″S. The mean annual rainfall varies with altitude, from 900 mm at around 550 m asl to 2,300 mm at 1,500 m asl. It is distributed into 2 distinct periods, a long rain season (*masika*) which lasts from March to May and short rains (*vuli*) which extends from October to January. The mean annual temperature varies from 25°C around 550 m asl to 19°C at 1,500 m asl.

The rocks are metasediments mainly consisting of hornblende pyroxene granulites, with plagioclase and quartz rich veins (Sampson and Wright, 1964). The area is mountainous with strongly dissected mountain ridges and foothills with very steep narrow valleys. The soils on the mountain ridges are *Endoskeletic* and *Leptic Cambisols* while on the foothills the dominant soils are *Chromic Lixisols* and *Profondic Acrisols* (FAO *et al.,* 1998). The major part of the Uluguru Mountains are under cultivation. The mountain ridges are mainly used for production of vegetables, beans and banana while on the foothills maize is the main crop (Kimaro *et al.*, 1999).

Determination of landslide distribution on different geomorphic units

Aerial photographs of 1964 at a scale of 1:35,000 were interpreted stereoscopicaly in conjunction with topographic map with a scale of 1:50,000 (map sheet 183/3) (Survey and Mapping Division, 1970) and geological map with a scale of 1:125,000 (Quarter Degree Sheet 183) (Geological Survey Department, 1961) to produce geomorphic map of the catchment at a scale of 1:10,000. This document was produced to serve as a base for locating landslides distribution on different geomorphic units.

The study was carried out on landslides which occurred during *El-Niño* rains in 1997/1998. In total, 23 landslides associated with *El-Niño* rains were identified. Information regarding the date of occurrence of individual landslide was obtained from the farmers. Position of each landslide was located by a Global Positioning System (GPS). Coordinates of each landslide were transferred onto geomorphic base map of the study area in a GIS environment to establish relationship between the occurrences of landslides and geomorphic units.

Determination of the effect of soil characteristics on the occurrence of landslides

Soil morphological characteristics such as soil depth, depth to the hard layer, saprolite and macro-porosity, considered to have strong influence on the occurrence of landslides, were studied in the field at each landslide. Disturbed and undisturbed soil samples were collected on which the following parameters were determined: sand, silt, clay ((Gee and Bauder, 1986)), bulk density, total porosity and water holding capacity of the soils (Blake and Hartage, 1986; Klute, 1986).

Establishment of the pattern of roads, pathways and irrigation channels

Roads, pathways, drainage network and irrigation channels were established from aerial photographs of 1964 at a scale 1:35,000 coupled with field traverse and mapping using GPS. Distances from landslides to the road and drainage lines were also determined. These features were digitised and incorporated in GIS.

Statistical analysis

Qualitative and quantitative statistics were employed in the exploratory analysis between frequency of the occurrence of landslides and related factors as described above. The degree of association between variables was measured by linear regression and calculation of the Pearson correlation coefficient R. Levels of significance (P) were obtained by F-tests based on analysis of variance. The effects of multiple factors on landslides were statistically analysed.

RESULTS AND DISCUSSION

Factors affecting the occurrence and distribution of landslides

Occurrence and distribution of El Niño-induced landslides

The spatial distribution of the El Niño landslides is shown in Figure 1. The data shows that most of the studied landslides occurred on the debris slopes, amphitheatres and incisions and V-shaped valleys. The high frequency of the observed landslides in these geomorphic units could be attributed to the steep slopes with slope gradient ranging from 20% to over 80% (Table 1) and vertical cutting of slopes along the main stream courses, soil depth, thickness of the soil solum and nature of the underlying horizon (Table 2) coupled by high precipitation.

