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Landslides in a densely populated county at the footslopes of Mount Elgon (Uganda): Characteristics and causal factors

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Abstract

Manjiya County on the Ugandan slopes of Mount Elgon is a densely populated mountainous area where landslides have been reported since the beginning of the twentieth century. The numerous fatalities and the damage done during the extreme rainfall events of 1997 to 1999 drew attention to this phenomenon. In order to better understand the causal factors of these landslides, 98 recent landslides in the study area, mostly debris slumps, were mapped and investigated. Together, they displaced 11 millions m^3 of slope material. Statistical analysis shows that landslides dominate on steep concave slope segments that are oriented to the dominant rainfall direction (northeast) and at a relatively large distance from the water divide. Based on landslide occurrence and impact, four different zones can be distinguished within the study area. Causal factors as well as landslide characteristics differ greatly between the four zones.

Besides the fact that steep slopes, high rainfall and typical soil properties and stratification turn Manjiya into an inherently unstable area, human interference cannot be neglected. Whereas deforestation has reduced the stability of the shallow soils on the eastern slopes of the study area, the excavation of slopes, mainly for house building, is an important destabilizing factor for the western slopes. The growing population density not only increases the risk on damage, but hampers the search for solutions for the landslide problem as well.

Keywords: Landslides; Mount Elgon; East Africa; Causal factors; Human interference

1. Introduction

Although mass movements are a recognized and well-studied geomorphic hazard due to their major role in the development of hillslopes in mountainous

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areas and their considerable economic and social consequences (Sidle et al., 1985), information on landslides in the East African highlands, is rather restricted (Ngecu and Mathu, 1999).

Nevertheless, mass movements have been reported in *Kenya* (e.g. Ngecu and Ichang'i, 1989; Davies, 1996; Westerberg and Christiansson, 1998; Ngecu and Mathu, 1999; Westerberg, 1999; Inganga et al., 2001), *Uganda* (e.g. Muwanga et al., 2001), *Rwanda* (e.g. Moeyersons, 1988, 1989a,b, 2003), *Tanzania* (e.g. Rapp et al., 1972; Christiansson and Westerberg, 1999) and *Ethiopia* (e.g. Ayalew, 1999; Temesgen et al., 2001; Nyssen et al., 2002). Although the East African highlands are a very heterogeneous region, they have a high vulnerability to slope instability in common. The high annual rain-

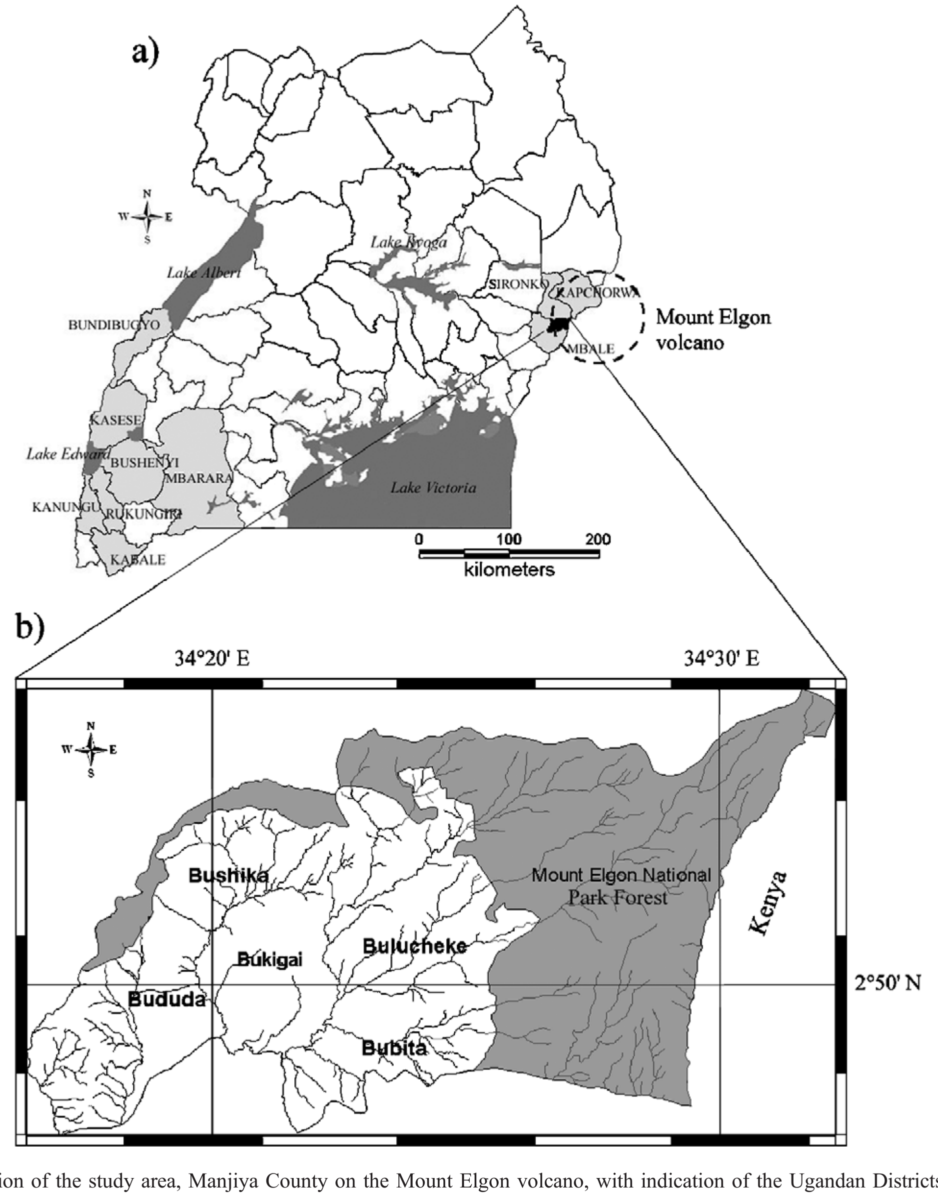


Fig. 1. a) Location of the study area, Manjiya County on the Mount Elgon volcano, with indication of the Ugandan Districts suffering from landslides, b) Manjiya County, the study area, with its five subcounties and the Elgon National Park.

fall, steep slopes, high weathering rates and slope material with a low shear resistance or a high clay content are often considered the main preconditions for mass movements in East Africa, turning it in an inherently susceptible area. The main causal factors for slope failure in these highlands, as found in international literature, can be divided into preparatory and triggering causal factors (Glade and Crozier, 2004). Preparatory causal factors, i.e. factors making slopes susceptible to movement over time without actually initiating it, often reported for this region include the increasing population pressure with slope disturbance and deforestation as a consequence and the reduction in material strength by weathering. Triggering causal factors on the other hand can be seen as external stimuli responsible for the actual initiation of mass movements. The triggering causal factors in the region can be earthquakes, excessive rainfall events and human disturbance such as slope excavation and terracing, inconsiderate irrigation and water leakage.

In many regions of the East African highlands, a clear insight into the local causes for mass movement is lacking. Therefore, the search for region-specific solutions is hampered. In Uganda, landslides are common in the mountainous areas of the districts Sironko, Kapchorwa, Mbale, Kabale, Rukungiri, Mbarara, Kasese, Bushenyi, Bundibudyo and Kanungu (Fig. 1a) but so far no systematic scientific research has been conducted on this topic (Muwanga et al., 2001). Manjiya County (Fig. 1b), situated on the southwestern foot slopes of the Mount Elgon volcano in Uganda, is the most sensitive area for landslides in Uganda. Mass movements associated with intense rainstorms are reported to have occurred sporadically in Manjiya since the twentieth century but the increase in fatalities and losses as a consequence of the enormous population growth draws attention to the phenomenon nowadays.