Effects of soil characteristics on the occurrence of landslides

Lithic Leptosols, Leptic Cambisols and Pachic Phaeozems occur mainly on the debris slopes, amphitheatres and V-shaped valleys. These soils overlying a saprolite and/ or hard rock at shallow depth from the soil surface (Table 2). The top of the hard rock and saprolite constitutes the bottom of the landslides along which slopes have been undermined. These surfaces formed the sliding plane of the studied landslide scars. The physical characteristics of the soils above the stable surface which are associated with the occurrence of landslides are shown in Table 3. The bulk density is low varying from 1.1 g/cm^3 to 1.3 g/cm^3. It is naturally associated with very high total porosity (39% to 52%), in which medium and coarse pores (6-13 dm^2) dominate.

Table 1: Characteristics of geomorphic units affected by *El Niño*-induced landslides

Geomorphic unit	Slope form	Slope gradient (%)	Total damaged land area (m^2)	Total soil loss (t/ha/year)
Debris slopes	Straight/concave	30->80	1240	8
Amphitheatres	Concave	25-60	414	124
Incisions and V-shaped valleys	Concave/side slope	25->80	1618	14

Table 2 Soil morphological characteristics of the landslide affected geomorphic units

Geomorphic units	Soil type	Depth (cm)	Sand (%)	Clay	Nature of the horizon
Debris slope	Epileptic Cambisols	0-35	65	19	grSL
		35+	-	-	hard rock
Amphitheatre	Endoleptic Cambisols	0-70	65	14	grSL
		70+	63	19	SL saprolite
V-shaped valley	Pachic Phaeozems	0-60	63	18	vgrSL
		60+	-	-	hard rock

grSL = gravely sandy loam, grSCL = gravely sandy clay loam, vgrSCL = very gravely sandy clay loam, SCL = sandy clay loam, SL = sandy loam

These characteristics are known to favour the occurrence of subsurface seepage and piping, which a number of authors have considered as pre-conditions for the triggering of landslides (Larsson, 1989; Mburu, 2001; Westerberg, 1999).