By studying the causal factors for landslides in the small mountainous area of Manjiya County, this paper tries to contribute to the restricted knowledge on landslides in East Africa. After a brief introduction of the study area and the spatial distribution and characteristics of its landslides, the preconditions, preparatory and triggering causal factors for mass movement will be discussed with attention to their spatial variation.

2. Study area

The 275 km^2 study area of Manjiya County is located at an altitude ranging from 1300 to 2850 m a.s.l. on the southwestern foot slopes of the Elgon Volcano. Geographically, the study area is bounded by latitude 2° 49′–2° 55′ N and longitude 34° 15′–34° 34′ E. Due to the high altitude, precipitation values are high in Manjiya with an annual average of 1800 mm (Aryamanya-Mugisha, 2001). Two distinct wet seasons can be distinguished, separated by a pronounced dry period from December to February and by a period of dispersed, less intense rains from July to early August (Fig. 2). Monthly precipitation values are only available for 2002–2003 in the study area, and do not represent the high inter annual variability. Mean annual air temperature is about 23 °C.

Mount Elgon (4322 m), an extinct Pliocene shield volcano on the border of Uganda and Kenya, is one of the East African volcanic rings partly associated with the Great Rift System. Although Manjiya County is situated on the slopes of this basaltic volcano (Fig. 1a), volcanic rocks and sediment are restricted to the northern and eastern remote corner of the study area and to some isolated dikes and plugs. The strongly weathered granites of the Basement Complex, which cover a large part of the East African Plain, dominate the geology of Manjiya (Davies, 1957). In the central part of the study area, known as Bukigai, a carbonatite complex bears witness of a pre-Elgon alkaline volcanism (King et al., 1972). The intrusion of this magmatic body has created a well-developed fenitized aureole in the granites surrounding this complex that is conspicuous up to three kilometers from the outer edge of the complex (Reedman, 1973). Fenitization implies the chemical alteration of the country rock by migrating fluids (contact metasomatism) with shattering and shearing of the country rock as a consequence, possibly leading to an increased sensitivity to slope instability.

The geomorphology of the study area is dominated by this carbonatite hill that has caused the doming of the country rock and has created a broad concentric valley around. The majority of the rivers in Manjiya collect into a single river in this valley, Manafwa, which finally drains in the Lake Kyoga swamps in the southeast. West of the concentric valley, gentle concave slopes can be found that con-

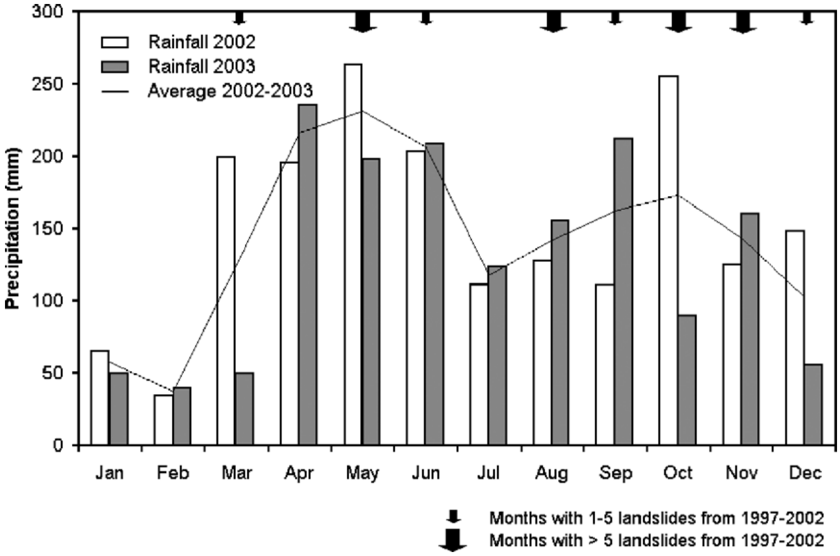


Fig. 2. Monthly rainfall for 2002–2003, measured with a rain gauge in Bulucheke (1350 m a.s.l., for location see Fig. 1b). Months with landslide occurrence from 1997 to 2002, as obtained from interviews with inhabitants and local instances, are indicated.

trast with the steeper rectilinear and sharply dissected slopes in the east.

The dominating soils in the study area, according to the WRB classification (Deckers et al., 1999), are Acrisols, Ferralsols, Nitisols and Luvisols. Ollier and Harrop (1959) assigned the soils to the Bududa and Bubutu series, which consists respectively of clay loams originating from the Elgon volcanics or the Basement Complex and of the non-laterised brown sandy loams originating from the Basement Complex. On the eastern slopes, deep Nitisols occur whereas on the steep slopes in the east, shallow soils dominate. Depending on the position on the slopes, Ferralsols and Acrisols can be found on the carbonatite hill (Breugelmans, 2003).

The 2002 census (Uganda Bureau of Statistics, 2004) calculated an average population density of 952 persons km^2 for Manjiya County, raising up to more than 1300 persons km^2 in the densely populated parishes in the west. This high and rapidly increasing density (with a 5.6% yearly growth since 1991) implies land scarcity in a region where subsistence agriculture is the main land use. Land parcels are therefore small (approximately 35 m^2) and even unstable slopes, often steeper than 80%, are cultivated. The main crops grown comprise banana, yam, cassava, maize, coffee and bean. Nowadays, forest constitutes 45% of Manjiya County, whereas before the large-scale deforestation since the 1930s, the forest was more extensive and most slopes east of Bukigai were under forest (Hamilton, 1984).

3. Methods and materials

3.1. Data collection

Field surveys were undertaken to get an insight into the spatial distribution and characteristics of the landslides. The surveys were restricted to the part of the study area outside the tropical lower montane forest of Mount Elgon National Park (Fig. 1b). Because of the fast regeneration of vegetation in this area, landslide scarps are difficult to recognize in the landscape. Only those scarps that were still clearly visible during the field survey of 2002 were accounted for in this study and mapped with GPS (Trimble GeoExplorer II). Landslides were classified according to Varnes (1978) during the field survey, based on their visible morphological characteristics. Varnes classifies landslides based on the type of movement and the type of slope material wherein they occur. The dimensions of the landslides were obtained by GPS and measuring tapes and slope angles were determined using clinometers. In addition, based on terrain investigation and interviews with local farmers, a database with information on each landslide (e.g. deaths, injuries and damage to houses and infrastructure) was constructed. One landslide, named the Busai landslide was mapped in detail to get an insight into the land use and human interference in Manjiya. 5 rain gauges were installed in the study area, out of which only the one located in Bulucheke (Fig. 1b), provided daily rainfall data.

3.2. Digital topography

Digital elevation data was generated from the existing 1 : 50 000-scale topographic maps of the study area (Lands and Surveys Department Uganda, 1967) by digitizing the contours. The vectorized contours with a 50-feet interval (appr. 15 m) were interpolated at a resolution of 5×5 m using the triangulated irregular network technique (TIN). Sink pits, grid cells that are surrounded by higher terrain, were removed. Maps with slope gradient, slope aspect and planimetric curvature for each pixel were deduced from the DEM using the algorithm of Zevenberg and Thorne (1987). The simulation of a stream channel network, based on flow accumulation assuming that one unit of rainfall is dropped homogeneously on each pixel of the DEM and is transported to the lower most pixel, was used to generate a map with information on the distance of each pixel to the most approximate valley-axes.

3.3. Statistical analysis

Based on the maps deduced from the DEM, a dataset with values of the different topographic variables for all pixels in the investigated part of the study area (97 km^2) was created. This dataset, together with the data on landslide characteristics collected in the field, enabled comparison of the topographic characteristics of the study area with the characteristics of the slopes with landslides. Differences or similarities in characteristics can be used to explain the causal factors for landslide occurrence and their spatial distribution. Chi-square statistics were applied to test the null hypothesis ('there is no significant difference between the values of the parameter for landslide sites and the whole study area', meaning that the predictor variable does not significantly influence landslide occurrence) while Cramer's V statistics were used to test the strength and type of association (SAS, 1990).

To analyze whether the topographic conditions for the occurrence of rotational slides differ from those for the occurrence of translational slides, logistic regression was applied. This non-linear regression method was chosen since the dependent variable (type of movement) is categorical and only has two possible solutions (rotational versus translational), thereby violating the assumptions of the ordinary linear regression (Allison, 1999). Logistic regression fits the logarithm of the odds (i.e. the probability of rotational mass movement divided by the probability of translational mass movement) as a linear regression function of the explanatory variables (slope, planimetric curvature, aspect, altitude above see level and distance to the water divide; none of them are correlated) through the maximum likelihood method (Hosmer and Lemeshow, 1989). The predictive power of the fitted model was evaluated considering a measure of association between predicted and observed values, called the Goodman–Kruskal Gamma. Gamma values range from 0 to 1, with larger values corresponding to stronger associations between predicted and observed values (Allison, 1999).

4. Results

4.1. Spatial distribution of the landslides

98 landslides were mapped and investigated in the study area (Fig. 4). Based on the distribution and concentration of the landslides, four zones can be demarcated. On the central carbonatite hill, called the Bukigai zone, no trace of mass movements could be found. The steep slopes in the east of the study area, including the Nusu Ridge zone and the Bukalasi zone, provide the highest number of landslides. Although fewer landslides occur in the western area, the Bududa/Bushika zone, they contribute considerably to the landslide problem of Manjiya, due to their large dimensions and the high population density of the area.

The spatial distribution of the landslides in Manjiya is closely related with the factors influencing the stability and their spatial variation. An attempt to explain this spatial variation of landslides will be made in Section 4.3.

4.2. Summary of the landslide characteristics

4.2.1. Geomorphic impact

Together, the 98 landslides replaced 11 millions m^3 of slope material in an area of approximately 154 km^2. Since the large and deep rotational landslides in the western part of the study area are only clearly visible in the landscape for about 25 years and the shallow landslides on the eastern slopes might already be recultivated after some years (Fig. 3), this figure is an underestimation of the long-term soil loss due to mass movement in the study area, where water erosion only plays a minor role. Although landslides from the beginning of the twentieth century could be located during the field survey, most of the mapped landslides are relatively young (Fig. 4). 70% occurred since 1997 and the majority (52%) during the heavy rains of 1997 to 1999. 29 landslides have dammed a river in Manjiya for a certain time span and river patterns as well as drainage areas have been redrawn by the landslides. The role of mass movements in the recent evolution of hill slopes should be considered substantial in the study area, given that most of the material from the slopes is deposited in the low-lying planes covered with swamps and lakes.

4.2.2. Socio-economic impact

Besides the significant impact of the landslides on the geomorphology of the study area, it is the impact on its inhabitants that calls for investigation and measures. Landslides with a disastrous impact on the livelihood of the inhabitants of Manjiya County are known since the beginning of the twentieth century. Although official numbers lack, fatalities due to landslides amount at least to 154 for this period. Through interviews with local inhabitants, 1933, 1964 and 1970 could be designated as disastrous years; respectively 25, 18 and over 50 people were killed by landslides. Recently, the exceptionally heavy rains of 1997 to 1999 displaced a large amount of slope material downslope. In 1997, at least 48 people were killed, the crops and dwellings of 885 families disappeared from the map, 5600 people became homeless, arable land was reduced causing land-scarcity and property conflicts, water supplies were polluted with a consecutively epidemic and finally Manjiya County was hit by food-shortage. According to the Ministry of Water, Lands and Environment (2003), the economic costs on the bridges and road repair after the

Fig. 3. The scarps of 19 surficial translational landslides, triggered on the steep slopes of the Bukalasi zone during the 1997 rains, are indicated. During the 2002 field survey, these landslides could not be traced anymore due to recultivation but two other landslides could be distinguished. The alternation of the exact location of landslides on this slope throughout the years together with the frequent occurrence of landslides during the wet seasons proves the instability of the entire slope.

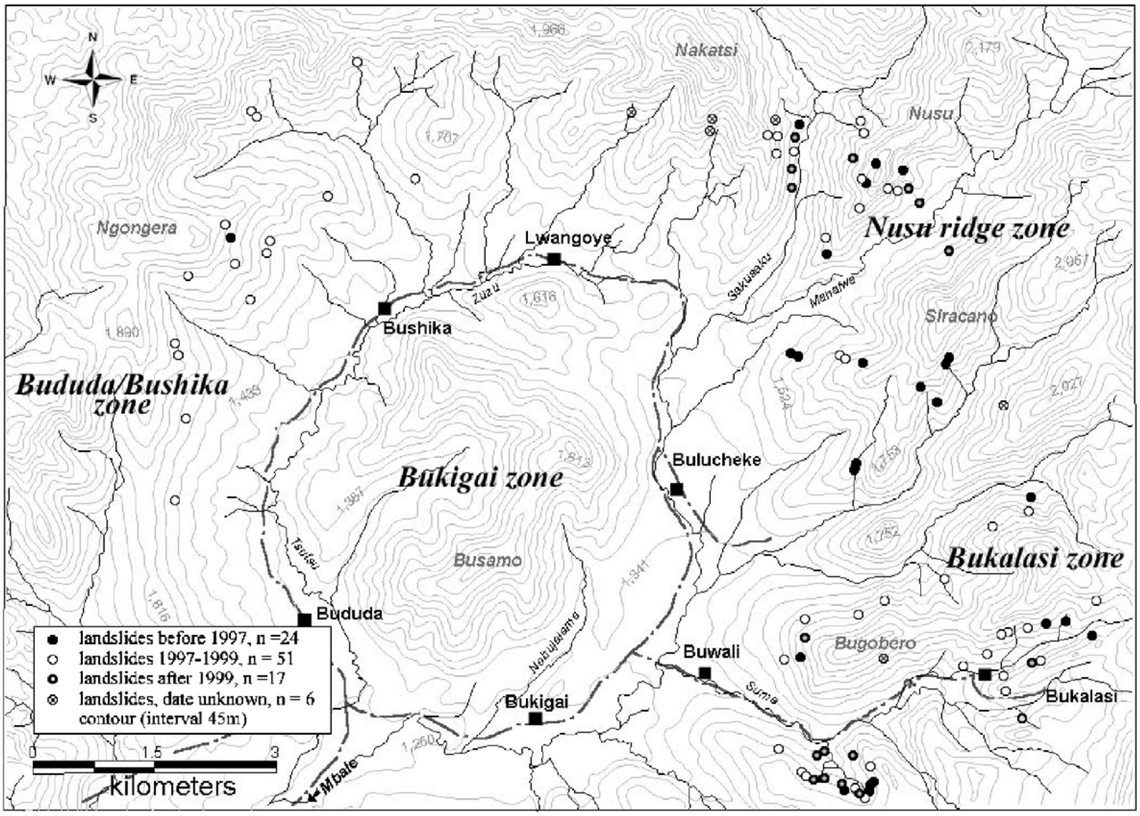


Fig. 4. Spatial and temporal distribution of landslides in Manjiya County. Each dot represents the position of a landslide scarp recorded during the field survey of 2002.

1997 heavy rains amounted 1 273 000 US Dollars for Mbale District. The high cost was due to debris from landslides in Manjiya that temporarily dammed channels. Fast flows were created that damaged infrastructure when the dams broke. Bridges were swept away and roads blocked with debris and huge boulders. Besides these direct costs, indirect costs such as decreased water quality and reduced land fertility could have amounted much more but are difficult to estimate. The high population density, together with the extension of hazardous unstable slopes in Manjiya, inhibits the prevention of such catastrophes in the future.