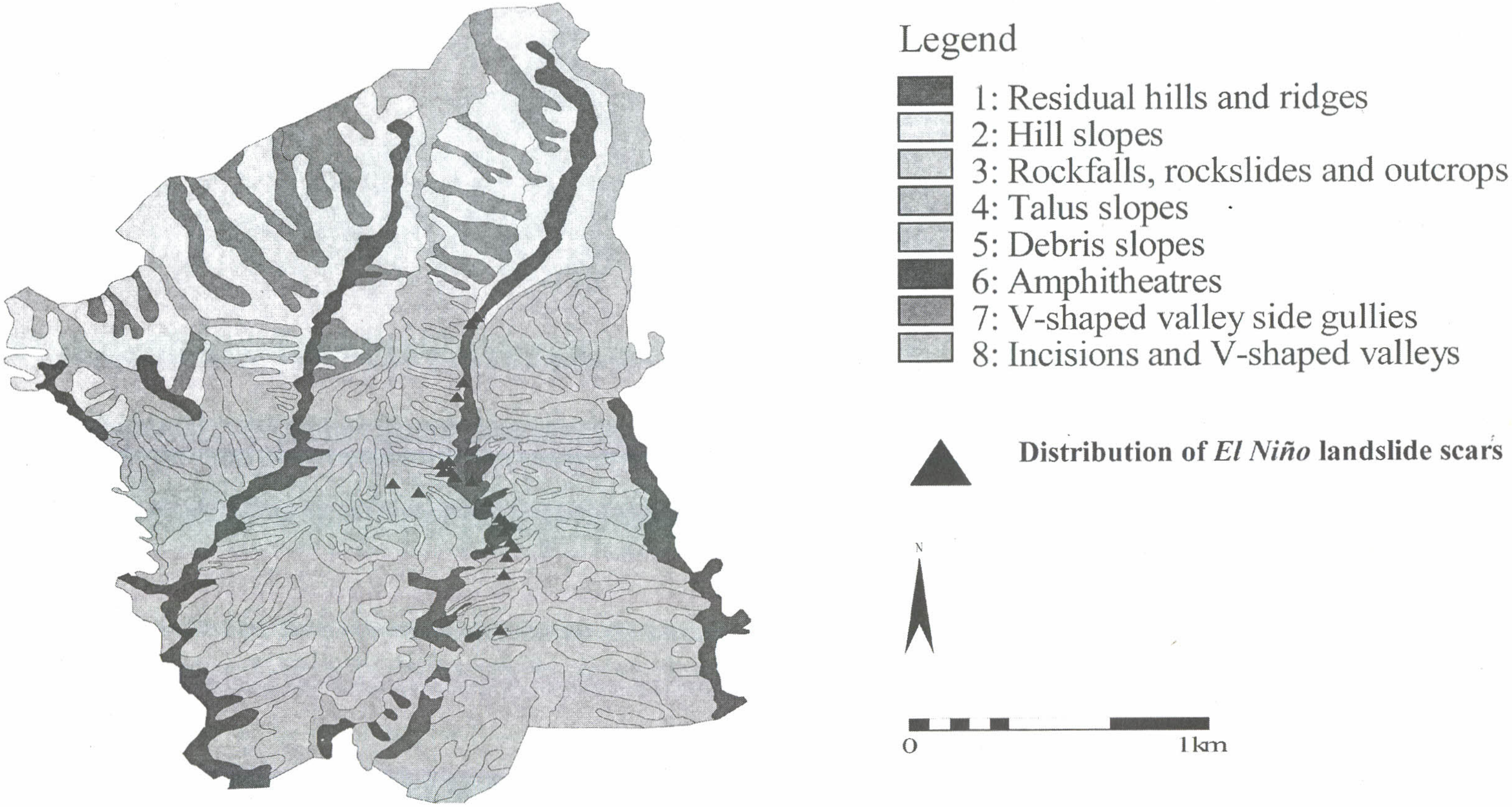

Figure 1 Spatial distribution of *El Niño*-induced landslides on different geomorphic units in the study area

Table 3 Physical characteristics of the soils above the stable surface of landslides associated with irrigation channel

Slide no.	Bulk density (gcm^{-3})	Total Porosity (%)	Surface water content at field capacity (% volume)	Number of medium/coarse pores per dm^2
LIR5	1.1	51.8	11.2	12
LIR16	1.1	50.8	10.2	13
LIR8	1.3	38.6	13.8	9
LIR3	1.2	43.2	13.2	6
LIR14	1.2	46.0	14.3	13
LIR9	1.2	48.4	16.2	13

Influence of pathways and irrigation channels on the occurrence of landslides

In the study area the pathways and irrigation channels were important source of runoff which contributed significant overland flow in the landslides prone areas. All 23 studied landslides associated with *El Niño* rains occurred along pathways and irrigation channels (Figures 2 and 3).