4.2.3. Classification of the landslides

Almost all types of landslides, defined by Varnes (1978), occur in the study area (Fig. 5). Most landslides in Manjiya occurred in debris, a mixture of rock fragments and fine earth. The dominating type of movement is rotational, similar to the slumps of the Ethiopian highlands (Ayalew, 1999; Nyssen et al., 2003) and the Aberdare Range in Kenya (Davies,

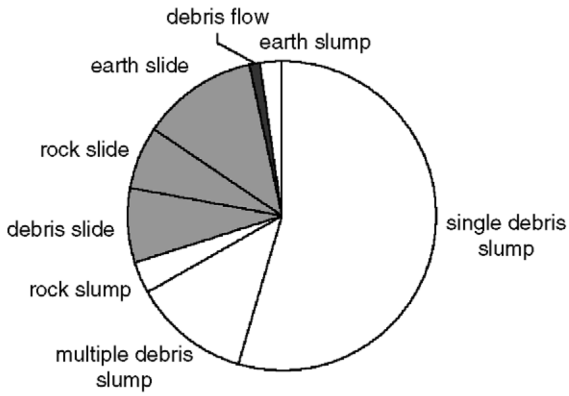


Fig. 5. Landslide types ($n = 90$) occurring in Manjiya County (according to the classification of Varnes, 1978).

1996; Ngecu and Mathu, 1999). The rotational character of the landslides was deduced from the morphological characteristics: i.e. a nearly vertical and deep scarp, multiple clearly visible reverse slopes with pools and water stagnation in the depletion zone. Downslope, the depleted soil material is often transported as debris flows.

Field observations show that the dominant type of movement differs from slope to slope throughout the study area. Logistic regression reveals that this spatial variation in type of movement, simplified as being either rotational or translational, is indeed topographically controlled (gamma = 0.77). Planimetric curvature turns out to be the parameter with the highest predictive power (P > Wald $\chi^2 = 0.028$). As has been proven for mass movements in other parts of tropical Africa (e.g. Thomas, 1994; Ayalew, 1999; Westerberg, 1999), rotational landslides in Manjiya (slumps, e.g. Fig. 6) are more likely to occur on concave slopes where runoff and subsurface water can easily concentrate. Moreover, rotational landslides dominate in deep soils at a larger distance from the water divide (P > Wald $\chi^2 = 0.04$). Here, thanks to the concentration of subsurface flow, the pore water pressure can build up sufficiently and the shear resistance can be reduced so as to cause rotational sliding. As these preconditions are fulfilled in a large part of the study area and much of these slopes are excavated, slumps dominate in Manjiya. For the occurrence of translational slides, a lesser increase in pore water pressure is needed (Westerberg and Christiansson, 1998). Therefore, the latter can be found at a smaller distance from the water divide (e.g. Fig. 3). Furthermore, the rectilinear slopes with shallow soils and a sharp contrast between solum and saprolite, where translational landslides generally occur, are inherently more unstable. As the occurrence of these shallow soils is restricted to parts of the Bukalasi valley and the Nusu ridge, less translational landslides can be found in Manjiya. On the other hand, these shallow slides reactivate frequently during major rainstorms. In contrast with what Westerberg and Christiansson (1998) observed in the Aberdare range, slope steepness does not seem to affect the type of movement significantly in Manjiya (P > Wald $\chi^2 = 0.12$) at a confidence level of 0.95. Neither does the orientation of the slopes (P > Wald $\chi^2 = 0.5$). The only debris flow in the study area can be found on a very steep slope (60%), close to the water divide.

4.2.4. Landslide dimensions

The dimensions of the depletion zone of the landslides vary widely throughout the study area and are summarized in Table 1. The two largest landslides

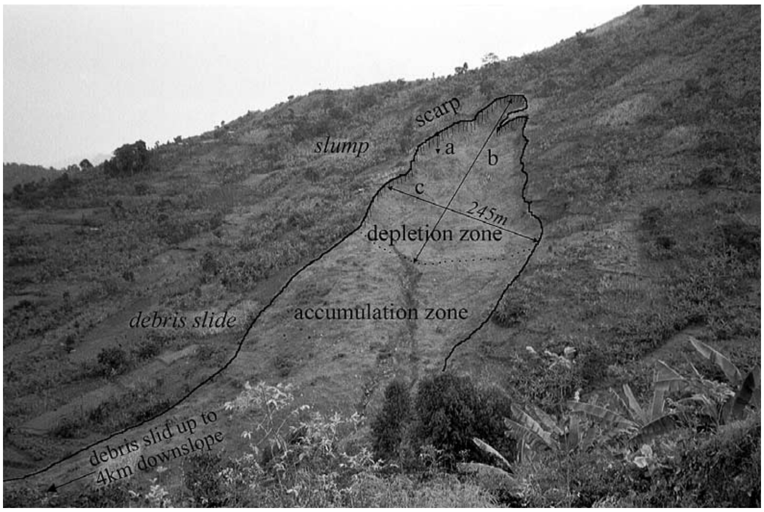


Fig. 6. Typical landslide for the Bududa/Bushika zone on a concave slope segment. The landslide is classified as a rotational one based on the characteristics of the depletion zone. For almost all landslides, the displaced material slides further down slope as a debris slide, forming the accumulation zone. The average scarp depth (a) amounts 4.8 m and the length (b) and width (c) of the depletion zone equals 450 by 245 m. 37 huts were damaged and 4 people were killed by this landslide that dammed the river Tsutsu for 4 days.

Table 1
Dimensions of the depletion zone (see also Fig. 6) of the 98 landslides in Manjiya

	Minimum	Mean	Maximum	SD
Length depletion zone (m)	8	96	950	130
Width depletion zone (m)	7	55	700	92
Average scarp depth (m)	0.4	2.6	12.0	1.9
Area of the depletion zone (m^2)	105	15,654	665,000	71,363
Displaced volume (m^3)	120	116,203	7,980,000	826,010

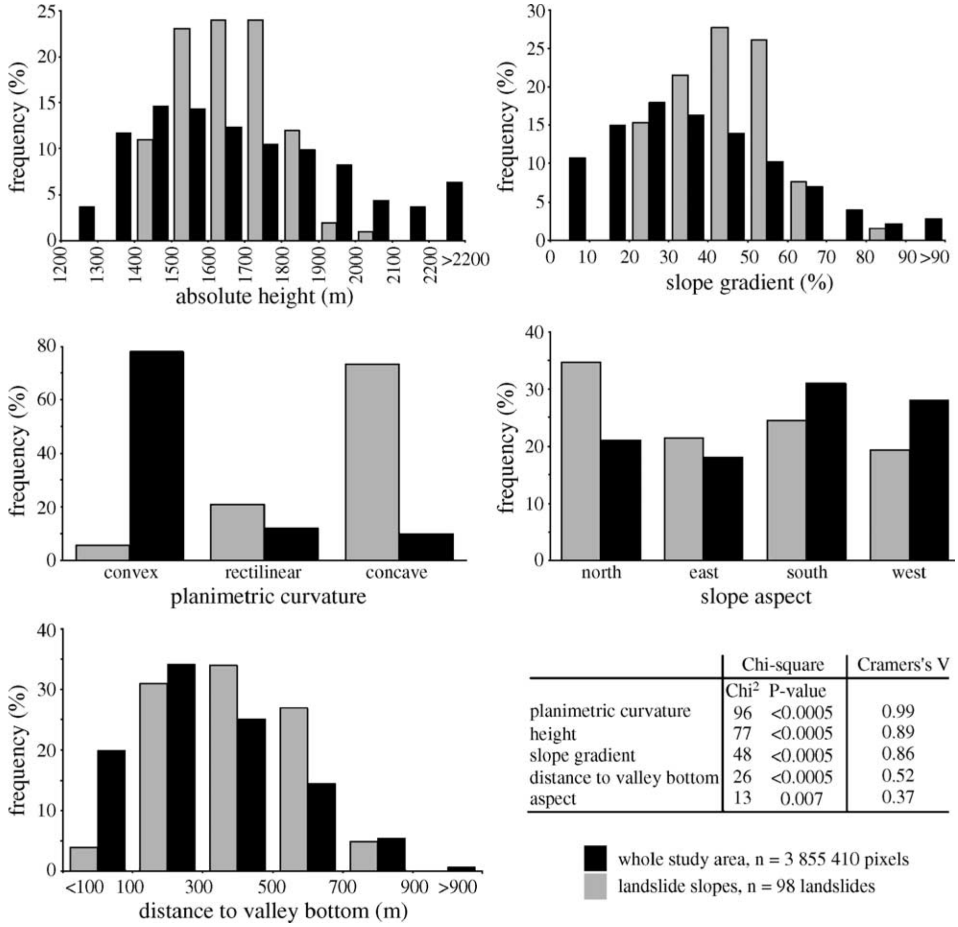
displaced 80% of the total displaced volume of 11 millions m^3 in the study area. Fig. 6 shows one of the typical large rotational landslides of the Bududa/ Bushika zone. T-tests reveal that the great variety in volumetric dimensions of the depletion zone (with a median volume of 2812 m^3) is generally controlled by the depth of the shear plane and to a lesser extend by its length and width. A length–width relationship of 1.3 exists (for $\alpha = 0.05$). Because of the extent of the accumulation zone of most landslides, no measurements of its dimensions were made.