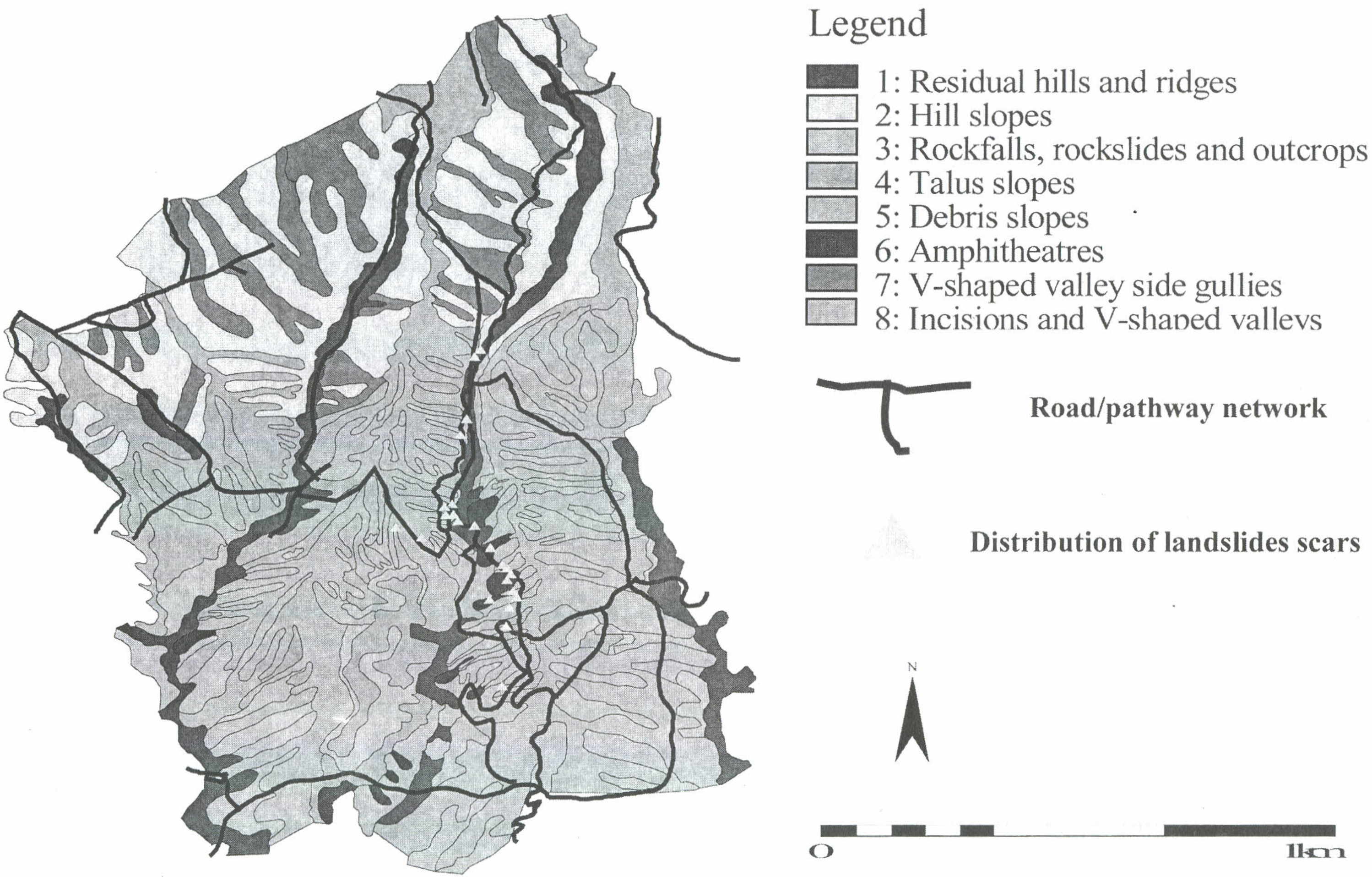

Figure 2 Spatial distribution of landslides associated with road and pathway network

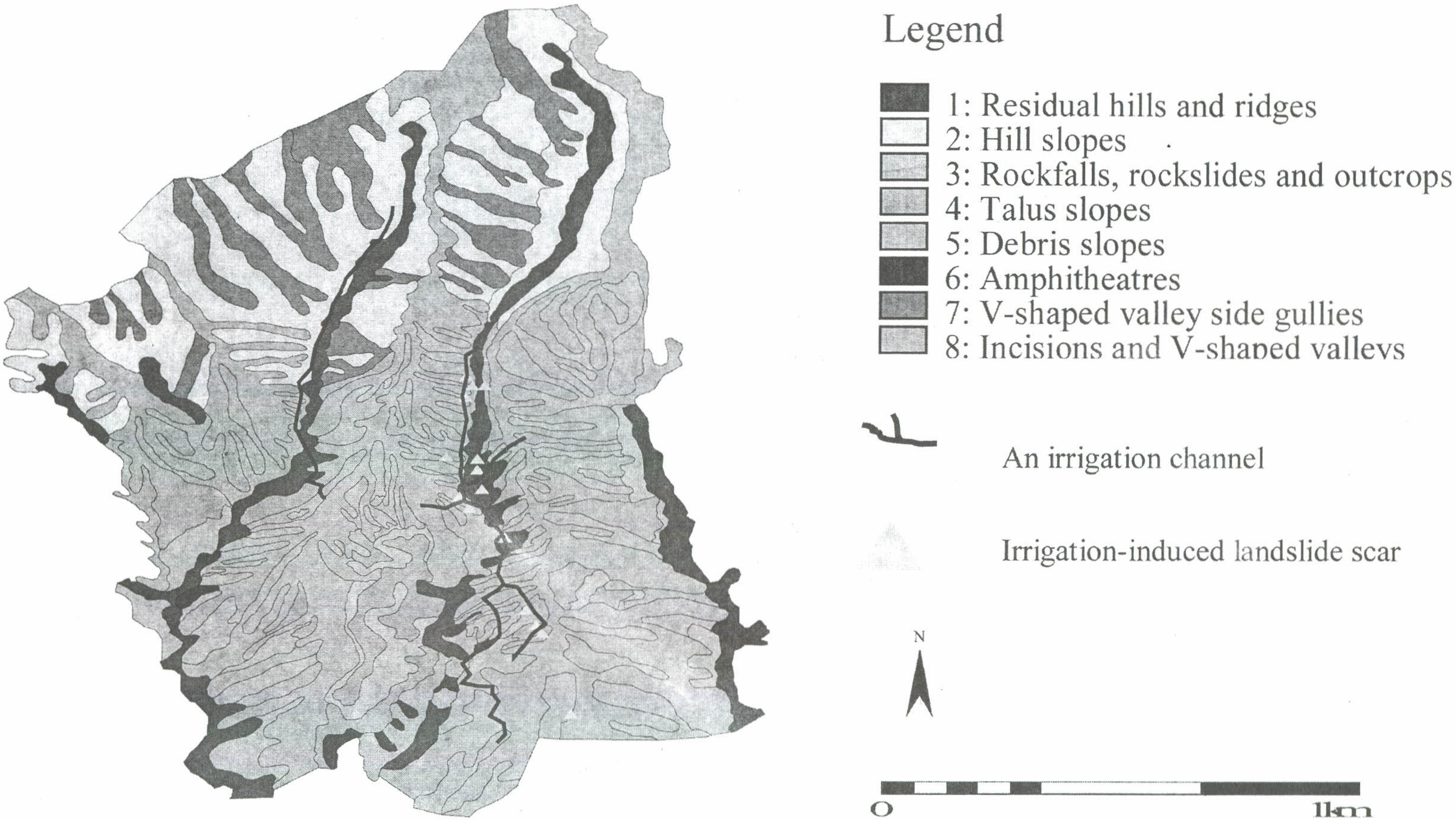

Figure 2 Spatial distribution of landslides associated with road and pathway network

About 12 landslides scars were located between 5 and 30 meters, nine between 30 and 60 metres and 2 at more than 60 metres on either side of the pathway. The observed distribution of landslides along pathways could be attributed to the undercutting of slopes, soil saturation by excess runoff and subsurface water flow from residential areas and pathways (Evans and Morgan, 1974). According to the observations made by Harden (1992) and Selby (1993) runoff from fields can be carried several hundreds metres downslope via pathways and flow into lower slopes where it can trigger landslides. The occurrence of landslides could also be attributed to high pore water pressure caused by water seepage, piping through medium and coarse pores (Table 2), high percolation rate of water (overland flow) from irrigation channels and pathways (Temple and Rapp, 1972; Westerberg, 1999). Studies on landslides in Northern Thailand by Turkelboom (1999) showed that debris flow which occurred on colluvial steep slopes were a result of soil saturation by flood irrigation and water flow from irrigation channels.