4.3. Causal factors

The search for possible recommendations or solutions concerning the landslide problem in Manjiya is only possible when the local causes are fully understood. A landslide can seldom be attributed to a single causal factor but should rather be seen as a result of preconditions, preparatory and triggering causal factors. Slopes can be divided as existing in one of the following three stages: stable, marginally stable and actively unstable (Crozier, 1986). Stable slopes are defined as those where the margin of stability is sufficiently high to withstand all the destabilizing forces. The slopes in the Bukigai zone, for example, can be considered stable slopes. Marginally stable slopes, such as most of the densely populated and deforested slopes in Manjiya, are those that will fail at some time in response to the destabilizing forces attaining a certain level of activity. Finally, active unstable slopes are those in which destabilizing forces produce continuous or intermittent movement. The three stability stages must be seen as part of a continuum with the probability of failure increasing from the stable end of the spectrum, through the marginally stable range to reach certainty in the actively unstable stage (Glade and Crozier, 2004). Preparatory causal factors can than be defined as causal factors that tend to place the slope in a marginally stable state by making the slope susceptible to movement without actually initiating it. Triggering causal factors on the other hand shift the slope from a marginally stable to an actively unstable state by initiating movement. Preconditions are those inherent static factors that act as catalysts to allow other destabilising factors to act more effectively. In what follows, by describing the preconditions and preparatory causal factors, it will become clear that most slopes in Manjiya are marginally stable. The description of the triggering causal factors explains how these slopes become actively unstable from time to time.

4.3.1. Preconditions

4.3.1.1. Topographic factors. In order to determine the topographic variables that create favourable preconditions for destabilising factors to operate more effectively in Manjiya, the values of these variables for the slopes exhibiting landslides are compared with those for all slopes in the study area. The values of most topographic variables for the landslides were achieved through field surveys, whereas the values for the whole study area were deduced from the DEM. The frequency distributions of Fig. 7 show that the distributions of the topographic variables for slopes with landslides deviate more or less from those for the topographic variables of the whole study area. Cramer's V and Chi-square tests confirm that the difference is statistically significant (significance level 0.95) for all topographic variables tested. Steep, plan concave slope segments oriented to the east and north–similar to the dominant rainfall direction–are the most favorable preconditions for mass movement, especially on relatively large distances from the water divide. The distance between the landslide and the valley



	Chi²	P-value	Cramers's V
planimetric curvature	96	<0.0005	0.99
height	77	<0.0005	0.89
slope gradient	48	<0.0005	0.86
distance to valley bottom	26	<0.0005	0.52
aspect	13	0.007	0.37

Fig. 7. Graphic and statistic comparison of the topographic variables absolute height, slope gradient, slope curvature, aspect and distance to the valley bottom for slopes with landslides and for all slopes of the study area. The data for the whole study area has been gathered by extracting information from the DEM for all pixels in the study area with a 5 × 5 m resolution. Topographic data for the landslides has been collected for each landslide separately through field surveys.

bottom is less important since undercutting of slopes by the river does not play a major role in mass movement in Manjiya.

Compared to other East African countries (Table 2), the critical slope for landslides in Manjiya is rather small, with landslides occurring on slopes from 14° onwards. Gentle slopes exhibiting landslides are situated in the Bududa/Bushika zone, where soil stratification and human interference are more important causal factors than slope steepness. On the other hand, no landslides were observed on the very steep slopes of the Bukigai zone, confirming the hypothesis that other than topographic factors play an important role in hillslope instability.

4.3.1.2. Lithology. Although the shear planes of most landslides are located within the soil in the Bududa/Bushika zone and on the sharp contact between the shallow soil (0.2–2 m) and the parent rock in the Bukalasi zone, the strong weathering and fracturing of the granite parent material definitely plays a role in the origin of the few landslides occurring in rock material. As mentioned before, the fenitization process enhances this weathering and shattering and can therefore be classified as a preparatory factor.

4.3.1.3. Soils. The deep slumps in the Bududa/Bushika zone occur in Nitisols (Breugelmans, 2003), soils with slight swell–shrink properties comparable

Table 2
Slope gradient thresholds and intervals for landslide occurrence in East Africa

Tropical areas	26 – 50°	Thomas, 1994
Humid tropics	>40°	Birot, 1960
Aberdare range (Kenya)	>20°	Ngecu and Ichangi, 1998
	>35°	Davies, 1996
Northern and southern Ethiopian highlands	20 – 45°	Ayalew, 1999
Northern Ethiopia	19 – 56°	Nyssen et al., 2002
Wondogenet (Ethiopia)	10 – 20°	Temesgen et al., 2001
Western Uluguru (Tanzania)	28 – 44°	Rapp et al., 1972
Southwest Rwanda	>25°	Moeyersons, 2003
Western Uganda	>26°	Doornkamp, 1971 (in Rapp et al., 1972)
Mount Elgon (Uganda), this study	14 – 41°	Knapen, 2003

to the expansive soils in Nyeri district (Kenya) where slumps frequently occur (Inganga et al., 2001). All landslide scarps in this zone show a similar profile of at least two buried soils, created by an alternation of stable pedogenesis phases and unstable phases of regressive erosion (Fig. 8). The superposition of a soil horizon with a silty clay texture (52% clay, B2t) on a coarser, sandy silt loam horizon (6% clay, A3/E3) of an older soil creates a pore discontinuity that hinders drainage. Black manganese mottles on the ped surfaces of the illuvial clay horizon (B2t) are an indication of the reduced drainage. Moreover, during and after heavy rain showers, water is observed to pour out of this B2t layer that is continuously saturated during the rainy season. The B2t horizon has a nutty structure and corresponds to the nitic horizon of a buried soil profile and thus rapidly expands upon wetting. As a result large forces are exerted on the soil, creating the possibility to overcome the sliding inertia.

The absence of landslides in the Bukigai zone can be partly attributed to the occurring soil type. Through analysis of profile pits (Breugelmans, 2003), the soils were designated as Acrisols and Ferralsols, physically stable soils without swell–shrink properties wherein landslides rarely occur. In addition, these soils are very erodibile and only suitable for agriculture when manured (Driessen and Dudal, 1991). Together with the lack of wells, this causes a low population density in Bukigai compared to the other regions where population pressure is an important preparatory factor.

While the variation in soil types and characteristics throughout the Nusu ridge and Bukalasi zone is large, some of them have a distinct boundary between the soil and the underlying rock in common. During heavy rains, water stagnates on this discontinuity, creating positive pore water pressures on this shear plane on which the soil can easily slide down.

4.3.1.4. Annual rainfall. The high average annual rainfall rate (1800 mm, according to Aryamanya-Mugisha, 2001) and the concentration of rain in two wet seasons cause high moisture contents and/or saturation of a large portion of the soil column over a great time span and should therefore be seen as predisposing factors creating a low margin of instability for the Elgon region.

4.3.2. Preparatory factors

Human presence can decrease the margin of hillslope stability drastically in densely populated and

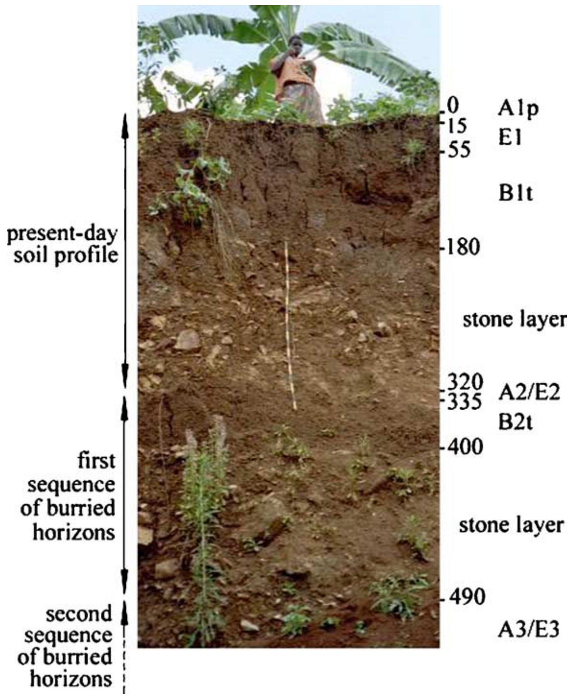


Fig. 8. Typical profile of different buried soils in the Bududa/Bushika zone. The depth of the different horizons varies throughout the area and the indicated depths (in cm) are only indicative. The dark brown layer (B2t) beneath the first stone layer that becomes saturated during rainfall events is clearly visible.

intensively cultivated steeplands as Manjiya County. Besides the valleys and the major road tracks, the gentle slopes of the Bududa/Bushika zone have the highest population density, implying the highest human impact on hillslope stability. Excavation of slopes and the concentration of runoff water through linear landscape elements (e.g. parcel boundaries, footpaths) are the main malefactors. The limited human presence in the Bukigai zones, partly together with the occurring soil type, explains the absence of landslides whereas the landslides in the Bukalasi and Nusu ridge zone are rather correlated with its topographic characteristics than its population density. The human role in landsliding in these eastern regions is restricted to the effects of deforestation in recent history.

4.3.2.1. Deforestation. Deforestation is considered one of the main preparatory causal factors in most east African highlands (e.g. Inganga et al., 2001, Rapp et al., 1972; Nyssen et al., 2002; Davies, 1996). Manjiya County has been deforested since the 1930s (Hamilton, 1984) but spatial and temporal information is lacking. Undoubtedly, the forest stretched much further eastwards, prohibiting slope failure on the steep slopes with shallow soils in the Bukalasi and Nusu ridge zone. Stability analysis shows that deforestation decreased the safety factor, which is a measure of the slope stability, through root decay by 30% to 60% on these slopes (Knapen, 2003). Another indication for the importance of a forest cover in prohibiting mass movements in the area, is the absence of landslides under forest on slopes with similar topographic and soil properties as in the Bukalasi and Nusu zone where landslides do occur (own observations, observations by the local population and by game rangers of the National Park).

4.3.2.2. Excavations. Another remarkable example of human interference in Manjiya, is the removal of lateral slope support. Since the bedding planes of the substrata are parallel to the slope in the Bududa/Bushika zone (Fig. 9), excavation is particularly destabilising here. Slopes can be excavated for various reasons as represented in Fig. 10a. First of all, house building on steep slopes forces people to dig away large parts of the slopes to create flat areas. The construction of footpaths can be another reason to excavate the slope. In addition, farmers often dig away parts of the slope in order to level their plots. The formation of step-like slopes by agricultural practices and intensified by natural processes removes the lateral support, causes water stagnation and increased infiltration, leading to an increased pore water pressure and landslide risk. Luckily, terracing is seldom applied, although the Ugandan National Environment Regulations for Mountainous and Hilly Areas Management (Kajura, 2001) still encourages this technique that triggers landslides. These strict regulations, that for example

Fig. 9. Typical dip of the bedding planes parallel to the slope in the Bududa/Bushika zone enhances slope failure.

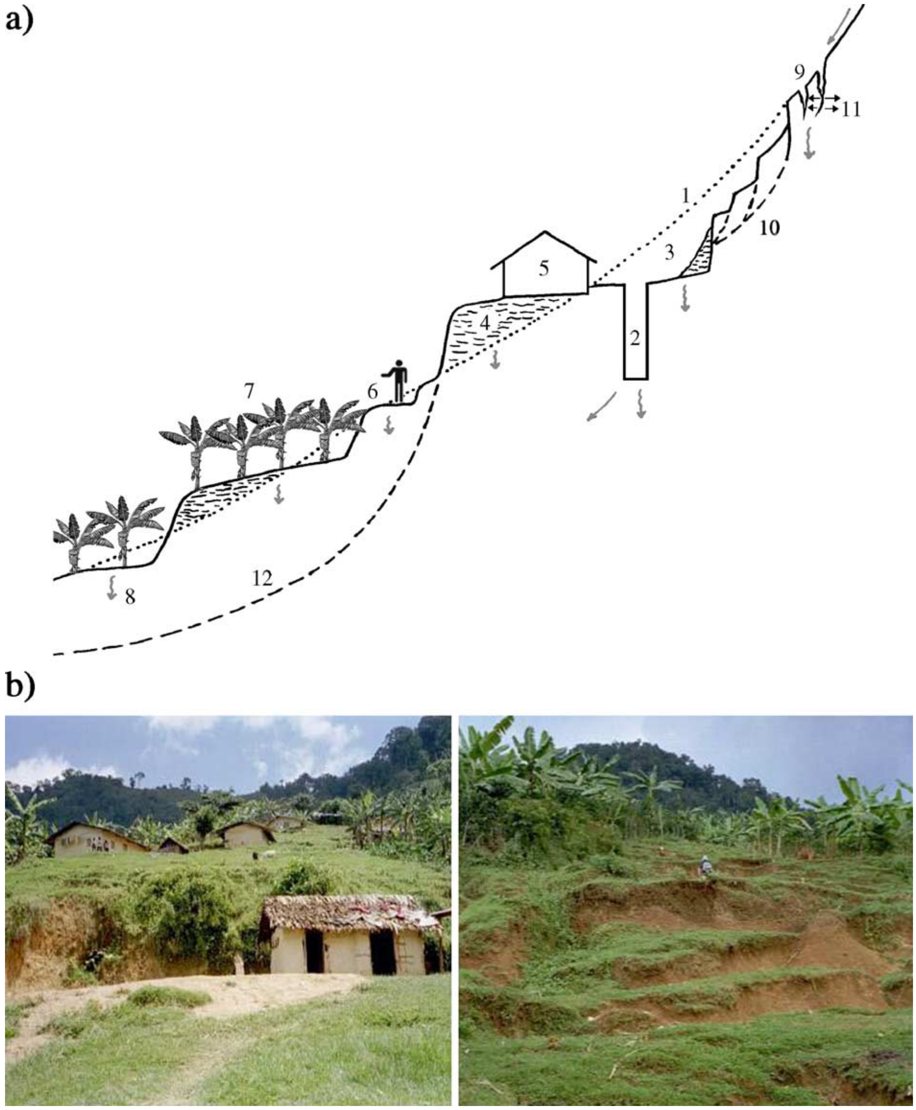


Fig. 10. a) Changes in the original topography (see 1) by digging septic tanks (see 2) and by excavation (see 3) and raising (see 4) of the slopes with the aim to build houses (see 5), to construct footpaths (see 6) or for agricultural purposes (see 7) can lead to water pounding and increased infiltration (see 8), the formation of fissures and tension cracks (see 9) and small slides (see 10) upslope the excavations. Hydrostatic pressure in water-filled tension cracks enhances slope failure (see 11) and the formation of a deep failure plane (see 12) is possible. b) Examples of a slope excavated for house building and the consequent small slides above the excavated zone.

prohibit cultivation of slopes steeper than 15%, are not known by the local population and certainly not followed in any of the subcounties. Due to the high population pressure, they are simply not applicable in Manjiya.