Multiple soil-terrain factors influencing the frequency of occurrence of landslides

Seven selected factors influencing the frequency of occurrence of landslides on different geomorphic units are given in Table 4. Significant correlations are observed between the controlling individual factors and the frequency of occurrence of the landslides (Table 4). Comparatively, distance to the road or pathways showed a high correlation ($R^2 = 0.9985$, $P<0.05$) with the frequency of landslides occurrence on different geomorphic units. This could be explained by the fact that road or path construction removes the toe support of the slope, increase the slope angle which weakened the shear resistance and hence making the slopes around the pathways more prone to sliding (Turkelboom, 1999). Soil physical properties also showed a high correlation (sand $R^2 = 0.9985$, $P<0.05$) with the frequency of landslides occurrence. The high sand content (Table 2) allows quick water saturation which in conjunction with steep slopes and shallow soil depth creates a favourable condition for sliding (Lopez and Zinck, 1991). Distance to the drainage line ($R^2 = 0.9736$), depth to the hard layer ($R^2 = 0.9423$) and clay content ($R^2 = 0.9022$) are the other important factors influencing the frequency of occurrence of landslides in the study area though not statistically significant ($P<05$). Incising streams and valleys increase the susceptibility of the area to landsliding which is also explained by the removal of toe support and over-steepened angles of the original slope (Westerberg, 1999).

Table 4 Parameters measured to establish the causes for the occurrence of landslides in different geomorphic units of the Morningside Catchment

Geoform	No. of slides	Measured parameters (Average values)						
		slope	DistDr	DistRd	DepthHl	Sand	Silt	Clay
		m/m		m			%	
Debris slopes	9	0.58	71	26	1.0	62	15	24
Amphitheatres	4	0.42	13	60	1.2	57	18	31
V-shaped valleys	8	0.65	66	33	1.0	60	17	23

DistDr = distance to the drainage line, DistRd = distance to the road or pathways, DepthHL = depth to the hard layer

Table 5 Relationships between selected soil and terrain parameters and the frequency of occurrence of landslides in the study area

Factor	Coefficient of determination(R^2)	Correlation coefficient (R)	Probability
Slope gradient	0.7274	0.8529	0.3497^{ns}
Distance to the drainage line	0.9736	0.9867	0.1039^{ns}
Distance to the road or pathways	0.9987*	0.9994*	0.0229*
Depth to the hard layer	0.9423	0.9907	0.1544^{ns}
Sand	0.9985*	0.9992*	0.0247*
Silt	0.7340	0.8676	0.3449^{ns}
Clay	0.9022	0.9498	0.2025^{ns}

^{ns} = not significant

When stepwise multiple linear regression was fitted on the basis of the number of landslides observed in different geomorphic units and the key influencing factors (Table 6) only distance to the road or pathways reflected a strong negative correlation (R^2 = 0.9979, $P<0.05$) among the analysed variables (Table 5). The regression model showed that over 99 % of the observed variations in the frequency of occurrence of landslides could be explained by the distance to the road or pathways. Since the number of landslides studied was very limited, it would be very difficult to make reliable conclusions from these results.

Table 6 Multiple regression statistics for predicting the occurrence of landslidesin the study area

Variable	Parameter estimate	F-value	Pr>F	Partial R^2	Model R^2
Intercept	11.9				
Distance to the road or pathways	-0.116	464.6	<0.05	0.9979	0.9979

CONCLUSIONS

In the study area landslides dominate the geomorphic units with slope gradient ranging from 25% to over 80%. The most affected geomorphic units are in the order: debris slopes > incisions and V-shaped valleys > amphitheatres. Factors which cause the occurrence of landslides are both soil and terrain related. The most important soil characteristics are presence of shallow soil solum with low bulk density and high macro porosity overlying a relatively less porous saprolite or hard bed rock. The terrain related factors include: undercutting of slopes by roads and pathways and presence of very steep concave side slopes. Water flow from roads and pathways and seepage from irrigation channels are pre-conditions for the triggering of landslides in the study area.

Further research to minimise the occurrence of landslides is suggested in the following areas:

- Changes in the land use setup
- Spatial organisation of rural infrastructure
- Organisation of the irrigation systems

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