In order to get an insight into the effect of human interference on slope stability, a landslide representative for the landslides in the Bududa/Bushika zone, named the Busai slide (for location, see Fig. 1b), was mapped in detail (Fig. 11). On a concave slope of 31%, 339 330 m^3 of slope material slid down slowly, destroying 97 houses and displacing about 700 people. This landslide took place in November 1997 at night, during a low intensity rainfall event that lasted

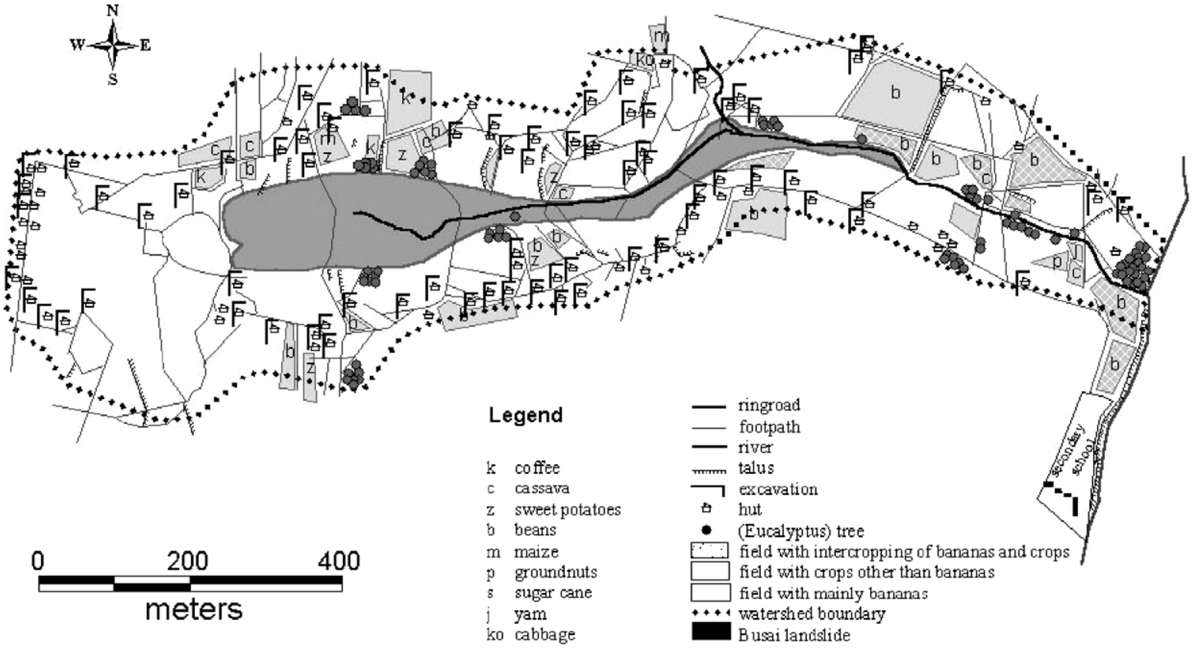


Fig. 11. Land use map of the Busai landslide catchment (see Fig. 1b for location) showing the large number of excavations and footpaths.

for 24 h. According to eyewitnesses, visible cracks of about 100 m in length first appeared across the slope and the water in these cracks gave an early warning to the inhabitants. To explain why these gentle slopes of the Bududa/Bushika zone can suddenly become unstable, the typical layering of the substrata and the prolonged high, but not exceptionally high antecedent rainfall are not sufficient. Human disturbance of the slope equilibrium should be taken into account. The watershed of the Busai landslide covers an area of 0.43 km^2 and the landslide itself an area of 0.05 km^2. The 105 houses and small agricultural plots with an average area of 50 m^2 (White, 1999) in the 0.38 km^2 area outside the landslide bear witness of the high population pressure in the watershed. For 72% of these houses, the slope is excavated to a depth varying between 0.15 and 4.5 m with an average excavation of 1.25 m. Inside the landslide zone, the slope was heavily excavated as well. The impact on slope stability must be considered significant. Total strain increases (Budhu, 2000) and runoff water can concentrate and will be favoured to infiltrate on the flat parts of the excavations. One can also deduce the density of the footpath network from the map. As these footpaths become true concentrated flow channels during heavy rainfall events, large water volumes are concentrated to the central zone of the watershed where existing cracks will fill with water and saturation of soil layers will favour instability.

4.3.3. Triggering factors

4.3.3.1. Seismicity. Even though situated in the East African Rift zone, the Elgon region rarely experiences earthquakes (Hollnack, 2001). Therefore, seismicity cannot be considered to be a main triggering factor in Manjiya, contrasting with some regions in southwestern Uganda and Kenya (Inganga et al., 2001) where earthquakes were responsible for a few landslides.

4.3.3.2. Extreme rainfall events. A distinct rainfall threshold for the initiation of landslides is difficult to assess for Manjiya County because of the range of landslide types and dimensions, the heterogeneity of the study area and the lack of known landslide dates and rainfall data. Manjiya experiences a pronounced inter annual variation in rainfall, often attributed to global weather patterns associated with the El Niño Southern Oscillation. Landslide events most frequently take place in years with exceptionally high rainfall, such as 1998, especially at the end of the rainy season when the soil saturation is maximized. Based on the few landslides for which the date of occurrence could be traced (Fig. 2), it is difficult to demonstrate this.

4.3.3.3. Concentration of runoff water. During intense rain showers, it can be observed that roads, small footpaths, plot boundaries and runoff ditches concentrate large volumes of runoff water and direct this to restricted infiltration zones (hollows). In the Bududa/Bushika zone, these linear features are numerous and cracks develop upon drying in the swell–shrink soils. As these cracks form a by-pass mechanism for rapid infiltration, oversaturation of the zone above the shear plane may occur with subsequent slope failure.

4.3.3.4. Excavations. Although slope excavation mostly decreases hillslope stability without actually initiating movement (see preparatory factors), examples are known in the Bushika zone where the excavation for house building was the direct triggering cause for slope failure and creep phenomena.

5. Discussion

The high population density and land shortage in the study area prevent people from abandoning the most landslide prone areas. As population pressure increases, not only the stability of the slopes will be reduced, but people will also be forced to cultivate even more unstable slopes. As a consequence of both, the risk on damage by slope failure will increase. In addition, the fact that Manjiya County is an inherently unstable area turns the search for solutions for the landslide problem into a true challenge. The instability can be partly reduced by tempering the human impact. Excavation or terracing of slopes and the construction of structures concentrating water to vulnerable zones should be avoided. Total reforestation with deep-rooted trees would reduce the landslide risk in the Bukalasi and Nusu ridge zone but is not realistic given the high population density. Nevertheless, planting tree rows in risk zones could locally enhance stability (Rapp et al., 1972). These measures can never completely impede the occurrence of landslides and it seems that the search for solutions will only come to results when the fast population growth takes a turn.

6. Conclusions

Manjiya County is an inherently unstable region where human interference plays a major role. Steep, plan concave slope segments at a certain distance from the water divide and oriented to the dominant rainfall direction (north to northeast) are the most sensitive to mass movement throughout the study area. Nevertheless, not all slopes are prone to landslides as the area is fairly heterogeneous in terms of lithology, soils and land use. The causal factors for the landslides vary spatially throughout Manjiya. On the steep slopes of the Bukalasi and Nusu zone, the surficial and abrupt boundary between solum and saprolite and recent deforestation play a major role. In the Bududa/Bushika zone on the other hand, human impact decreases stability significantly on the Nitisols that are already sensitive due to their bedding and stratification. Bukigai is the only zone where, as a consequence of the soil type, no landslides occur. Although this area is safe, it is not suited for settlement as the soil is less fertile and water is in short supply.

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References

Allison, P.D., 1999. Logistic Regression Using the SAS System: Theory and Applications. SAS Institute, Inc., Cary, NC.

Aryamanya-Mugisha, H., 2001. State of the environment report for Uganda 2000/2001. Technical Report, National Environment Management Authority Uganda, Kampala, Uganda.

Ayalew, L., 1999. The effect of seasonal rainfall on landslides in the highlands of Ethiopia. Bulletin of Engineering Geology and the Environment 58, 9–19.

Birot, P., 1960. Le Cycle d'Erosion sous les Differents Climats. Batsford, London.

Breugelmans, W., 2003. The influence of soil, land use and deforestation on the occurrence of landslides in Mount Elgon area, Eastern Uganda. M.Sc. Thesis, Department of Land Management, Catholic University Leuven, Belgium.

Budhu, M., 2000. Slope stability. In: Anderson, W. (Ed.), Soil Mechanics and Foundations. John Wiley and Sons Ltd., Chichester, UK, pp. 522–553.

Christiansson, C., Westerberg, L.O., 1999. Highlands in East Africa: unstable slopes, unstable environments. Ambio 18, 419–429.

Crozier, M.J. (Ed.), 1986. Landslides: Causes, Consequences and Environment. Croom Helm Ltd., London. 252 pp.

Davies, K.A., 1957. The Building of Mount Elgon (East Africa). The geological survey of Uganda, Entebbe.

Davies, T.C., 1996. Landslide research in Kenya. Journal of African Earth Sciences 23 (4), 41–549.

Deckers, J.A., Nachtergaele, F.O., Spaargaren, O.C., 1999. World Reference Base for Soil Resources. Publishing Company Acco.

Driessen, P.M., Dudal, R., 1991. The Major Soils of the World. Lecture Notes on their Geography, Formation, Properties and Use. Department of Soil Science and Geology. Agricultural University Wageningen, The Netherlands.

Glade, T., Crozier, M.J., 2004. The nature of landslide hazard impact. In: Glade, T., Anderson, M., Crozier, M. (Eds.), Landslide Hazard and Risk, pp. 43–74.

Hamilton, A.C., 1984. Deforestation in Uganda. Oxford University Press, Nairobi, Kenya.

Hollnack, D., 2001. Some aspects on the seismic risk in East Africa. Documenta Naturae 136, 85–92.

Hosmer, D.W., Lemeshow, S., 1989. Applied Regression Analysis. Wiley, New York.

Inganga, S.F., Ucakuwun, E.K., Some, D.K., 2001. Rate of swelling of expansive soils: a critical factor in the triggering of landslides and damage to structures. Documenta Naturae 136, 93–98.

Kajura, H.M., 2001. The national environment (mountaineous and hilly areas management) regulations, 2000. The Republic of Uganda, Statutory Instruments Supplement to the Uganda Gazette No. 5, Volume XCIII.

King, B.C., Le Bas, M.J., Sutherland, D.S., 1972. The history of the alkaline volcanoes and intrusive complexes of eastern Uganda and western Kenya. Journal of the Geological Society London 128, 173–205.

Knapen, A., 2003. Spatial and temporal analysis of landslides in Manjiya County, Mount Elgon area, eastern Uganda. M.Sc. Thesis, Department of Physical Geography, Catholic University Leuven, Belgium.

Ministry of Water, Lands and Environment, 2003. Briefing Document on Climate Change and its Impacts.

Moeyersons, J., 1988. The complex nature of creep movements on steep sloping ground in Southern Rwanda. Earth Surface Processes and Landforms 13, 511–524.

Moeyersons, J., 1989a. La nature de l'erosion des versants au Rwanda. Annuals of the Royal Museum for Central Africa Tervuren, Series Economische Wetenschappen 19 (396 pp.).

Moeyersons, J., 1989b. A possible causal relationship between creep and sliding on Rwaza hill, Southern Rwanda. Earth Surface Processes and Landforms 14, 597–614.

Moeyersons, J., 2003. The topographic thresholds of hillslope incisions in southwestern Rwanda. Catena 50, 381–400.

Muwanga, A., Schuman, A., Biryabarema, M., 2001. Landslides in Uganda—documentation of a natural hazard. Documenta Naturae 136, 111–115.

Ngecu, W.M., Ichangi, D.W., 1998. The environmental impact of landslides on the population living on the eastern footslopes of the Aberdare ranges in Kenya: a case study of Maringa village. Environmental Geology 38 (3), 259–264.

Ngecu, W.M., Mathu, E.M., 1999. The El Nino-triggered landslides and their socioeconomic impact on Kenya. Environmental Geology 38 (4), 277–284.

Nyssen, J., Moeyersons, J., Poesen, J., Deckers, J., Mitiku, H., 2002. The environmental significance of the remobilization of ancient mass movements in the Atbara–Tekeze headwaters near Hagere Selam, Tigray, Northern Ethiopia. Geomorphology 49, 303–322.

Ollier, C.D., Harrop, J.F., 1959. Memoirs of the research division, series 1-soils, number 2. The soils of the eastern province of Uganda. Kawanda Research Station, Kampala, Uganda.

Rapp, A., Berry, L., Temple, P., 1972. Landslides in the Mgeta area, western Uluguru mountains, Tanzania. Studies of soil erosion and sedimentation in Tanzania. Bureau of Resource Assessment and Land use Planning, University of Dar es Salaam and Department of Physical Geography, University of Uppsala.

Reedman, J.H., 1973. Potash Ultra-fenites at the Butiriku carbonatite complex in southeast Uganda. Annual Report, Research Institute for African Geology, vol. 17. University of Leeds, pp. 78–81.

SAS Institute, 1990. SAS/STAT User's Guide, vol. 2. SAS Institute, Carry, NC.

Sidle, R.C., Pearce, A.J., O' Loughlin, C.L., 1985. Hillslope Stability and Landuse. American Geophysical Union, Washington DC, USA.

Temesgen, B., Mohammed, M.U., Korne, T., 2001. Natural hazard assessment using GIS and Remote Sensing methods, with particular reference tot the landslides in the Wondogenet area, Ethiopia. Physics and Chemistry of the Earth, Part C: Solar, Terrestrial and Planetary Science 26 (9), 665–675.

Thomas, F.T., 1994. Landsliding and other mass movement. Geomorphology in the tropics: a study of weathering and denudation in Low Latitudes. John Wiley and Sons Ltd., Chichester, pp. 165–189.

Uganda Bureau of Statistics, 2004. The 2002 Uganda Population and Housing Census. (www.ubos.org/2002census.html).

Varnes, D.J., 1978. Slope movement types and processes. In: Scuster, R.L., Krizek, R.J. (Eds.), Special Report 176, Landslides;

Analysis and Control. National Research Council, Washington DC, pp. 11–33.

Westerberg, L.O., 1999. Mass Movement in East African Highlands: Processes, Effects and Scarp Recovery. Dissertation 14, Department of Physical Geography, Stockholm University, Sweden.

Westerberg, L.O., Christiansson, C., 1998. Landslides in East African Highlands. Slope instability and its interrelations with landscape characteristics and land use. Advances in GeoEcology 31, 317–325.

White, S.P., 1999. Environmental issues in Mbale district 1998–1999. Report on a Survey of Environmental Issues Carried Out in All Villages in Mbale in May–June 1998 as Part of the District Environment Planning Process. Mount Elgon Conservation and Development Project, Mbale, Uganda.

Zevenberg, L.W., Thorne, C.R., 1987. Quantitative analysis of land surface topography. Earth Surface Processes and Landforms 12, 47–56.